

Surface Engineered Materials in the Lunar Environment: Results from the Regolith Adherence Characterization (RAC) Payload Mission

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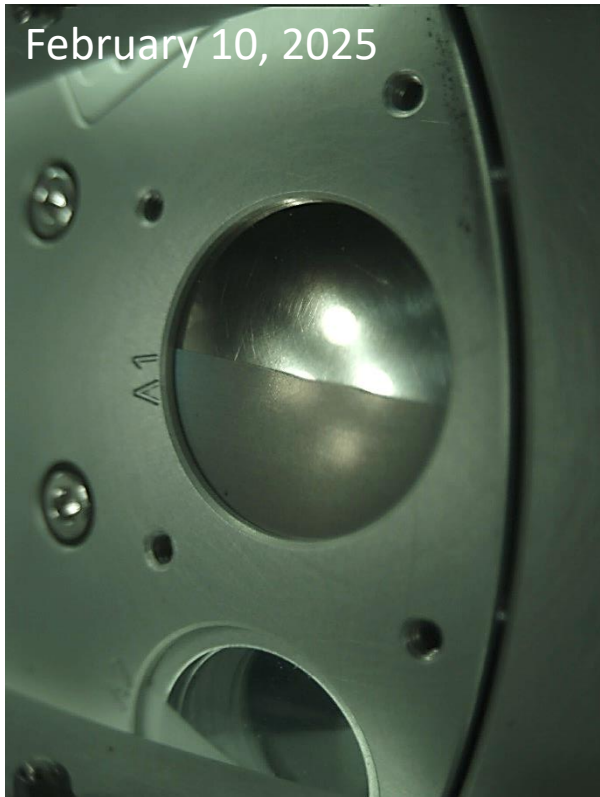
American Geophysical Union 2025 Conference
New Orleans, LA
December 15-19, 2025

*Corresponding Author: c.j.wohl@nasa.gov

Image credit NASA unless otherwise indicated



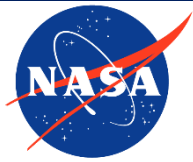
Photos of Ti-6Al-4V Surfaces on the RAC Payload



Why are we doing this experiment? Where did this occur? Why did we pick these samples?

Image credit: Aegis Aerospace

Natural vs. Anthropomorphic Lunar Dust Exposure



Dust Accumulation from Natural Phenomena
100 $\mu\text{g}/\text{cm}^2$ annually¹



Dust Accumulation from Human Activity

Lunar landing:
Apollo 14, 848 $\mu\text{g}/\text{cm}^2$

Lunar rover:
Dust traveling ~ 20 m away from rover

ISRU and construction:
Unknown, likely highly variable



Image generated using Gemini AI

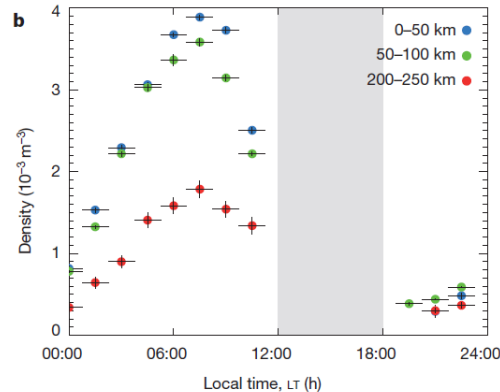
1. Wohl, Christopher J., et al., "Lunar Dust Considerations for Vertical Solar Arrays, Volume 1: Lunar Environment and Dust Interactions," NASA Technical Memorandum, 2024, TM-20240003496.

What, Where, and Why of Lunar Dust



Particle Counts

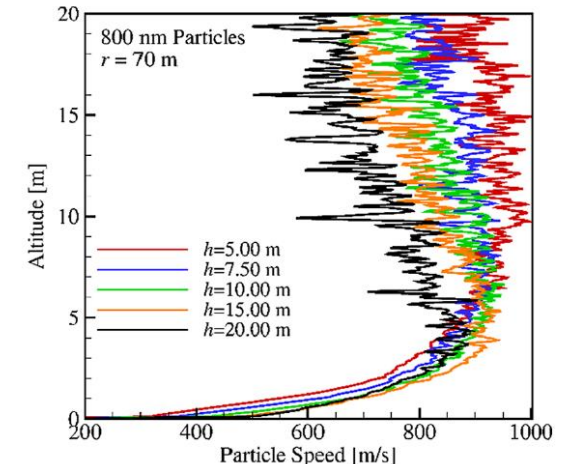
Lunar Dust Experiment (LDEX) Results



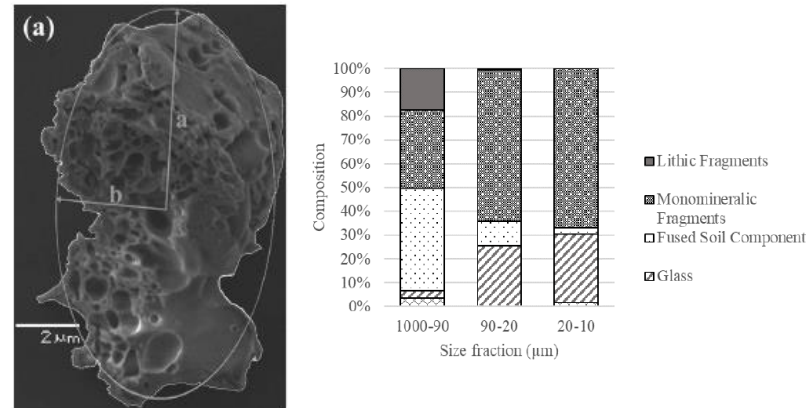
Particle counts as high as $4 \times 10^{-3} \text{ m}^{-3}$ up to 50 km off the lunar surface. Increased particle counts at terminator.

Single engine plume impingement can generate particle velocities $> 1000 \text{ m/s}$.

Particle Velocity

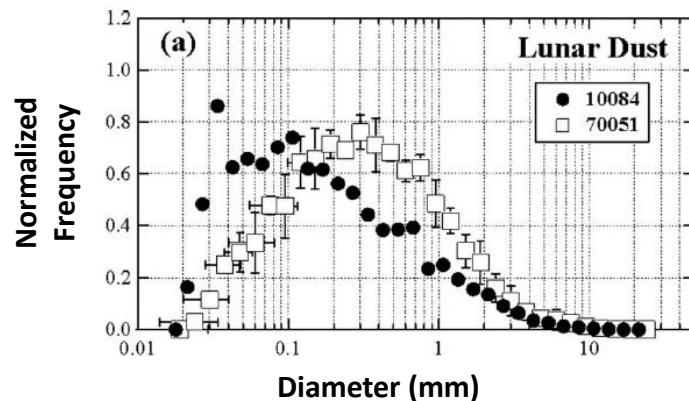


Particle Morphology



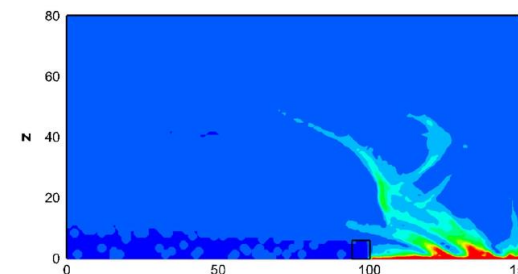
Smooth, glassy spheres $\leftrightarrow$ High angularity agglutinates

Particle Size



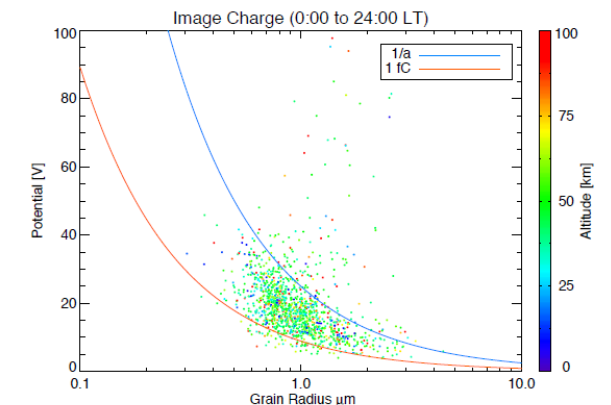
Lunar dust particles range from nm to up to 50 μm in diameter.

