The Effects of Dust on Huma
Lunar Exploratio

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Outline

- Seals leaking
- Thermal control degradation
- Optical degradation
- Mechanical friction and jamming
- Health effects
- Methods of Removal and Cleaning
- Plume (launch and landing) effects

But first, the background…

- Why does the Moon have so much more dust than the Earth?
- Our bodies are adapted to a less dusty environment
- Our technologies, too
- Low gravity enhances suspension in an atmosphere
- Vacuum enables ballistic travel of dust but eliminates suspension

Seals Leaking


LOCK
OPEN

Thermal Control Degradation

- Dust has a high solar absorptivity and lower thermal emissivity than engineered materials
- Coating surfaces with dust increase heat absorption and reduce heat emission
- This can cause electronics to be hotter, performing worse and failing earlier

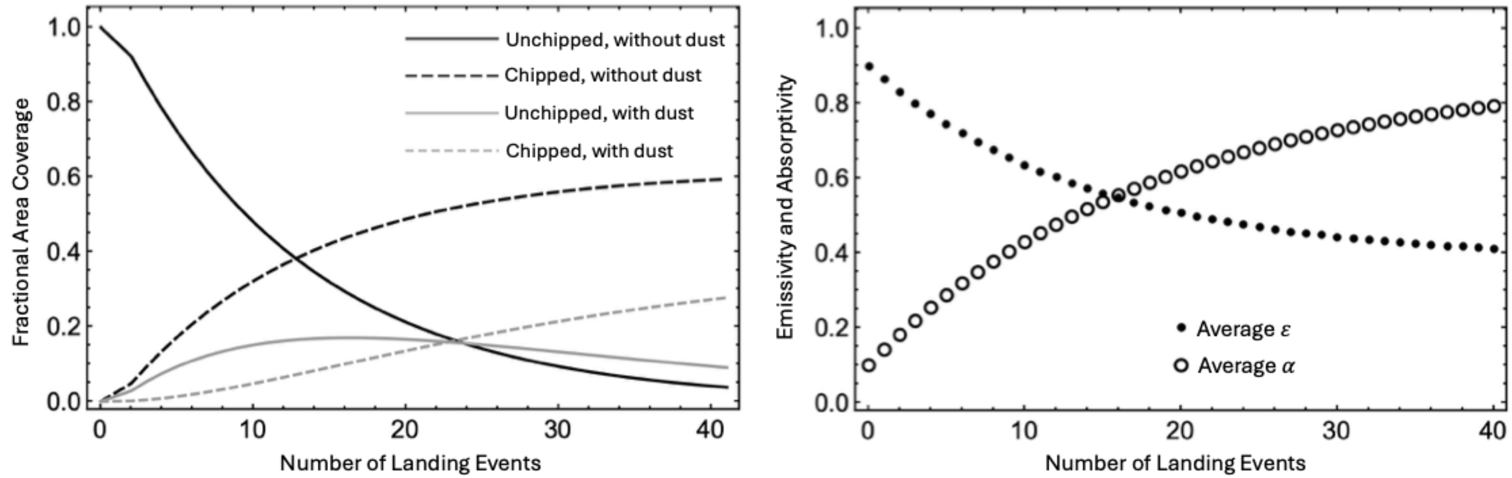


Figure 10. Change of thermal parameters for Case A (baseline). Left: Fractional area chipped and/or dusted. Right: Resulting emissivity ε and solar absorptivity α.

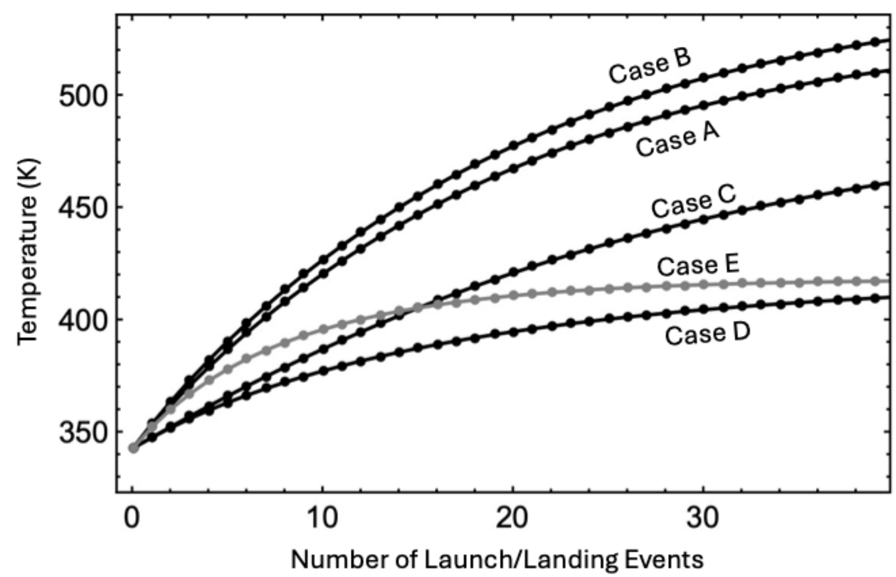


Figure 11. Modeled temperature vs. launch/landing events for each case.

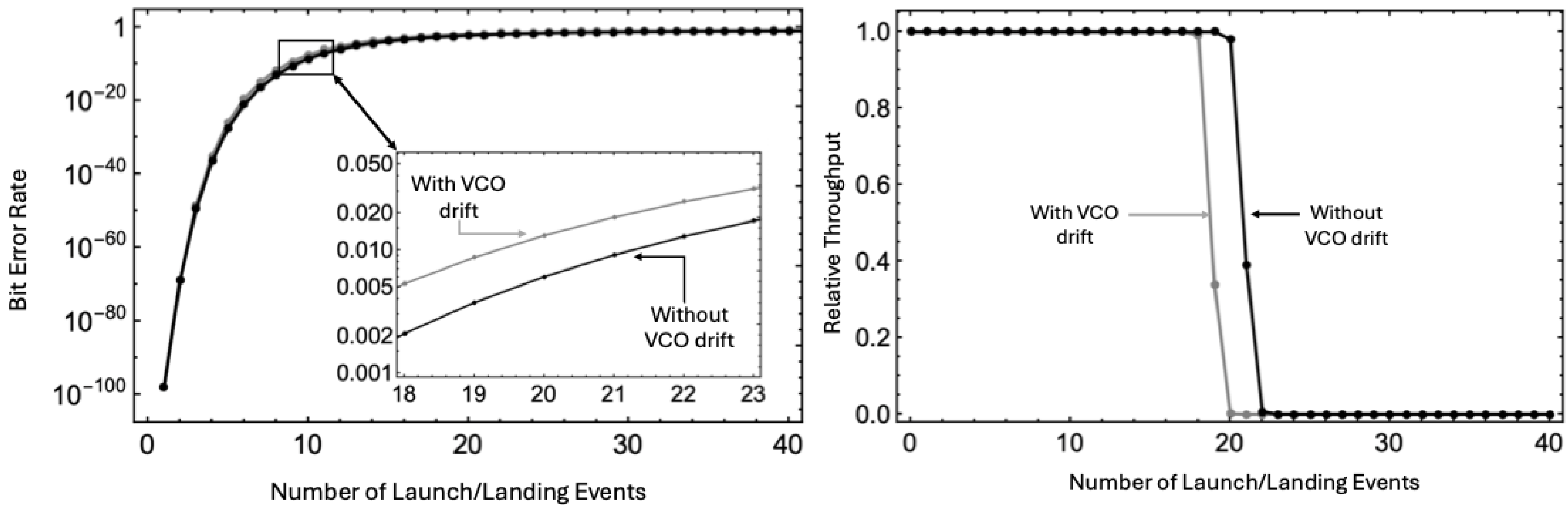


Figure 12. Left: Bit Error Rate. Inset: zoomed at 18 to 23 events. Right: Relative throughput after error correction. Estimated effects of VCO drift cause communications degradation only about 10% sooner.

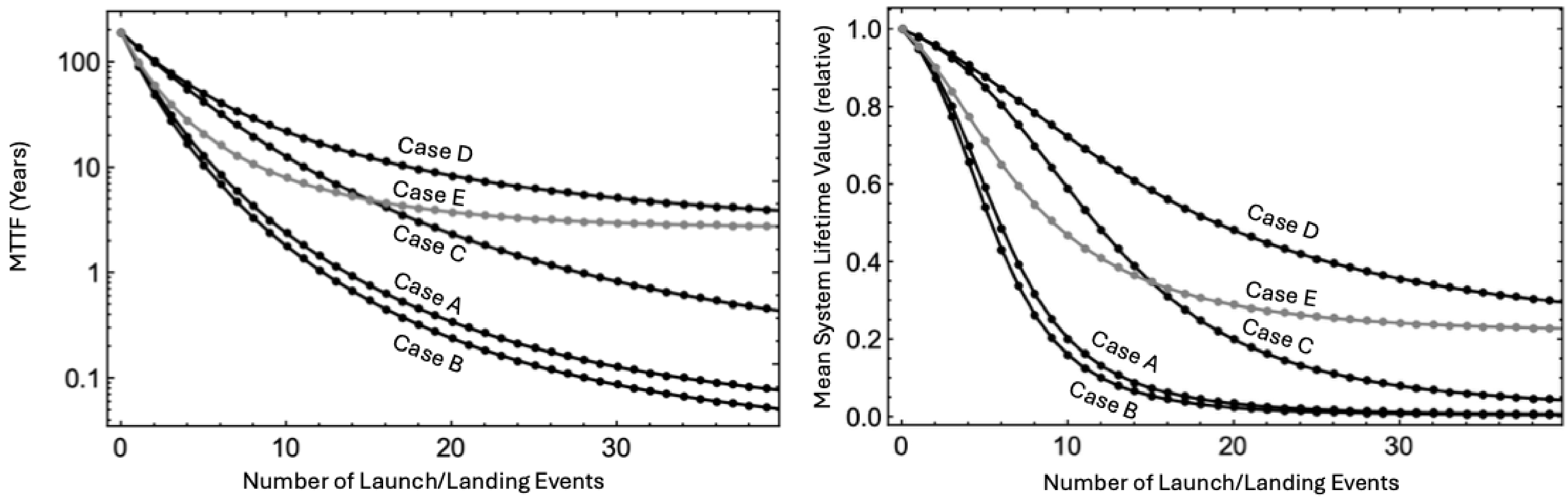


Figure 13. Damage to electronics systems exposed to launch/landing events. Left: Mean Time To Failure. Right: Mean System Lifetime Value (relative to initial value).

