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

Joshua M. Weisberger, Paul M. Danehy, Timothy W. Fahringer, and Brett F. Bathel, and Olivia K. Tyrrell

NASA Langley Research Center

Advanced Measurements and Data Systems Branch

Ryan J. Thompson and William D. Hutchins

University of Virginia, Department of Mechanical and Aerospace Engineering

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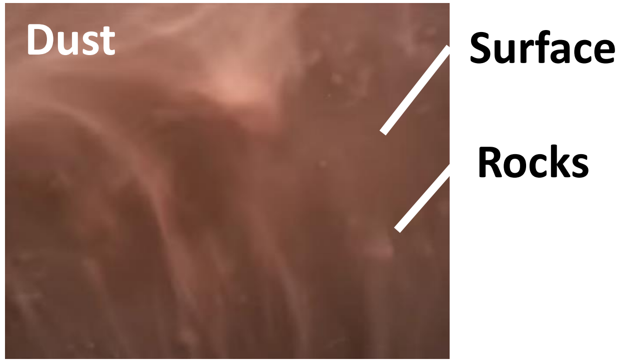
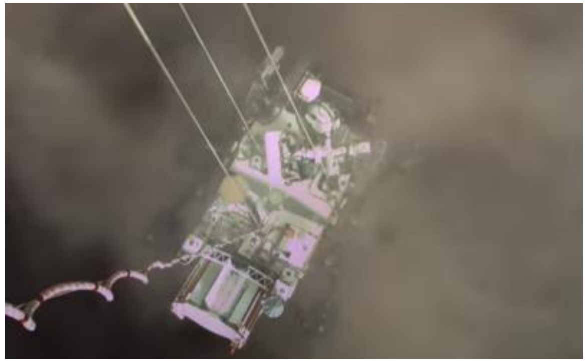
Motivation for the Measurement

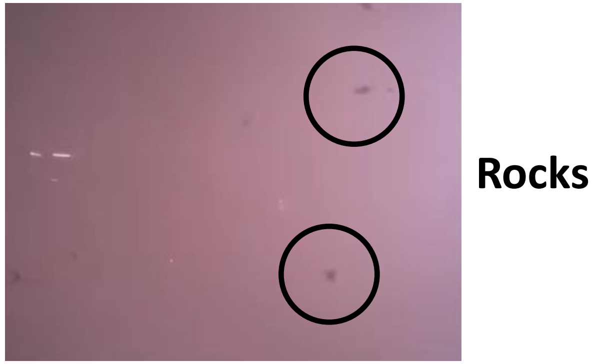
- <u>What is the problem?</u>
  - When landing on the moon or Mars, it is difficult to simulate/predict the impact of the rocket plume on the regolith
    - How much is displaced, how fast it travels, and where it will go
    - Size and shape of the crater after landing
  - Can cause damage to lander and nearby existing equipment
  - CFD simulations of this flow require experimental validation
    - Entire region not a continuum, flow is compressible, particle physics must be incorporated

- <u>Why is it hard?</u>
  - Ground tests on earth cannot entirely replicate lunar/Martian surface conditions (gravity, atmosphere, regolith, etc.)
  - Requires a non-intrusive diagnostic that can be included on a lunar/Martian lander
  - Need simple imaging techniques

Perseverance Landing[1]



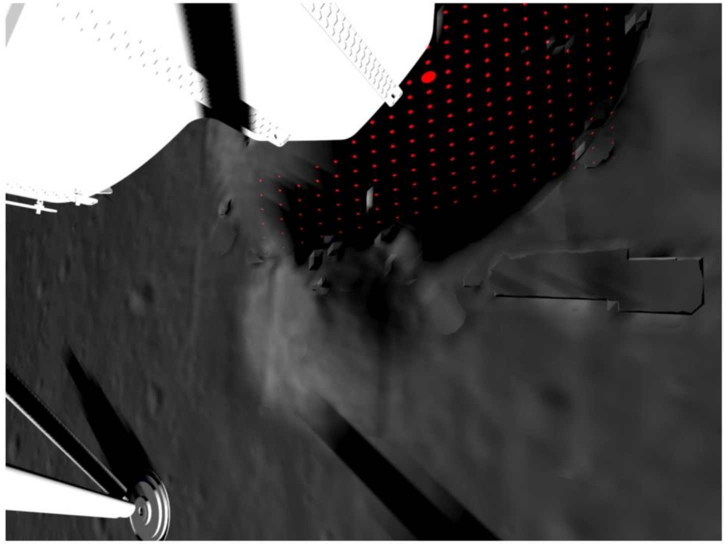


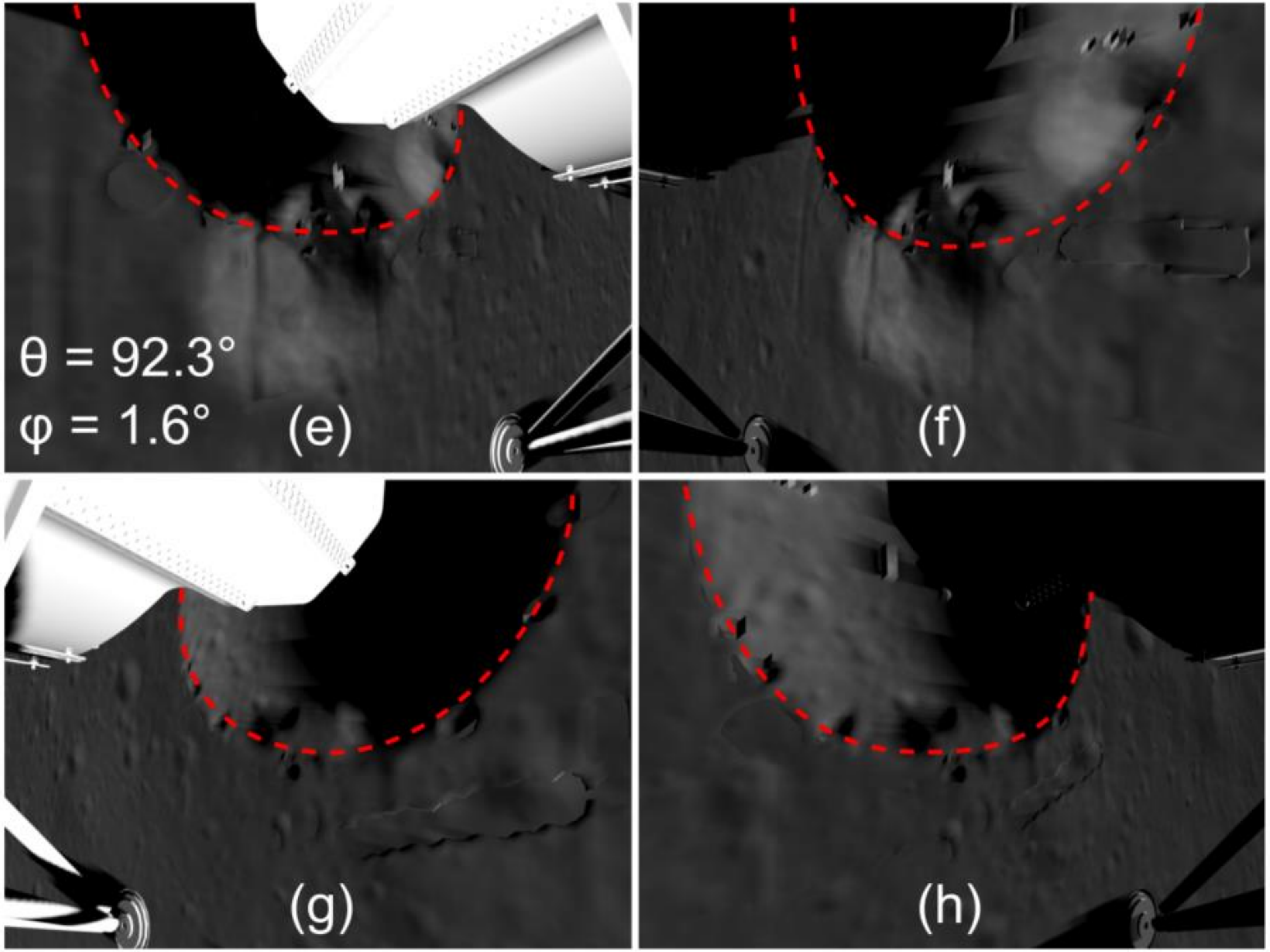


Motivation for Active Illumination Imaging

- CAD render of four camera views (e-h) of a crater (dashed red) below central nozzle
  - Depending on sun illumination, crater will be partially/fully shadowed
  - Without active illumination, crater depth maps cannot be calculated from stereo images

