

Development of a Terrain Mapping/Crater Evolution Measurement using Diffractive Optical Elements

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When landing on the moon, understanding the interaction of the engine exhaust plume with the lunar surface is critical for the success of the descent and landing flight phases. Two evaluation tools currently used are computational simulations and ground test measurements. Computational simulations require experimental measurements for comparison/validation, but ground test measurements cannot accurately emulate all aspects of an actual lunar landing. Flight tests remain the only method of obtaining fully representative data. A terrain mapping/crater evolution measurement system was developed for potential inclusion on a future lander mission. This system uses two stereo cameras viewing a laser dot grid pattern projected on the ground, where the grid is created by shining a laser through one or two diffractive optical elements. CAD simulations of the stereo imaging system are first used to validate the proposed design. Laboratory tests of the system using both a large-scale fixed-geometry crater and a small-scale evolving-geometry crater validate the use of the system for terrain mapping measurements. High-speed, front-illumination shadow particle tracking of particles ejected from the evolving-geometry crater is also performed, demonstrating another diagnostic that can be used to further the understanding of plume-surface interactions.

I. Introduction

For spacecraft making the journey to the moon, the entry, descent, and landing (EDL) phases of flight are critical for the mission's success. The Apollo missions provided myriad videos, images, and analysis of the descent and landing phases, and provided insight into how the engine's exhaust plume interacted with the surface of the moon [1–5]. However, many aspects of this plume-surface interaction (PSI) are still not fully described, and it is currently an active research topic in preparation for future planetary spaceflight missions [6]. Understanding how a lunar lander engine's exhaust plume interacts with the lunar surface/regolith is important for multiple aspects of a mission. If too much lunar regolith is ejected from below the lander, the surface for the landing site could become significantly cratered and pose a tipping hazard for the lander upon touchdown. The speed and trajectories of the ejected regolith/particles from the plume can damage nearby scientific installations, existing structures, and potentially the lander itself.

Use of one or more cameras and/or external illumination to determine the two-dimensional or three-dimensional shape of objects or terrain is an ongoing topic of research. Stereo imaging is a particularly attractive option for terrain mapping due to its relatively inexpensive and simple implementation. Although exact lunar conditions cannot be replicated, PSI ground tests are used to gain a better understanding of the physics on earth in order to determine knowledge gaps that must be filled with flight tests to other planets [7–9]. Simulations are being used to evaluate both the stereo imaging aspect and the plume-surface interaction aspect of this problem [10–16]. These simulations are

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motivated by the reporting about dust/erosion/blowing during planetary landings [1–4, 17, 18]. Terrain mapping and topography diagnostics have thus been seen as a necessary tool in previous planetary missions [19–29].

Preparations for several unmanned lunar lander missions with scientific instrumentation are ongoing under the Commercial Lunar Payload Services (CLPS) initiative [30]. One of the scientific instruments is the Stereo Cameras for Lunar-Plume Surface Studies (SCALPSS), where stereo imaging of the lunar surface before, during, and after the landing will measure the undisturbed landing site and crater evolution [31, 32]. The first two planned missions of this measurement system will not use active/structured illumination, and will obtain depth/shape maps of the lunar surface when characteristic features are visible and identifiable in both camera views.

A limitation of stereo imaging systems that rely on natural light is shown pictorially in Fig. 1, with sunlight azimuth and elevation indicated. These CAD-rendered images show a view from a characteristic camera mounted on a lunar lander, with a view looking down at the surface below the main engine nozzle. On the ground, the rough location of a 25.4 mm crater is outlined in dashed red. In Figs. 1a–d, the camera position remains fixed while the sunlight illumination is simulated at various azimuthal and elevation angles. In Fig. 1a, the sun is in a position such that nearly the entire crater is shadowed, and a depth map of the crater cannot be obtained due to a lack of surface features visible in this (or any other) camera. As the sun moves through a lunar day (Figs. 1b–d), the crater is illuminated, albeit with some thin shadow lines of the lander legs (b,c) and some shadowing from the land body itself (d). While the crater shape can be computed when no shadows are visible, or even when a shadow traverses over the crater during the day, all measurement capability is lost during times when the crater is shadowed (a). For further demonstration, the azimuth and elevation of Fig. 1a are used for the renders of Figs. 1e–h, where four different camera views from the lander body are shown. While different camera views are able to potentially see un-shadowed portions of this crater, the portion that is fully in the shadow is still not resolvable for depth map calculations.

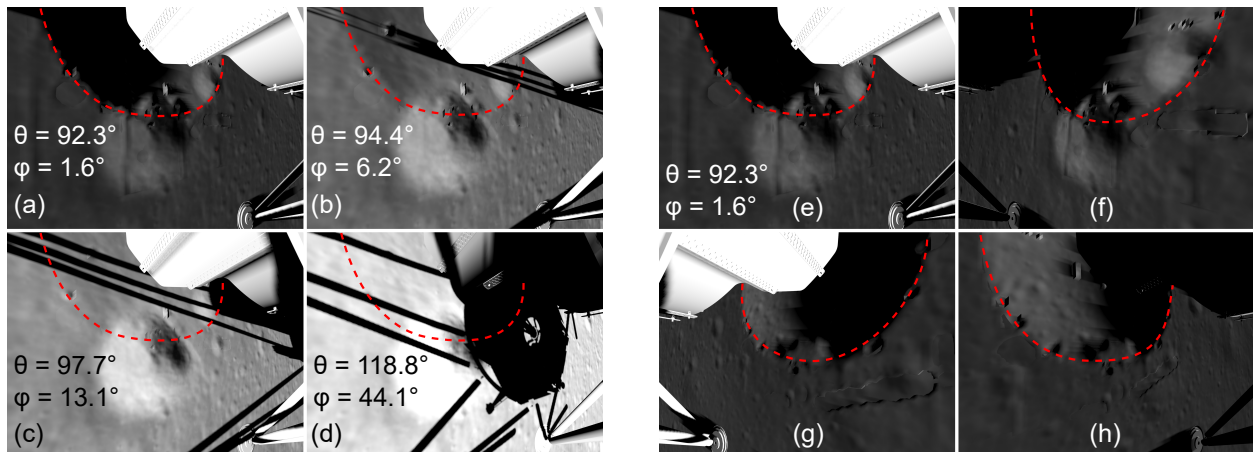


Fig. 1 CAD renders of a 25.4-mm-deep crater below the main engine nozzle for (a–d) four azimuth/elevation combinations of the sun during a lunar day, and (e–h) four cameras mounted at different positions on the lander for the single azimuth/elevation angle of (a).

While floodlights on the lunar lander can potentially be used to sufficiently illuminate the surface, they will only be viable after landing, and may not provide enough light during landing itself, when the important crater shape evolution must be measured. Using a structured illumination source, where a laser shines through a diffractive optical element (DOE) to project a grid of laser dots on the ground, crater depth measurements can be obtained even in regions entirely hidden by shadows. This is shown in the CAD render of Fig. 2, which is the same camera position as Fig. 1g, but now with a laser grid projected onto the ground below the nozzle in the crater.

In this paper, a structured illumination terrain mapping and crater evolution measurement system is described. To validate the measurement technique, CAD simulations of a representative lunar lander with stereo cameras and laser grid illumination are used to produce rendered images of both undisturbed flat ground and of a characteristic crater below a nozzle exhaust plume (Section II). A large-scale fixed-geometry crater model is then used to test the system in the laboratory, and by using two DOEs rotating relative to each other, the projected laser grid dot density can be changed (Section IV). Single-element DOEs are also tested with a separate laser source. Finally, a small-scale PSI test is conducted to measure the changing crater shape due to flow issuing from a compressed air jet nozzle (Section V),

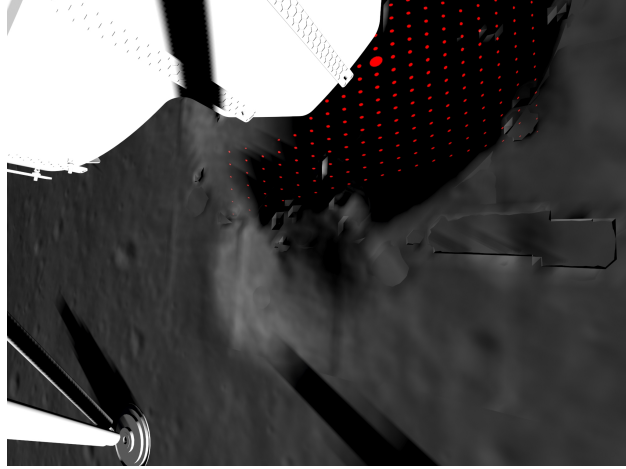


Fig. 2 Single camera render (corresponding to camera view of Fig. 1g) of partially-shadowed crater, with active laser grid illumination.

while also making measurements using a front-illumination high-speed particle tracking system (Section VI). In this paper, specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply endorsement by the U.S. Government.

II. Computer-Simulated Crater

A model of a representative lunar lander was used as the instrumentation bed for the CAD simulations, seen in a top-view render in Fig. 3a. The world coordinate system origin was located directly below the center of the lander, with the $z = 0$ position on the flat ground. In the top-view of Fig. 3b with the lander model removed, two cameras (labeled 3A and 5A) are shown positioned in their representative positions on the lander legs, with both looking at the crater centered below the main engine nozzle. Camera 3A is positioned at $(-33, -28, 75)$ inches and camera 5A is positioned at $(33, -28, 75)$ inches, both relative to the world coordinate system origin. Camera 3A is rotated 40° about the x -axis and -50° about the z -axis, while camera 5A is rotated 40° about the x -axis and 50° about the z -axis. The crater is seen centered below the lander, and a 19×19 laser dot grid is positioned illuminating the crater such that the central dot intersects the ground at the center of the crater. This does not coincide with the center of the crater on an equivalent flat-ground, since the laser beam is angled with respect to the ground.