Optical Degradation

- Dust obscures light transfer through the lens
- Removing dust can abrade the lens
- Surface smoothness is crucial for focus quality of a lens

Apollo 12 Camera Mirror Ruined

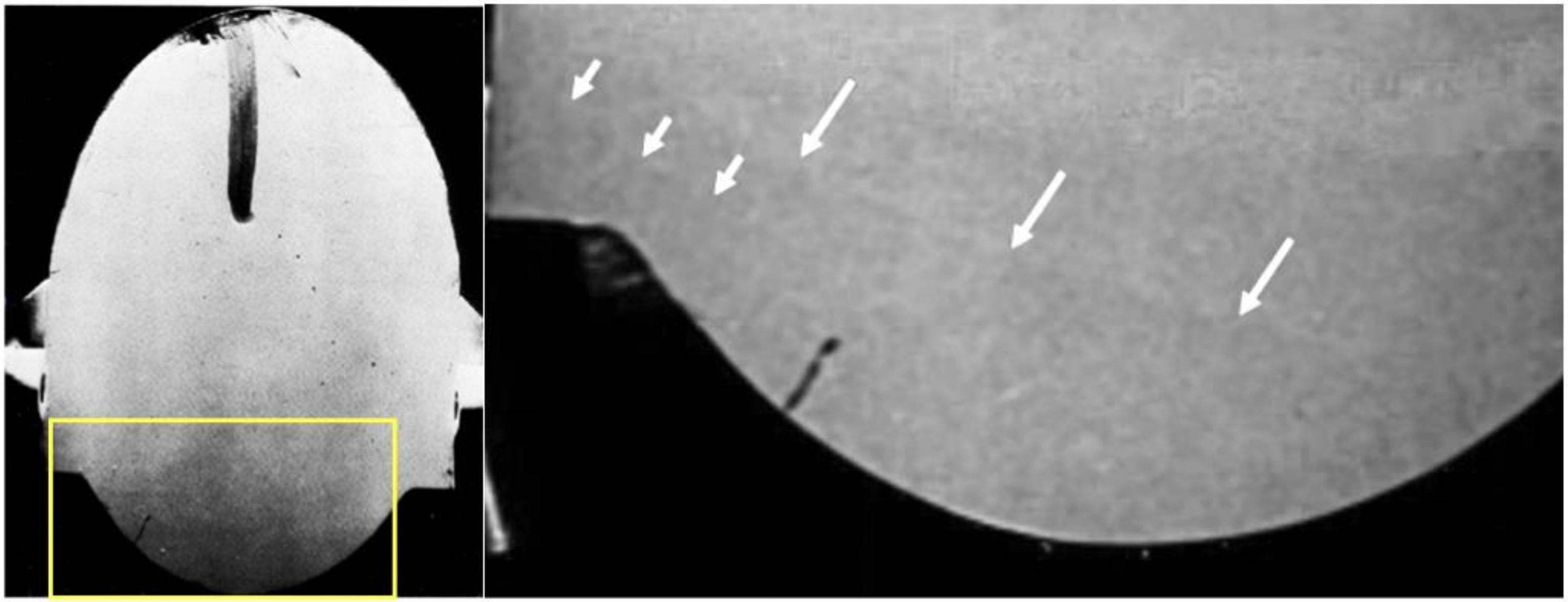


Figure 8. Surveyor 3 camera mirror after return to Earth by Apollo 12. Left: entire mirror showing astronaut Scott's gloved finger-swipe in the dust near the top. Yellow box is location of detail on the right. Right: Detail of the bottom of the mirror. White arrows indicate locations of two sandblasting shadows from fountain flow that sprayed the camera during the landing, from Metzger (2020).

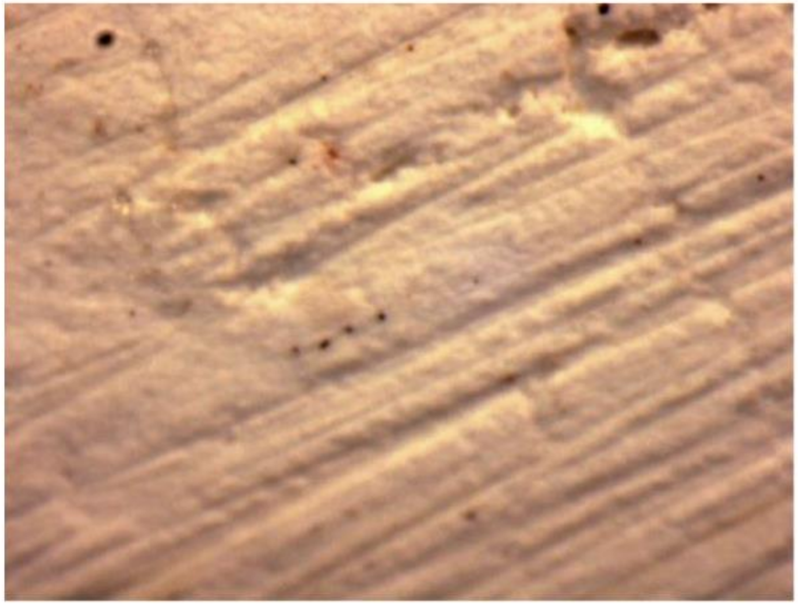


Figure 3. Abrasion lines are clearly visible on the 100x photomicrograph of AZ93 that has been brushed with a nylon bristle brush[11].

Credit: **Abby Zinecker Howard and Sarah Stewart, NASA/JSC,** "Thermal Impacts of Lunar Dust For Rovers." In *Annual Thermal and Fluids Analysis Workshop (TFAWS)*. 2024.

Experimental or Theoretical?

Some theory:

To quantify this, we may use the Strehl Ratio from optics, which for small wavefront errors is approximated by $S \approx \exp\left(-\sigma_\phi^2\right)$, where the phase variance $\sigma_\phi^2 \approx f(1-f)\phi^2$, and $f =$ fraction of chipped area of the lens. $\sigma_\phi^2 \approx f\phi^2$ for small f, and the phase error $\phi = 2\pi(n-1)d/\lambda$ for shallow chipping, where $n =$ refractive index of the lens, $d =$ chip depth, and $\lambda =$ wavelength.

In optics, $S = 0.8$ is commonly used to describe the onset of noticeable degradation, but the requirement must be determined on a case-by-case basis for each instrument. A system will have totally lost value when the data it obtains are too poor to improve existing datasets, or it may be near total loss when the lost opportunity cost from continuing use of a degraded sensor, producing data of lower quality than desired, exceeds the replacement cost. An example can provide a sense of the scale.

More theory…

Assume a mid-infrared spectrometer from 80.5 km low lunar orbit has 3 meter pixel resolution ($\theta = 3.06 \times 10^{-5}$ angular resolution for mid IR $\lambda = 5\ \mu$m and aperture $D_A = 16.3$ cm) but the requirement to improve upon existing datasets is to stay better than 5 meter resolution ($\theta = 6.21 \times 10^{-5}$ angular resolution). The total angular point spread function width can be approximated as

$$\theta \approx \sqrt{\left(\frac{\lambda}{D_A}\right)^2 + \left(\frac{\sigma}{D_A}\right)^2}$$

where $\sigma = \lambda\sigma_\phi/2\pi$ is the RMS (root mean square) wavefront error. This requires $\sigma <$ $8.08\ \mu$m to satisfy the resolution requirement. Using $n = 1.5$ for glass and $d = 10\mu$m for a chip's depth, the resolution becomes unacceptable when $S \approx 0.098$ and $f = 0.26\%$ of the surface of the lens has been chipped.

Abrasion of Optics

- Do we have enough experimental data on abrasion of optics?
- We lack data on sandblasting of optics, since doing vacuum tests are hard on Earth
- The limit of acceptable abrasion will be specific to each application
- Some sensors will be far more sensitive than others

Mechanical Friction and Jamming

- In Lunabotics competitions, robots must operate only 15 minutes at a time in dust
- Squeaking, increased friction, reduced performance
- The competition motivates dust mitigation
  - Design to avoid flinging dust
  - Design to keep out dust
  - Design tolerance for dust
  - Operate to avoid flinging dust

Experiment or Theory

A recent calculation showed that the Apollo LM blew 11 to 26 tons of soil into an elevation angle between 1° and 3° [Metzger, 2024], which is a solid angle of 0.219 sr. Scaling up the landing mass from the 7.5 t LM to a 40 t future lander, the total ejected mass may be 60 to 140 t, so the mass per solid angle would be 274,000 to 640,000 kg/sr. At 1 km, the mass impacting per area will be 0.274 to 0.640 kg/m^2. For a bearing gap opening of 25 μm by 10 mm, the total mass entering the gap will be 0.068 to 0.16 μg, which is 3 to 8 times the minimum for jamming. This is a worst-case since not all the dust entering the gap will end up in the raceway, but after 20 launch and landing events the total dust to have entered the gap will be 60 to 160 times the minimum, so the probability of jamming will be significant.

This was the best I could do working from theory.
Theory is not the right approach.
Are experimental data adequate?

Need for Robotic Repair Technology

- In my opinion, we MUST develop a technology strategy for complete modularization and robotic autonomous repair
- Due to high hardware and transportation costs, must minimize the mass that must be replaced
- Isolate common mechanical failures into robotically replaceable modules
- Reliability engineering shows this will make an extreme reduction in cost

Health Effects

- I am not an expert on this. The following is merely anecdotal…
- Irritant to eyes
- Dries the skin, clogs pores, may cause a reaction
- Inhalation of 1-10 micron size is a severe health danger
- We know little about the effects of these minerals
- Crew reported “gunpowder” smell, presumed to be the result of “hanging bonds” (chemical reactivity) of the dust

Methods of Removal and Cleaning

- Air filtration
  - Renewable HEPA filters
  - Water filtration
  - Magnetic or electrostatic
- Surface removal
  - Brushing (generally bad!)
  - Magnetic
  - Electrostatic (Dynamic dust screens0
  - Pneumatic
  - Cryogenic (Ledenfrost)

Methods of Prevention

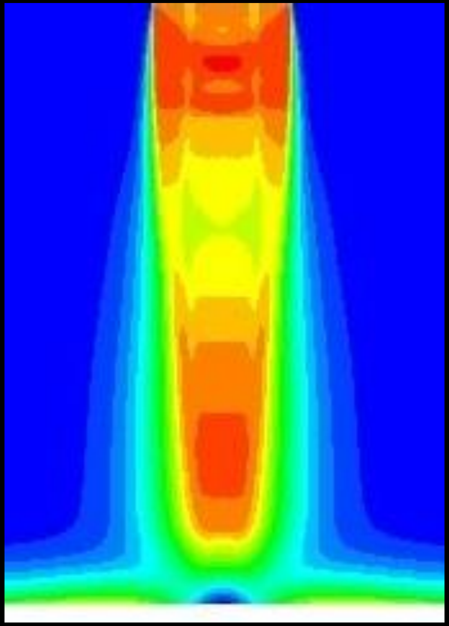
- Boots over reciprocating joints
- Fur (!!!)
- Landing pads
- Dust free surfaces
- Suit ports
- Control wheel rotation
- Multi-tier engineering approach
  - Full-court press

Outline for Plume Effects

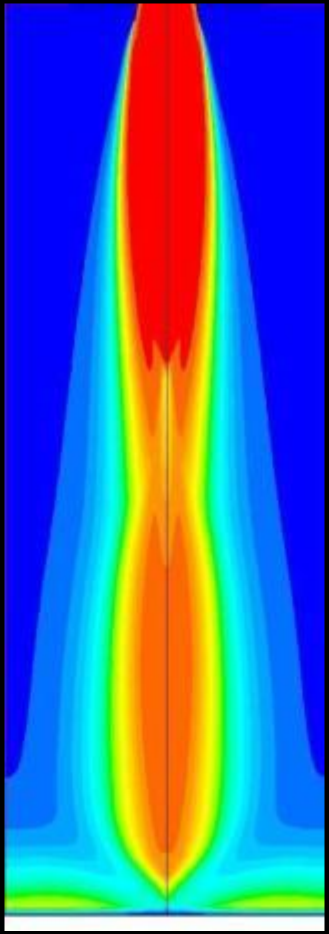
- Overview of phenomenology
- Why is this important
- Where do ejecta go, and how fast?
- At what height does the erosion begin?
- How much ejecta is blown?
- Multiple engines
- Recent Results