Simulated Lofted 10 μm Dust



Electrostatic Environment

LDEX Results



Laboratory vs Operational Environment Evaluation

Parameter	Laboratory	Lunar Surface
Gravity	9.8 m s ⁻²	1.62 m s ⁻²
Pressure	Controllably Variable	10 ⁻¹² Torr
Temperature Range	Controllably Variable	127°C to -173°C
UV Exposure	Controllably Variable	26.8 W m ⁻² (UVC/UVB)
Radiation Exposure	Controllably Variable	60 μSv h ⁻¹



Image generated using Gemini AI

The most straightforward thing to do is to take testing off planet.

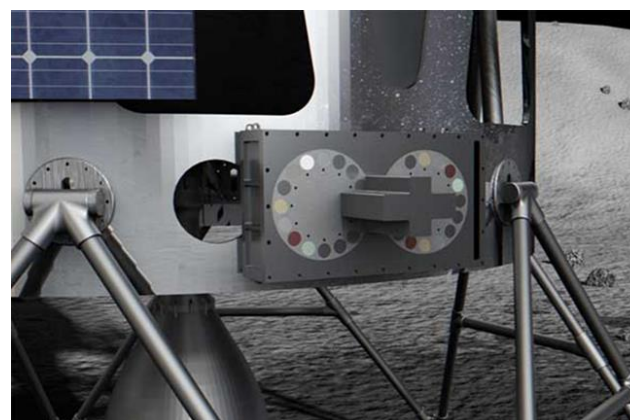


Evaluation off Planet

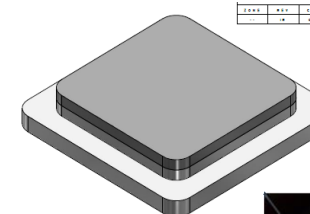
Materials International Space Station Experiment (MISSE) Samples

Copper Zirconium	Bulk Metallic Glass	Considered for RAC Payload
Boron Carbide (B4C)	Ceramic	Considered for RAC Payload
Chrome Carbide	Ceramic	LO-DuSST, high wear surface
Chromium Oxide	Ceramic	LO-DuSST, high wear surface
Laser Patterned Kapton	Polymer	On RAC Payload (Back-up)
Laser Patterned FEP	Polymer	On RAC Payload
Laser Patterned Low Creep/Relaxation Polymer	Polymer	Considered for RAC Payload
Laser Patterned Low Creep/Relaxation Composite	Polymer	On RAC Payload

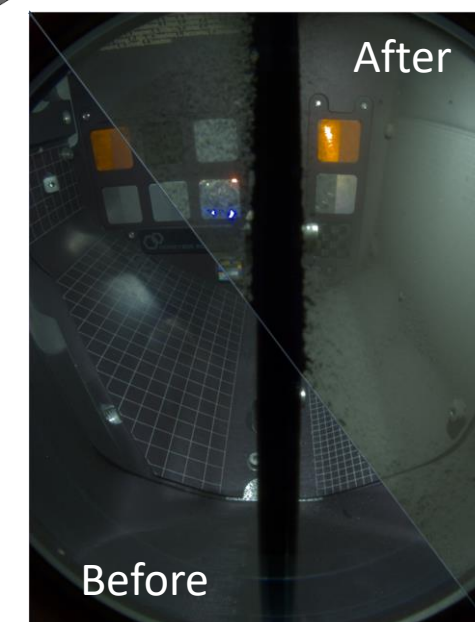
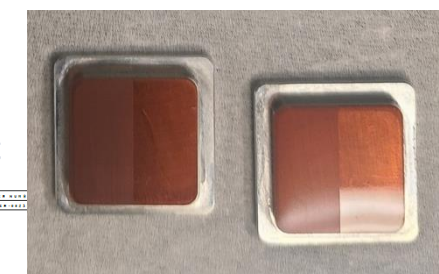
Regolith Adhesion Characterization (RAC) Payload



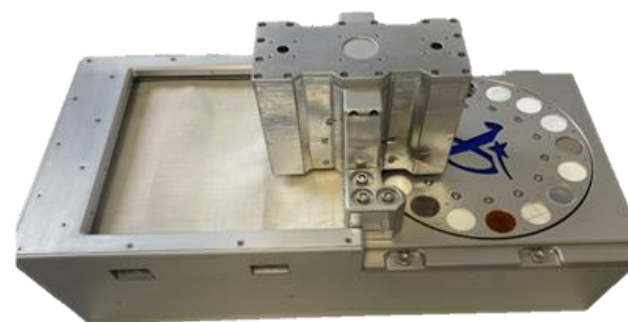
Coupon
Schematic



Honeybee Robotics PlanetVac



Launched on July 15, 2022 (SpaceX CRS-25)
Returned to Earth on April 15, 2023 (CRS-27)



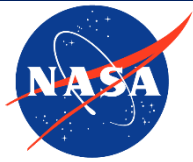
Images credit: Aegis Aerospace

Both payloads launched on SpaceX Falcon 9 -
Firefly Blue Ghost lander, on January 15, 2025.
Landed on the Moon on March 2, 2025!

Image credit: Honeybee Robotics

6





Regolith Adherence Characterization (RAC) Payload

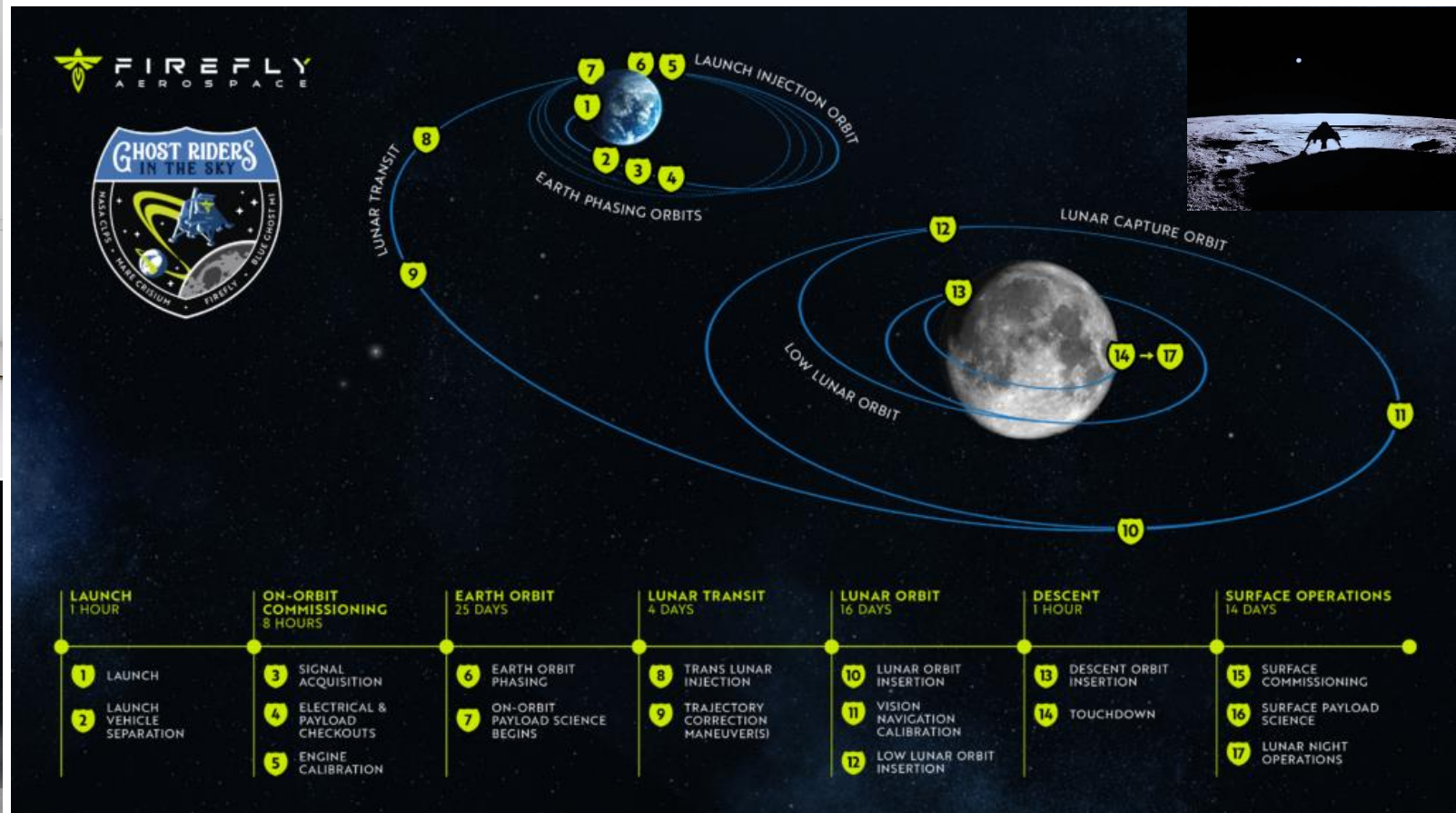
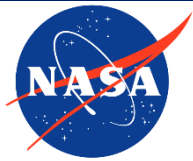
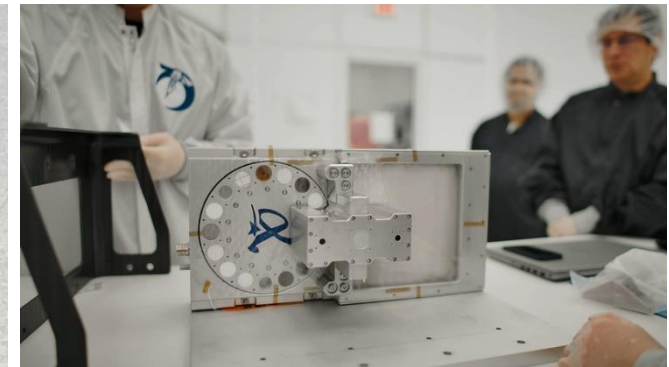