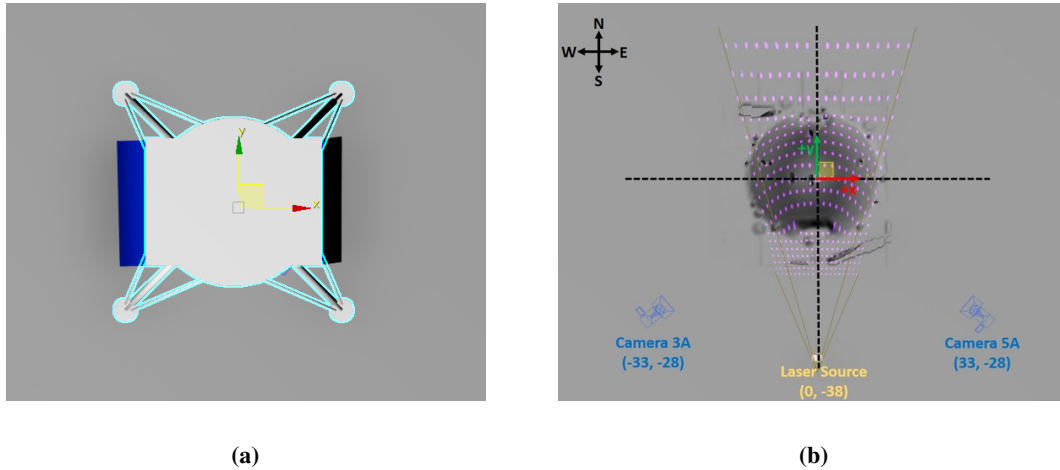


Fig. 3 Top view of the (a) simplified lander and (b) crater, laser source/grid, and camera locations.

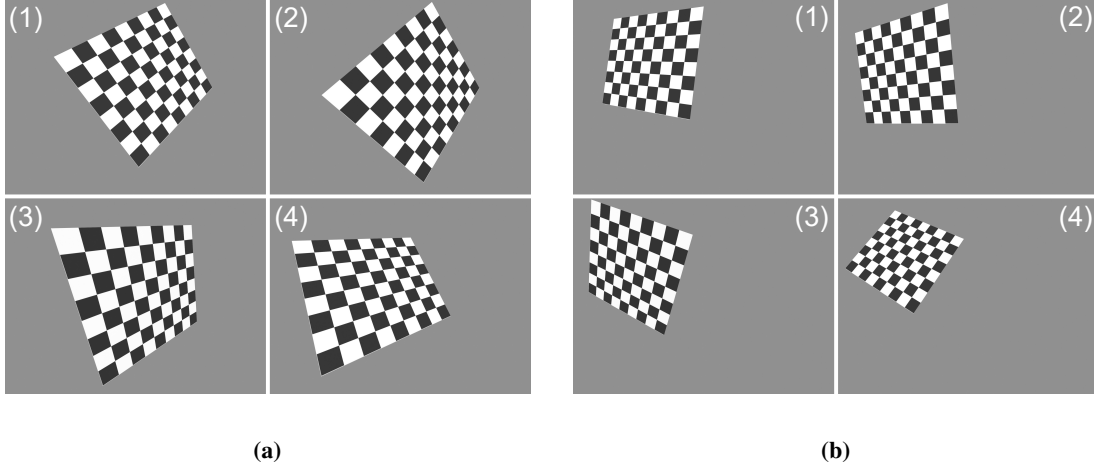


Fig. 4 Four views (1-4) of the calibration target used for extrinsic calibration of cameras (a) 3A and (b) 5A.

The intrinsic and extrinsic calibrations of the cameras were computed using a rendered 8×9 checkerboard with 5 inch squares, for a total board dimension of 40×45 inches. The intrinsic calibration for each camera was computed separately, with ten images used for each calibration which provide coverage over the full camera field-of-view, with both orthogonal and angled views of the calibration plate for each camera. For the extrinsic calibration, four image pairs were used where the checkerboard was visible in both cameras' field-of-view, as shown in Fig. 4a for camera 3A and Fig. 4b for camera 5A. The mean reproduction error for the intrinsic calibration for cameras 3A and 5A are 0.13 pixels and 0.54 pixels, respectively, and for the extrinsic calibration is 1.25 pixels. Further stereo image pair renderings are needed to lower the extrinsic calibration reproduction error.

A simulated laser grid was first projected from a location equidistant between both cameras and onto the flat ground (with the crater model removed). To capture the evolution of the measurements with descent of the lander, four altitudes of the lander above the ground were simulated: 3 m, 2 m, 1 m, and 0 m (post-landing). The camera positions and views remained fixed for all altitudes, while the laser grid was repositioned for each such that the central dot was always at the world coordinate system origin (and centered on the crater when included). Without this repositioning, the grid would no longer be in-view of the two cameras at higher altitudes. Renderings of the projected laser grid on the flat ground for the four altitudes are shown in Fig. 5, with corresponding camera views stacked vertically. Note that the grid size appears to stay the same as the altitude decreases because the laser grid divergence and the camera divergence are comparable. The camera calibrations are used to rectify the two captured laser grid images, after which these rectified images are thresholded and binarized for ease of laser dot identification. The correspondence of the identified laser dots between images is established, and the disparity between these dots is computed. The camera calibrations are then again used to transform the disparity calculations back to world coordinates in three-dimensional space, allowing for a depth map of the ground to be constructed. Since the projected laser dots have a finite diameter, the centroid of the identified dot is used for the calculations. The depth maps for each altitude are shown below their corresponding renderings in Fig. 5, where the laser dots are identified with black dots and the central dot is largest. Even with the laser grid repositioned at an altitude of 3 m, some of the corner dots were cut off in each camera view and could not be used to compute the depth at those positions (dots must be visible in both cameras for a depth measurement). Note that the colorbar scale used for each depth map is different ((m) ± 10 mm, (n) ± 4 mm, (o,p) ± 2.5 mm). For true flat ground measurements, the depth should be 0 mm, but depth errors are visible in these results, centered about 0 mm. While the color bar limits are the same for Fig. 5o and Fig. 5p (± 2.5 mm), the peak values for Fig. 5p are approximately 0.25 mm smaller. Also of note is that for higher altitudes (3 m and 2 m), the resulting depth maps have a rough plane of symmetry along the vertical direction, while as the altitude becomes lower, this plane of symmetry becomes slightly skewed. Further processing of the data is required to determine the various sources of error in this simple baseline case.

The crater model was then included in the CAD simulations in place of the original flat ground. The data for the crater was taken from measurements of a spherical-cap shaped sled using a photogrammetric imaging system. The camera positions/orientations continued to remain fixed, and the crater model, once placed in its position on the ground, also remained fixed. As the altitude of the lander was changed, the laser grid was angled such that its central dot was located at the center of the crater. Renderings of the projected laser grid on the crater for the four altitudes are shown in

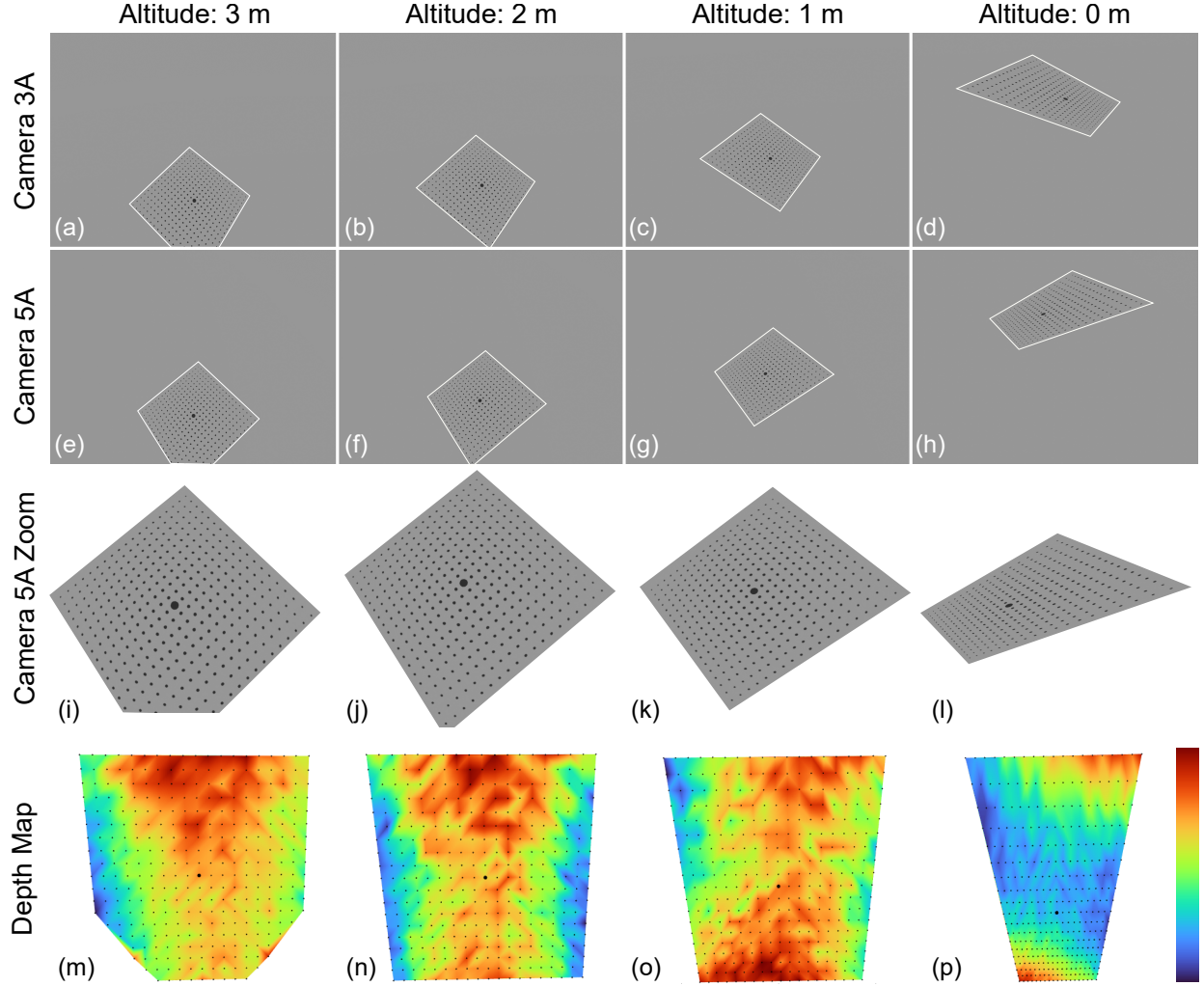


Fig. 5 Flat ground renderings with projected laser grid (outlined in white), with images from (a-d) camera 3A and (e-h) camera 5A (zoomed views of grid in i-l), and (m-p) corresponding depth maps for lander altitudes of (a,e,i,m) 3 m, (b,f,j,n) 2 m, (c,g,k,o) 1 m, and (d,h,l,p) 0 m. Colorbar full-scale limits are (m) ± 10 mm, (n) ± 4 mm, and (o,p) ± 2.5 mm.