Overview of Phenomenology

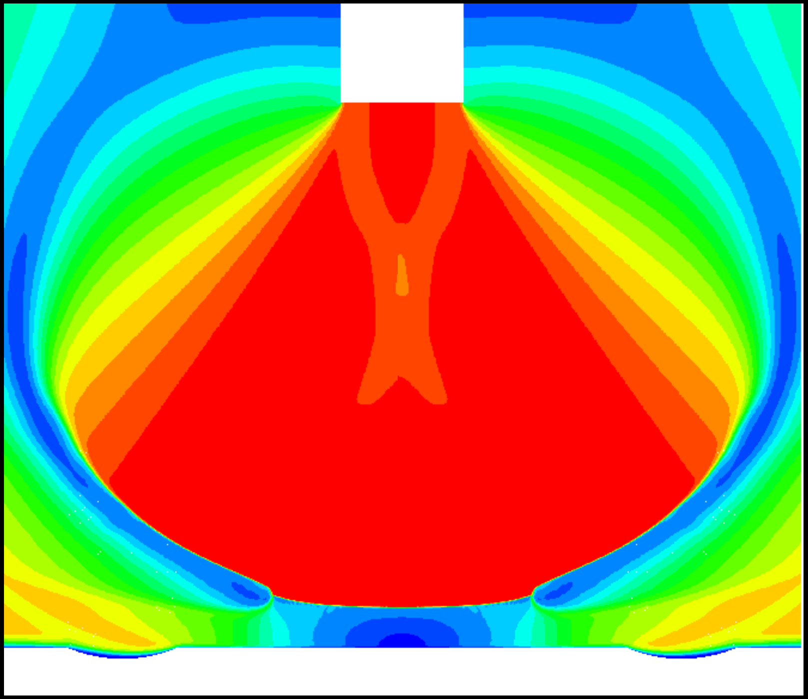
Different Effects in Different Environments



Earth

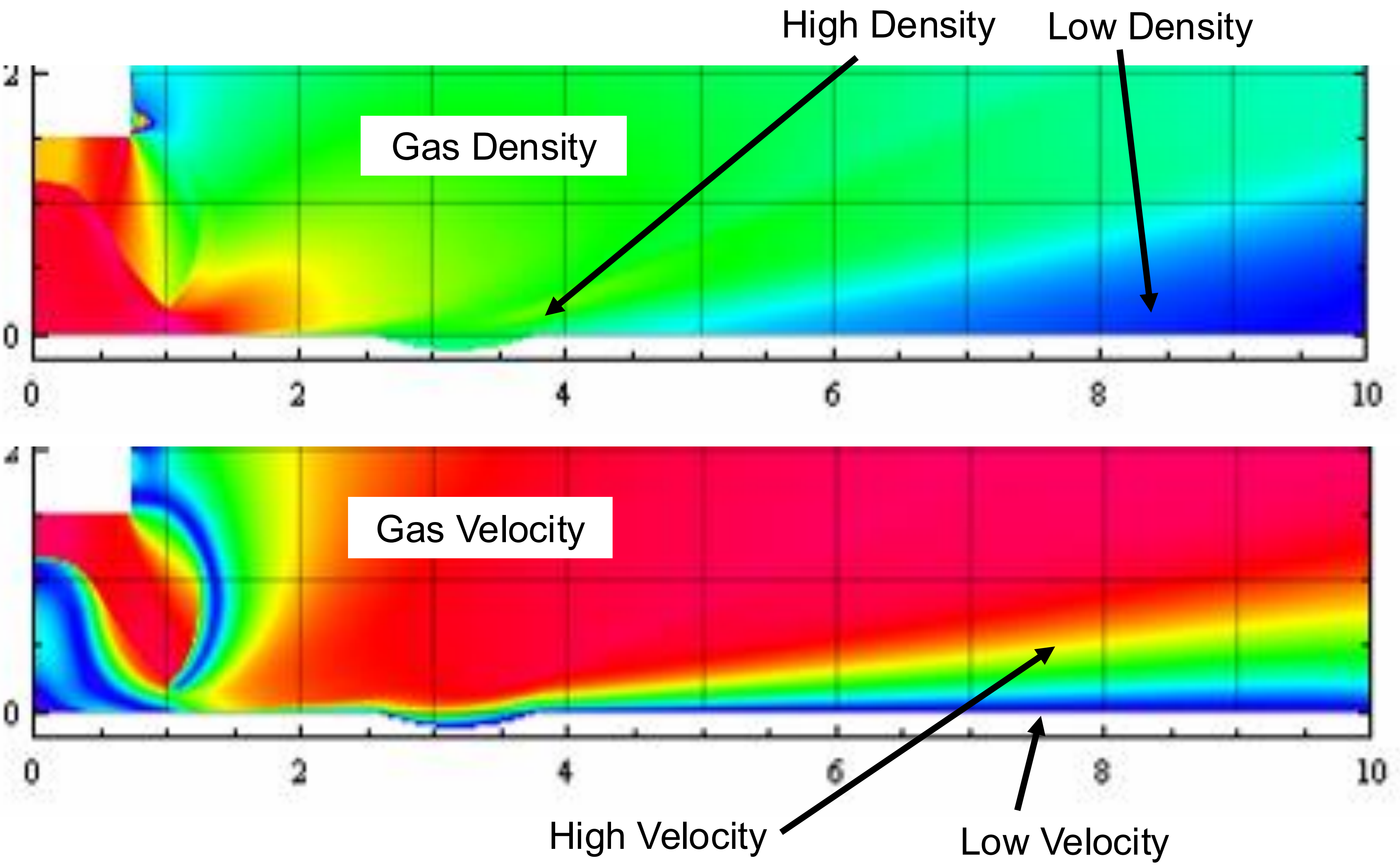


Mars



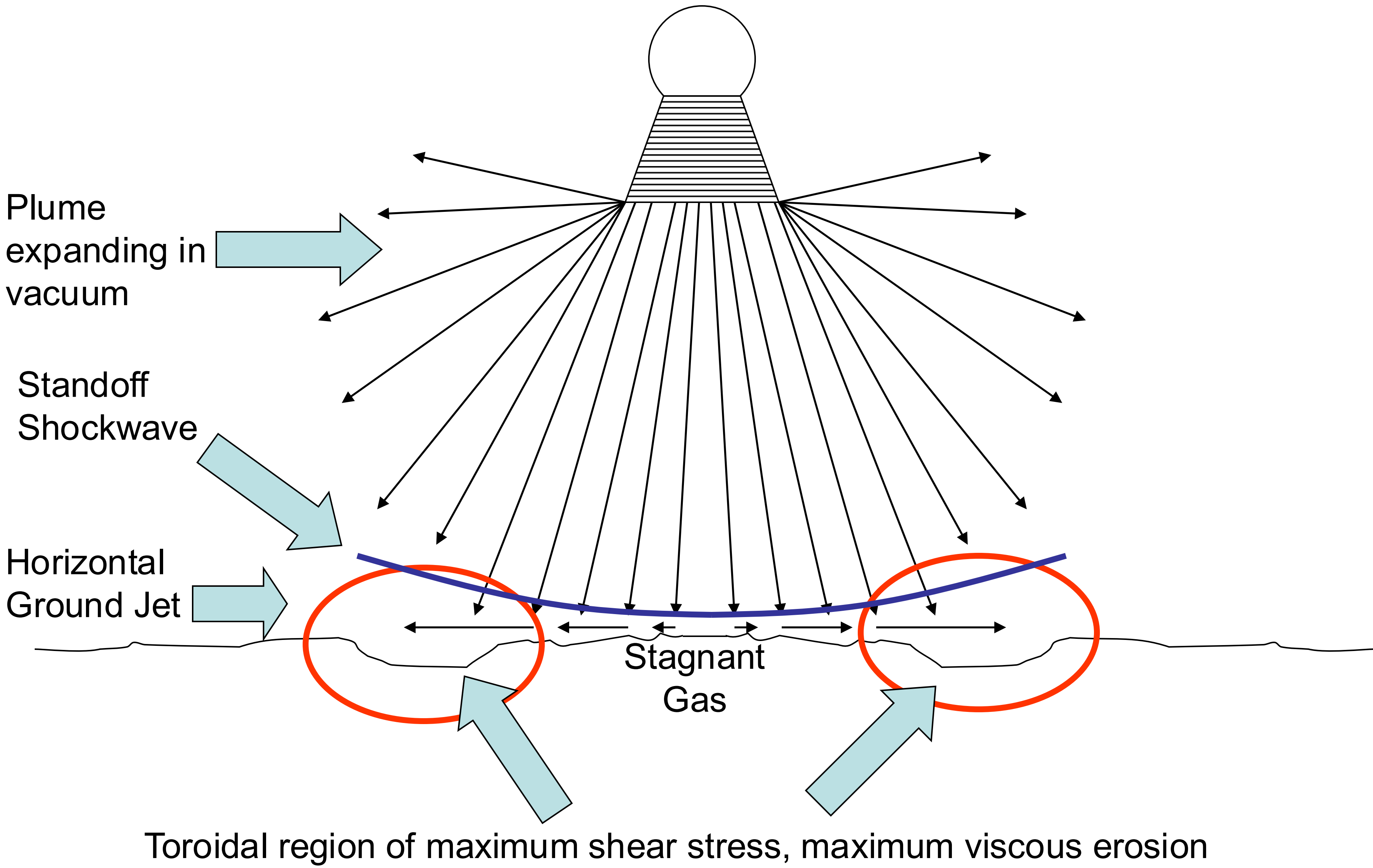
Moon

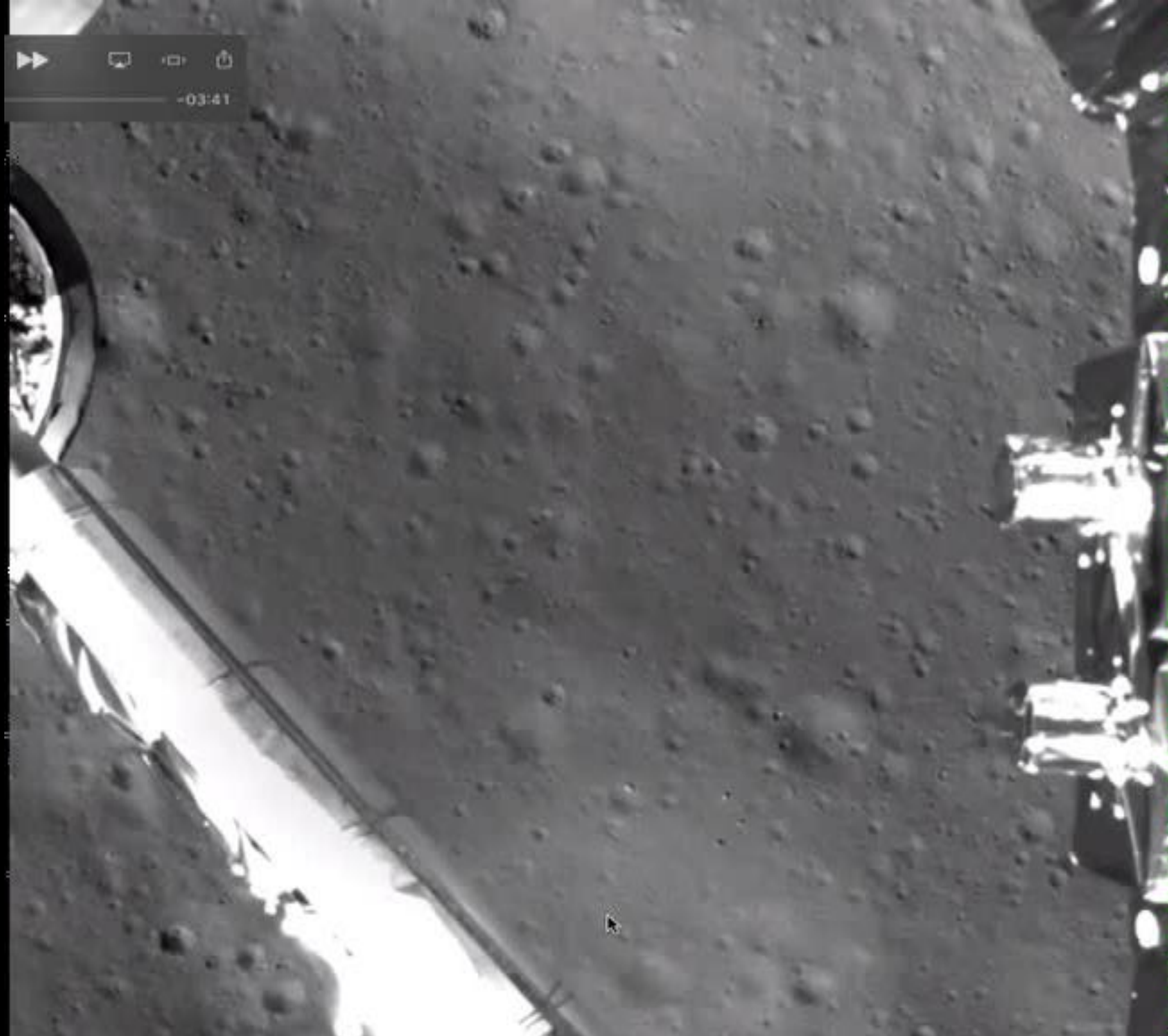
Boundary Layer of the Horizontal Jet



Source: John E. Lane, Philip T. Metzger, Christopher D. Immer, and Xiaoyi Li, “Lagrangian Trajectory Modeling of Lunar Dust Particles,” Earth & Space 2008, Long Beach, CA, Mar. 3, 2008