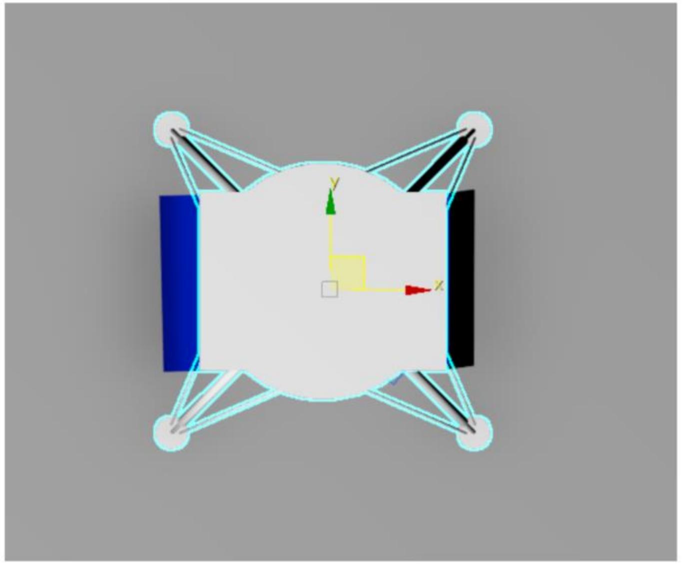
- Projected laser grid onto the crater (bottom image) allows for depth map calculation even when crater is fully shadowed





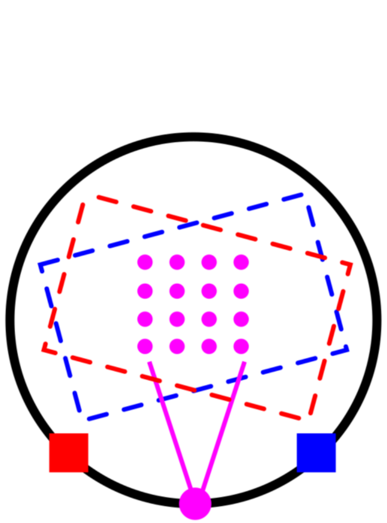
Computer-Simulated Concept Validation

- Cameras and laser grid projection placed at representative locations on lunar lander (e.g., lander legs and outside nozzle heat shield)
- Four lander altitudes (0 m, 1 m, 2 m, 3 m) used to simulate camera and laser views
- Camera views are stationary at all altitudes, but laser grid is moved such that center dot always corresponds to crater center
  - Laser grid is projected from an angle (cannot be projected from inside engine nozzle)

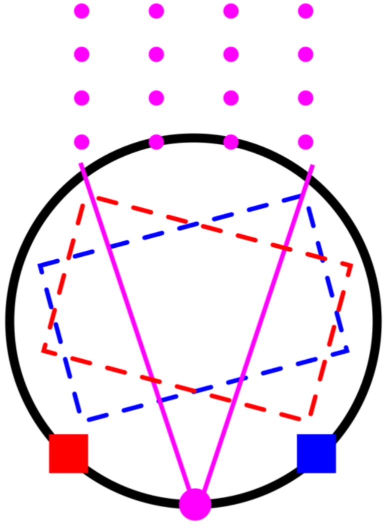


Lander Top View

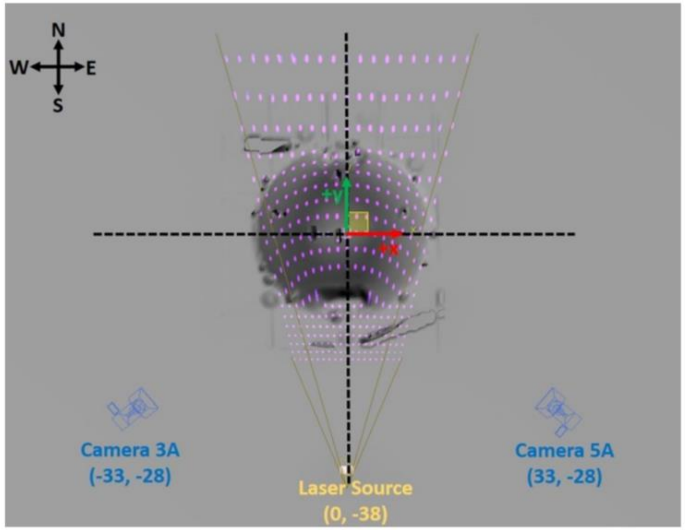
- Two schematics show grid moving outside imaging region at higher altitudes if grid projection is not adjusted
- Grid of 19 x 19 dots projected for all CAD renders



Lower Altitude



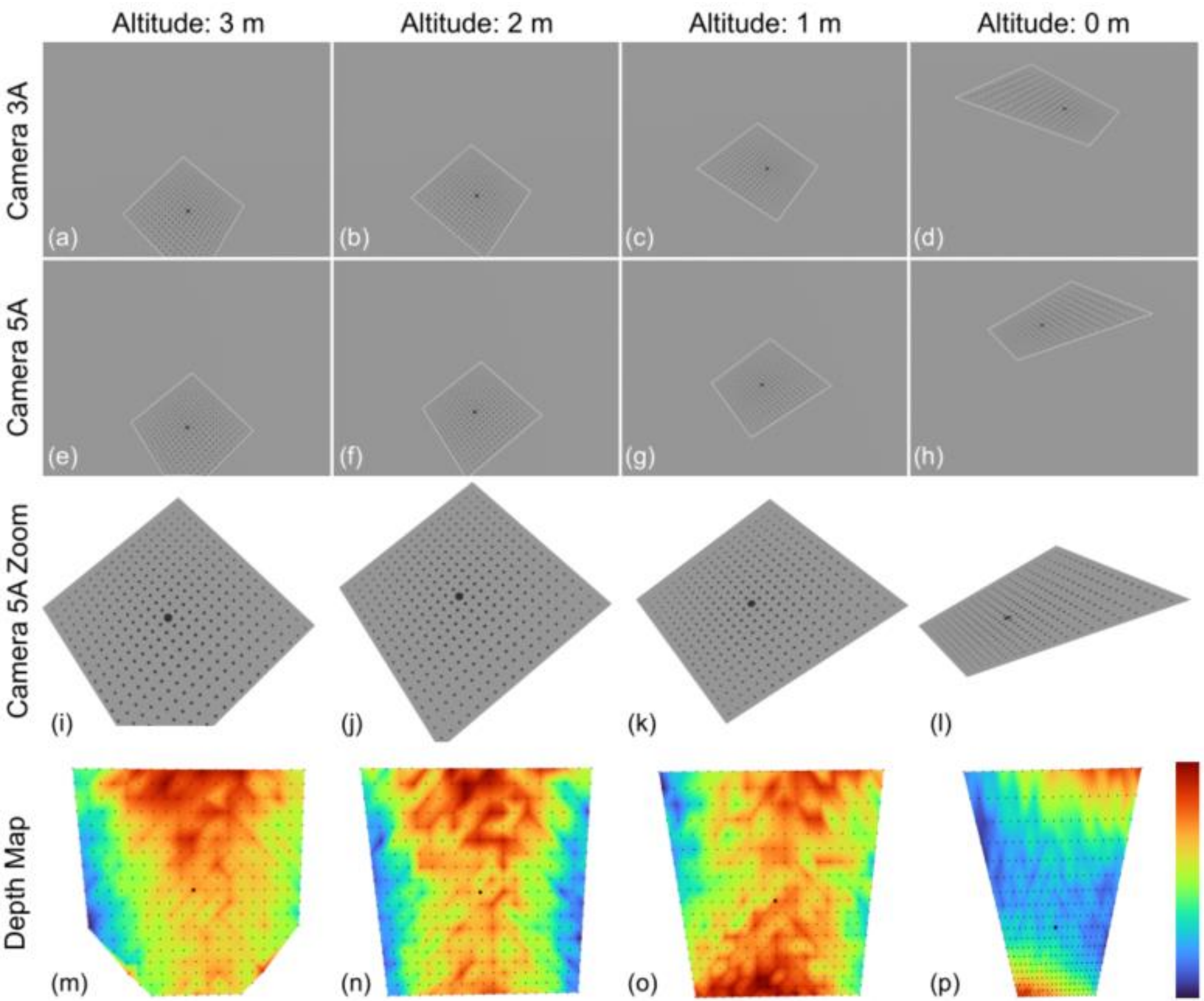
Higher Altitude



Crater Top View (Lander Invisible)

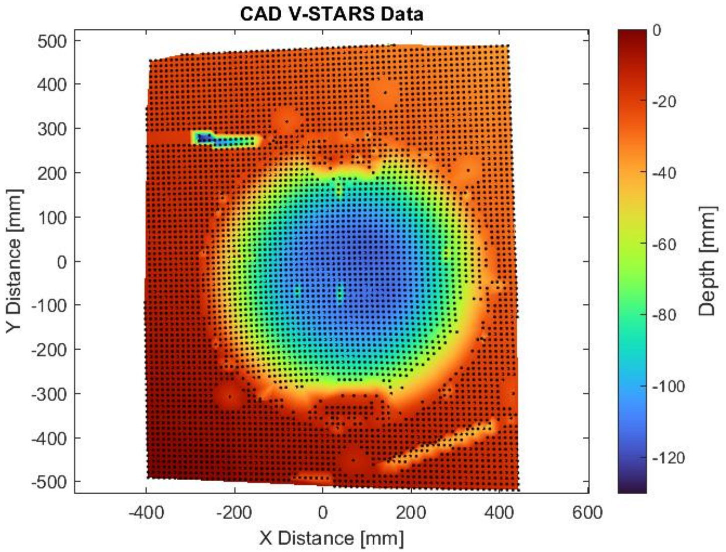
Computer-Simulated Concept Validation // Flat Ground