Fig. 6, with corresponding camera views stacked vertically. The depth map calculation procedure is the same as the flat ground calculations. These resulting depth maps in Fig. 6 all have the same colorbar limits, from the undisturbed flat ground outside the crater at 0 mm, to the maximum crater depth of approximately -110 mm. The measured crater shape remains roughly the same for all altitudes, and compares favorably to the coordinates of the model itself. Small divots in the flat ground outside the bottom-right edge of the crater are visible in Figs. 6n-p, but are not visible in Fig. 6m because a laser dot was not projected onto that particular region of the model. At the highest altitude of 3 m, only approximately 40 laser dots are included within the crater extents, while when the lander is on the ground at 0 m, more than four times as many laser dots are used to measure the crater shape. This motivates the need for different projected DOE grids, or potentially an adjustable system, as described in Sections III and IV. The resolution of the cameras must be used to determine the optimal grid density and spacing though, since if the size and/or spacing of the dots at a higher altitude is decreased too much, the camera resolution becomes the limiting factor in the measurements.

When using only a collimated laser beam passing through the DOE without an imaging lens, the size of the dots on the ground are roughly the same size as the laser beam diameter for every altitude. If the laser beam is made to diverge, then each spot in the grid would diverge continuously the farther away it traveled. For ease of imaging and dot identification, some finite size of the dots is desired. The dot size required will be dictated by the camera's resolution,

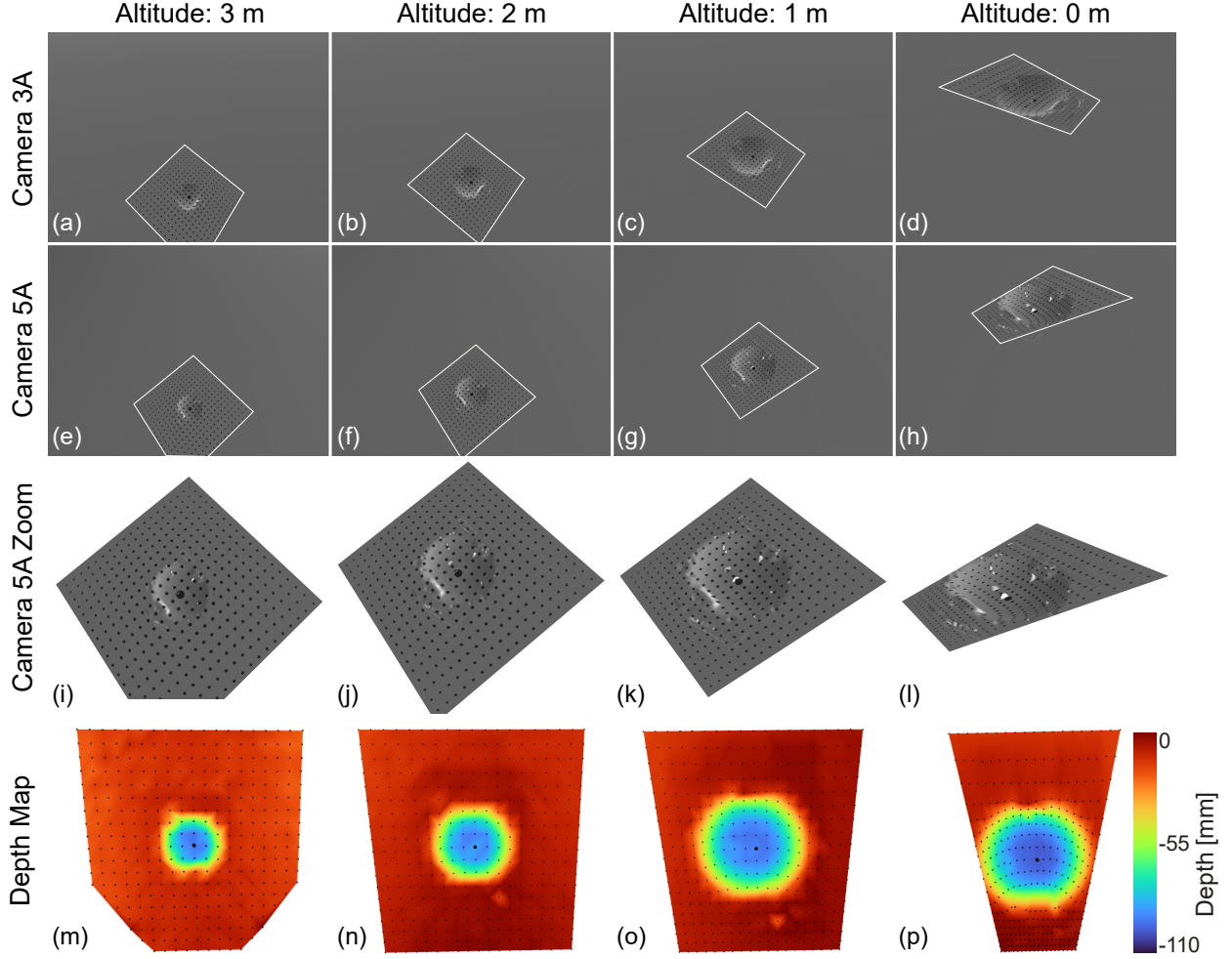


Fig. 6 Crater renderings with projected laser grid (outlined in white), with images from (a-d) camera 3A and (e-h) camera 5A (zoomed views of grid in i-l), and (m-p) corresponding depth maps for lander altitudes of (a,e,i,m) 3 m, (b,f,j,n) 2 m, (c,g,k,o) 1 m, and (d,h,l,p) 0 m.

that is, how many pixels define a single laser dot. Due to the angle of the laser beam with respect to the ground, and also due to the angular spread from the DOE itself, each projected dot is an ellipse, not a circle (this would be true of every dot except the central dot even when the projection axis is orthogonal to the impingement surface). The centroid of each dot was used for the calculations in this section to obtain one measurement point per projected laser dot, but by using an ellipse fitting algorithm, the major and minor axes of each dot can be determined, and the end-points of these axes can be used to add four extra points to the measurement. More advanced algorithms can also be included for the image processing, and will be the subject of future development of this system.

III. Laser Grid Projection

Two types of grid projection systems were used for the measurements in this paper. The first is an inexpensive, off-the-shelf laser pointer with two in-line rotating DOEs, seen pictured in Fig. 7a. This unit plugs into a USB port, and projects a red pattern of dots, with each dot roughly 3 mm in diameter. As the two DOEs are rotated relative to each other, different intermediate grid patterns are displayed, three of which are shown imaged onto a white sheet of paper in Figs. 7b-d. If the positions of the two DOEs are fixed relative to each other, and are both then rotated together, the projected grid pattern can be rotated. This dual-DOE system has the benefit of providing grid pattern adjustability, which is useful for obtaining different levels of measurement density at varying altitudes during a lunar landing with

fixed focal length cameras, for example.

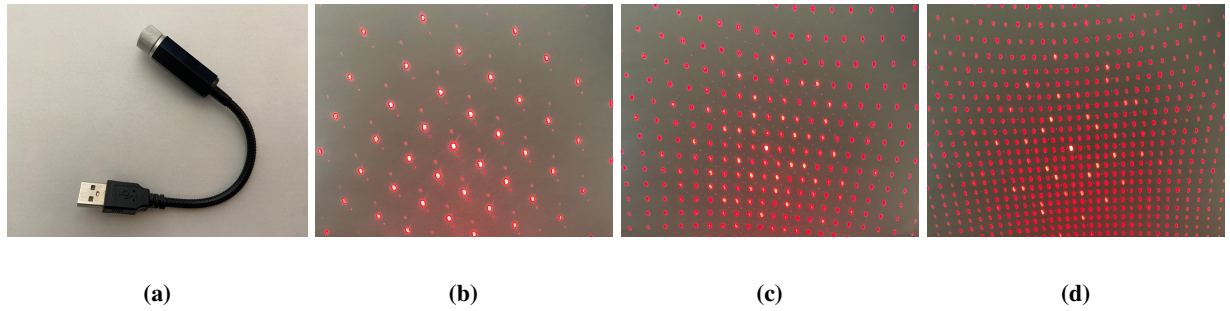


Fig. 7 (a) Picture of adjustable two-element laser/DOE system, with (b-d) three characteristic projected grid patterns.