Viscous Erosion

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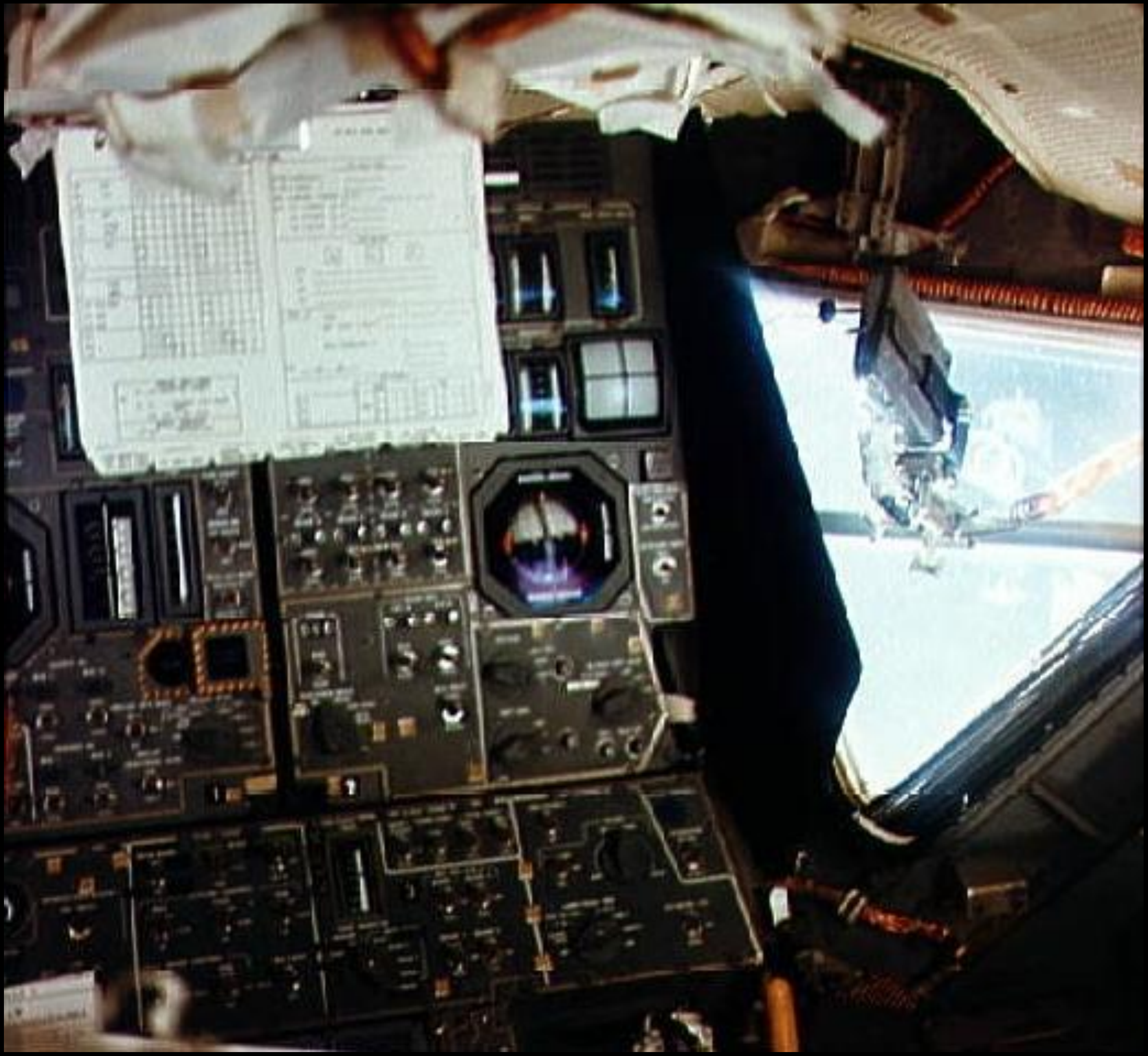
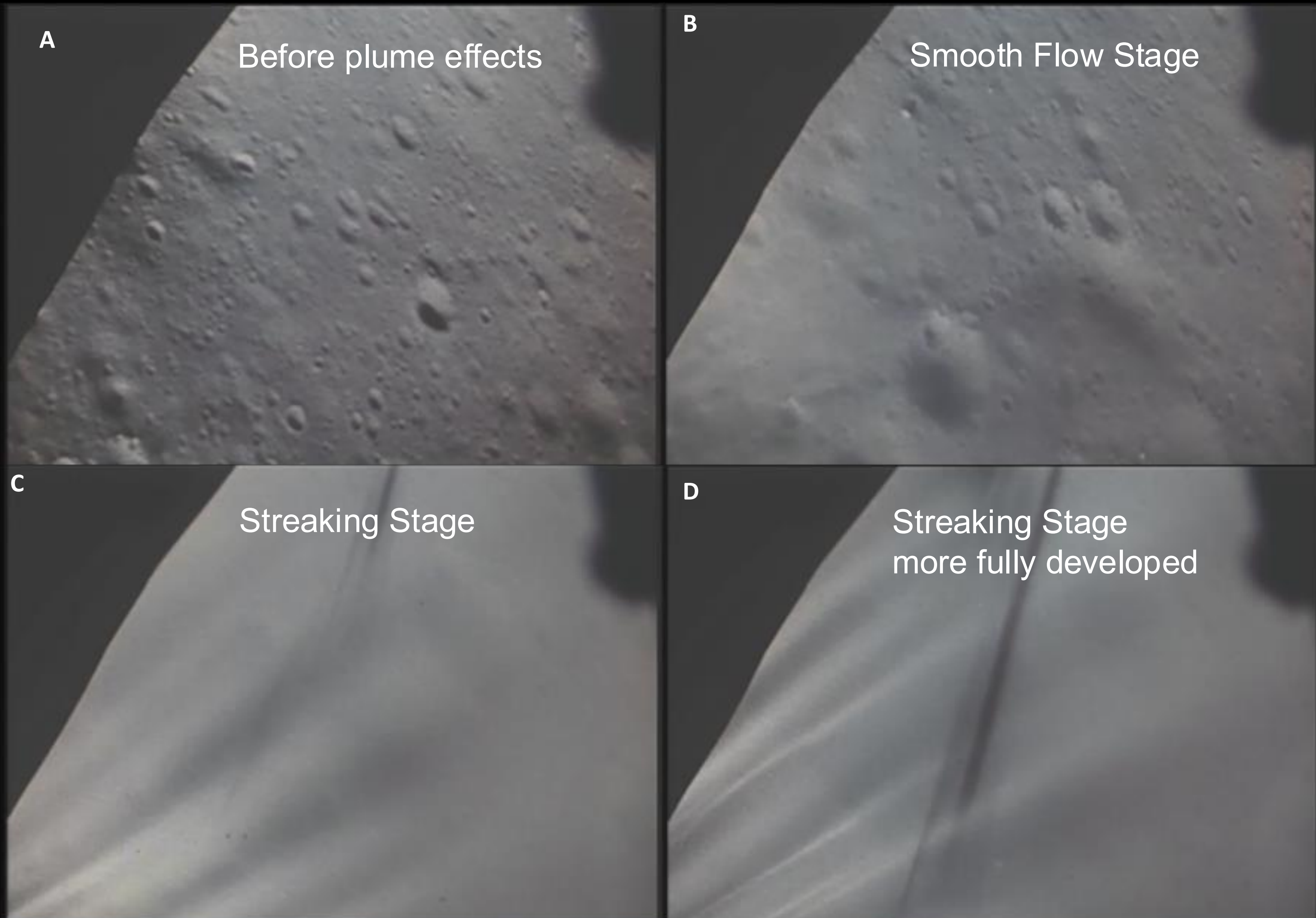
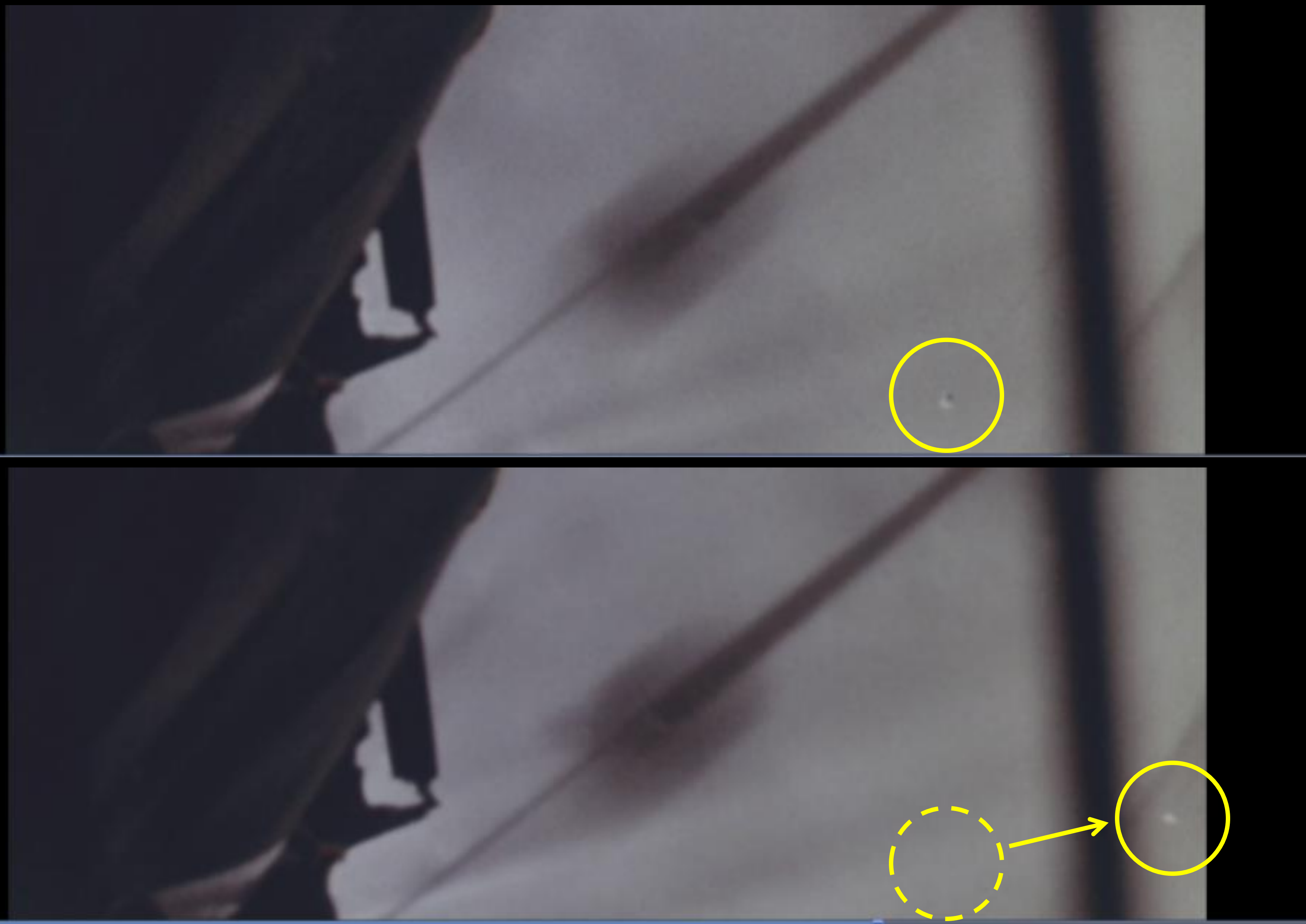
Lunar Module Sequence Camera