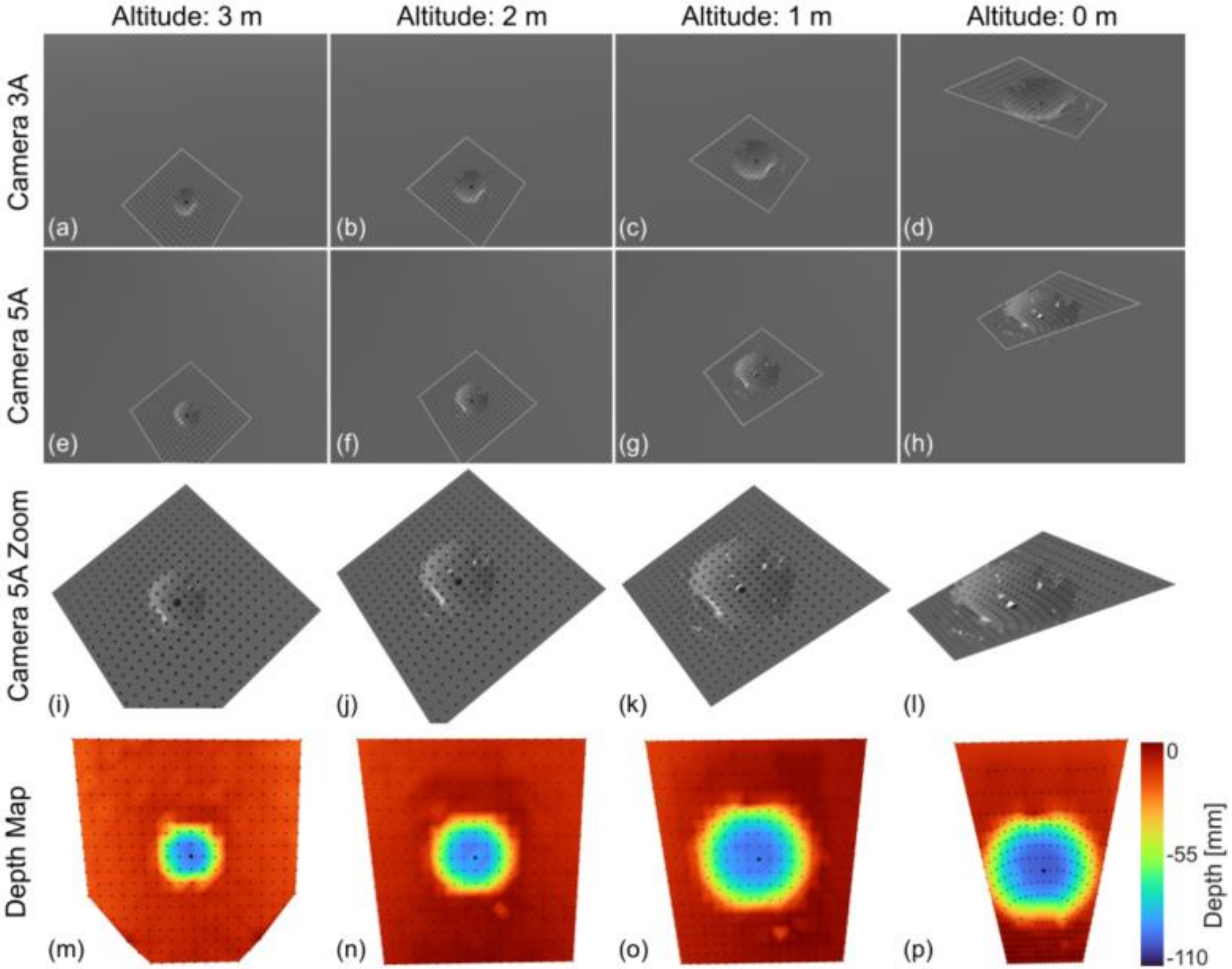
- Ten calibration images used for intrinsic camera calibrations, and four for extrinsic
- Renders of four altitudes for both cameras shown in top two rows
- Zoomed-in views of the projected grid for Camera 5A in third row
- Computed depth maps for each altitude in bottom row
  - Colorbar: (m) +/- 10 mm, (n) +/- 5mm, (o,p) +/- 2.5 mm
  - Terrain is generally flat, with larger errors at higher altitudes
  - Errors become skewed at lower altitudes
  - Check calibration and dot-center-finding algorithm



Computer-Simulated Concept Validation // Crater

- Using hemisphere-cap snow sled photogrammetric model for CAD render
- Computed depth maps for each altitude in bottom row
  - Depth of computed crater remains the same
  - More grid points define crater at lower altitudes



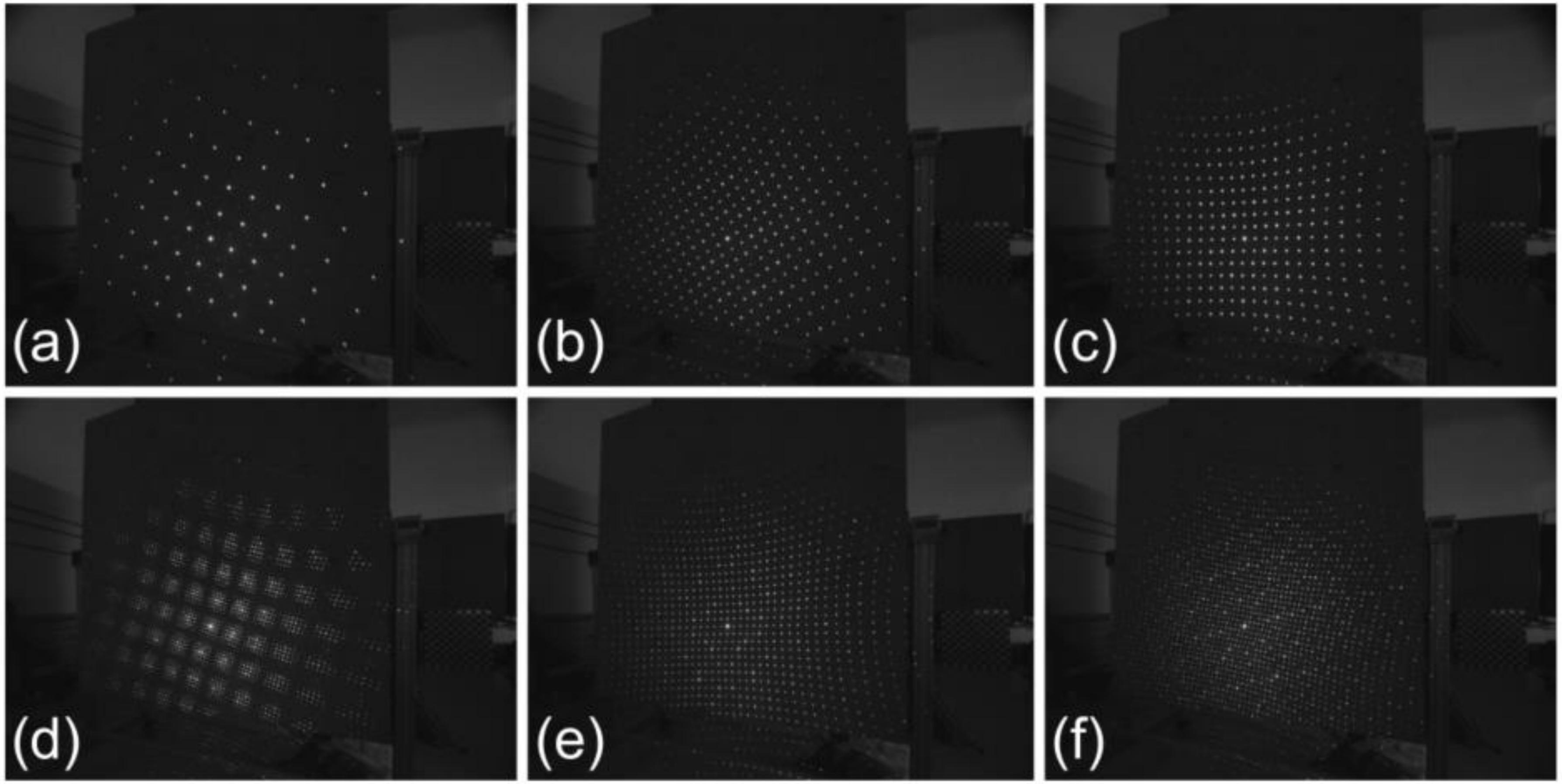


- Low-cost, off-the-shelf, USB-powered DOE (right image)
  - Includes two in-line DOEs, allowing for an adjustable pattern
  - Large angular divergence allows large spatial coverage at short distances

