National Aeronautics and
Space Administration

PSI Flight Measurement Development Status

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Plume-Surface Interaction (PSI) - Why is it important?

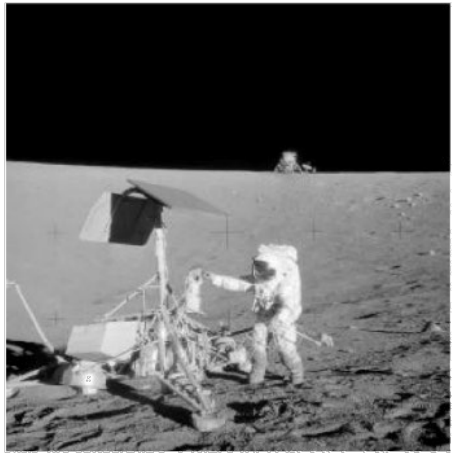
- Lunar dust is a significant obstacle to achieving a sustainable human presence on the Moon, and lunar landers will be a major source of dust transport across the lunar surface.

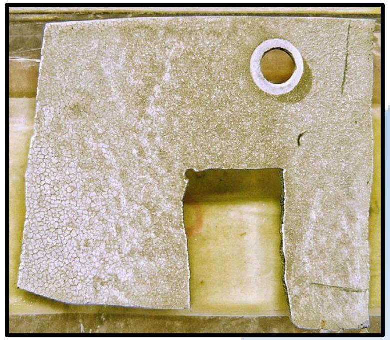
- ***There is currently a lack of lunar flight data from plume-surface interaction (PSI) effects during descent and landing which is necessary to anchor computational and engineering models to be used to enable safe and low risk design of future landers, surface elements and surface operations.***

Dust

Blowing Rocks

Terrain Modification

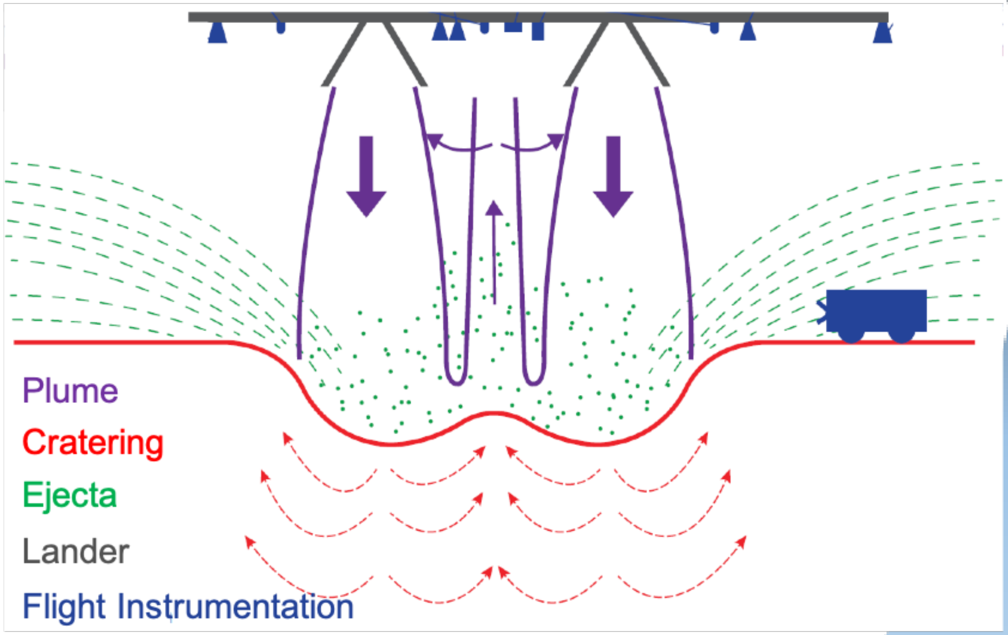




Sandblasting of Surveyor III by Apollo XII

Understanding PSI

- Rocket plume-surface interaction (PSI) is a complex, multi-phase discipline that describes the lander environment due to the impingement of hot rocket exhaust on the regolith of planetary bodies.
- Understanding PSI means understanding the effects of, and being able to correctly model the:
  - surface regolith
  - rocket plume
  - erosion of the surface
  - characteristics of the ejecta (what and where)
  - induced environments underneath the lander
- Facilities and/or capabilities for ground testing (e.g., full scale engines in a vacuum into lunar regolith) do not currently exist.
  - Current (and planned) ground test data still requires significant extrapolations for estimating CLPS (and HLS) scale effects.