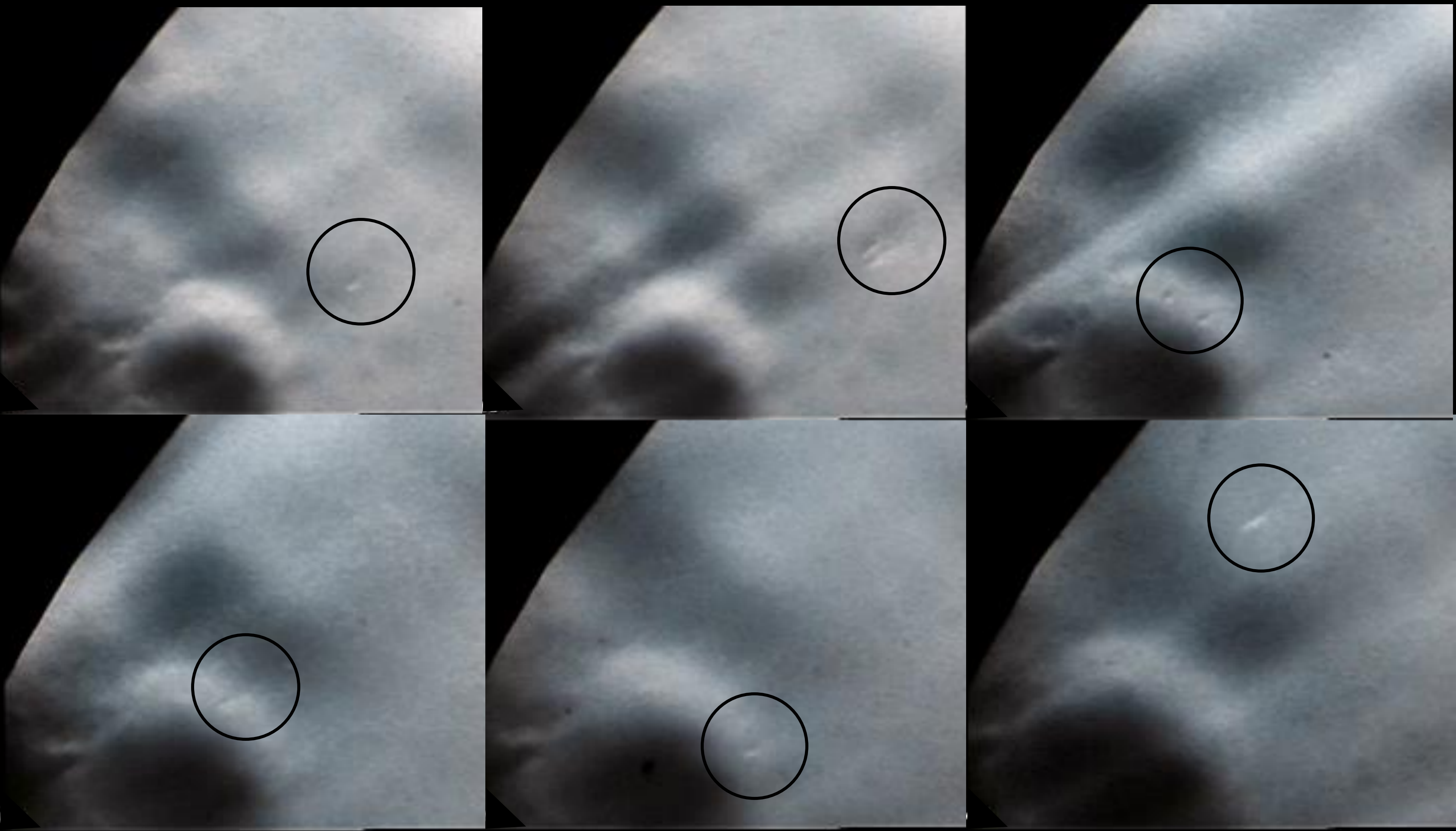

A
Before plume effects
B
Smooth Flow Stage
C
Streaking Stage
D
Streaking Stage
more fully developed


E
Terrain Modification Stage
F
Terrain Modification Stage
G
Clearing Stage
H
After plume effects