- Intermediate rotations of one DOE relative to the other changes the density of the projected pattern

- Six relative DOE rotations shown in (a-f)
  - Patterns in (a), (c), and (d) are used for results presented later

- Pattern adjustability can be useful for varying altitude measurements



Laser Grid Projection (2/2) // Single-Element DOE

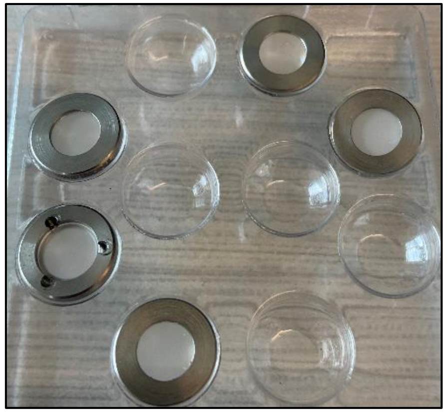
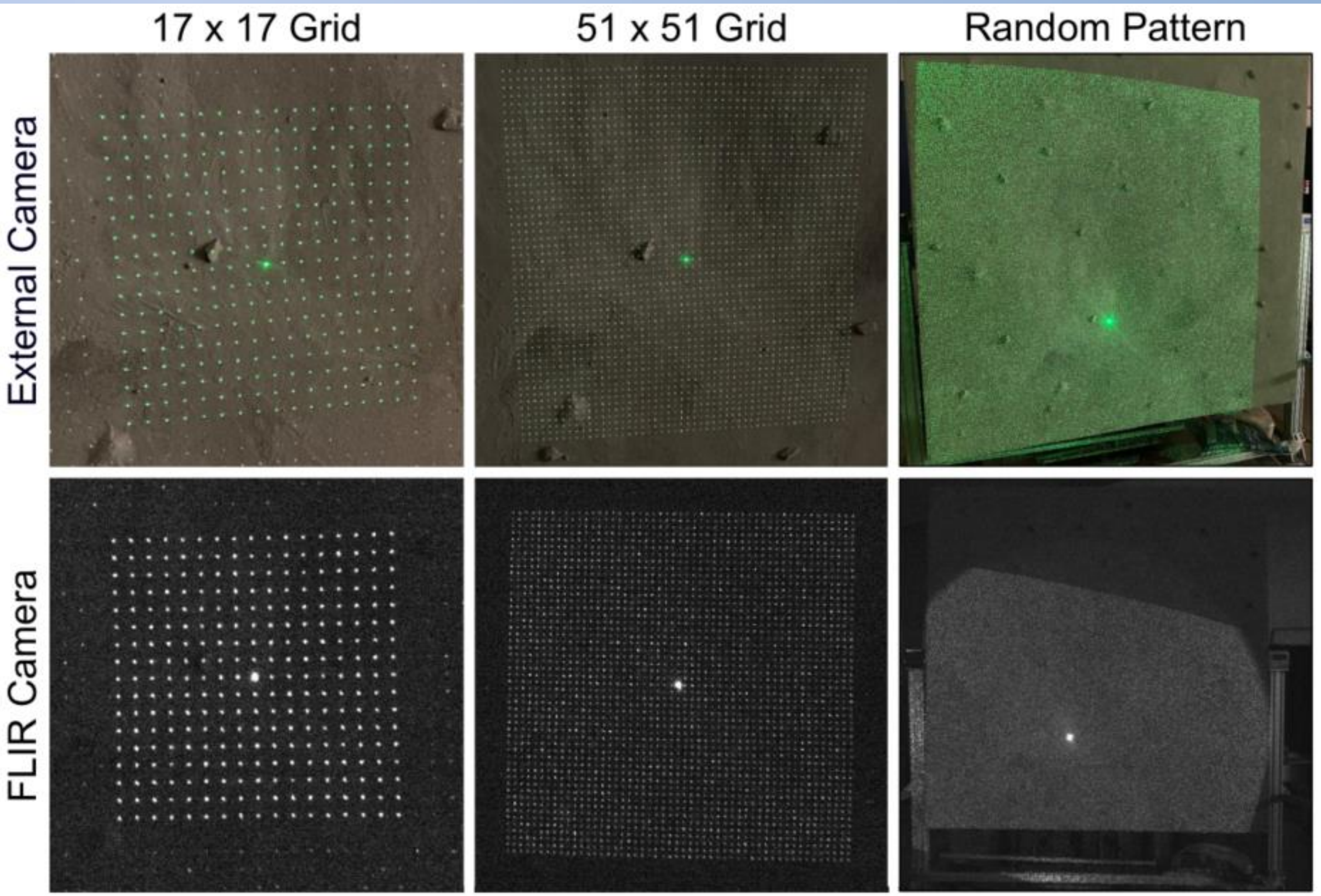


Image of five DOEs

- ~7.25 mm diameter unmounted
- ~12.5 mm diameter mounted

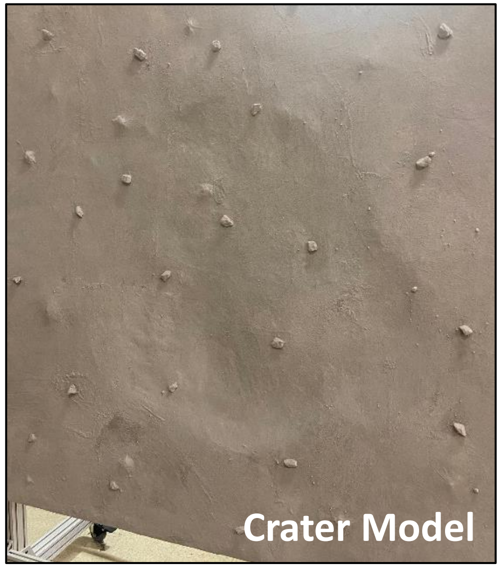
- Single-element, plastic DOEs used for regular grids and random patterns
  - Illuminated with a 532 nm laser
- Three DOE projected patterns shown at the right
  - Coarse 17 x 17 grid
  - Finer 51 x 51 grid
  - Extremely fine random pattern
- Bright central point uses power than could otherwise be distributed to surrounding points
  - However, provides a useful fiducial for location corresponding dots in the stereo images