Image credit: Firefly Aerospace



Timeline from Sample Selection to Lunar Surface Images

- ❖ August 21, 2020: initial recommended materials submitted
 - ❖ 3 Ceramic materials, 3 metallic materials, 5 polymeric materials, 2 composite materials
 - ❖ Received approval for 1 metallic sample, 2 polymeric samples, and 1 composite sample
- ❖ March 25, 2021: samples were received by Aegis Aerospace
- ❖ December 14, 2021: samples integrated into the RAC payload
- ❖ February, 2024: RAC payload installed on Firefly's Blue Ghost Lander
- ❖ January 15, 2025: Firefly's Blue Ghost Lander launched aboard SpaceX Falcon 9 Rocket
- ❖ March 2, 2025: Firefly's Blue Ghost Lander successfully lands on the Moon
- ❖ March 15, 2025: last photos received from RAC payload

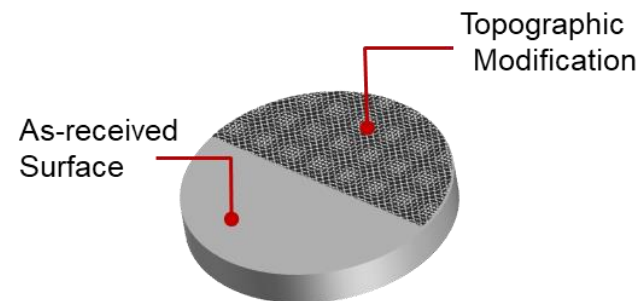


*Image credit: Aegis Aerospace
and Firefly Aerospace*

Materials Selected for RAC Payload

Material	Primary Use
Titanium Alloy (Ti-6Al-4V)	Prolific use in exploration vehicle construction
Fluorinated Ethylene Propylene (FEP)	Transparent polymer with properties similar to Teflon®, which is used extensively in exploration vehicles and space suits
Low Creep, Low Relaxation Composite (LCLR)	Bismaleimide-based carbon fiber-reinforced composite designed for deployable structures
Kapton® HN (Dupont)	Polyimide with extensive space heritage

❖ Samples were topographically modified on half of the surface providing 2 samples in the space of 1 specimen



Surface Topographical Modification

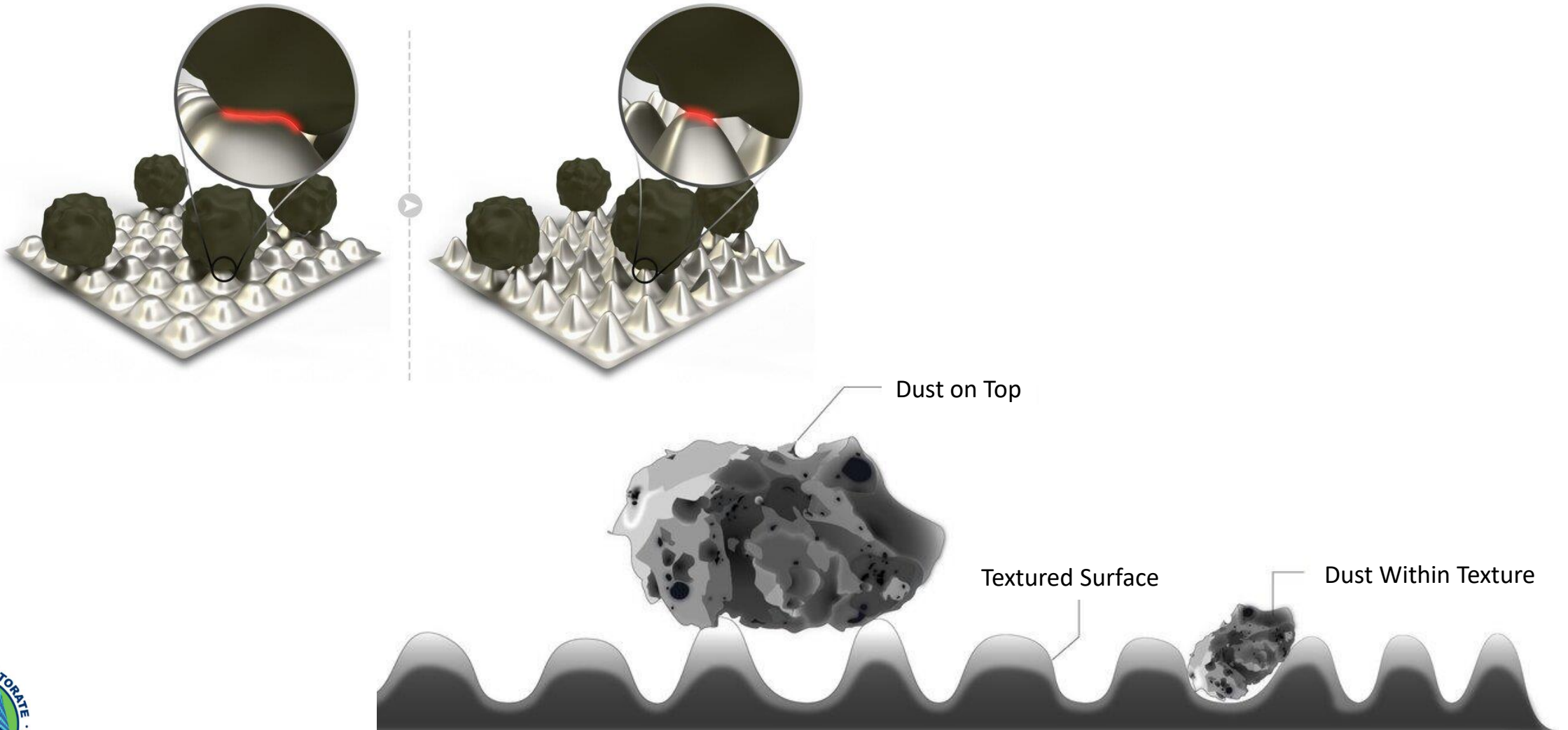
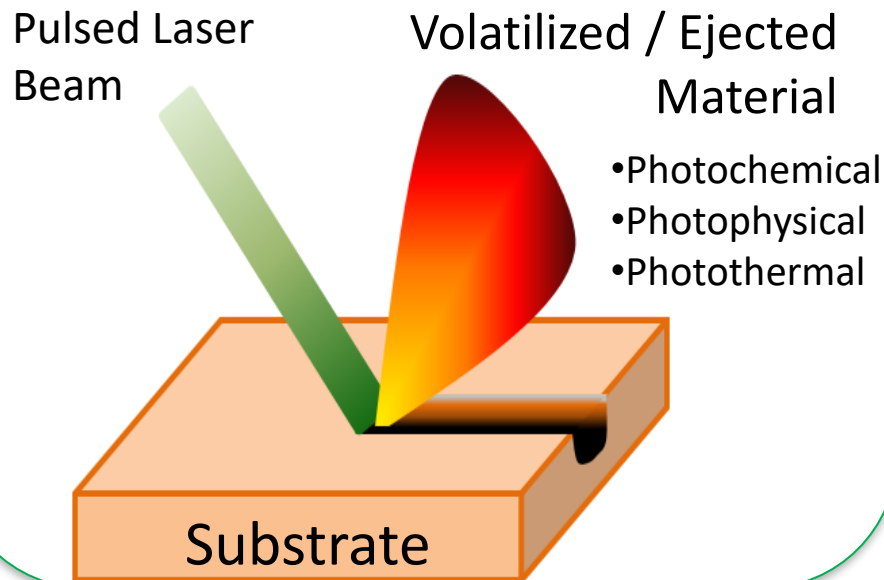