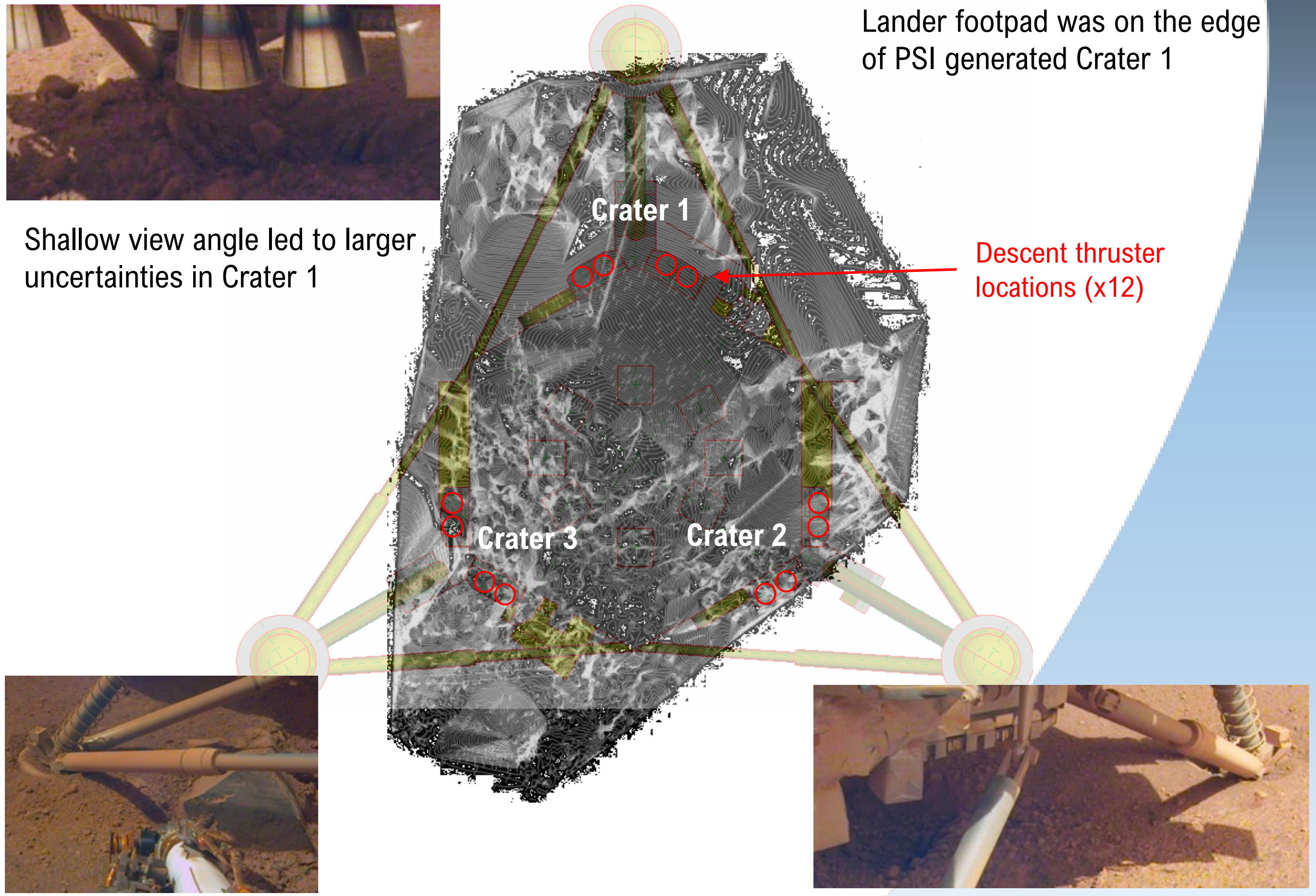
plume-surface interaction

spacecraft rocket exhaust interacting with unimproved planetary surfaces

fluid granular physics

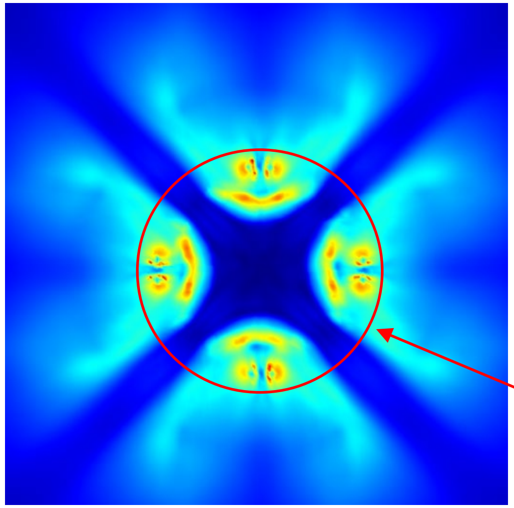
Measuring Erosion With Stereo Photogrammetry

- Stereo Photogrammetry can be used to determine the location of a physical object in 3D space through the process of comparing 2 or more images of that object taken from known relative locations.
- This process can be extended to generate a 3D map of a surface (e.g., Digital Elevation Map).
- Attempts have been made to measure erosion due to PSI during previous Mars landings (e.g., InSight) using "pseudo" photogrammetry.
  - data collection was added to the operations plan AFTER landing rather than prior to launch
  - utilized existing camera(s) to take multiple images from 2 or more locations (e.g., via robotic arm)
  - uncertainty in camera characteristics, location and pointing introduces **significant** errors to the measurement



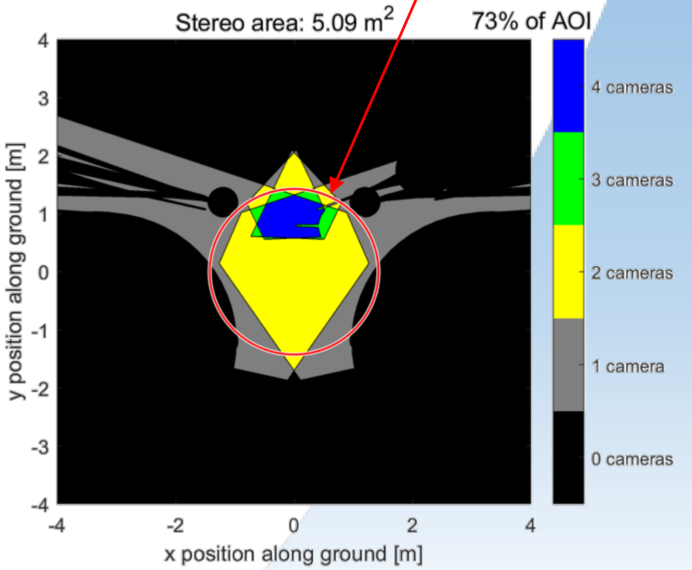
SCALPSS Overview

- The Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) is the first ever dedicated instrument for directly measuring PSI erosion accurately from the lunar surface.
  - pre-flight camera characterization and calibration (e.g., distortion coefficients)
  - high resolution images from known (e.g., measured and calibrated) camera locations and with known pointing directions (e.g., external calibration)
- Future versions of the SCALPSS instrument will also be able to take measurements of the ejecta sheet using a (laser or passive) dot grid projection system.