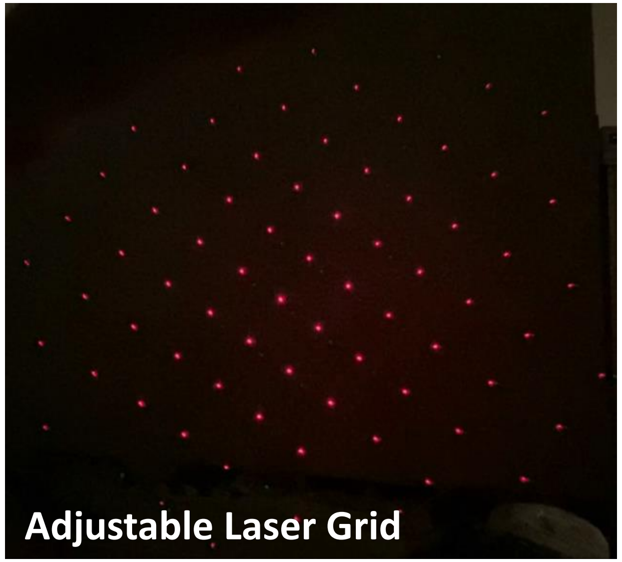


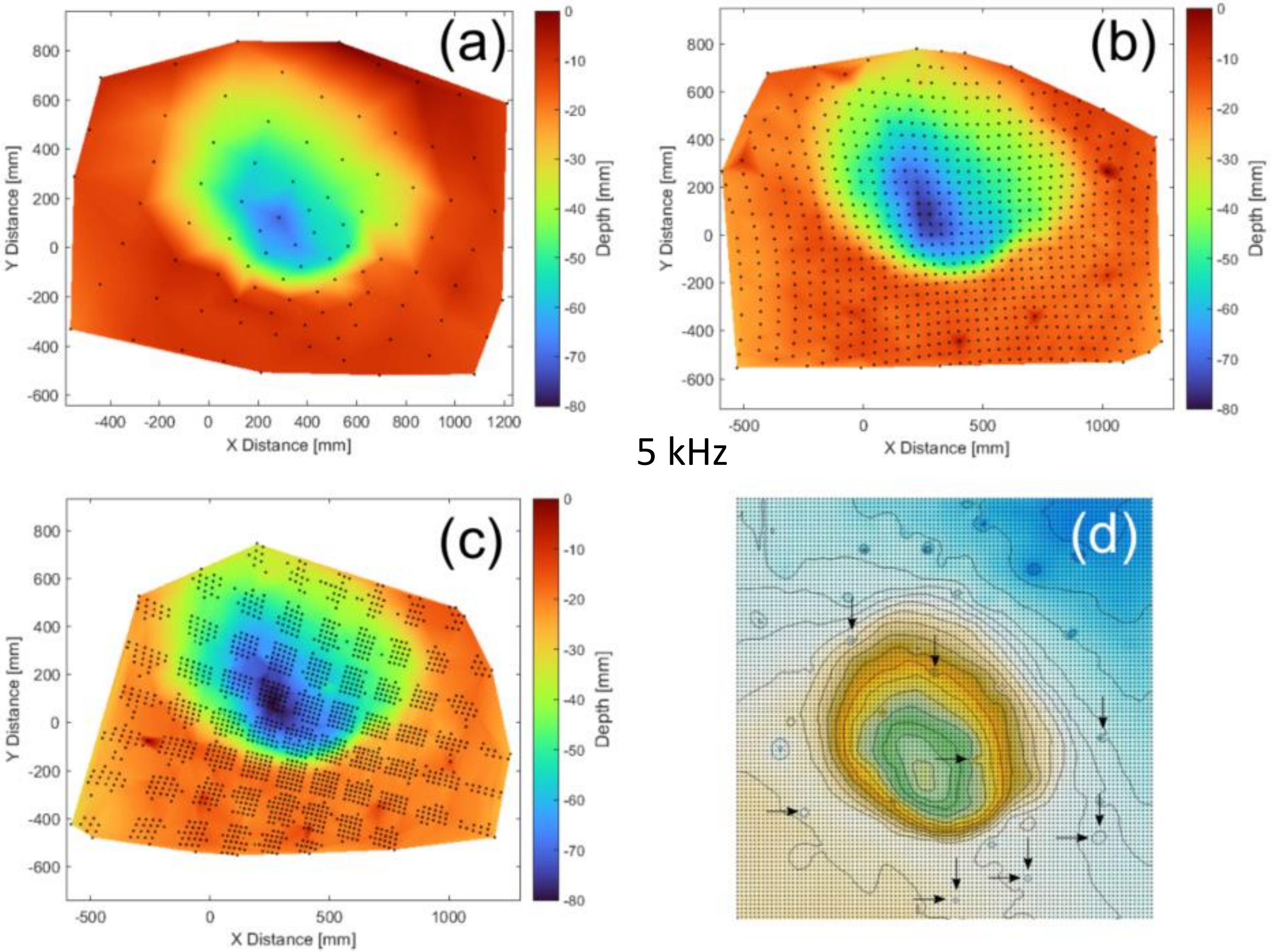
- Random dot pattern was not investigated in this manuscript
  - Has the potential to be used with a cross-correlation processing algorithm to yield higher spatial resolution than regular grid patterns

Fixed-Geometry, Large-Crater Results – Adjustable DOE

- Large (6’ x 6’), fixed-geometry crater model used with adjustable dual-DOE laser grid projection
- Three intermediate patterns used for depth map calculations
  - (a) Coarse, (b) medium, (c) fine
- Photogrammetric measurement of crater model (d) provides a ground-truth
  - Note: the crater shape changed between photogrammetric measurements and stereo imaging measurements, so only qualitative comparisons can be made here



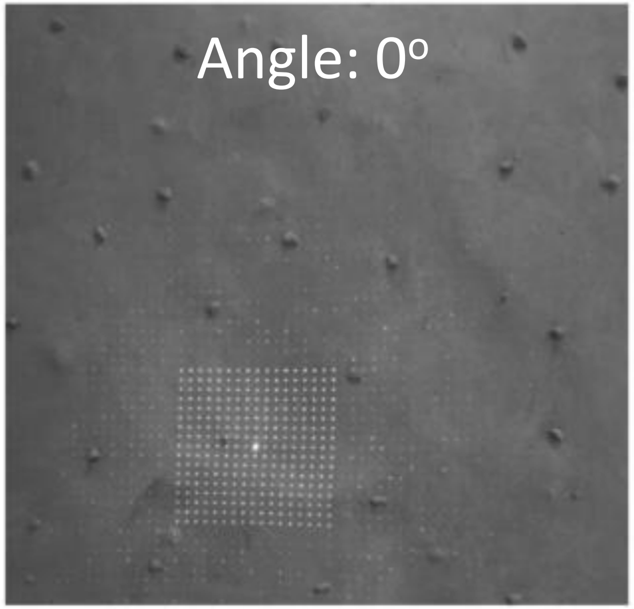


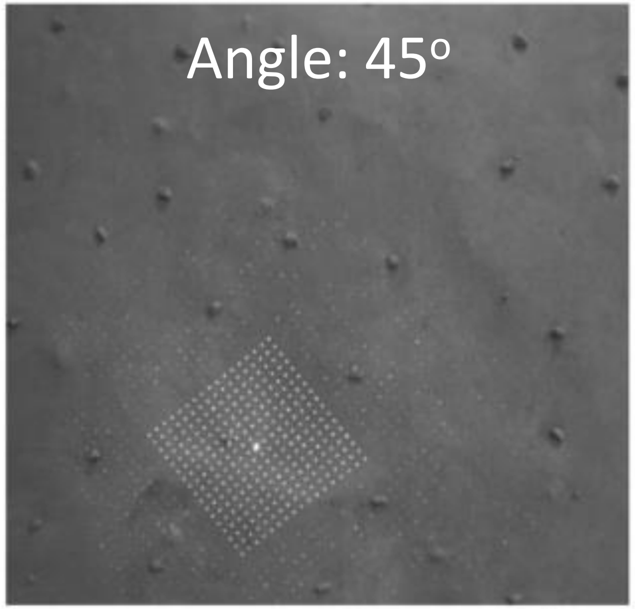


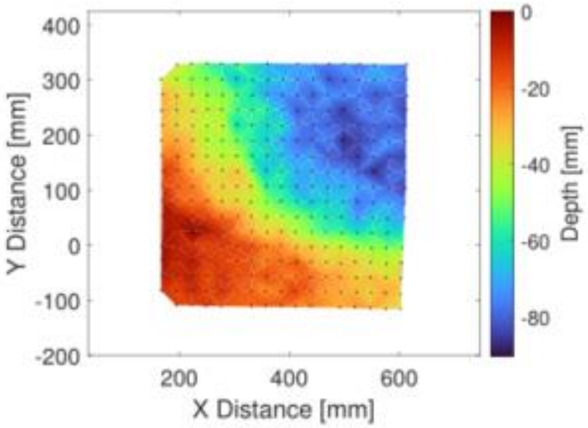
- All depth maps qualitatively match photogrammetric measurement
  - Some rocks are visible when a laser dot is projected onto the rock, and is visible in both cameras

Fixed-Geometry, Large-Crater Results – Single Rotating DOE

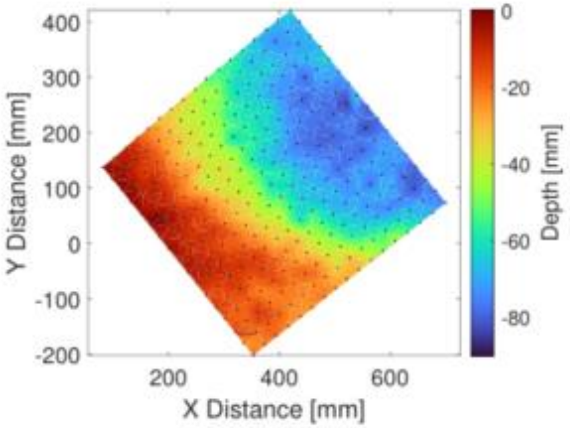
- Single DOE used with 532 nm laser illumination
- Rotated DOE to two distinct angles (0°, 45°) about its center point
- Coverage of crater is lower due to smaller angular divergence of the DOE used
- Depth maps for both angles show similar topography
- Post-processing combination of both depth maps results in higher spatial resolution