Image Credit: Smart Material Solutions, POC: Dr. Stephen Furst, ACS Appl. Mater. Interfaces, 2023, 15(10), 13678-13688.

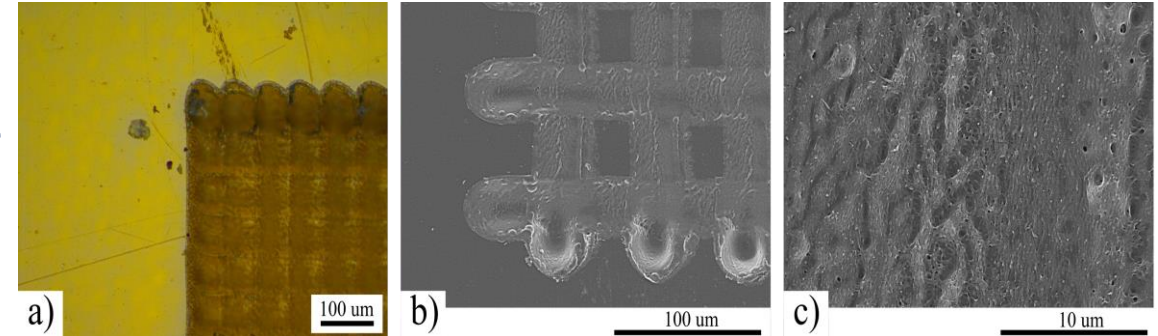
Surface Topographical Modification

Laser Ablation

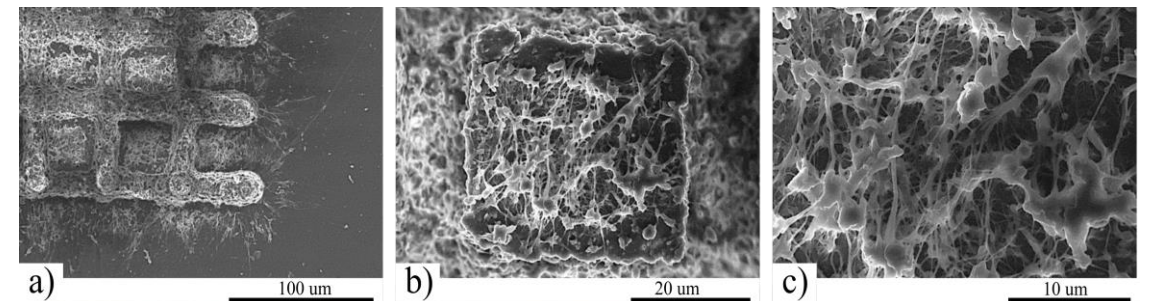
Laser Ablation Patterning



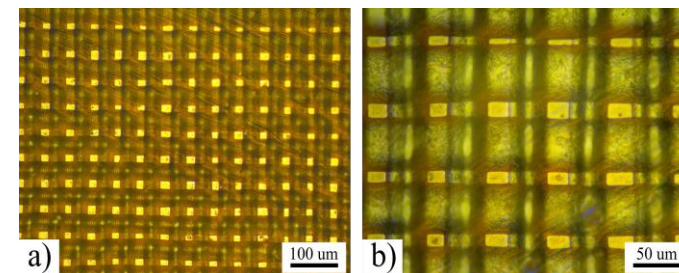
Polyimide



Fluorinated Ethylene Propylene (FEP)