SCALPSS 1.1 (Blue Ghost) pre-flight prediction of erosion using CFD

lander diameter

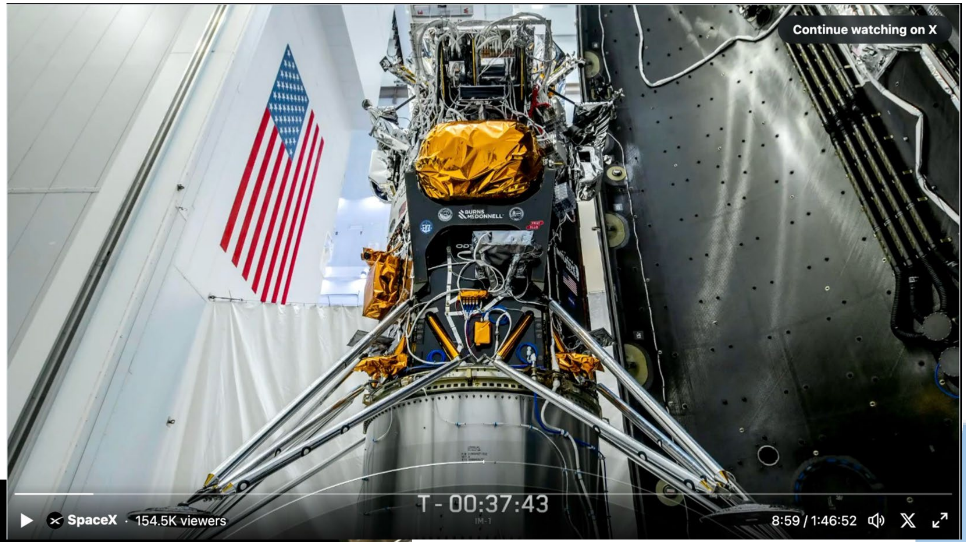


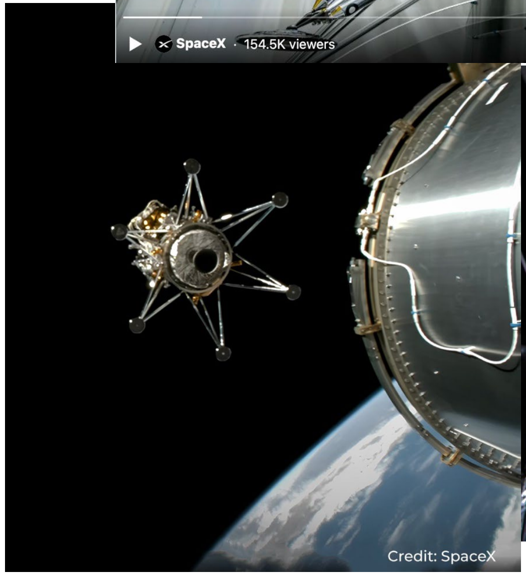
SCALPSS 1.1 (Blue Ghost) estimated stereo coverage using 2-4 cameras *(increased data reduces uncertainties in measurement)*

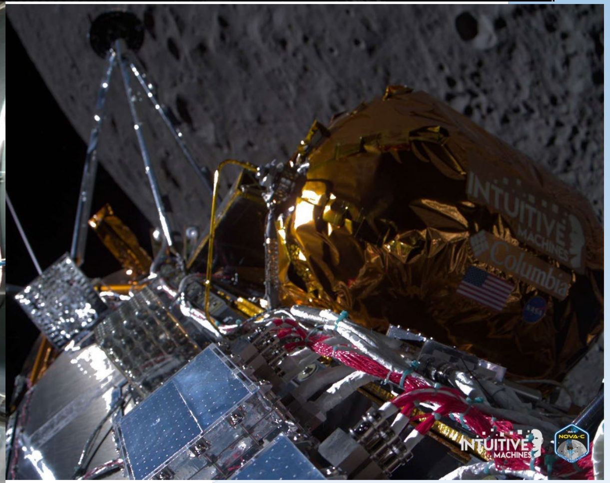
SCALPSS 1.0 (CLPS / Intuitive Machines)

Funded by SMD/NPLP (CLPS TO2) beginning in FY19.