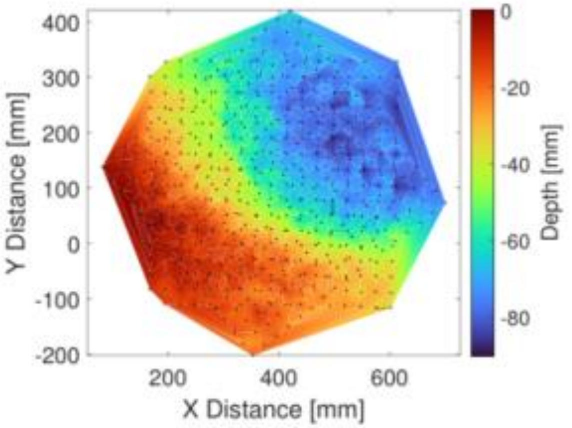




Angle: 0°



Angle: 45°



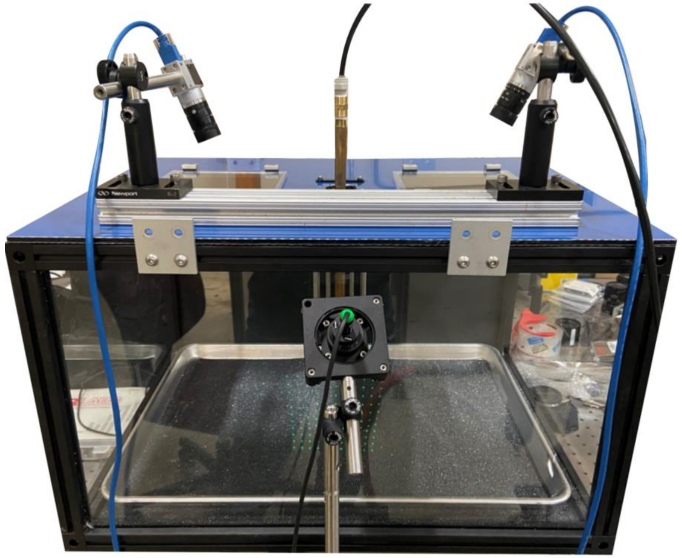
Combined

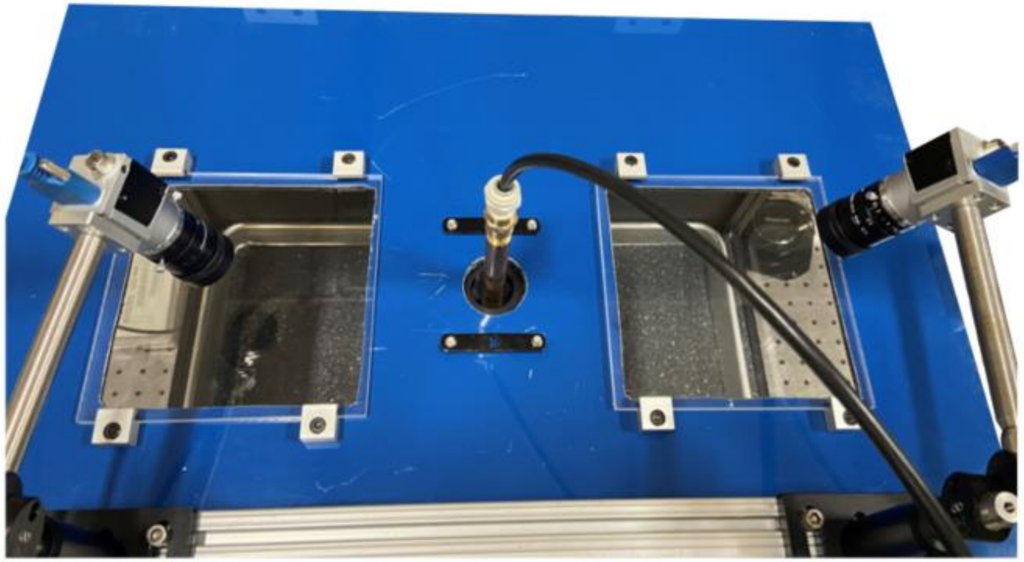
Plume-Surface Interaction Testing

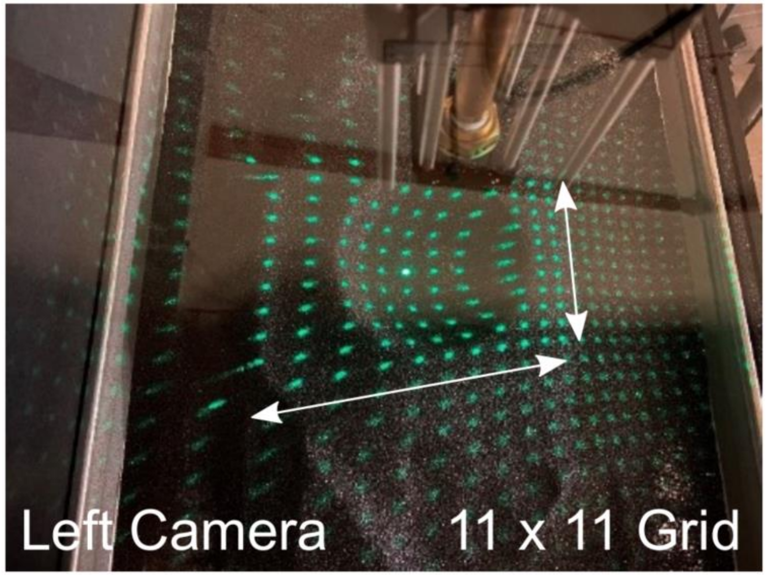
- Enclosure constructed, three full side windows, two small top windows
  - Side: shadow particle tracking
  - Front: laser grid projection
  - Top: stereo camera imaging

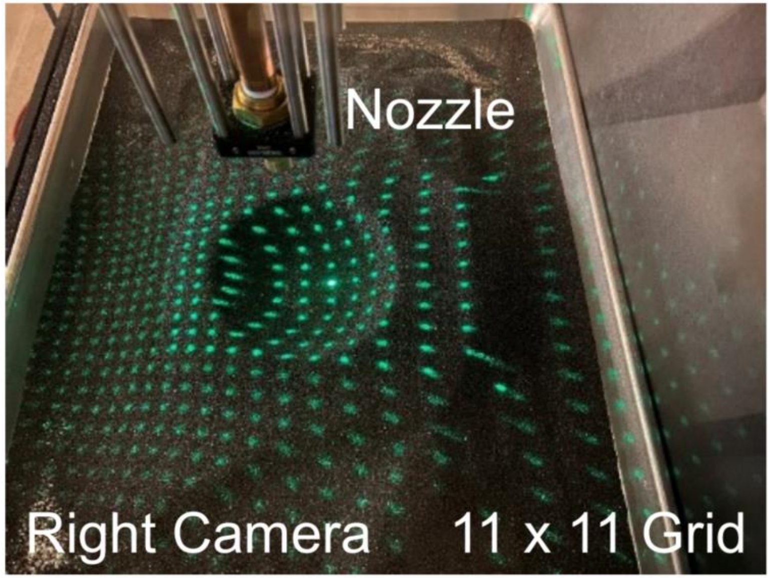
- PSI testing:
  - Cameras using 532 nm filter to attenuate other wavelength scatter from particles
  - Cameras triggered from same source and synced
  - Images acquired before, during, and after nozzle impingement on particle bed

- Bottom images:
  - Images through left-camera window and right-camera window show final crater shape with laser grid projection