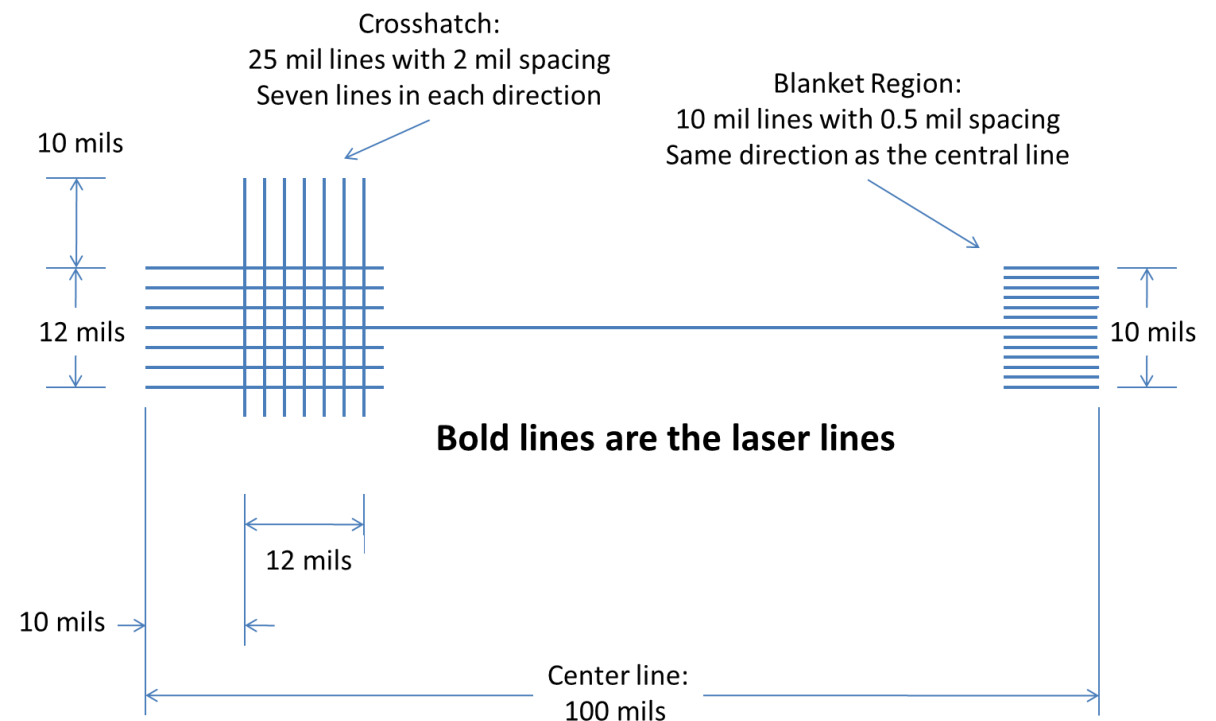


Low Creep-Low Relaxation Epoxy

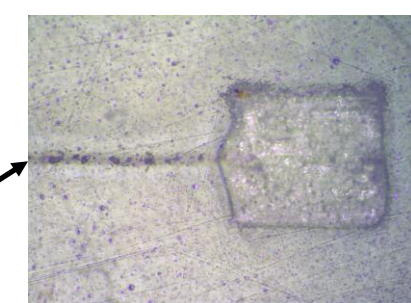
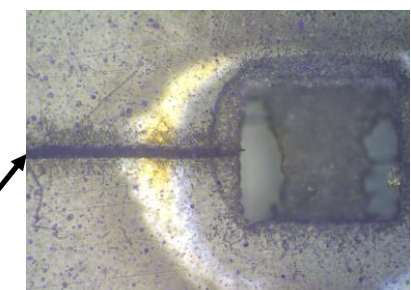
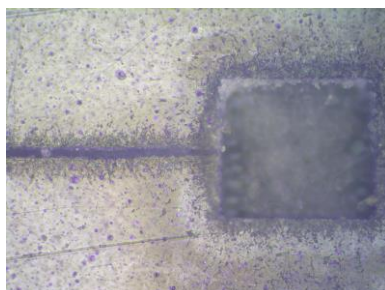
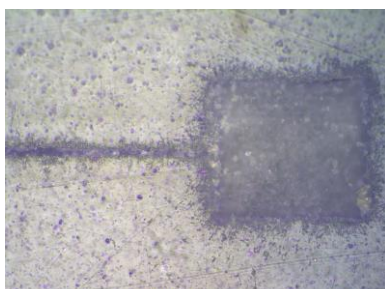
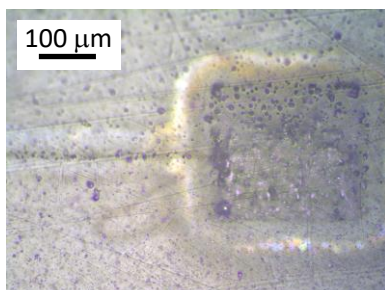
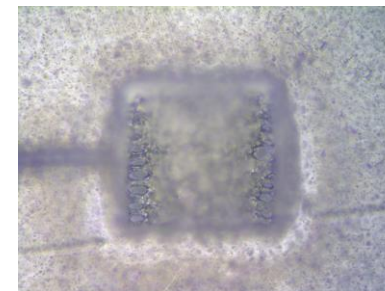
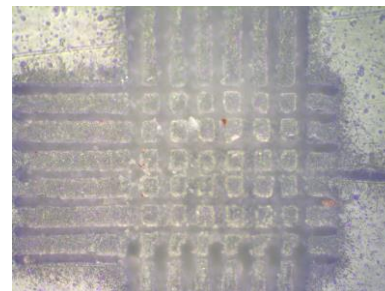
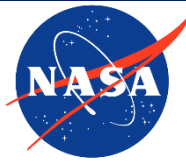


Laser Ablation Parameter Determination

- ❖ A “key” pattern was utilized to determine laser ablation conditions
- ❖ Straight line region
 - ❖ Single pass depth/width
 - ❖ Debris build up
 - ❖ Heat affected zone (HAZ)
- ❖ Crosshatch region
 - ❖ Feature height/depth
 - ❖ Difference in topography from ablated and pristine surfaces
 - ❖ Multi-pass depths
 - ❖ Closely-spaced lines
- ❖ Blanket region
 - ❖ Ablation path overlap
 - ❖ Resultant topography for fully ablated surface



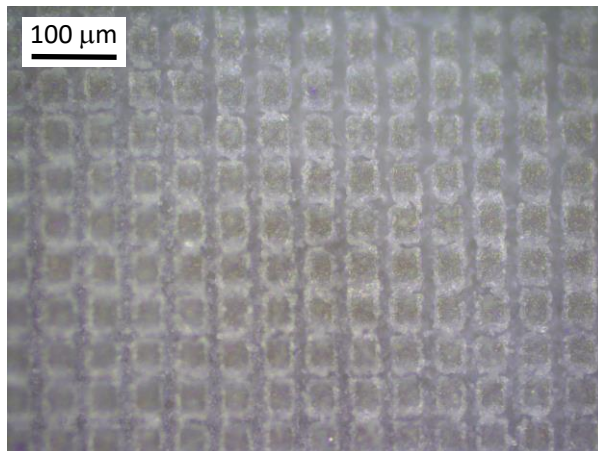
Laser Ablation Parameter Determination for FEP



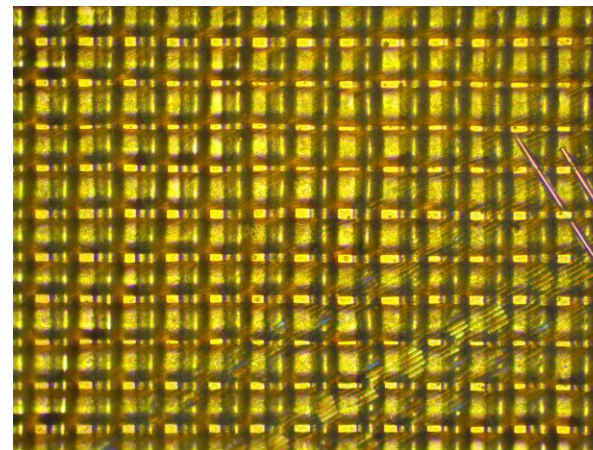
Power, %	Power, W	Frequency	Scan Speed	Microscopy Notes
10%	1.03 W	200 kHz	30 in/s	not enough power
20%	2.24 W	200 kHz	30 in/s	Almost enough power
30%	3.48 W	200 kHz	30 in/s	Distinct cross hatch patterns, lots of debris creating heirarchical surface, blanket area is hot mess, maybe cut through
40%	4.18 W	200 kHz	30 in/s	Blanket cut through, too much power
10%	0.44 W	400 kHz	30 in/s	Not enough Power
20%	1.17 W	400 kHz	30 in/s	Not enough Power
30%	2.11 W	400 kHz	30 in/s	Not enough Power
40%	2.67 W	400 kHz	30 in/s	Not enough Power

Down-selected Laser Ablation Parameters

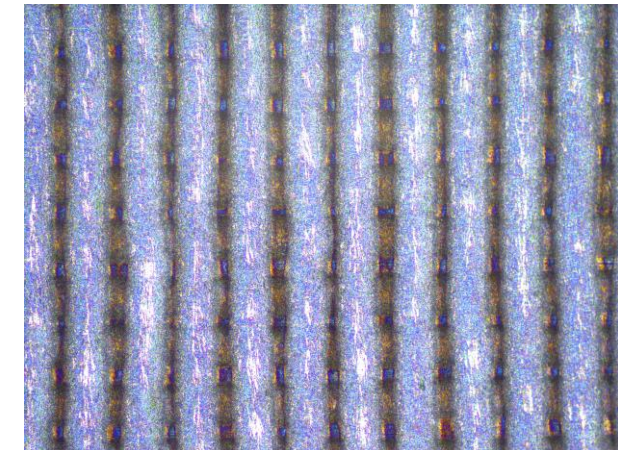
Material	Wavelength, nm	Power, W	Frequency, kHz	Line Spacing, μm
Kapton [®] HN (Dupont)	355	2.1	400	63.5
Fluorinated Ethylene Propylene (FEP)	355	2.8	200	50.8
Low Creep, Low Relaxation Composite (LCLR)	355	1.2	400	50.8
Titanium alloy (Ti-6Al-4V)	1064	12.2	400	63.5