- Primary Objective: Collect stereo images of the disturbed lunar surface post landing to estimate the volume of regolith eroded due to PSI.
- Secondary Objectives: Collect stereo images during descent (possibly beginning prior to the onset of PSI)
- Configuration: 4 ea. 3.2 MP cameras (3.37mm focal length) on individual camera mounts, Data Storage Unit, USB Hub *(Mars2020 EDLCam heritage)*
- Payload Delivery: October 2020
- Payload Integration to Lander: August 2023
- Launch: 15 February 2024
- Lunar Orbit Insertion / Landing : 22 February 2024

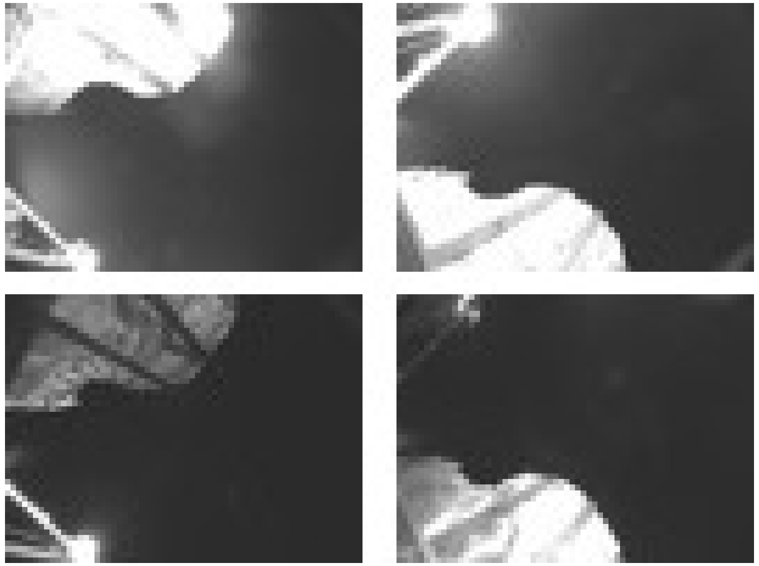


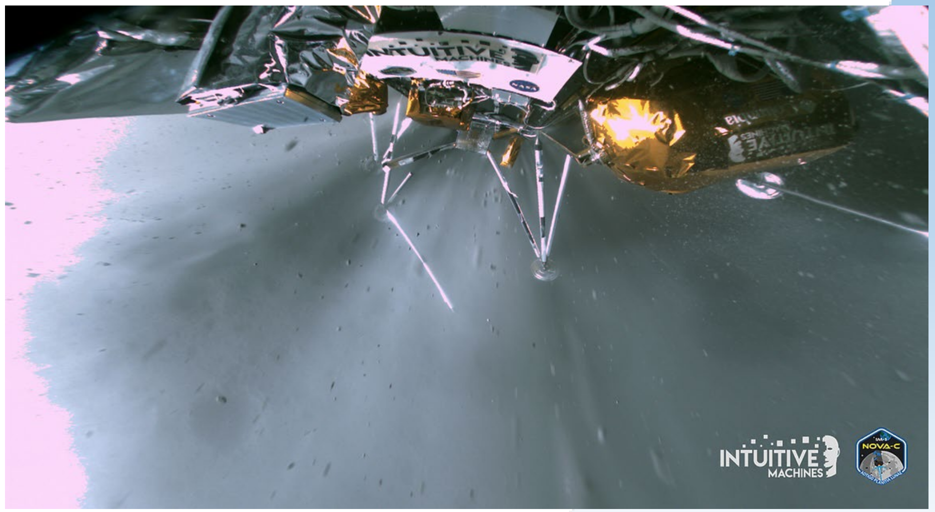

Credit: SpaceX



SCALPSS 1.0 Payload Performance

- The SCALPSS 1.0 payload did survive launch and was able to perform a nominal transit checkout.
- The lunar orbit checkout was canceled due to troubleshooting being done on the lander.
- During descent, the payload was not powered on as expected due to erroneous altitude data on the lander resulting in a faster than expected descent and ”hard/skip” landing.
    - evidence seems to indicate that the payload was powered on at the correct “time”, however, the lander was already on the ground at that point
- Due to these and other lander faults as well as the final lander orientation (on its side), no PSI data was collected.
- Late in the surface mission (day 5 of 6-day surface mission), **the payload was able to operate successfully on the lunar surface** in both “checkout” and “manual” modes.
    - one camera was inoperable due to high temperatures (predicted)
    - lander FSW was updated to utilize redundant command channel
    - due to the lander orientation and sun position, images taken were oversaturated
    - the payload team was not given the opportunity to correct for this and collect additional imaging data