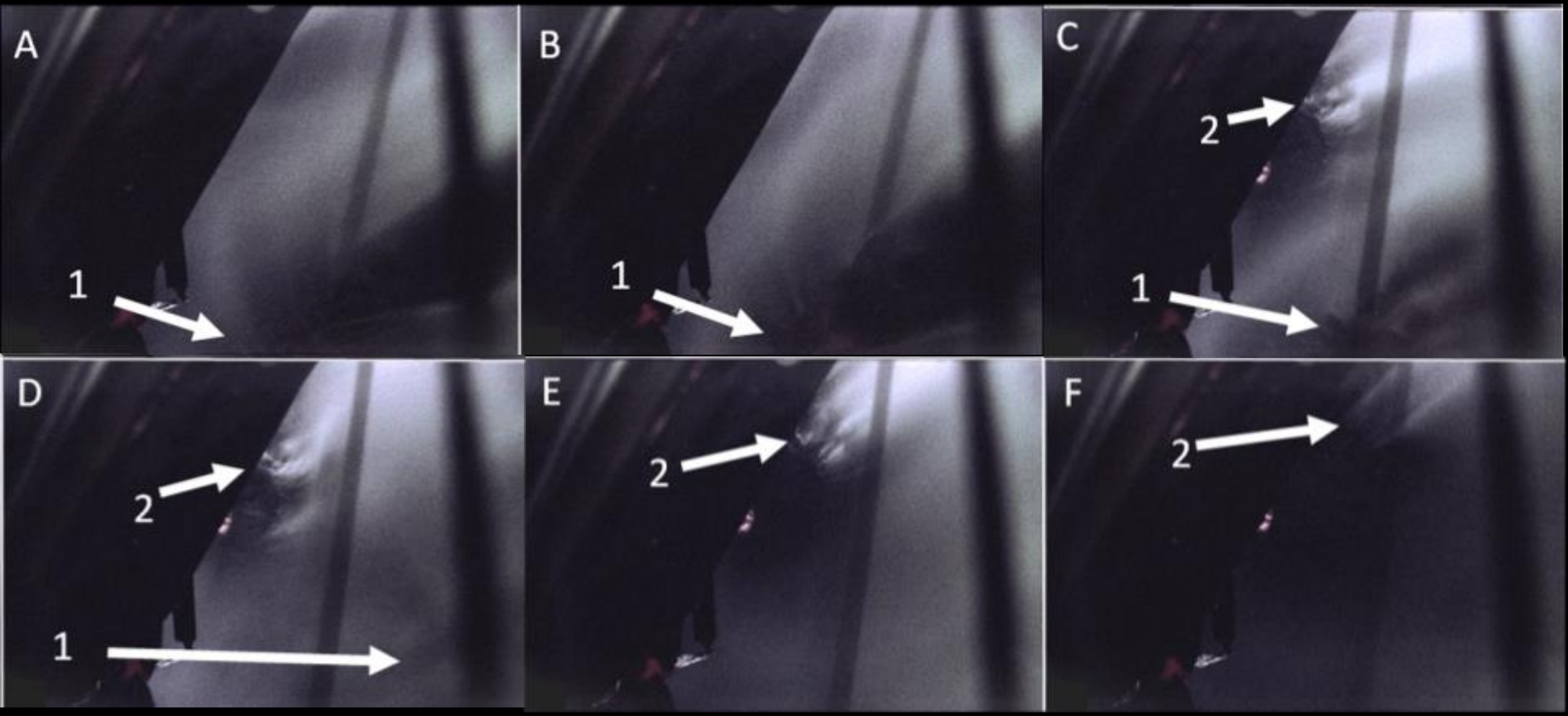
Rocks Blowing



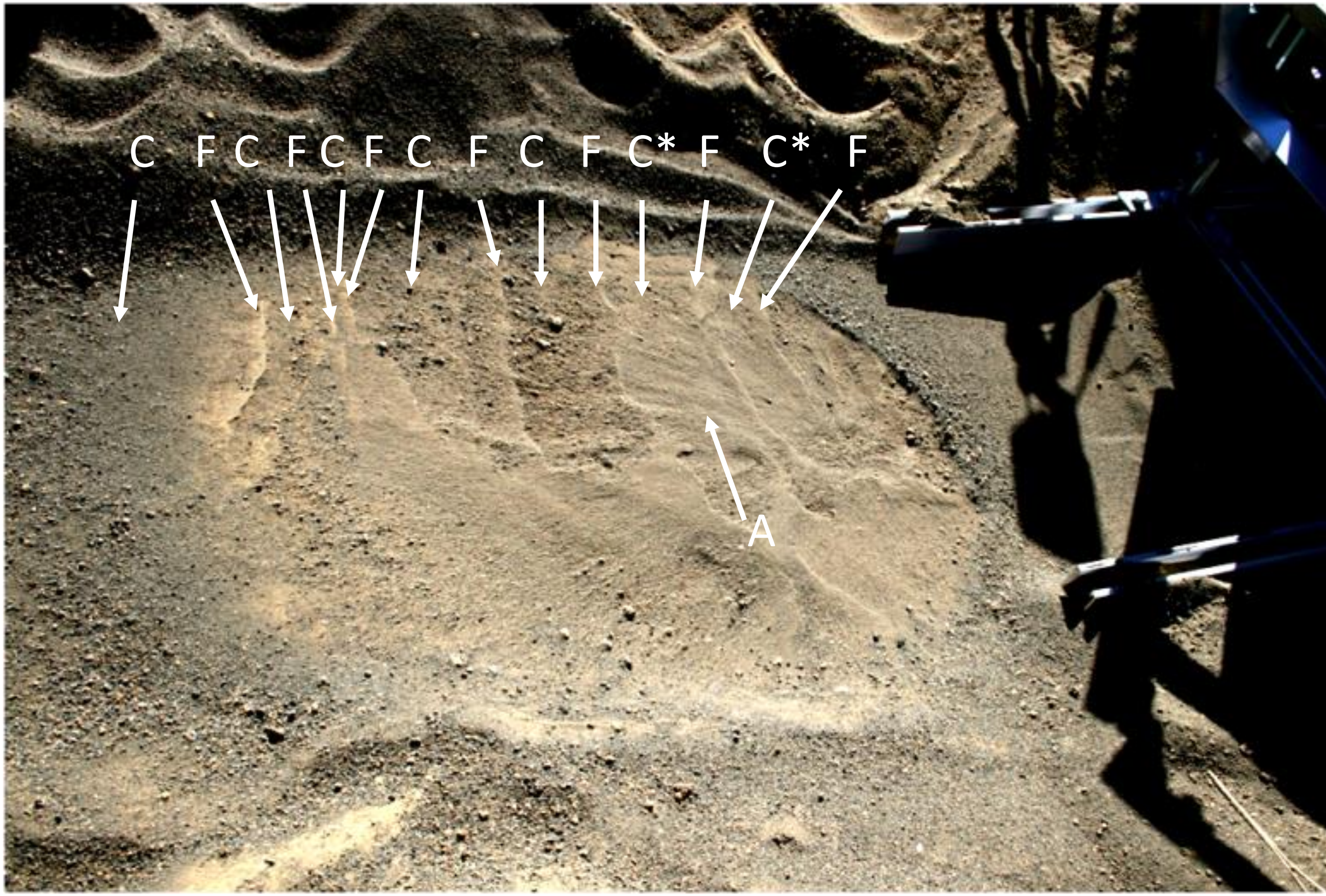
Dust Tails



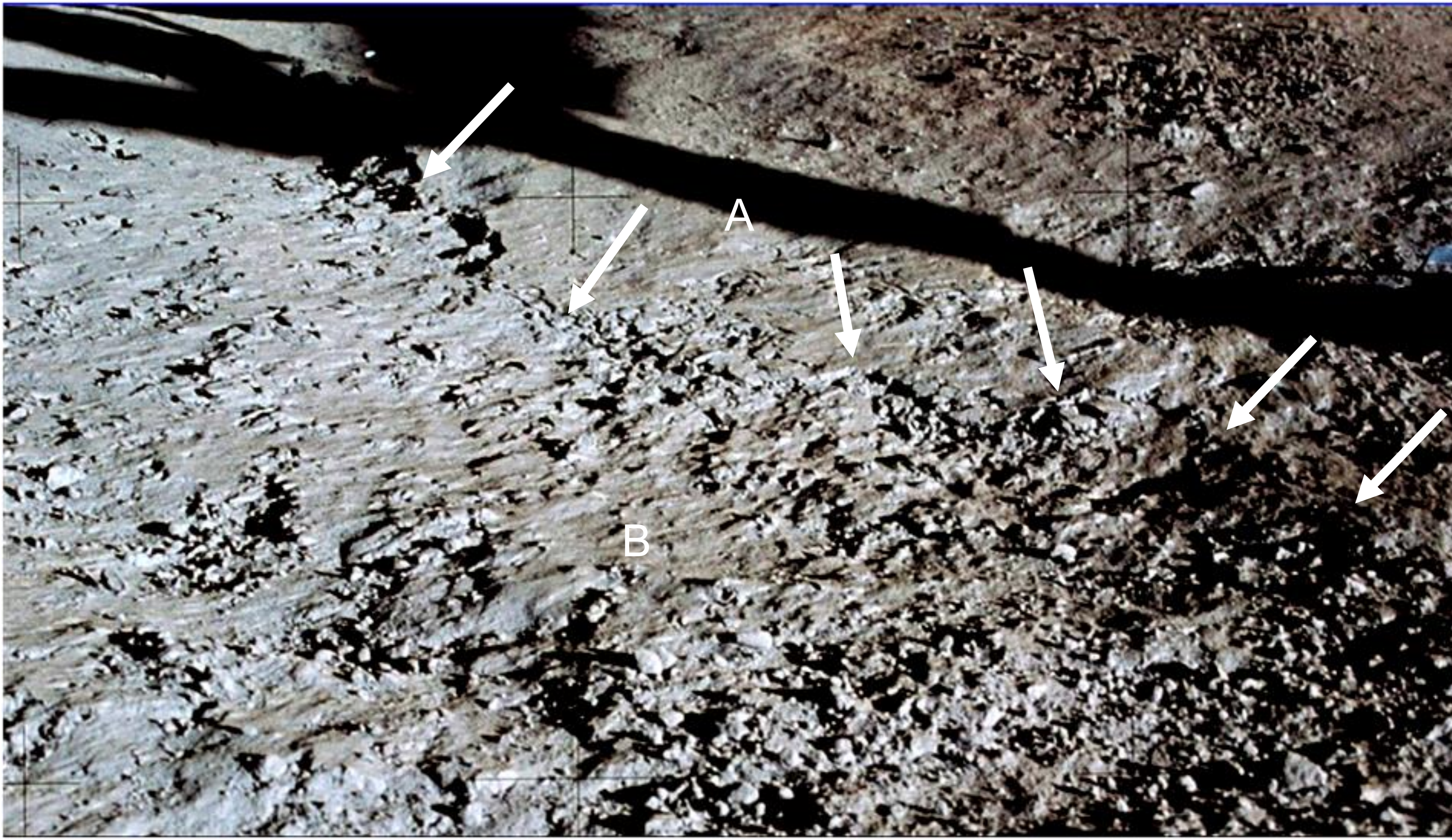
Terrain Modification



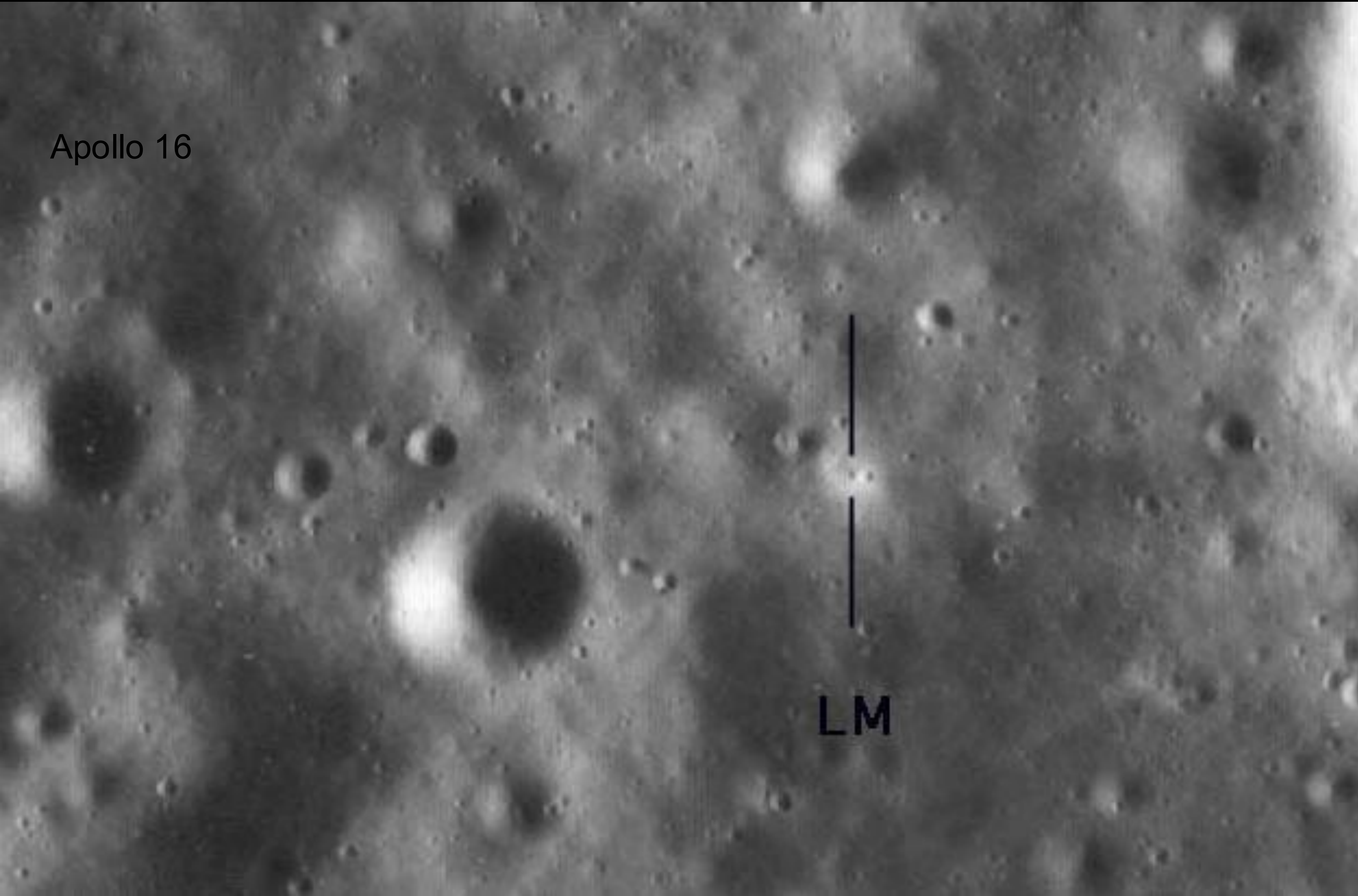
Plume Test on Mauna Kea




C
A
B

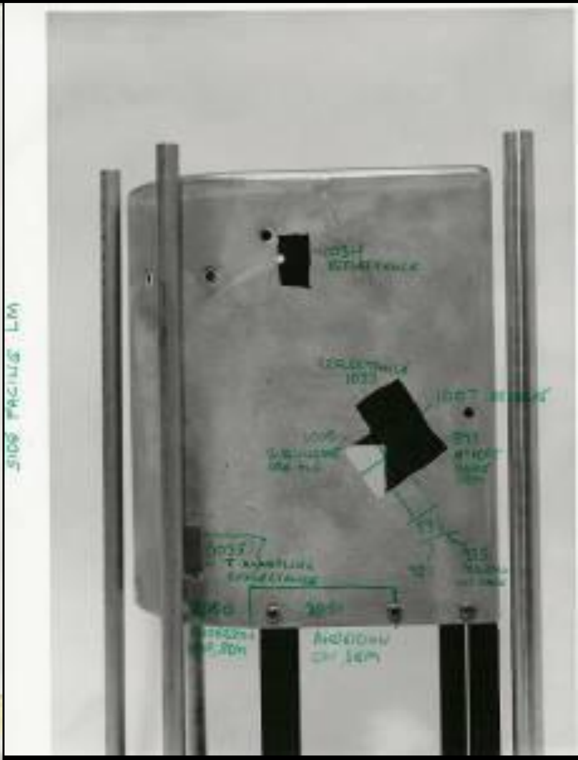

A
B

Surface Brightening of Landing Site

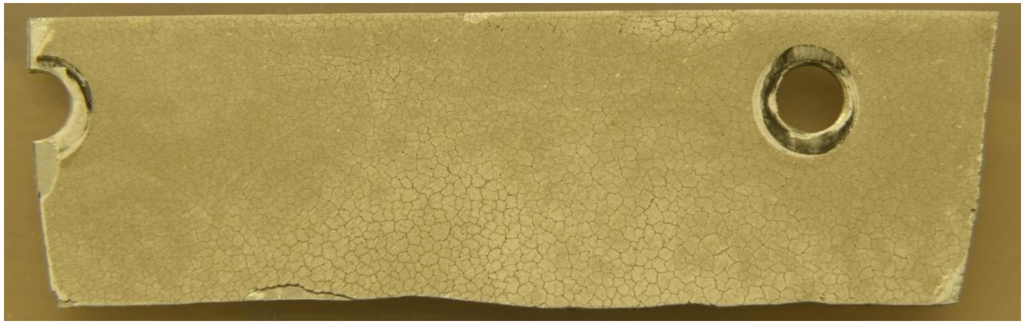


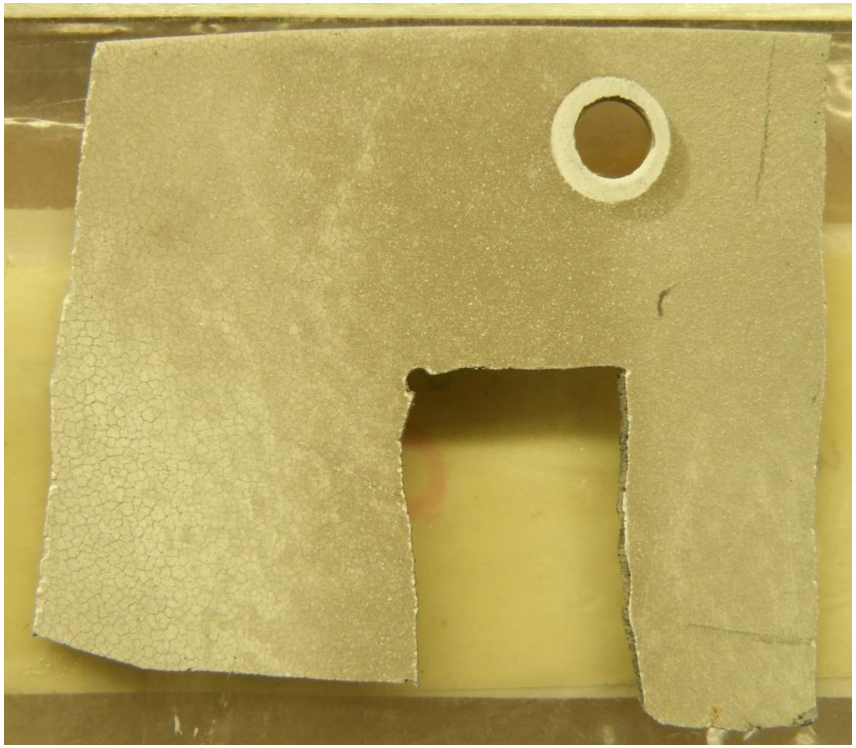
Why Is This Important?