FEP



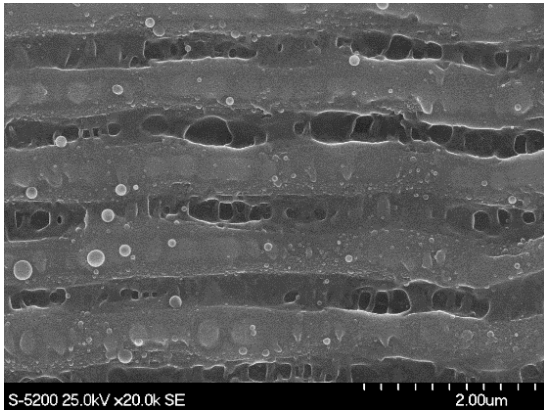
LCLR



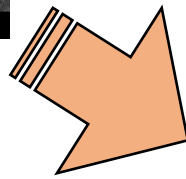
Ti-6Al-4V

Surface Topographical Modification

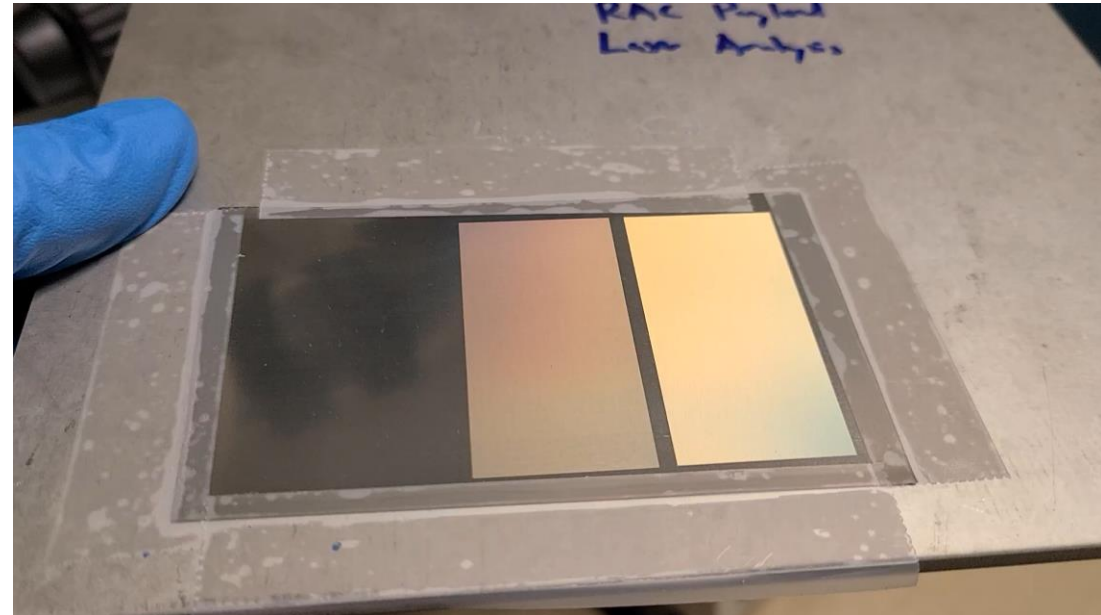
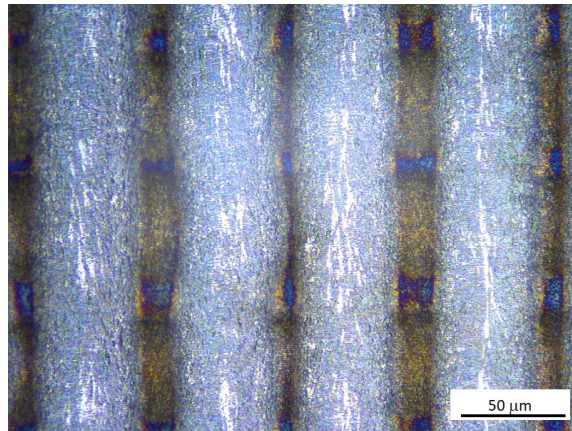
Laser Ablation



Nanometer-scaled Laser-Induced Period Surface Structure (LIPSS)



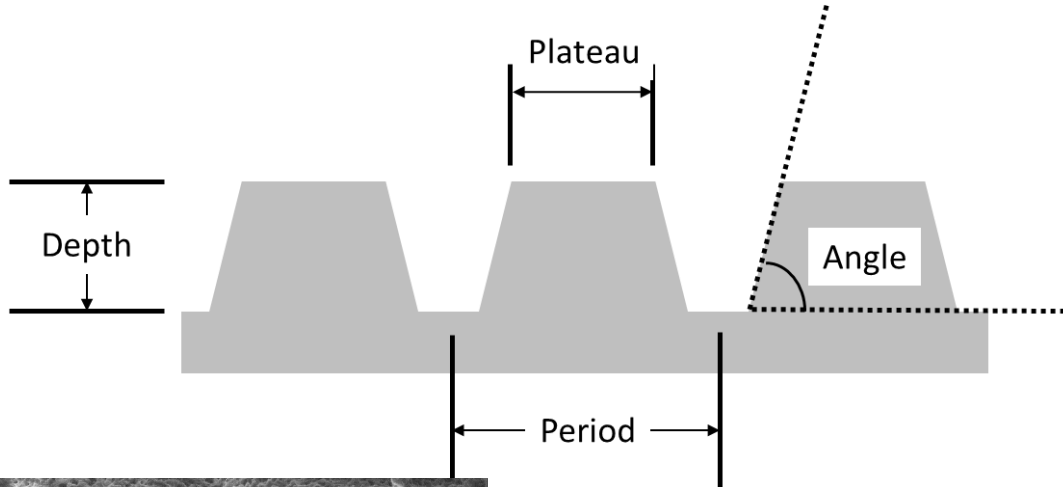
Micrometer-scaled Direct-write Laser Patterning



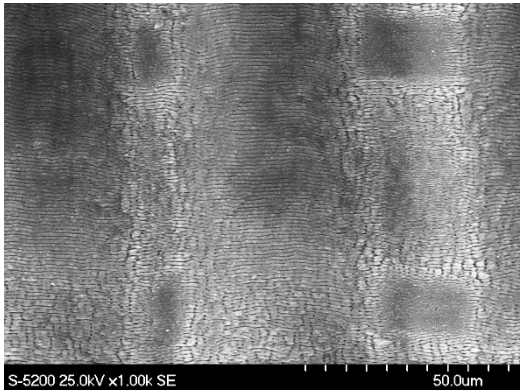
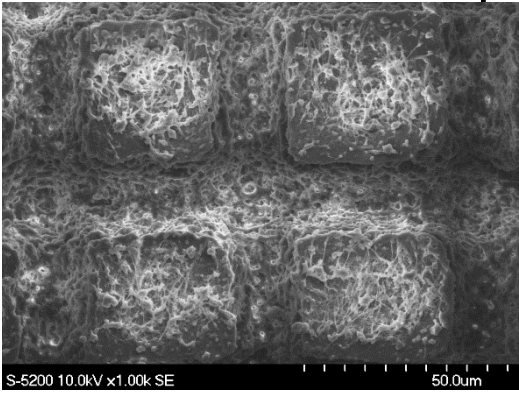
Das, Lopamudra; et al., "Extending Lunar Presence: Dust Adhesion Mitigation Materials and Surfaces to be Evaluated on the Lunar Surface," *Acta Astronautica*, 2024, 219, 532-541.

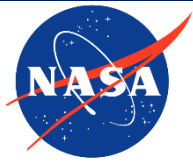
Characterization of Surface Topography

Material	Period, μm	Plateau, μm	Angle, $^\circ$	Depth, μm
Kapton [®] HN	66.1 ± 1.7	6.0 ± 0.2	10 ± 1	5.7 ± 0.5
FEP	52.0 ± 0.3	32.0 ± 1.0	26 ± 4	5.6 ± 1.0
LCLR	50.6 ± 1.8	12.0 ± 1.6	17 ± 1	5.5 ± 0.1
Ti-6Al-4V	61.2 ± 1.0	14.1 ± 5.0	1.8 ± 0.1	0.73 ± 0.08



Scale: 1" = 25 μm





Other Characterization Results

Material	Surface	*Advancing Water Contact Angle, °	Receding Water Contact Angle, °	**Average Roughness, μm
Kapton® HN	As received	78±3	58±5	0.04±0.01
	Laser patterned	90±1	75±3	1.76±0.11
FEP	As received	106±7	95±1	0.02±0.01
	Laser patterned	141±6	119±3	1.49±0.44
LCLR	As received	95±1	79±1	0.07±0.01
	Laser patterned	81±0	66±0	1.54±0.15
Ti-6Al-4V	As received	86±0	73±0	0.04±0.01
	Laser patterned	117±21	97±16	0.25±0.03