Individual plastic DOEs (Holoeye™) were used for further testing of a standalone grid projection system, where the laser was not integrated directly with the DOEs. A 300 mW 532 nm Excelsior CW laser (Spectra-Physics™) was transmitted through a rotating linear polarizer, which was used to selectively attenuate the transmitted laser power through the DOE, although the transmitted laser power was not measured for these tests. The transmitted laser grids were incident on a large crater model (see discussion in Section IV), where it was imaged with an external camera (cell phone) in addition to a machine vision camera (monochrome FLIR™ camera) fitted with a 3.37 mm lens which was used for stereo imaging, similar to those used in the upcoming SCALPSS missions [31, 32]. Images of projected grid patterns from three DOEs are shown in Fig. 8. The first two columns show regular square dot patterns, the first column comprising a 17×17 dot pattern, and the second column comprising a 51×51 dot pattern. The laser power was not changed between the two images, and so the decrease in individual dot intensity (excluding the central dot) when moving to the finer grid is visible; the same laser power is distributed to more dots, decreasing each dot's intensity. The central dot for both grids is also much brighter than the other dots, which again uses valuable intensity that could otherwise be distributed to all other dots. This is a consideration for the design of a flight system, where laser power and its distribution in the grid pattern is a vital aspect of the design (see Section VII). These projected grids can be rotated about their central axis by rotating the DOE, and the projected size of the grid extents and inter-dot spacing depends on the distance to the target. For the 17×17 grid at 200 cm away from the crater, the spacing between the dots is 27.5 mm, and the total width/height of the projected square is 435 mm. For the 51×51 grid at the same distance, the spacing between the dots is 14 mm, and the total width/height of the projected square is 654 mm.

The projected patterns shown in this section have all been regular patterns, and stereo imaging depth data can only be determined at each laser grid point. Another option is to use a more densely-spaced random dot pattern DOE, an image of which is shown in the top-right image Fig. 8 projected onto the large crater model. An image of what the camera sees is shown in the bottom right image of Fig. 8, although note that these two images do not correspond to the exact same positioning of the random dot pattern on the target. While a very low laser power was used for the 17×17 and 51×51 grids, nearly the full 300 mW of laser power was required for sufficient projected intensity for the random dot pattern. The processing of this closely-spaced, pseudo-random pattern can proceed using a cross-correlation approach (or perhaps an optical flow approach), which can increase the resolution of the depth map relative to the coarse regular dot patterns. The DOE is mounted approximately 200 cm away from where the center bright spot is incident on the crater model. This particular dot pattern comprises nearly 52,000 individual laser points, which due to the intensity distribution over this many dots, requires much more laser energy to have sufficient intensity for the cameras within a reasonable exposure time. This exposure time limitation is not a limitation for static ground testing, where longer exposure times are possible since the setup is static, but during a lunar descent, the exposure time dictates the smearing of the signal depending on the speed of the lander. The FLIR™ camera result shows a noisy image that may not be able to be easily resolved at this imaging distance. Note that the spread of the points will be higher at higher altitudes of the lander, but not appreciably so. A custom design is most likely needed to make this work well for a given application.

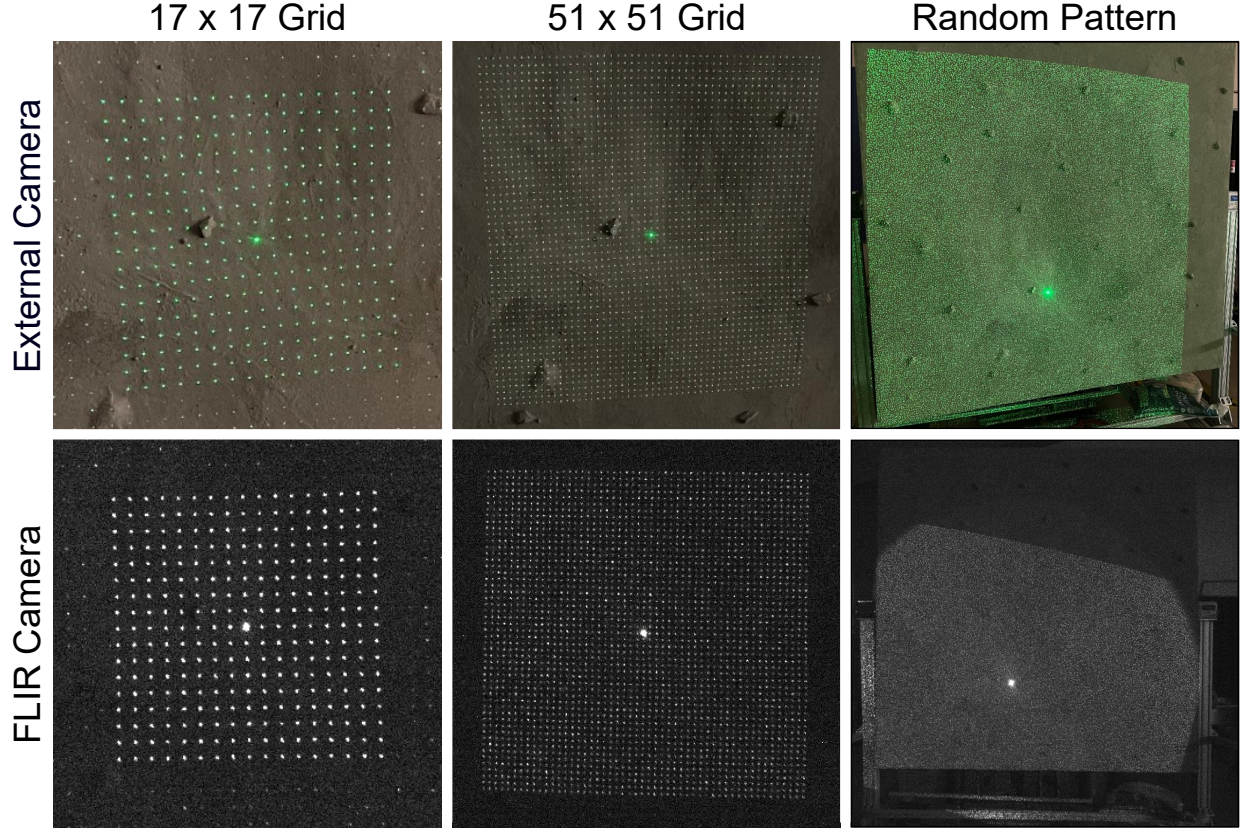


Fig. 8 Images of various laser projection grids (columns) taken with (top row) an external cell phone camera and (bottom row) the FLIR™ camera. Note that the FLIR™ camera images are cropped from their full resolution for clarity.

IV. Large-Scale Fixed-Geometry Crater Model

A large 183×183 cm fixed-geometry crater model was used for laboratory testing of the stereo imaging system, and was designed to have an asymmetrical crater outline of approximately 120 cm in diameter with a depth of approximately 50 mm to 80 mm. The crater model was constructed using a wooden backing structure with chicken wire and two to three layers of paper mâché to define the fine surface structure. The top layer of paper mâché was painted with a thick layer of grey latex paint and dusted with a dry concrete mixture to add texture and simulate the lunar regolith. Intermittent rocks were positioned over the model to provide larger-scale features characteristic of the lunar surface. The exact geometry of the crater model was measured using an industrial photogrammetric system (V-STARS, Geodetic Systems, Inc.) to provide a ground-truth for comparison. The use of the PRO-Spot dot projection with this system allows for measurements up to approximately $4 \mu\text{m}$ with 1 cm spatial resolution. To increase the resolution of the data set, four separate slightly overlapping regions of the crater were independently measured and then stitched together in Autodesk 3DS Max™. Note, however, that between this data set and the laser/DOE measurements, the crater shape became slightly distorted, and so only a qualitative comparison is made in this paper. This ground-truth photogrammetric system cannot be used for the lunar landing measurements since it is an imaging system. That is, the projected dots used for the measurements are imaged onto the measurement object using a lens, which means the projected dots will move out of focus if the model is moved far enough away from the plane of sharpest focus. The benefit of the laser grid projection is that the sharp dot pattern is projected at every position of the model relative to the laser and camera system, and does not use a lens for imaging.

Two FLIR™ Chameleon3 USB3 cameras (CM3-U3-13Y3C-S-BD) with 3.37 mm focal length lenses (PeauProduction) were used to image the crater. The cameras were mounted to an optical table with approximately 1085 mm separation (sometimes termed the *baseline*), which is similar to that used in the upcoming SCALPSS missions [31, 32].

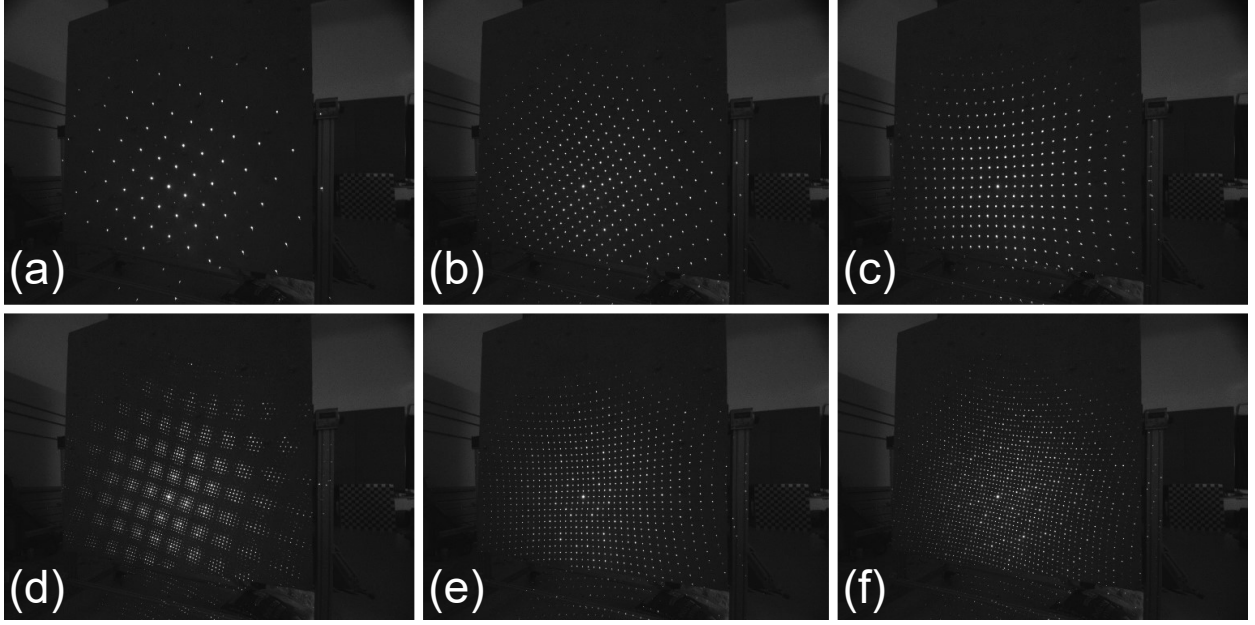


Fig. 9 Six different projected grid patterns produced by rotating two diffractive optical elements relative to one another in front of a laser beam. Resulting depth maps from (a,c,d) are shown in Fig. 10.