Surveyor III Coupons

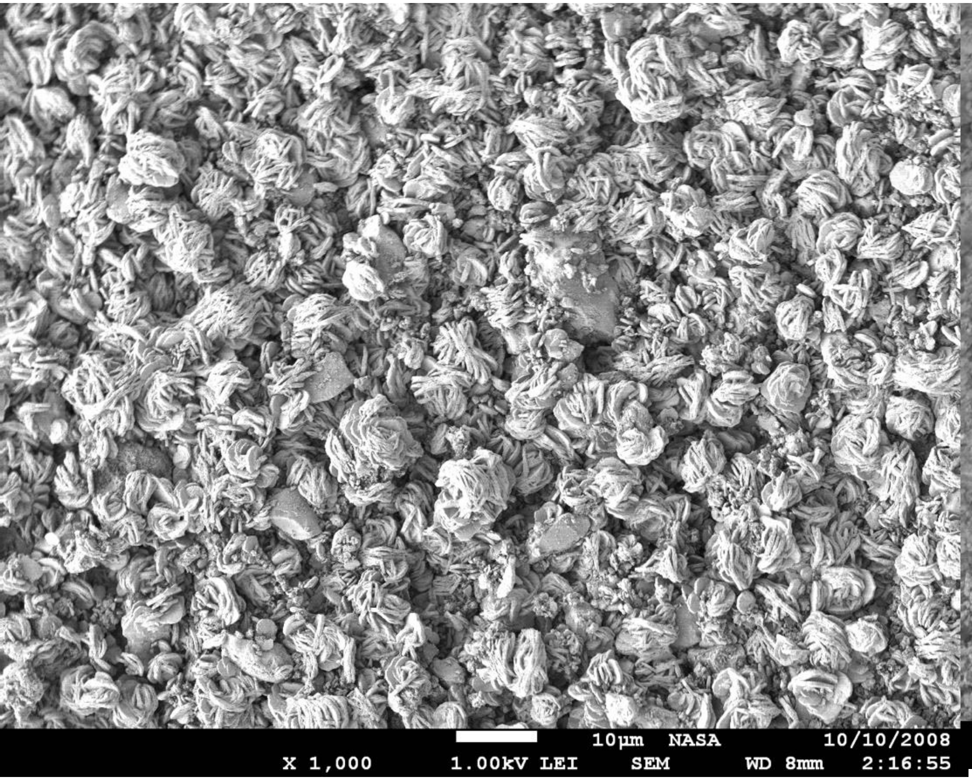


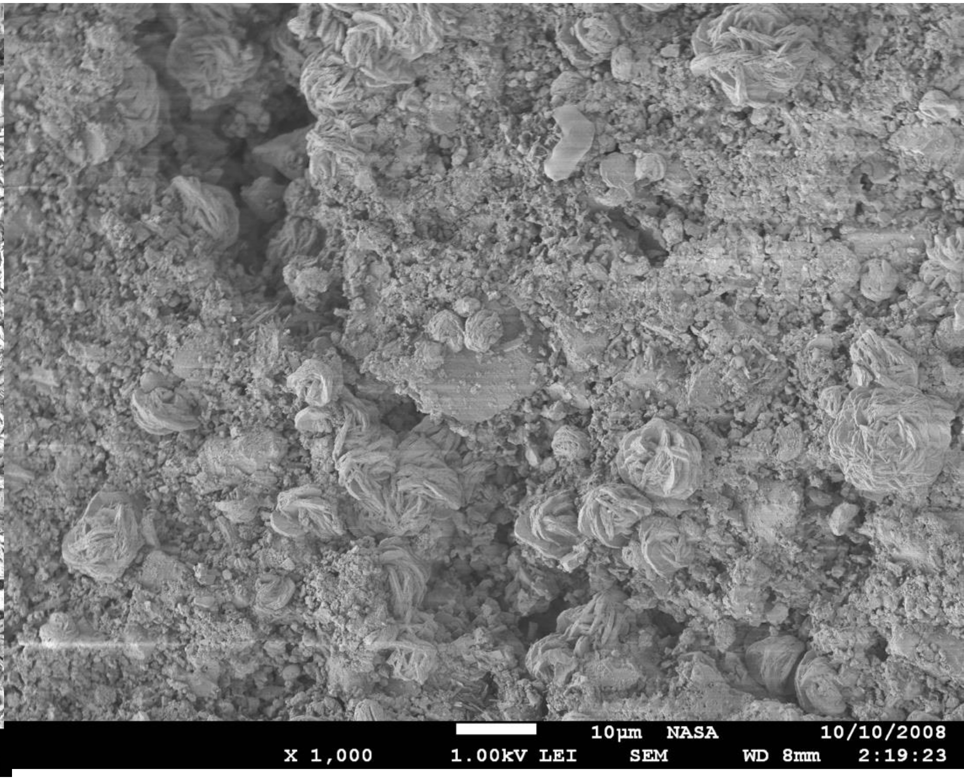
Surveyor III Coupons



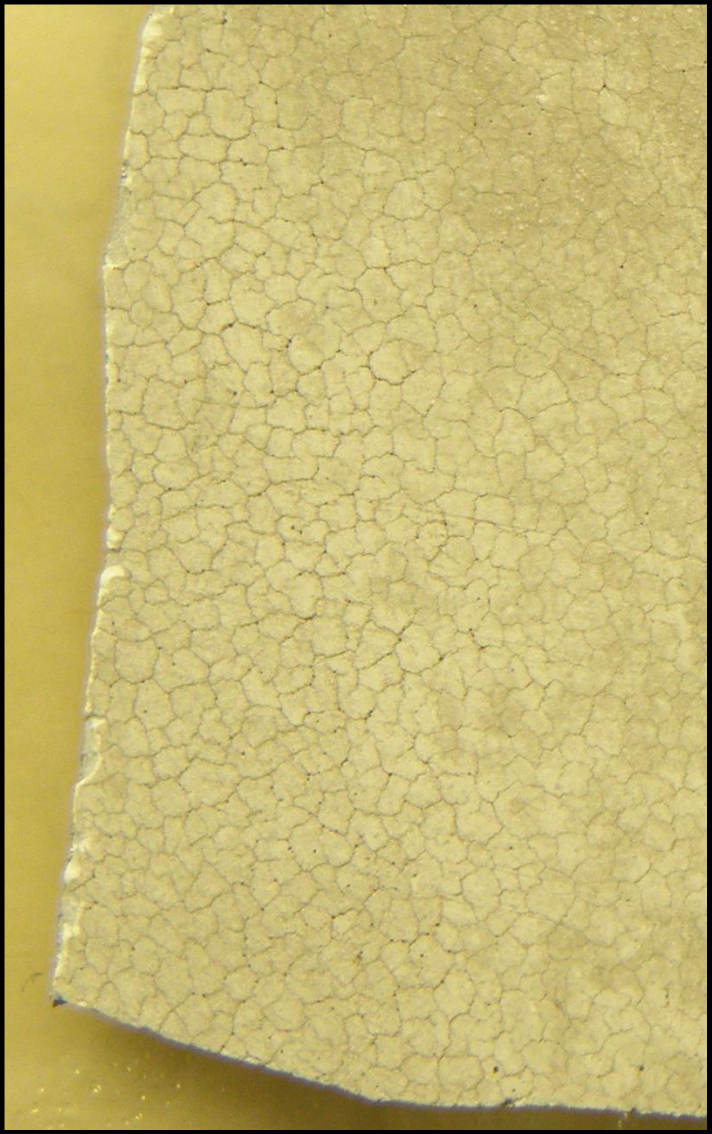


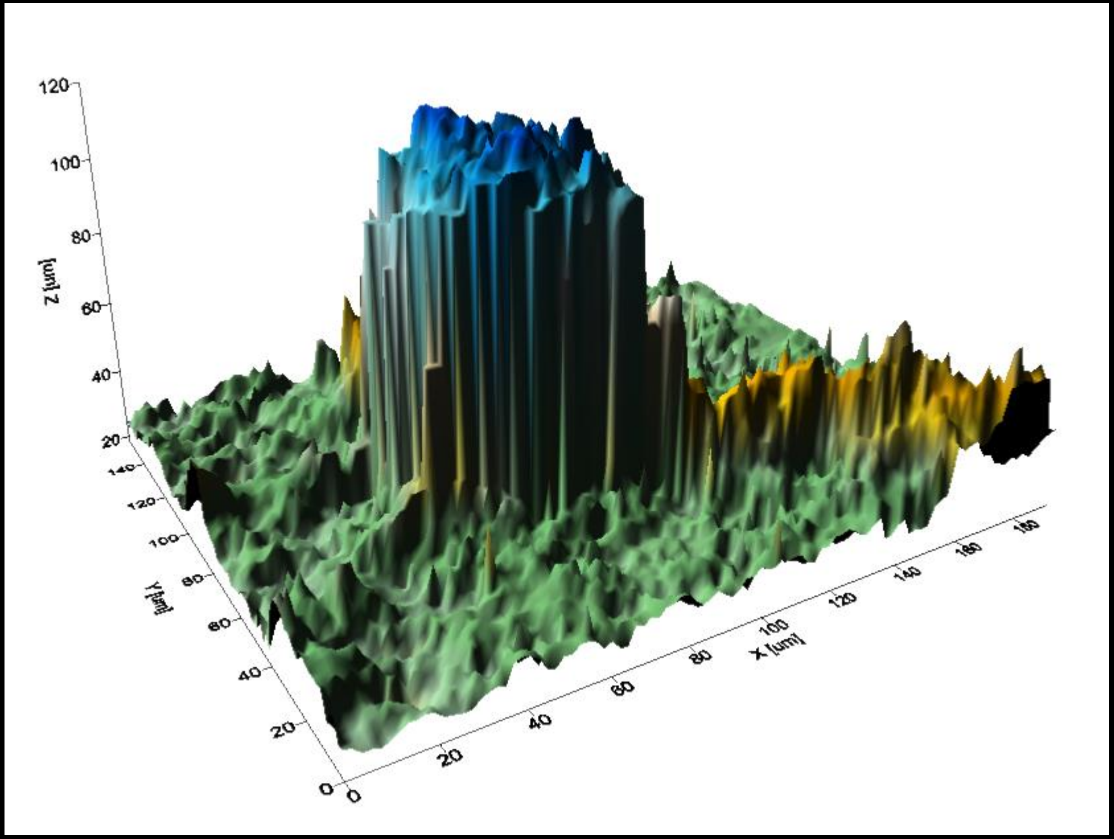
SEM Imagery


10μm NASA 10/10/2008
X 1,000 1.00kV LEI SEM WD 8mm 2:16:55