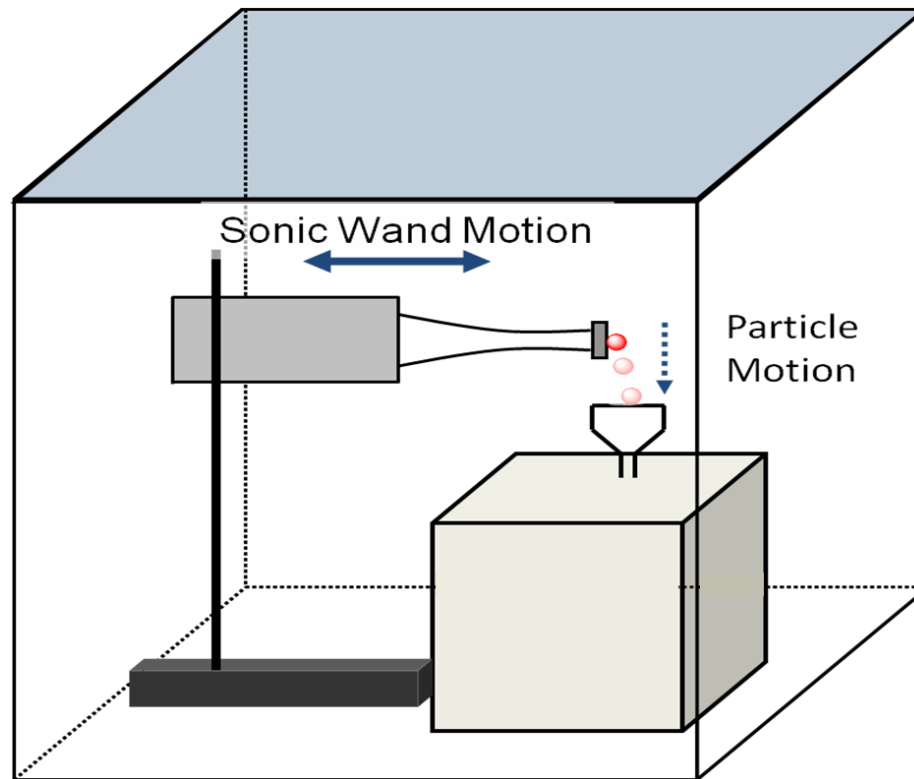


*Advancing and receding water contact angles were determined using a First Ten Angstroms (FTA) 1000B goniometer with 8 μl water droplets and tilting axis measurements.

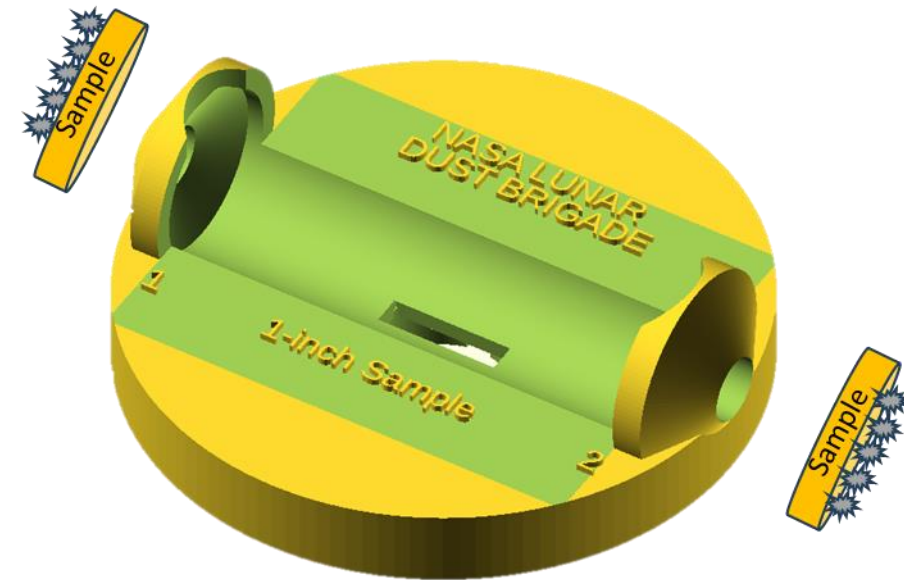
**Average roughness values were determined using a Bruker Dektak XT profilometer with a stylus tip radius of 12.5 μm, force of 3 mg, travel distance of 0.5 mm, and scan duration of 60 s.