The laser and DOE were mounted approximately centered between the two cameras as it was in the CAD simulations. The laser grid was projected on the crater model surface, and the cameras were angled such that the central laser dot was approximately centered on both fields-of-view. The left and right cameras were approximately 1345 mm and 1420 mm from the central dot on the crater, respectively. A red laser pointer with two rotating plastic DOEs provided a bright, adjustable laser grid pattern (Section III). Six different patterns capable of being produced with this adjustable laser/DOE combination are shown in Fig. 9, imaged by the right camera. The grids in (a), (c), and (d) are used to compute depth maps seen in Fig. 10. While the bright central dot uses laser power that can otherwise be used to increase the brightness of the surrounding dots, it does provide a convenient known anchoring point between cameras, which is useful when it would otherwise be difficult to determine dot connectivity between the images with a large number of dots in a regular pattern.

A large 8×7 checkerboard calibration target was used for both the intrinsic and extrinsic camera calibrations, using 4.75 inch squares for a total board size of 38×33.25 inches. Each camera's intrinsic calibration was computed separately, after which an extrinsic stereo calibration was computed using different images visible to both cameras simultaneously. For the left camera, 84 images were used for the intrinsic calibration, with a resulting mean reproduction error of 0.15 pixels, while for the right camera, 61 images were used with a resulting mean reproduction error of 0.14 pixels. For the extrinsic calibration, two image pairs were used with a resulting mean reproduction error of 0.52 pixels.

Depth maps are computed for the crater model using three of the laser grid densities/configurations shown in Fig. 9. Depth maps corresponding to Figs. 9a,c,d are shown in Figs. 10a,b,c, respectively. The maps show a top-view of the crater (viewing the x - y plane), where the small black dots are the laser grid dots that are visible in both stereo camera views, and are thus used for the calculations. All colorbar limits are the same, from 0 mm (flat ground) to -80 mm (approximately the deepest part of the crater model). With the increasing laser grid density, the crater shape becomes more defined, and rocks can also be identified when a laser dot happens to coincide with one. This is less likely for coarser grids, and so no rocks are visible in the depth map of Fig. 10a. Note that the flat ground outside the crater appears to be higher for (a) than for (b) and (c). This is due to the relative z -axis scaling that is used to display the depth maps, where the depths are all shifted such that the highest part of the map is at 0 mm. Thus, when a rock is identified, as in (b) and (c), the level ground is shifted down by the height of the rock, and the rocks appear to have a depth of 0 mm. In Fig. 10d, the ground-truth depth map is shown, and is scaled to roughly the same size as the stereo-measured depth maps to allow for qualitative visual comparisons. The bulk computed crater shape compares favorably to this ground-truth, and identified rocks in the depth maps of (b) and (c) are shown with appropriately oriented arrows.

The grid of Fig. 9d, with resulting depth map in Fig. 10c, is an intermediate non-regular grid, as can be seen by

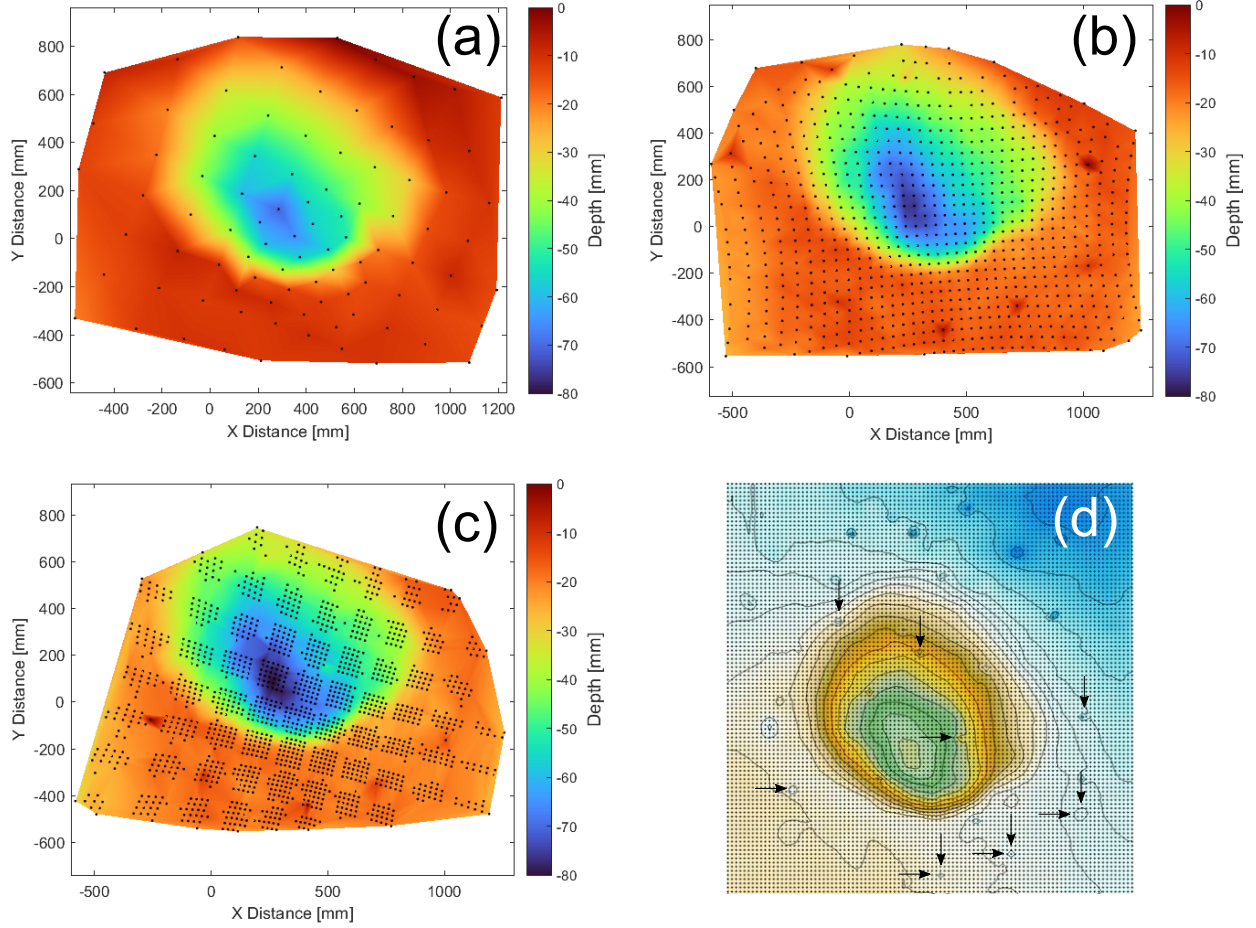


Fig. 10 Crater model laser/DOE reconstructed depth maps for (a) the coarsest dot pattern, (b) the medium density dot pattern, and (c) the highest density dot pattern, along with the (d) ground-truth V-STARS crater model data. Black arrows in (d) show identified rocks in crater reconstructions (b) and (c), respective to arrow direction. Quantitative comparisons cannot be made here due to damage to the crater model between V-STARS data acquisition and the data taken in this paper.

smaller sub-regions of rectangular patterns with high density. In Fig. 10c, only a few of these regions appear to be filled with every data point, for example near the bottom edge of the crater. This is because the laser intensity is distributed over more dots, and due to the decrease in intensity of some of these sub-region edge dots, they are not identified with enough confidence in the processing step. The number of missing dots from these sub-regions increases near the edge of the total grid pattern. This demonstrates the need to balance laser power with number of projected dots.

Using the same large crater model and stereo camera system, the adjustable laser/DOE system was replaced with the 532 mm laser with a fixed 17×17 DOE pattern. This DOE has a significantly smaller angular spread than the adjustable system, and so the grid was only projected onto a portion of the crater, namely the lower-left portion as seen in Figs. 11a,b, where in (a), the grid is oriented at a nominal 0° , and in (b), the DOE is rotated to orient the grid at 45° . The depths maps for the 0° and 45° stereo images are shown in Fig. 11c and Fig. 11d, respectively, where the flat surface outside the crater is seen near the lower-left, and the crater center is near the upper-right. While a 17×17 grid is relatively sparse, by taking two images at different rotational orientations and combining the data sets as shown in Fig. 11e, a more dense map can be computed. This is a useful option if only a single DOE is available, but it will still need to be rotated which limits its usefulness during the landing descent of a spacecraft, or a transient crater evolution ground test.