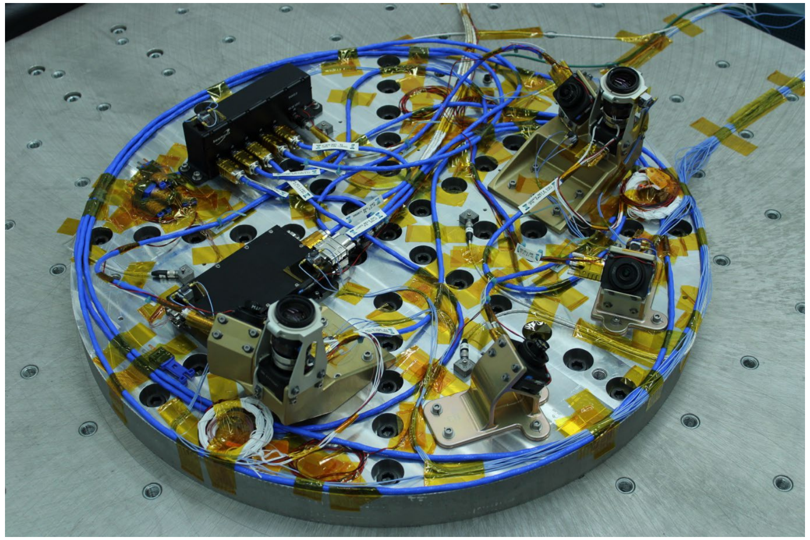




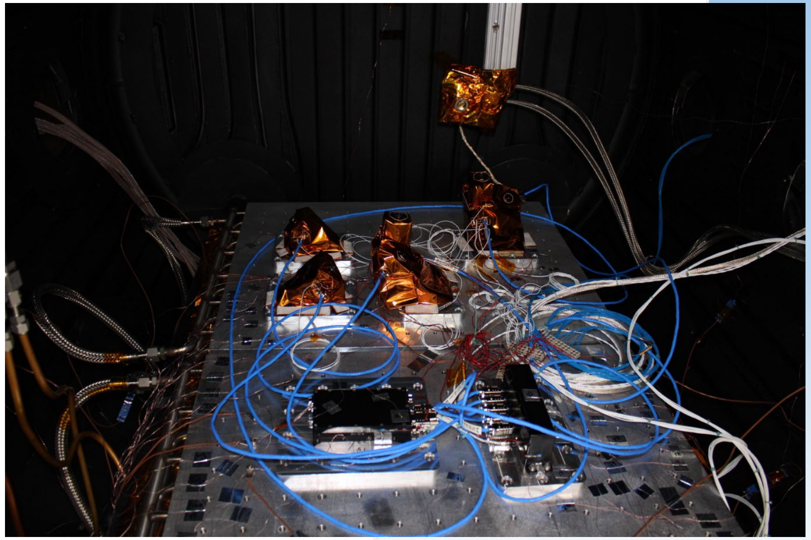
SCALPSS 1.1 (CLPS / Firefly Aerospace)

Funded by STMD/GCD (CLPS 19D) beginning in FY20.

- Primary Objectives: Collect stereo images of the lunar surface prior to being disturbed (pre-PSI), during descent (transient), **and** post landing to better estimate the volume of regolith eroded due to PSI; determine when PSI onset occurred.
- Secondary Objectives: Detect and measure ground obscuration due to PSI ejecta.
- Configuration: 6 ea. 3.2 MP cameras (2 @ 3.37mm, 2 @ 5.4mm, and 2 @ 50mm focal lengths) on 4 camera assemblies, Data Storage Unit, USB Hub (*SCALPSS 1.0 heritage*)
  - utilizes full data handling capabilities of DSU design
- Payload Delivery: October 2022
- Payload Integration to Lander: April 2024
- Launch: “late 2024”
- Lunar Orbit Insertion / Landing : “early 2025”
  - ~30 day lunar transit
  - ~15 days in lunar orbit



SCALPSS 1.1 Vibration Testing

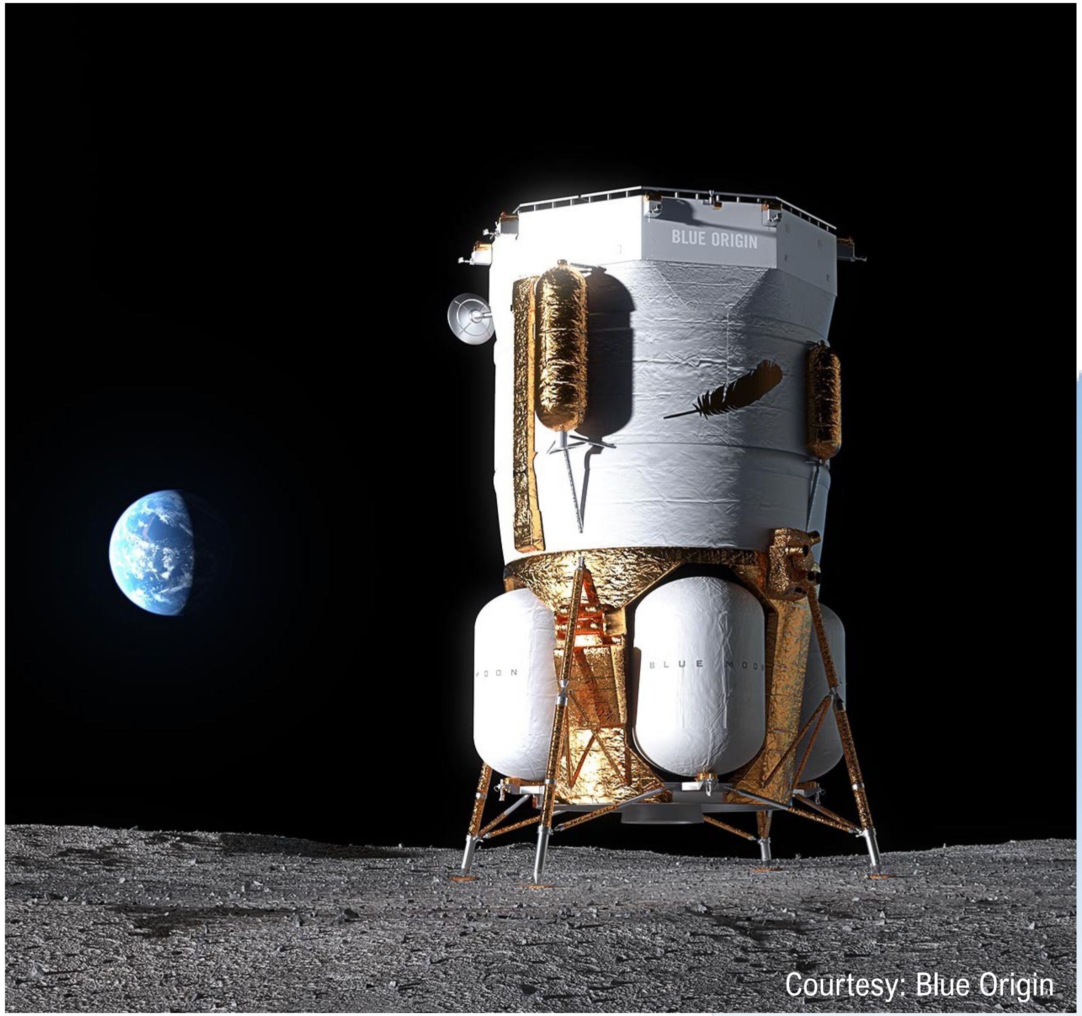


SCALPSS 1.1 TVAC Testing

SCALPSS 1.x (Blue Origin Mk1-SN001)

Funded by STMD/GCD and SMD (CLPS CT-3) beginning in FY24 as part of the SCALPSS 1.1 Project utilizing spare SCALPSS 1.0/1.1 hardware.