Evaluation of Adhesion Mitigation Efficacy

Ultrasonic Wand Instrument

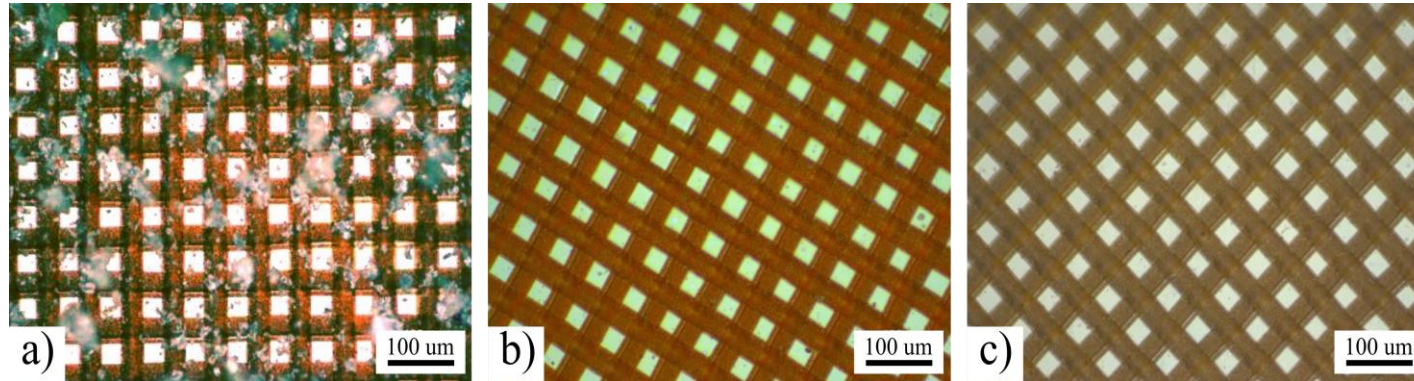


Centrifuge Instrument



Evaluation of Mitigation Efficacy

Sonication Instrument-Laser Patterning

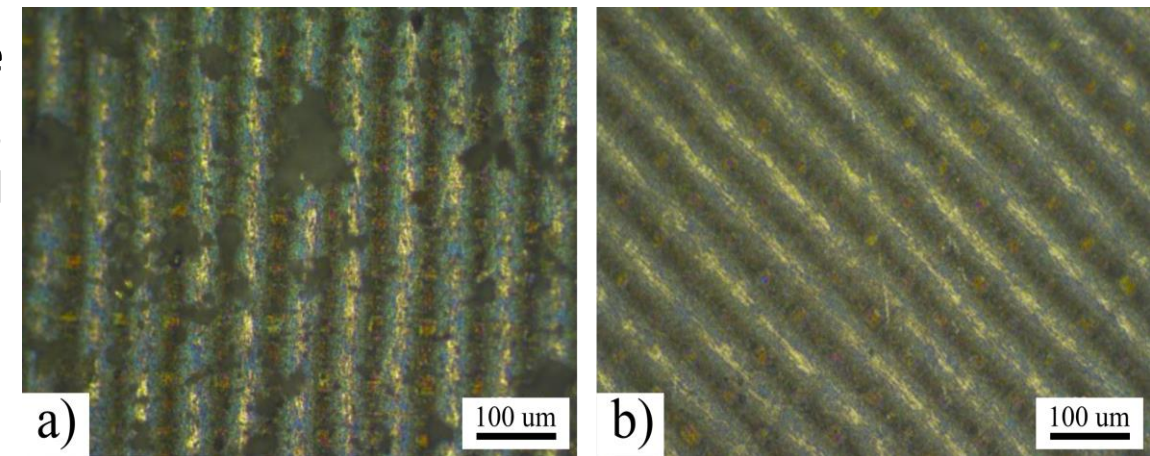


Polymeric Surface

—Left to Right: Contaminated Surface, Cohesion Removal, Full Test

Titanium Surface

—Left to Right: Contaminated Surface, Cohesion Removal



Sample Integration

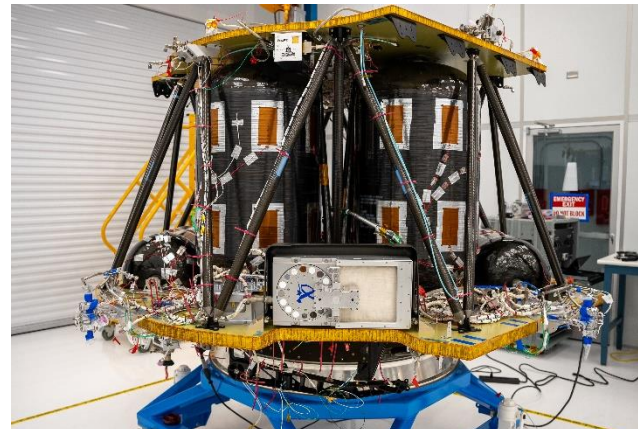
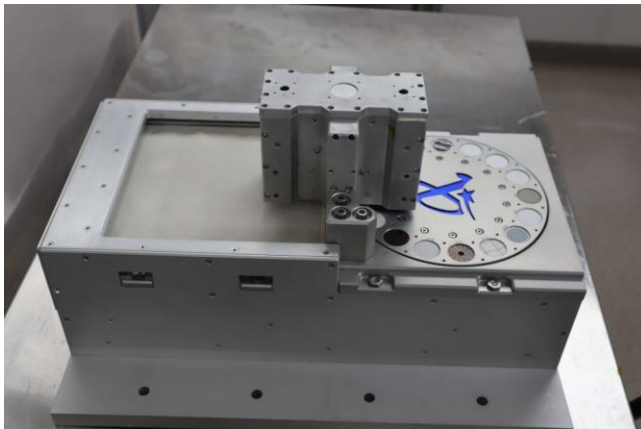
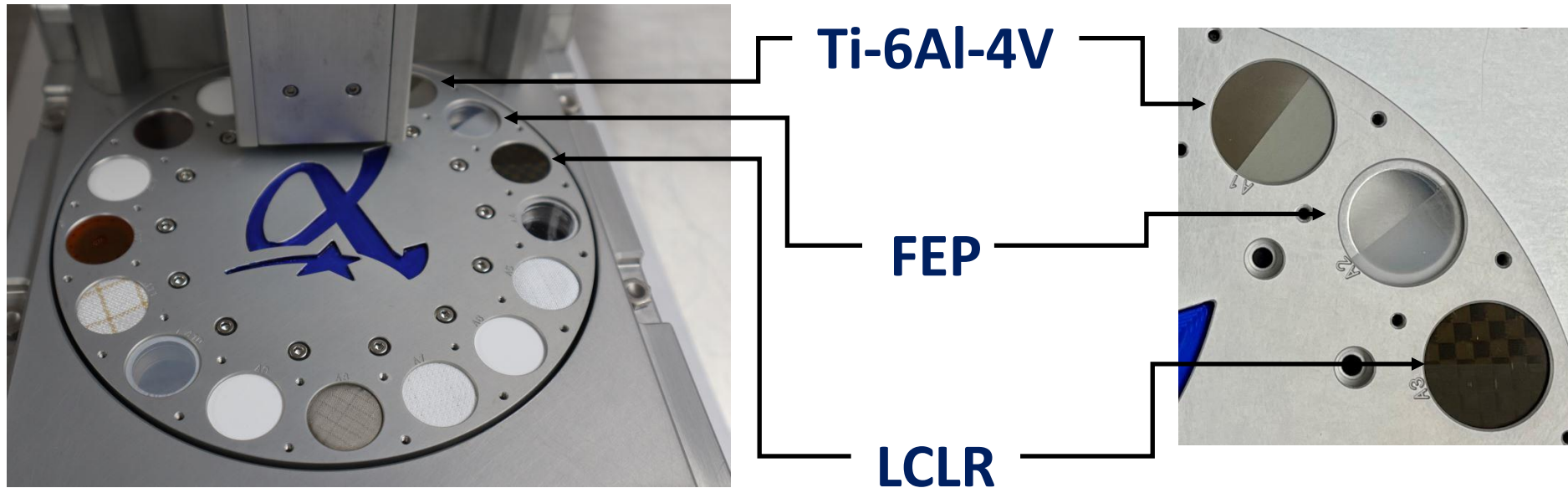


Image credit: Aegis Aerospace

Photos from the Lunar Surface

Ti-6Al-4V

FEP



LCLR

Pre-Flight

February 10, 2025



**Landing
+0 Days**

March 2, 2025



**Landing
+1 Days**

March 3, 2025



**Landing
+11 Days**

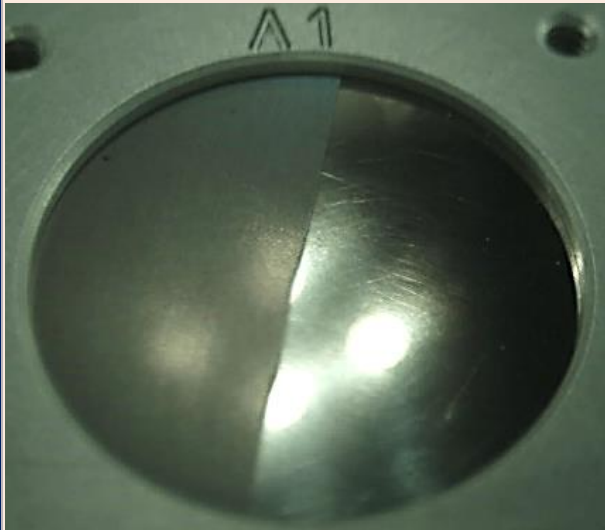
March 13, 2025



Image credit: Aegis Aerospace

Close Up Images of the Ti-6Al-4V Surface

February 10, 2025



Pre-Flight

March 2, 2025



Discoloration on the
Right Side, Some
Lunar Dust
Contamination

March 3, 2025



Lunar Dust Coverage

March 13, 2025



Cleaned Surface



Image credit: Aegis Aerospace 22

How did the Surface Get Contaminated ... and Cleaned?!

❖ RAC Photo Capture Timelines (UTC)

❖ 2 March: 13:40 to 14:44

❖ Contamination Event

✅ LPV Operation

❖ 3 March: 17:11 to 18:16

❖ Cleaning Event

❓ Unknown

❖ 13 March: 21:59 to 23:05

❖ 14 March: 22:18 to 23:22

❖ 15 March: 22:48 to 23:47

Honeybee Robotics

LPV operation

3 March

05:53 UTC, 09:06 UTC

12:11 UTC, 15:18 UTC

Honeybee Robotics

LISTER excavation

4 March 08:12 UTC



LPV: Lunar PlanetVac

LISTER: Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity

How did the Surface Get Contaminated ... and Cleaned?!

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Honeybee Robotics

LPV operation

3 March

05:53 UTC, 09:06 UTC

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LISTER excavation

4 March 08:12 UTC

Natural Phenomena

Lunar Day

Solar Eclipse

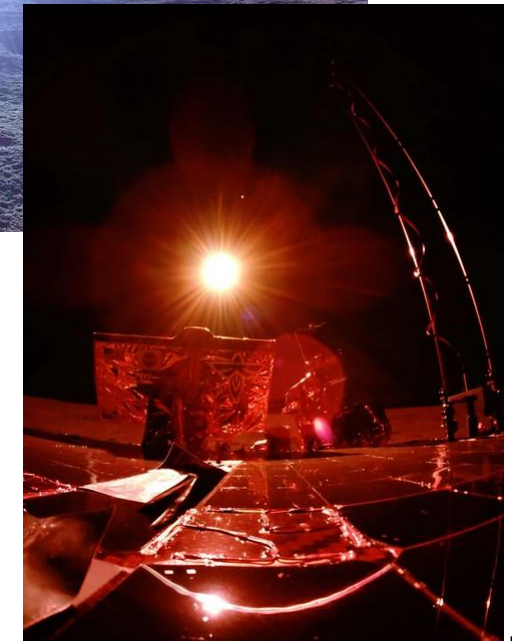
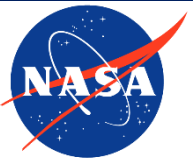


Image credit: Firefly Aerospace

Conclusions

- ❖ With few opportunities to evaluate materials in a lunar environment, determination of which materials is critical
- ❖ An array of materials solutions will be required to address the breadth of the need for lunar dust adhesion mitigation
- ❖ Evaluation of candidate surfaces is complex and will not be able to completely represent the lunar surface unless it is conducted on the lunar surface
- ❖ Proximal activities can strongly influence lunar dust accumulation





Acknowledgements

❖ NASA Langley Research Center

❖ John Hopkins, John Rice, Eric Hoffman, RTOW
COVID Team, SCALPSS- Olivia Tyrrell

❖ Aegis Aerospace

❖ Jeff Buell, Jessica Piness, Allison Goode

❖ Firefly Aerospace