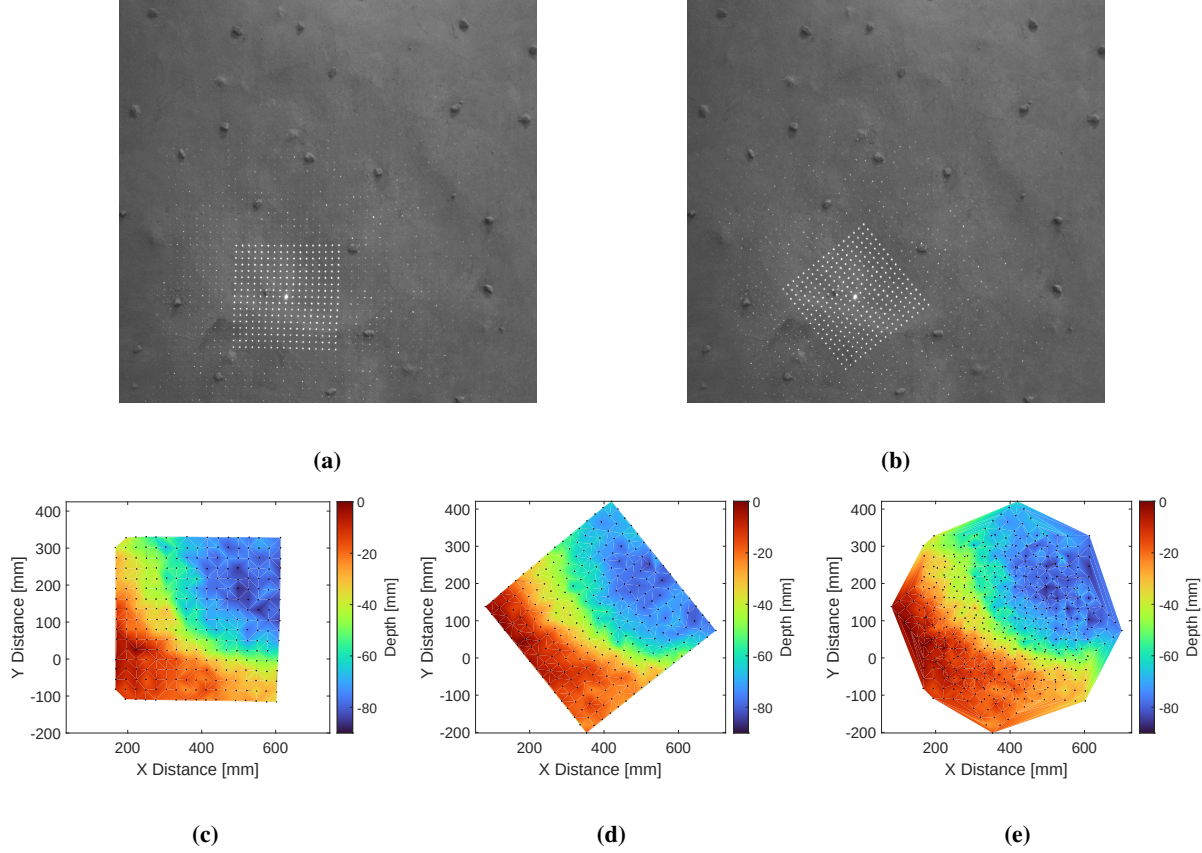


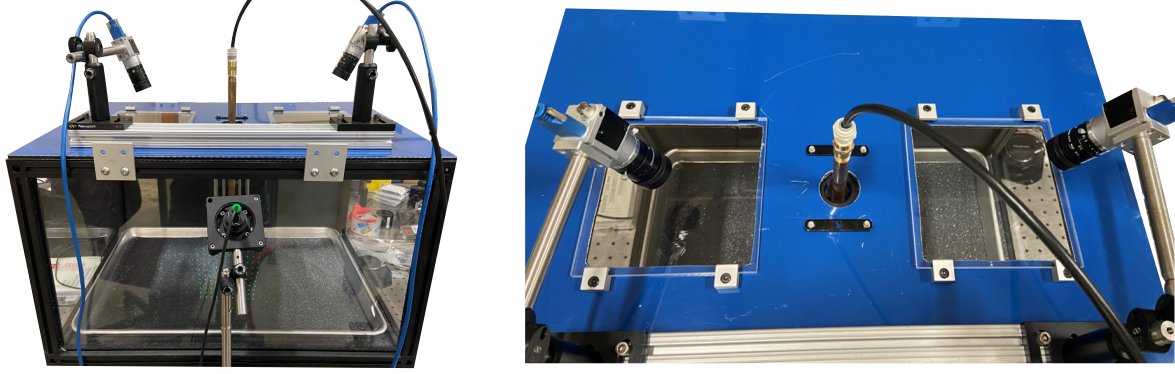
Fig. 11 Images of the 17×17 laser grid projected onto the crater model at (a) 0° and (b) 45° , with resulting depth maps at (c) 0° , (d) 45° , and (e) a combination of 0° and 45° depth maps.

V. Plume-Surface Interaction Crater Evolution

A small-scale enclosure was constructed to acquire image sequences during a plume-surface interaction (PSI) test using compressed air exhausted through a small nozzle, and impinging on a bed of particles. The enclosure shown in Fig. 12 is constructed with three acrylic side windows for optical access, a removable rear panel for calibration, cleanup, and resetting, and a top panel with two acrylic window inserts for the stereo camera optical access. The nozzle passes through the center of the top panel, and is connected to the laboratory compressed air bottle through a flow meter for air pressure adjustments. The $254 \mu\text{m}$ silicon carbide lapping grain particles (McMaster-CarrTM, 4780A36) are placed in a tray resting on the floor of the enclosure. These particles are substantially larger than expected lunar regolith particle sizes, but provide an initial proof-of-concept of the measurement. Prior to a test, the particles are moved to the center of the tray and are flattened to provide an initial level ground.

Two identical machine vision cameras (BaslerTM, acA1920-150um) with 25 mm focal length lenses (TamronTM) are placed on top of the enclosure, each viewing the particle bed below the nozzle through their respective acrylic window viewing ports. A low power (0.9 mW) 520 nm USB laser (ThorlabsTM, PL201) with a 3 mm diameter beam was projected through a DOE (HoloeyeTM, DER-243) to produce an 11×11 laser grid. A bandpass filter centered at 525 nm with a 45 nm bandwidth (Edmund OpticsTM, #86-984) was used to eliminate window reflections and non-laser reflections from the particles. The central dot of the resulting projected grid is brighter than the rest, making it a useful marker for identifying matching grid points in both camera images. While the DOE was constructed for lasers operating at 633 nm, the green laser provided a smaller angular deviation, resulting in a tighter projected grid, with more dots defining the crater than a red laser would provide. A blue laser was also available for an even smaller angular deviation, but the intensity of the light projected onto the particle bed was too low to be used. The laser grid was shined onto the particle bed from the side window of the enclosure (opposite the removable panel, see Fig. 12a).

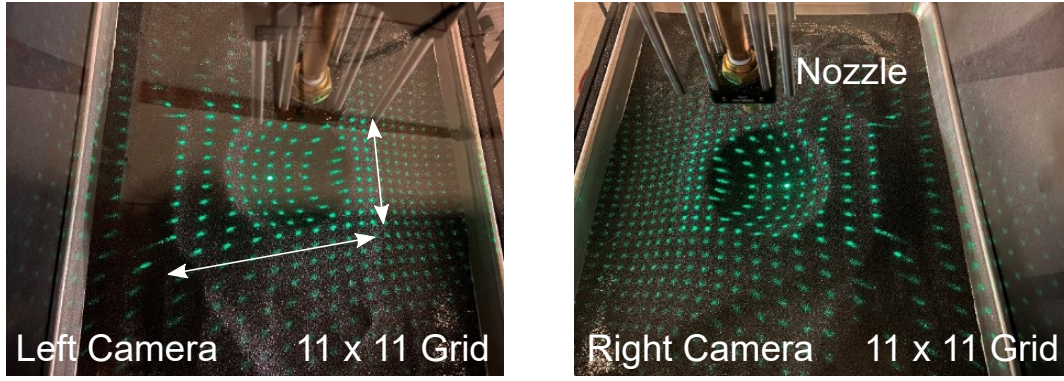
The bright central dot was placed directly below the nozzle, centering the grid on the flat ground. Due to the angle of



(a)

(b)

Fig. 12 Plume-surface interaction enclosure (a) side view with laser grid projection at the center, and (b) top view with stereo camera imaging window ports.



(a)

(b)

Fig. 13 Images taken with an external cell phone camera through the (a) left and (b) right top viewing ports, showing the final crater shape with projected laser grid illumination.

the laser grid from the side window, as the crater deepens during a test, the central dot will no longer be centered below the nozzle. This does not pose a problem however, as the central dot placement is simply used to align both cameras prior to the test to ensure maximum field-of-view coverage of the eventual crater. Images taken with an external cell phone camera through the left and right viewing ports on the lid of the enclosure are shown in Fig. 13. The final crater shape is visible, along with the projected laser grid. Due to the laser angle, one side of the crater has more dots defining its shape, while the side closer to the laser has fewer due to the steep incline from the crater center to the crater edge. The higher orders of the DOE are also visible as faint dots outside the brighter 11×11 grid. If these dots are visible in images during a test, they can also be used for depth calculations. These higher order dots outside the main grid pattern are also seen in Fig. 8 for the 17×17 grid in images taken with both the external camera and the FLIRTM camera.

The cameras were pointed at the central dot of the grid on the flat ground (Fig. 14a for the left camera), and the aperture ring and focus ring locked in place. The enclosure lid (with cameras attached) was lifted off the enclosure and placed on the optical table to perform the calibrations, since space was limited inside the enclosure to obtain the necessary views of the calibration target. A smaller 9×8 checkerboard calibration target was used due to the smaller field-of-view of the measurements inside the enclosure. The size of the squares was 7 mm for a total calibration target size of 63×54 mm. For the left camera, 127 images were used for the intrinsic calibration, with a resulting mean reproduction error of 0.89 pixels, while for the right camera, 121 images were used with a resulting mean reproduction error of 0.94 pixels. For the extrinsic calibration, 25 image pairs were used with a resulting mean reproduction error of

0.99 pixels. After calibration, the lid was carefully placed back on top of the enclosure for testing.