- Primary Objectives: Collect stereo images of the lunar surface prior to being disturbed (pre-PSI), during descent (transient), **and** post landing to estimate the volume of regolith eroded due to PSI; determine when PSI onset occurred.
- Secondary Objectives: Detect and measure ground obscuration due to PSI ejecta.
- Configuration: 4 ea. 3.2 MP cameras (3.37 mm focal lengths) Data Storage Unit, USB Hub *(SCALPSS 1.1 heritage)*
    - utilizing custom camera mount design optimized for Mk1 lander
- Payload Delivery: Dec 2024
- Payload Integration to Lander: ”early 2025”
- Launch: March-May 2025

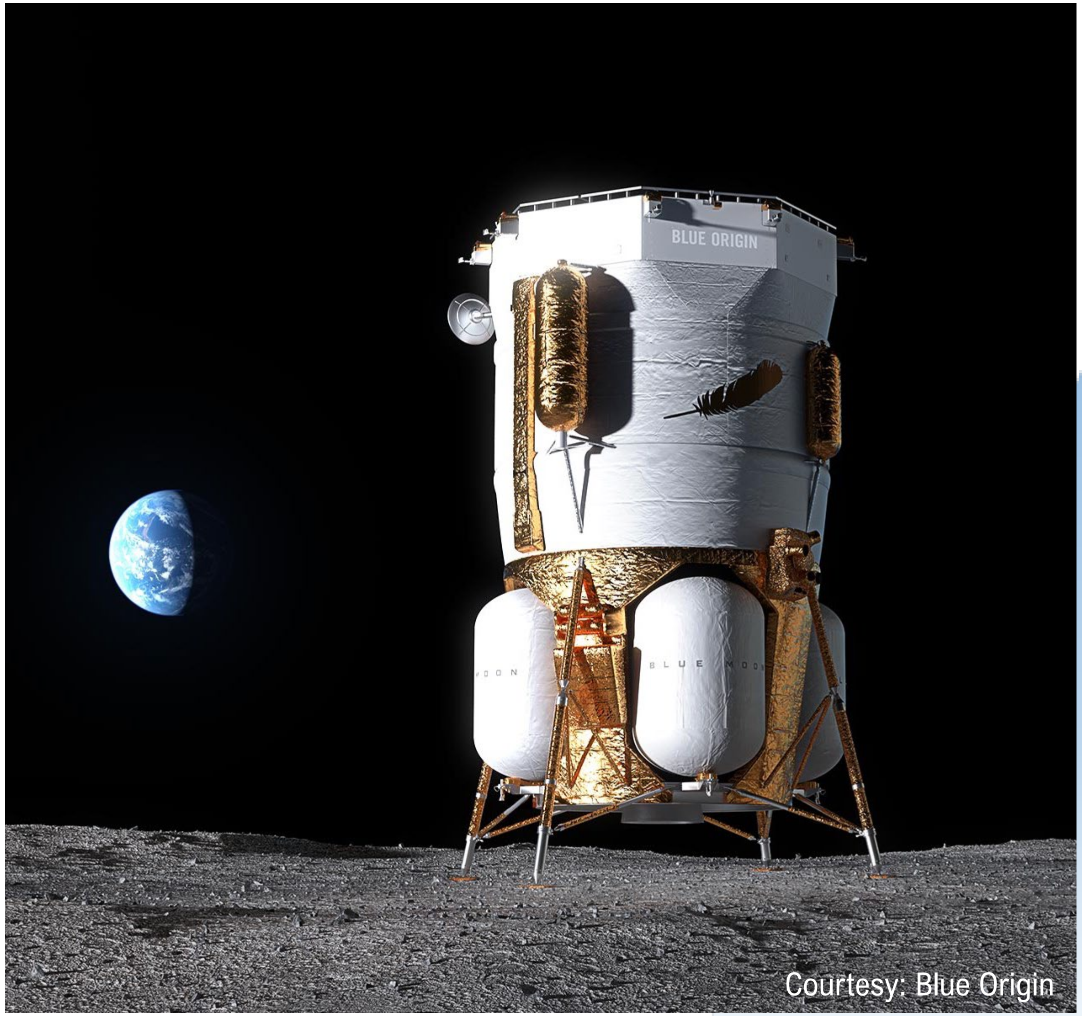


Courtesy: Blue Origin

SCALPSS 2.0 (Blue Origin Mk1-SN002)

Funded by STMD/GCD beginning in FY24 as part of the PSI Instrumentation Project.