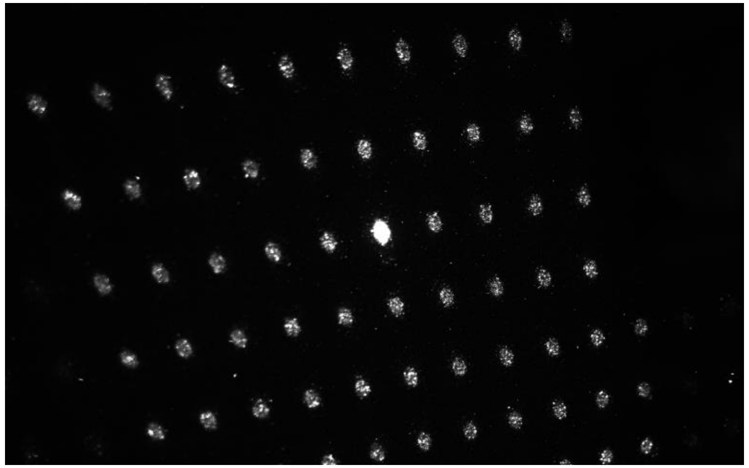


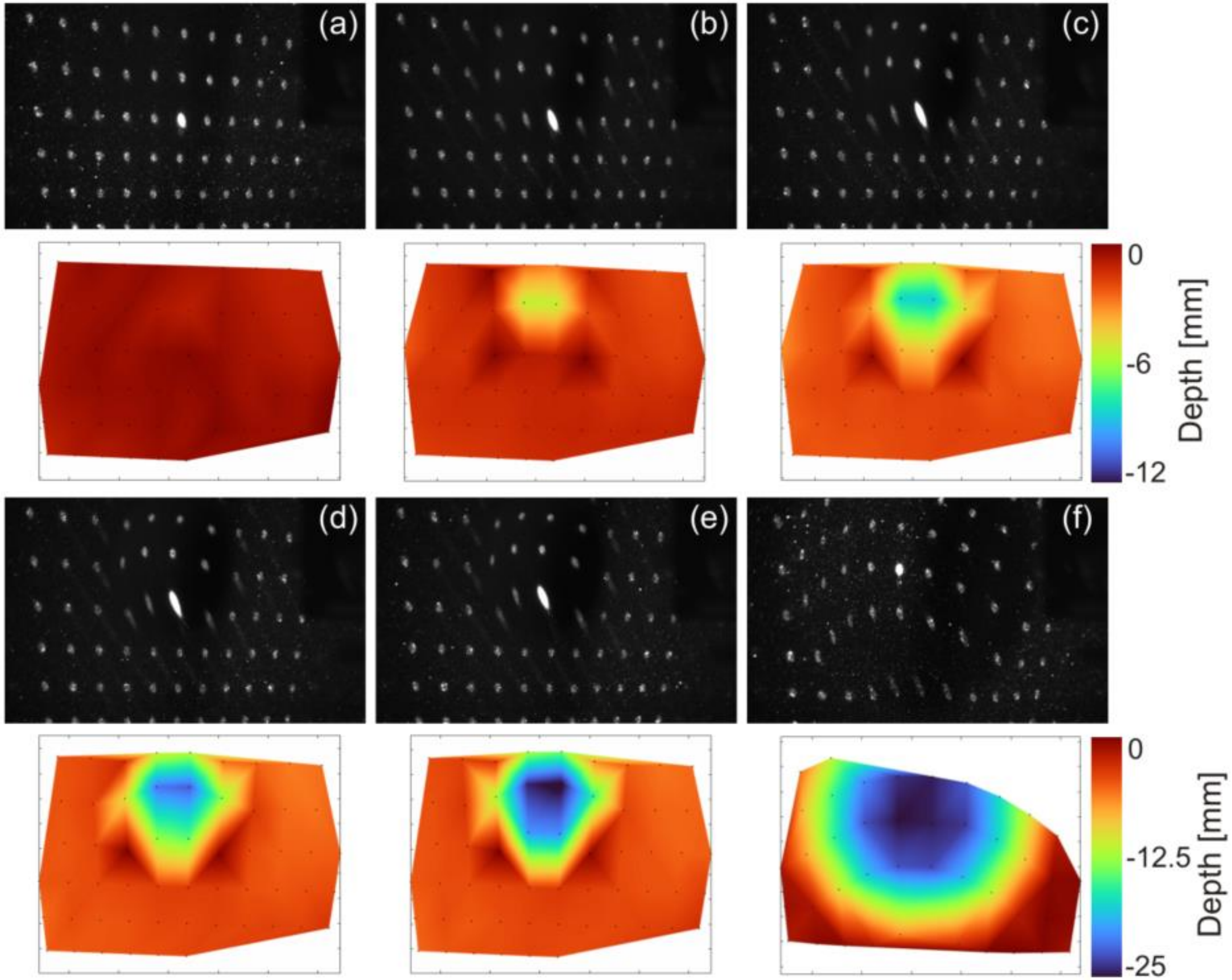




Plume-Surface Interaction Testing

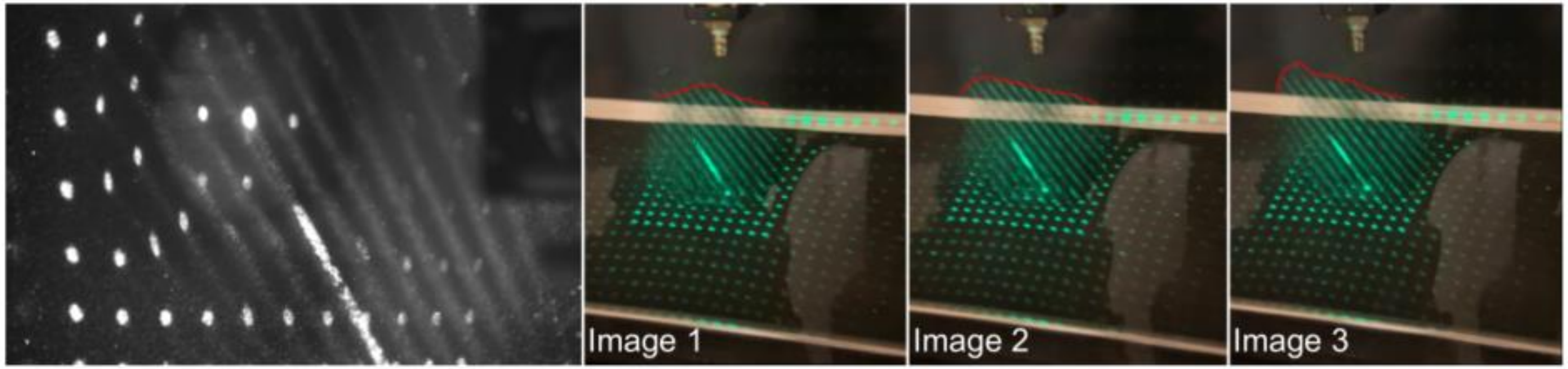
- First five frames acquired during PSI test, with computed depth maps below
  - Evolution of crater evident, but at low spatial resolution due to DOE choice
- Final crater terrain map at bottom right shows depth of approximately 25 mm
- Obscuration of dots from ejected particles visible in bottom video
  - Will cause crater depth map to have missing data points
  - Could be problematic during lander descent
  - May be useful for ejecta sheet monitoring

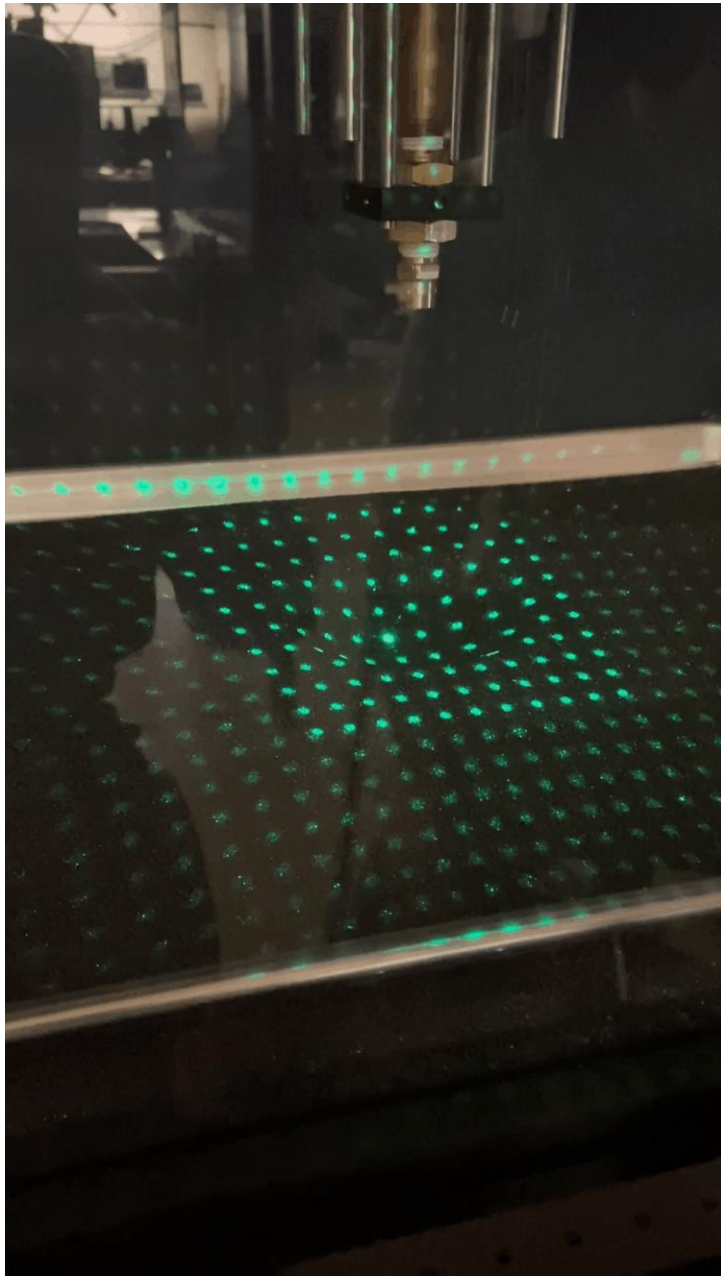




Ejecta Sheet Measurement and Mapping

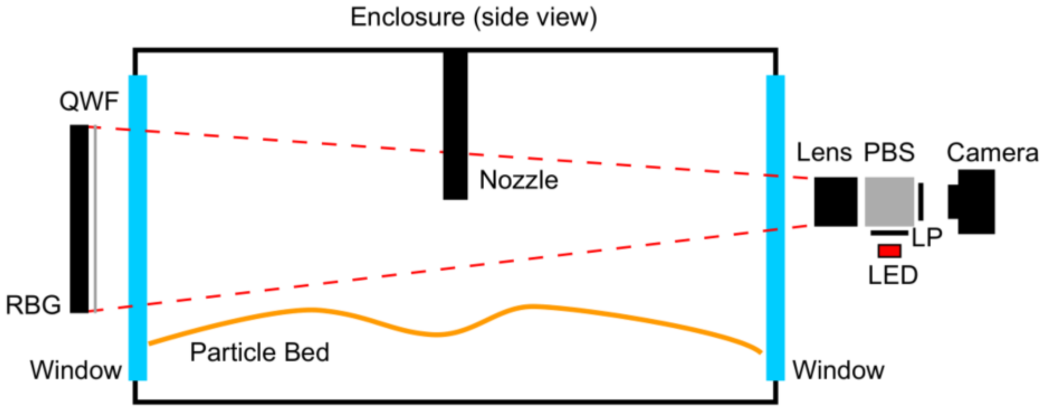
- Different viewing angles result in different scattered/reflected light from the laser grid
  - Right: Cell phone video changing perspective during a PSI test
- Determine the best way to define the edge of the ejecta sheet, and what will be useful for further testing
  - Bottom: Red lines in three images at bottom define "top" of ejecta sheet
- Stereo imaging of sheet for quantitative spatial sheet measurements