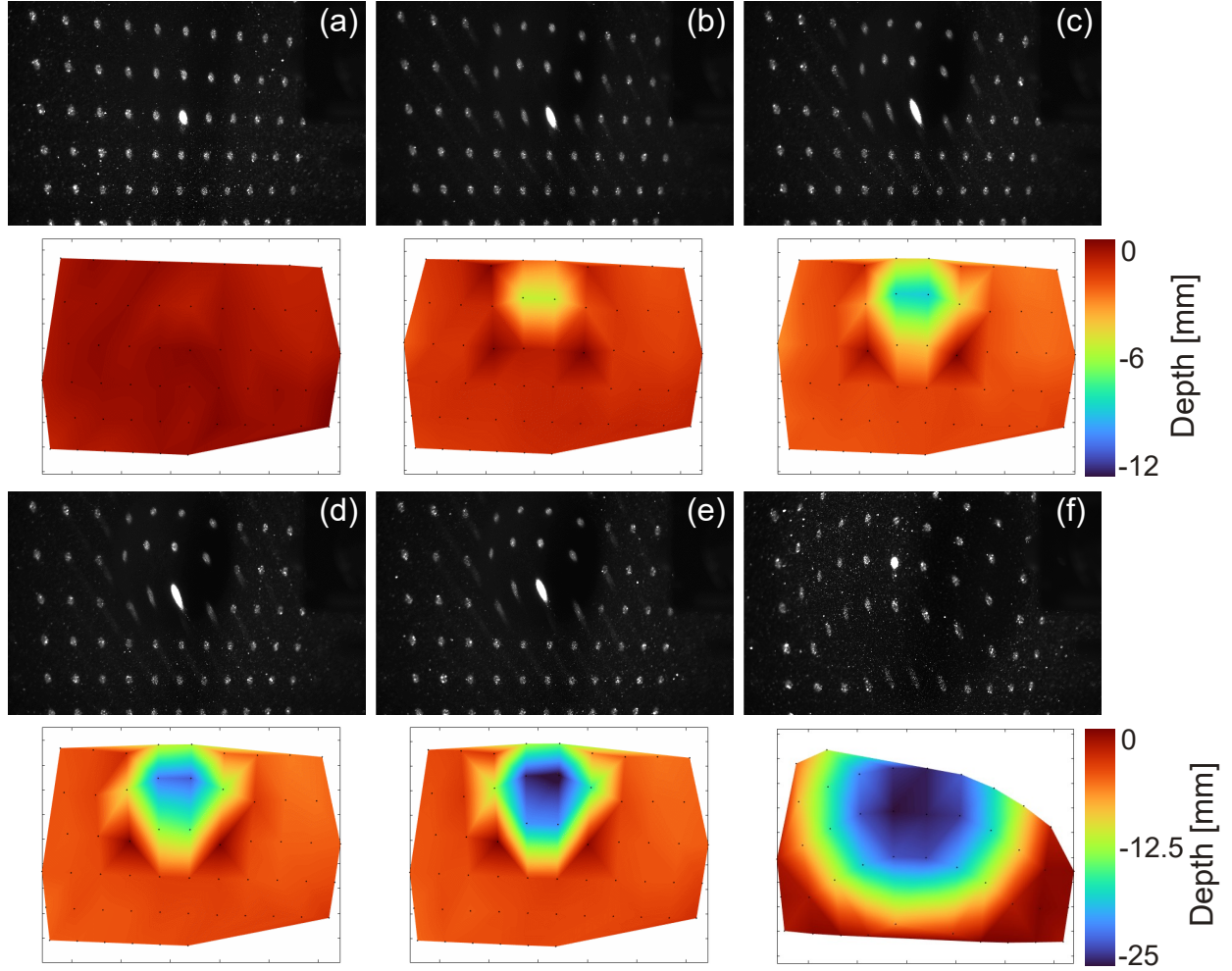


Fig. 14 Left camera image sequence and computed stereo depth maps for the small-scale plume-surface interaction testing. Images (a-e) are the first five frames of the test, whereas (f) is the post-test crater image. Colorbar limits are the same for (a-e) at [0 mm, -12 mm], but is different for (f) at [0 mm, -25 mm].

Images from the left camera during a PSI test are shown in Fig. 14. Frames (a-e) are sequentially the first five frames of the test, with frame (a) taken just before the nozzle flow is turned on. Frame (f) is taken after the nozzle flow has been turned off after the test, showing the final crater shape. The computed depth maps are shown below their respective camera images, where the colorbar limits are the same for (a-e), but is different for (f). The laser dots used for the calculations are shown with black dots. With each successive frame, the crater shape evolves and deepens. The resolution of the laser grid is fairly coarse, but the general circular shape can be inferred. For the post-test crater depth map, the circular shape and depth of the final crater are more evident, although due to the angle of incidence of the laser relative to the crater, there is an absence of grid points on the near (bottom) edge of the crater. This can be remedied by introducing the laser from above instead, or by using two different laser/DOE units at complementary positions to obtain full coverage over all expected crater geometries. The full grid is not visible in these camera views due to the camera lens used (25 mm), as this was the shortest focal length lens available for testing with this camera at the time. For future testing with this small-scale enclosure, a shorter focal length lens will be used.

While this projected grid method can be used for depth measurements, it is noted that depending on the optical density of the induced plume and dust cloud (ejecta sheet), there are points during the testing that the projected laser dots on the ground will not be visible, as is shown in the left image of Fig. 15, near the right side of the crater center. If the laser/DOE position is known relative to the two cameras, a depth measurement can still be calculated when a dot is

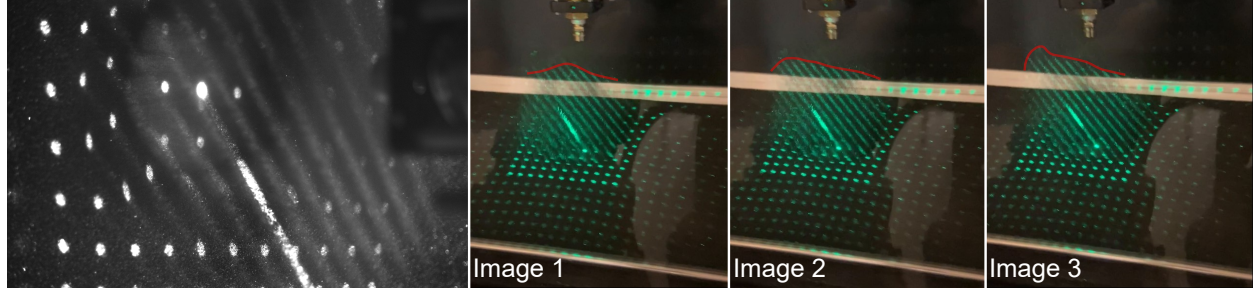


Fig. 15 (Left) Contrast-enhanced image from left-camera sequence during PSI test showing obscured particle dots due to ejecta sheet. (Right) Three images taken with an external cell phone camera through the side window of the extents of the ejecta sheet, with a rough outline of the top of the sheet shown in red.

visible on only one camera. If dots are not visible on either camera, a depth measurement cannot be determined at that position. However, knowledge of the ejecta sheet optical depth and height above the ground is also a useful metric to be able to measure, and the right three images of Fig. 15 show that the ejecta sheet extents can potentially be calculated by determining the edge of the scattered signal from the projected laser grid, as shown with the red lines. This scattered signal can also be seen in the contrast-enhanced left image of Fig. 15. This ejecta sheet monitoring method requires further investigation.

VI. Shadow Particle Tracking

A high-speed, front-illumination particle shadow tracking measurement system was used for simultaneous measurements during the PSI testing of Section V, and is shown schematically in Fig. 16. On the right side of the enclosure, incoherent light at 640 nm from a pulsed laser source (Cavitar Cavilux™ HF) passes through a linear polarizer (LP), and is reflected onto the main optical axis of the system with a polarizing beamsplitter cube (PBS). This linearly-vertically polarized (*lvp*) light is transmitted through a lens and through the enclosure. On the left side, the *lvp* light passes through a quarter-wave film (QWF), which is oriented such that it converts the *lvp* light to right-circularly polarized (*rcp*) light. Upon reflection at the retroreflective background (RBG), the light is converted from *rcp* to left-circularly polarized (*lcp*) light, which is then converted to linearly-horizontally polarized (*lhp*) light after passage through the QWF. This light then travels back through the enclosure, through the lens, and is transmitted by the PBS, through an appropriately-oriented LP, and into the high-speed camera (Photron™ SA-Z). The depth-of-field (DOF) of this shadow particle tracking system is narrow, and so only particles at the focus plane, centered under the nozzle at the middle of the crater, are in focus.

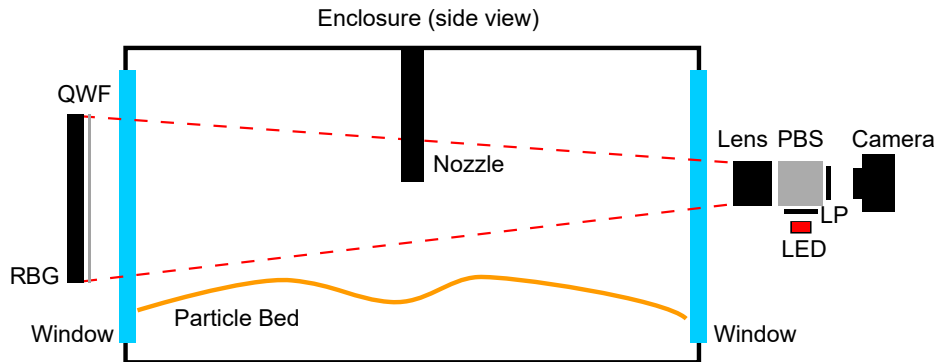


Fig. 16 Side-view schematic of high-speed, front-illumination shadow particle tracking setup, with light projection denoted by red dashed lines.

Prior to acquiring a DOF target scan, an image of a calibration target at the focal plane must be acquired to set the

scale of the image. A 52 mm-square dot target (clear soda lime glass with opaque chrome dots) was placed at the nozzle plane, the camera system was focused on this pattern, and an image was acquired. A translation stage assembly with a mount for the DOF target was then placed in the enclosure. A MATLAB™ program was used to control both a National Instruments™ (NI) 9181 chassis and 9402 module, and the translation stage for the DOF target. A scan was performed to acquire approximately 200 images through the imaging system's DOF in steps of 0.25 mm. Five of the resulting images of the DOF target (LaVision™) are shown in Fig. 17 for positions on both sides of the best-focus (0 mm).