- Primary Objectives: Same objectives as SCALPSS 1.1 *with improved coverage and/or resolution*, and the addition of measurements of the ejecta sheet structure (ejecta angles, sheet morphology, etc.)
- Secondary Objectives: Measure ejecta particle size and velocity.
- Configuration: 6 ea. **12.3 MP** cameras (3.37 - 50mm focal lengths), Mini-Suite Electronics (MSE-lite), and laser dot grid projector
    - will also test a passive reflector for generating dot grid
- Payload Delivery: December 2025 (TBR)
- Payload Integration to Lander: March 2026 (TBR)
- Launch: “mid 2026” (TBR)
- Lunar Orbit Insertion / Landing : TBD



Courtesy: Blue Origin

Moving Forward – PSI Instrumentation

- In FY24, the PSI Instrumentation (PSII) Project was established to manage the following activities:
  - Development and operation of photogrammetry measurement system in support of the HLS PSI Ground Test in FY24-25.
  - Development of Stereo CAmeras for Lunar Plume-Surface Studies (SCALPSS) 2.0.
  - Development of Mini-Suite Electronics (MSE) which is a centralized payload control and data storage and transfer to simplify interface with lander to multiple sensors of varying (interface) types.
    - MSE-lite is a smaller version of the MSE with a focus on LAN interfaces for a SCALPSS 2.0 imaging system.
- The PSII Project is also beginning to coordinate with STMD/STED on expanding current PSII activities, including:
  - Manifest SCALPSS 2.0 payload for future CLPS opportunities.
  - Re-start of PSI Mini-Suite payload development
  - PSI payload / instrumentation support on future HLS and Artemis opportunities.

PSI Mini-Suite

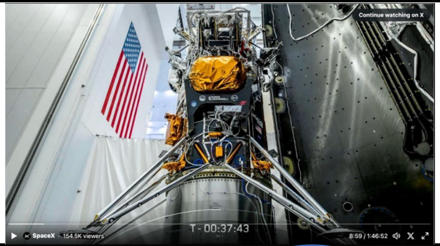
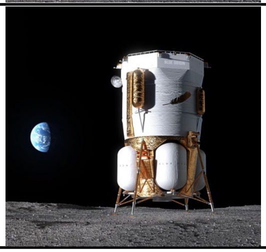
- As early as FY25, the PSII Project hopes to restart development of the PSI Mini-Suite Payload
  - Formerly known as CLPS PSI Mini-Suite (or PLUMES) Project in FY23
  - This will significantly expand the types of flight data available for PSI model development and verification
  - Intended to be compatible with CLPS, HLS, and/or Artemis
- Mini-Suite Electronics (currently in development as part of PSI Instrumentation Project)
  - An expanded version of MSE-lite used for SCALPSS 2.0
  - Improved data interface(s) to lander (100+ Mbps capability)
  - Improved data handling capabilities
  - Capable up to 2 GBbs write speed to memory
  - Designed to be modular, flexible, and expandable to accommodate additional sensors with various data interfaces (e.g., serial, USB, LAN, LVDS, Spacewire, etc.)
  - Smart power management / switching capability for sensors
- Will accommodate SCALPSS 2.0 along with other PSI sensors in development, ***for example***:
  - Lunar Lander Base Instrumentation (LLBI): Measure the environment induced (temperature, heating, and pressure) below the lander base by landing thruster(s) and PSI. (LaRC)
  - Particle Impact Event (PIE) Sensor: Measure velocity/energy of regolith particles from PSI. (GRC)
  - Dust Ejecta Radar Technology (DERT): millimeter-wave doppler radar measurement of particle velocity and direction of particles resulting from PSI. (KSC)

Summary

- PSI creates significant safety and operational risks to lunar landers, surface assets in the vicinity of the lander, and the landing site itself.
- As a first of its kind, SCALPSS will provide the much-needed flight data to validate the design tools to be used for designing the next generation of lunar exploration.
- Although unable to collect PSI data, the SCALPSS 1.0 payload was able to verify that the hardware could successfully operate in the lunar environment.
- The SCALPSS 1.1 payload, with its flight planned for late this year, is ready to provide a wealth of data and information regarding the PSI erosion for CLPS scale landers.
- The SCALPSS 1.x payload on the Blue Origin Mk1 test flight will add to this information by providing data at much larger lander thrust level (close to HLS-scale).
- The next generation SCALPSS instrument, SCALPSS 2.0, will build upon the capabilities and successes of the SCALPSS 1.0/1/x payloads by improving the quality of the erosion data, while also attempting to collect the first direct measurements of the ejecta environments.
- The capabilities of the MSE under development should enable the flight of a full PSI suite of sensors, to collect data in all areas of interest (erosion, ejecta, induced environments) in preparation for a sustained human presence on the lunar surface.

Backup

Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) Current Flight Opportunities