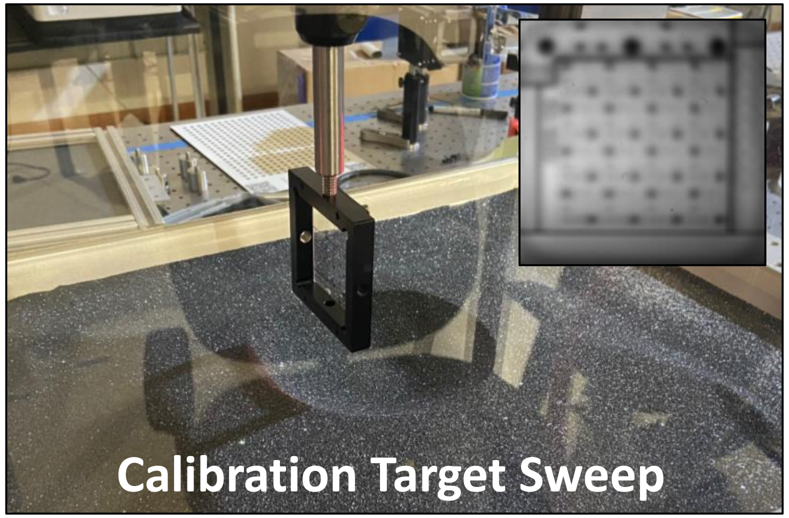


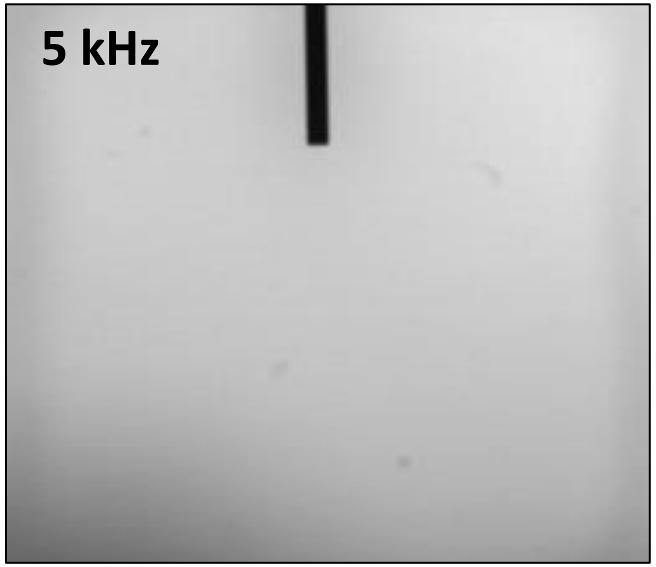


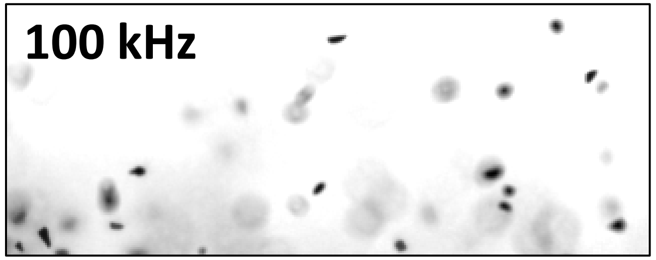
Front-Illumination Shadow Particle Tracking

- Typical particle tracking systems use back-illumination to image shadows of the particles on the camera sensor
- Projecting light from same side as camera front-illuminates particles, with light reflecting on other side at a retroreflective background
  - Useful for testing with limited optical access on the opposite side
  - Able to measure particle size/shape/position, number density, particle velocities (from two frames), and mass flux
- Calibration target swept through focus to provide depth-of-field information
- Two frame rates (and field-of-views) demonstrate:
  - Sharply focused particles at the plane of focus
  - Blurred particles away from plane of focus
  - Velocity and size or particles can be determined



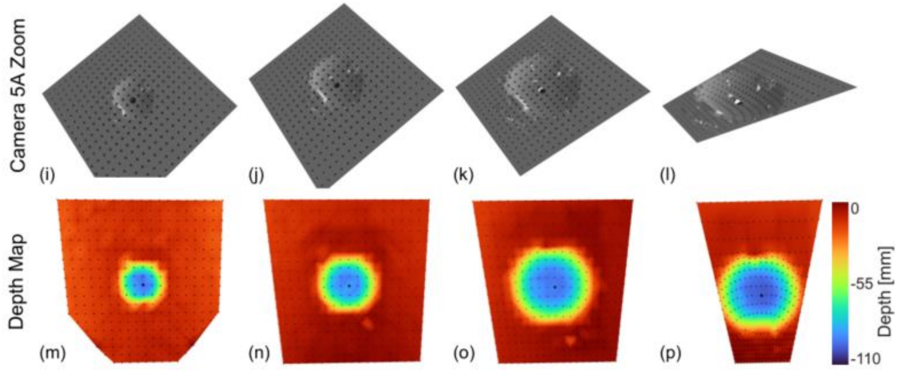

Calibration Target Sweep

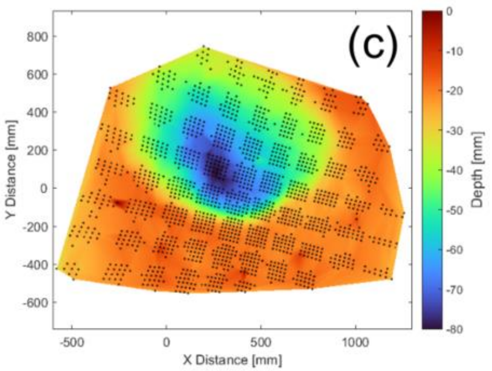

5 kHz

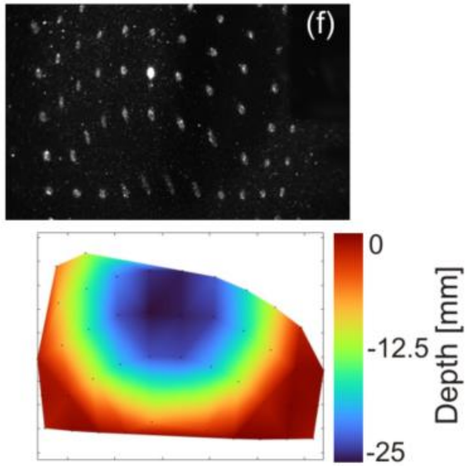

100 kHz

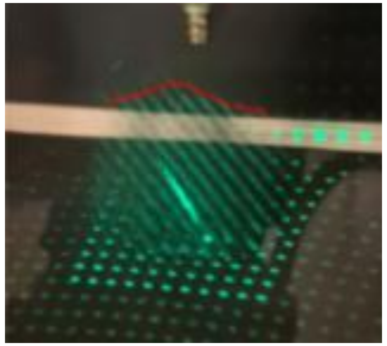
What Was Accomplished

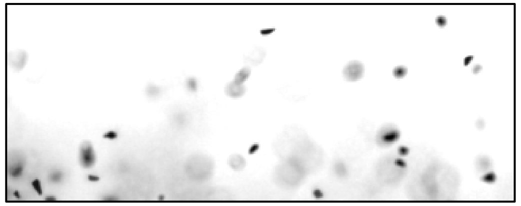
- Computer-simulated validation of structured laser illumination concept using both flat ground and crater renders
- Qualitative validation for large-scale fixed-geometry crater model measurement
  – Dual-DOE adjustable grid projection
  – Single-DOE fixed grid projection
- Small-scale, plume-surface interaction test with laser grid projection and depth map calculations
- Potential feasibility of ejecta sheet measurements
- Front-illumination shadow particle tracking for ground test measurements











SCALPSS References:

[1] Thompson et al., "*Stereo Camera Simulation for Lunar Surface Photogrammetry*," AIAA SciTech 2021 Forum, AIAA-2021-0358.

[2] Tyrrell et al., "*Design of a lunar plume-surface interaction measurement system*," AIAA SciTech 2022 Forum, AIAA-2022-1693.