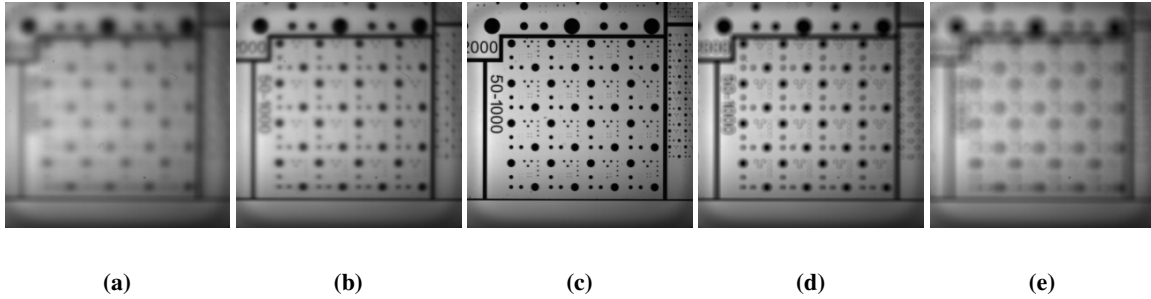


Fig. 17 Five images of the DOF target scan at positions corresponding to (a) -25 mm (b) -12.5 mm, (c) 0 mm, (d) 12.5 mm, and (e) 25 mm, where 0 mm corresponds to the position of best-focus at the center of the enclosure, directly beneath the center of the nozzle.

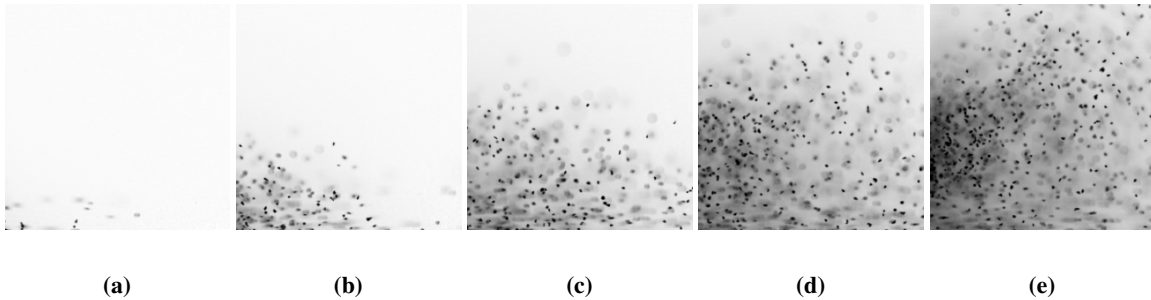


Fig. 18 Low-speed (20 kHz, 1024×1024 pixels) particle shadow imaging of the ejected particles from the crater, where each image is 100 frames, or 5 ms, after the previous image.

Images from an image sequence acquired at 20 kHz are shown in Fig. 18. This allowed for full-frame image acquisition (1024×1024 pixels) using the Photron™ SA-Z high-speed camera. The images displayed in the figure are separated by 100 frames, or 5 ms, to show the evolution of the bulk ejected particles. There is a mix of sharply in-focus particles from the plane centered below the nozzle, and out-of-focus particles from positions either in front of or behind the center plane. Using the calibration results from the images of Fig. 17, the LaVision™ ParticleMaster Shadow module in DaVis 10 was used to compute a particle size distribution, which matched the known lapping grain particle sizes relatively well. Images acquired at 100 kHz are shown in Fig. 19, with each successive frame separated by $0.5 \mu\text{s}$. While the field-of-view is necessarily reduced to achieve these higher framing rates, the tracking of particles can be accomplished with finer detail. Two particles are highlighted in these images, one in blue and the other in red. These are tracked over the five displayed frames, indicating that fine resolution of the velocity measurements can be achieved. The red-highlighted particle in particular is also seen to be rotating as it travels, which will affect the particle size measurement by the software, since these particles do not have a spherical shape.

Further analysis of these image sequences will provide relevant quantities such as individual particle sizes, particle size distribution, particle velocities, mass flux, etc. The number, trajectory, and speed of the particles is of particular importance for lunar landings, where impacts from particles on landing site adjacent infrastructure, or on the lander itself, are critical to understand for mission success. The terrain mapping and particle tracking measurements will be performed simultaneously for future ground tests to compare how particle sizes, trajectories, and velocities/fluxes in a particular region change as the crater shape evolves. The placement of the test apparatus in a vacuum chamber will give further insight into the differences between atmospheric and near-vacuum particle ejection characteristics, and will

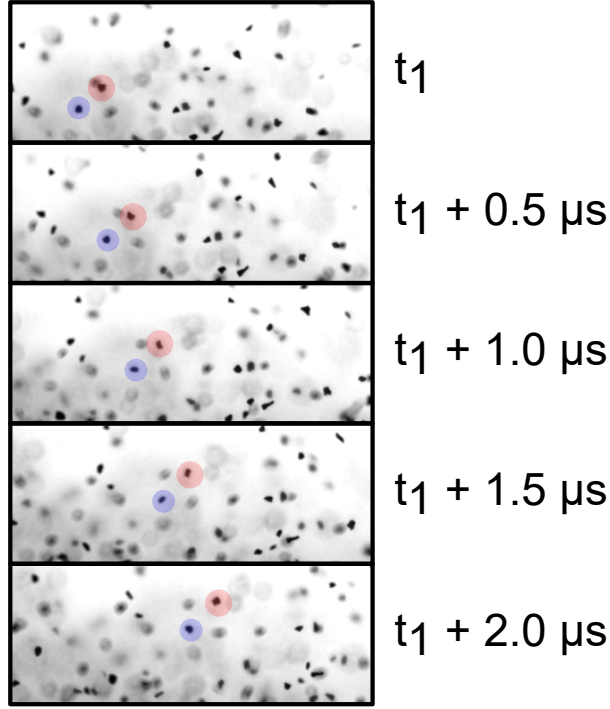


Fig. 19 High-speed (100 kHz) particle shadow imaging of the ejected particles from the crater, where each image is $0.5 \mu\text{s}$ after the previous image.

provide a more complete picture of the relevant PSI physics.

VII. Flight Implementation Considerations

Testing of the active structured illumination terrain mapping system outlined in this paper demonstrates its feasibility as a viable diagnostic for future lunar landing missions. However, there are many ancillary aspects of the system that must be addressed prior to inclusion on a flight vehicle, as itemized below in no particular order. Note that these issues are not limited to this active illumination technique.

- 1) Due to the discrete nature of the projected grid, it is possible that rocks (even large ones) may not be identified.
- 2) To increase the number of projected grid points, a higher intensity laser is required to retain the same intensity of each dot, which will require more power.
- 3) There must be sufficient laser intensity such that a short camera exposure can be used to avoid smearing of the images. Smearing will depend on camera exposure and lander velocity. A pulsed laser, or even a double-pulsed PIV-type laser can be considered, enabling a combined shape measurement with particle tracking.
- 4) The laser grid spreads with a constant angular deviation from the DOE to the surface. Thus, for a certain DOE and laser wavelength, the projected grid points will have a larger spacing for higher altitudes. Different DOEs may be required for different altitudes depending on the required resolution of the measurements. The resolution of the cameras and the DOE projected dot size and density must be accounted for simultaneously.
- 5) The pointing angle of the projected laser grid and the cameras cannot be easily changed, meaning they will be optimized for a certain altitude and viewing angle. To obtain measurements at varying altitudes during a descent, a trade-off of optimum viewing at low altitudes may be needed.
- 6) Rotation of the grid pattern has the opportunity to fill in measurement gaps and lead to a higher density measurement than achievable with a fixed pattern (for the same grid density). This would require syncing with a camera, but also does not provide a time-resolved measurement unless images are acquired at high frame rates. This may not be possible for a lunar lander, but can certainly be done for ground test measurements.

- 7) Reflections off the lapping grain particles during the PSI testing of Section V posed a challenge for imaging. Using a narrow bandpass filter on the cameras helped to isolate the laser dots from other visible wavelength reflections. Reflection of the laser off the non-spherical lunar regolith particles may pose similar challenges, and using a bandpass filter could limit the cameras' use as a general imaging system when not using structured illumination.
- 8) The ejecta sheet obscuring the crater itself means projection of the laser dots on the surface may not be visible on one or both cameras during the descent/landing phase, and potentially even after landing depending on dust settling time. While the crater may not be able to be mapped in its entirety during the descent and landing phases, perhaps the geometry/extent of the ejecta sheet can be determined. Using different laser wavelengths and cameras may allow for imaging through the dust cloud.

VIII. Conclusions

A stereo imaging system using a projected laser grid for active illumination has been developed. Two cameras separated by a large baseline separation distance are pointed such that they view substantially the same field-of-view on a surface. Between the two cameras, a laser is transmitted through a diffractive optical element to project a pattern of dots onto the surface. This active illumination of the surface allows for stereo imaging and depth map calculations even in dark/shadowed conditions.

To first verify the system's feasibility, CAD renders were used to simulate the system, imaging both a flat ground surface and a crater model. The flat ground and crater depth maps give confidence to the measurement system approach, although the accuracy and precision of these results remain to be determined.

A physical system was tested with a large-scale, fixed-geometry crater model, fabricated using chicken wire, paper mâché, and concrete/sand/rocks. Depth maps computed using an adjustable projected pattern show similar feature definition of the crater, with increasing resolution with increasing numbers of projected dots. Rocks are also visible when laser dots are projected onto them. A smaller-scale system was used for a plume-surface interaction test where a compressed air jet impinged on a bed of small particles, creating a time-varying crater structure. The structured illumination stereo system was able to map the evolving crater shape, although obscuration of the laser dots on the surface due to the ejecta sheet can impact the crater reconstruction. A front-illumination particle tracking measurement was also implemented for these PSI tests, which may be useful for coupling crater shape evolution measurements with particle trajectories, velocities, and fluxes.

While the system described in this paper can be used for ground-test measurements, it is potentially ideal for implementation on a flight vehicle (e.g., a lunar lander) due to its low weight and power requirements. If a stereo camera system is already developed for a lander, then the only additions required are the laser and diffractive optical element. Although there are many considerations for its inclusion on a lander, the structured projection stereo imaging system is an enticing measurement technique for use in limited visibility environments.

Acknowledgments

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