	Lander	Configuration	Status
SCALPSS 1.0	• CLPS TO#2 – Intuitive Machines • Payload Delivered: October 2020 • Lander Integration: August 2023  	• 4 ea. 3.2 MP cameras (3.37mm focal length) on individual camera mounts, Data Storage Unit, USB Hub (Mars2020 EDLCam heritage)	• Launch: 15 February 2024 • Landing: 22 February 2024 • Payload survived launch and successfully completed transit checkout. • Payload survived landing and successfully operated in the lunar environment. • No PSI erosion data collected due to lander anomaly.
SCALPSS 1.1	• CLPS 19D – Firefly Aerospace • Payload Delivered: October 2022 • Lander Integration: April 2024 	• 6 ea. 3.2 MP cameras (2 @ 3.37mm, 2 @ 5.4mm, and 2 @ 50mm focal lengths) on 4 camera assemblies, Data Storage Unit, USB Hub (SCALPSS 1.0 heritage)	• Payload Calibration: June 2024 • Launch: NET mid-November 2024 • Landing: NET early-January 2025
SCALPSS 1.x	• Managed by SCALPSS 1.1 Project • Blue Origin Mk1-SN101 • Payload Delivery: *Dec 2024* • Lander Integration: *Jan 2025* 	• 4 ea. 3.2 MP cameras (3.37mm focal length) on individual camera mounts, Data Storage Unit, USB Hub (SCALPSS 1.0 and SCALPSS 1.1 spare hardware)	• CLPS RTFP is complete; awaiting Blue Origin proposal and contract award (expected soon) • Launch: *Mar 2025* • Landing: *TBD*
SCALPSS 2.0	• Managed by PSI Instrumentation Project • Blue Origin Mk1-SN102 • Payload Delivery: *Dec 2025 (TBR)* • Lander Integration: *Mar 2026 (TBR)* 	• 6 ea. 12.3 MP cameras (3.37mm - 50mm focal lengths) on 4 camera assemblies, Mini-suite electronics (MSE-lite), dot grid projection (laser and/or passive)	• STMD/STED continuing to coordinate with Blue Origin to get an agreement in place in support of this opportunity. • Launch: *June 2025 (TBR)* • Landing: *TBD*

Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) Payload Evolution

	SCALPSS 1.0 (Intuitive Machines Nova-C: Q1 CY2024)	SCALPSS 1.1 (Firefly Aerospace Blue Ghost: Q4 CY2024)	SCALPSS 2.0 (Lander TBD: Q2 CY2026 target)

Measurement Objectives	• Capture post-landing 3D site alteration morphology
	  - Measure crater depth/size and erosion volume
	• *Capture pre-PSI (2D) landing topography*
	• *Detect PSI onset*
	• *Record transient site alteration morphology*
	• *Measure ground obscuration (onset and extent)*
	• *Measure dust settling density as a function of time*
	
	Primary objective
	Secondary objective
		• Capture post-landing 3D site alteration morphology
		  - Measure crater depth/size and erosion volume
		• **Capture pre-PSI 3D landing site morphology**
		• **Detect PSI onset**
		• **Record transient site alteration morphology**
		• *Measure ground obscuration (onset and extent)*
		• *Measure dust settling density as a function of time*
		
		New primary objective
		New secondary objective
			• Capture post-landing 3D site alteration morphology
			  - Measure crater depth/size and erosion volume
			  - **improved coverage and/or resolution**
			• Capture pre-PSI 3D landing site morphology
			  - **improved coverage and/or resolution**
			• Detect PSI onset
			• Record transient site alteration morphology
			  - **improved coverage and/or resolution**
			• **Measure ground obscuration (onset and extent)**
			• **Measure ejecta sheet structure**
			  - **Ejecta angles, sheet morphology, etc.**
			• ***Measure ejecta particle velocities***
			• ***Measure ejecta particle sizes***
			• *Measure dust settling density as a function of time*

Camera System	• (4) FLIR Chameleon 3 USB (Monochrome)
	  - 3.2 MP, 3.45 μm/pixel
	  - 3.37 mm focal length lens (14 fps descent; NDR post-landing)
	  - Configuration / coverage optimized for post-landing surface imagery
		• (**6**) FLIR Chameleon 3 USB (Monochrome)
		  - 3.2 MP, 3.45 μm/pixel
		  - **(2) 50 mm focal length lenses (10 fps pre-onset and early descent)**
		  - **(2) 5.4 mm focal length lenses (15 fps descent; HDR post-landing)**
		  - (2) 3.37 mm focal length lenses (15 fps descent; HDR post-landing)
		  - Configuration / coverage optimized for **both pre-onset and** post-landing surface imagery
			• (6) FLIR **Blackfly S GigE** (Monochrome)
			  - **12.3 MP**, 3.45 μm/pixel
			  - 3.37 – 25 mm focal length lenses (10-14 fps pre-onset and descent; HDR post-landing)
			• **Laser grid projection**
			• **Active illumination (TBD)**

Electronics	• Mars 2020 EDLCam Data Storage Unit (DSU) “build-to-print”
	  - (1) USB 3.0 data port to USB Hub to (4) cameras
	  - RS-422 data interface to lander (limited to 3 Mbps)
		• Mars 2020 EDLCam Data Storage Unit (DSU) “build-to-print”
		  - (1) USB 3.0 data port to USB Hub to (4) cameras
		  - **(2) USB 2.0 data ports to (2) cameras**
		  - RS-422 data interface to lander (limited to 3 Mbps)
		• **Utilized full data handling capabilities**
		  - **Limited to 450 MBps write speed to memory**
		
		New to design
		Design limit
			• **Mini-Suite Electronics (MSE)**
			  - **(6) 1 Gbps ethernet ports to (6) cameras**
			  - **Improved data interface(s) to lander (100+ Mbps capability)**
			• **Improved data handling capabilities**
			  - **Capable up to 2 GBps write speed to memory**
			• **Designed to be modular, flexible and expandable to accommodate additional sensors with various data interfaces (e.g., serial, USB, LAN, LVDS, Spacewire, etc.)**
			• **Smart power management / switching capability for sensors**

Modeling PSI Induced Environments

- Computational Fluid Dynamics (CFD) capabilities for simulating PSI are maturing, but flight data is needed to validate model predictions.
- Loci/CHEM-DIGGEM: A hybrid CFD/Engineering model fully integrates DIGGEM capability with CFD to fully couple simulated gas phase and modeled crater formation due to viscous erosion from impinging plume.

Loci/CHEM-DIGGEM Simulation