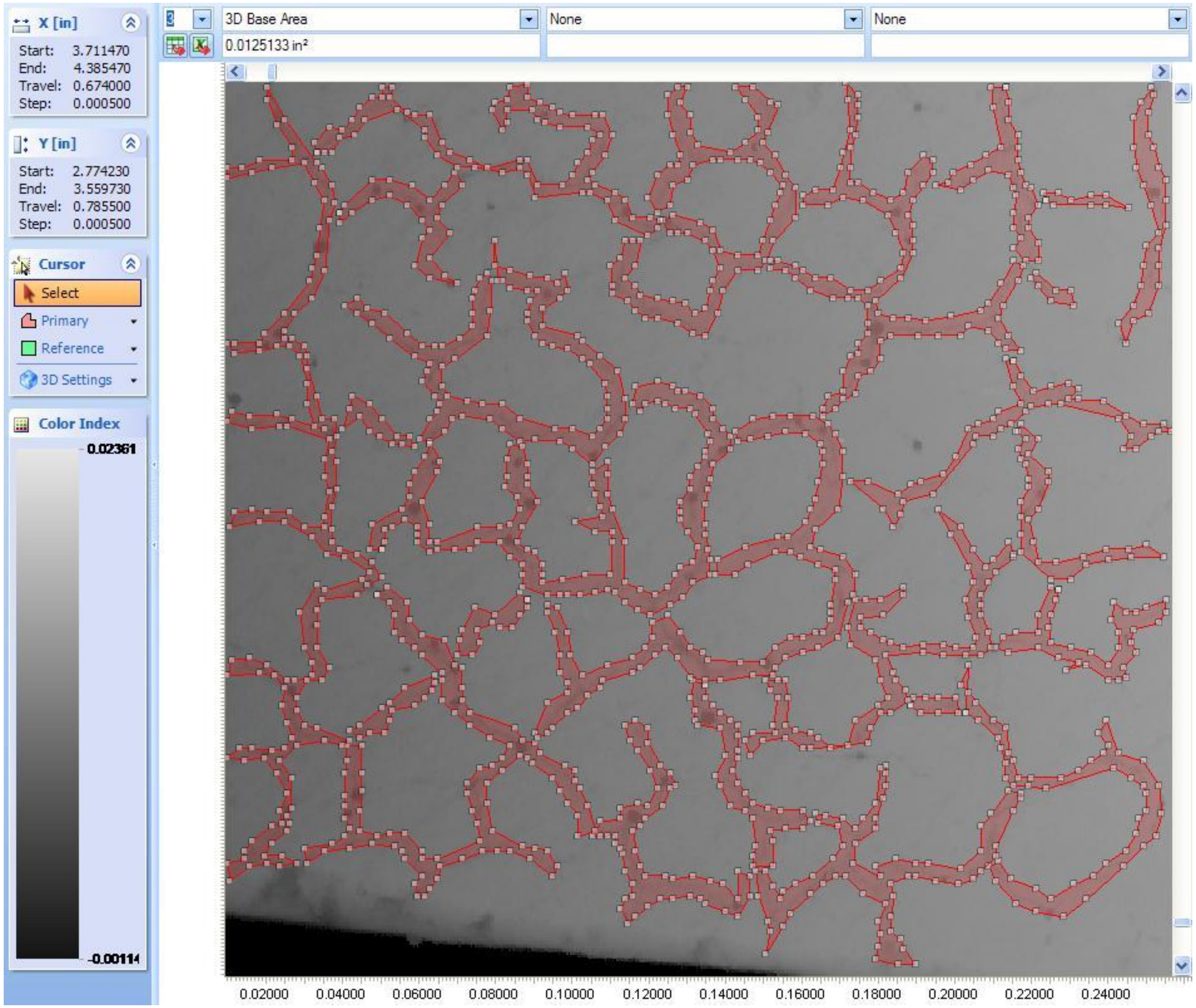

10μm NASA 10/10/2008
X 1,000 1.00kV LEI SEM WD 8mm 2:19:23

Pits and Cracks





Correlation of Pits and Cracks

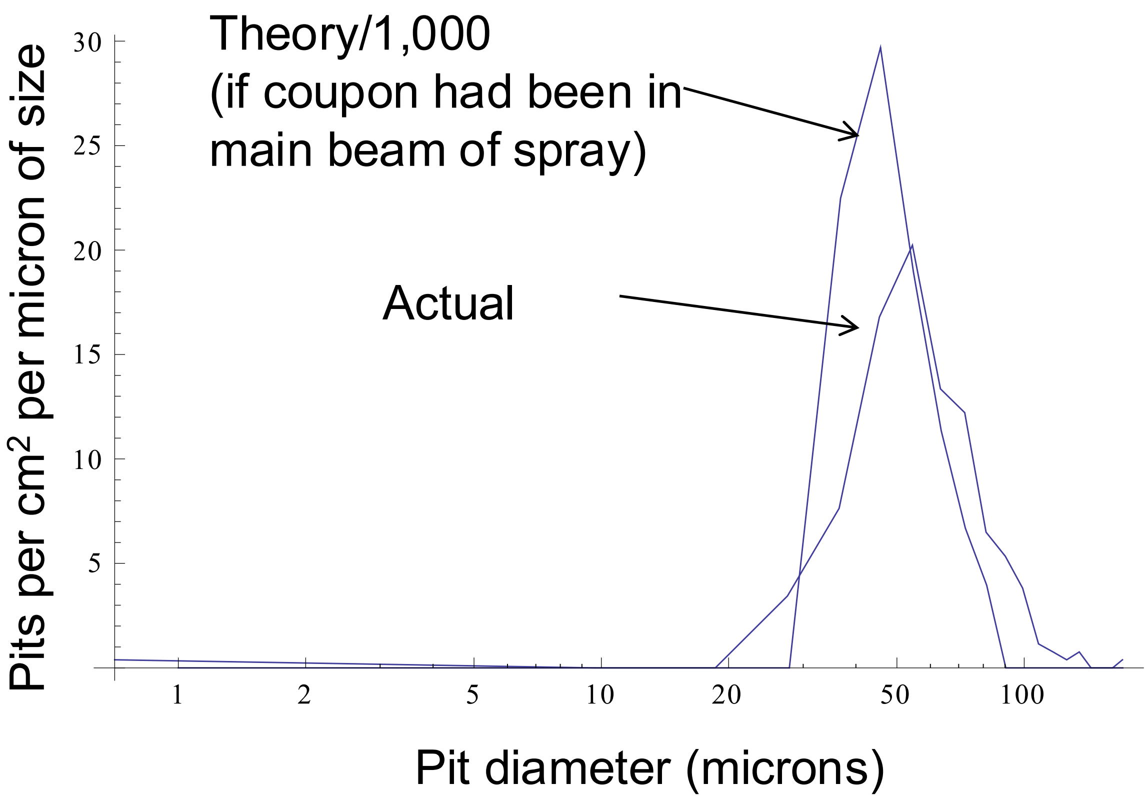


Cracks are 22% of area

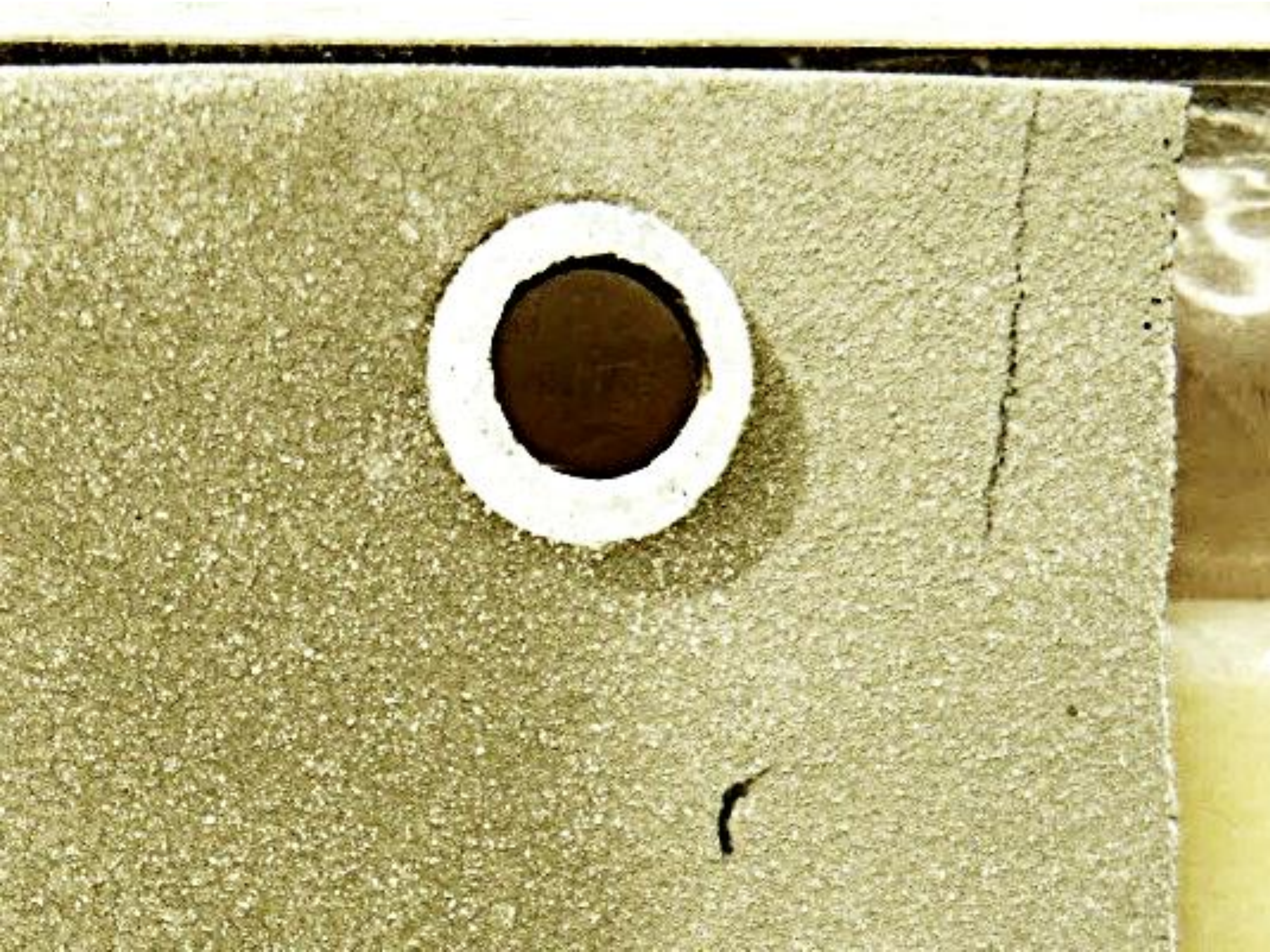
66% of pits are on cracks

Pits and cracks are causally related

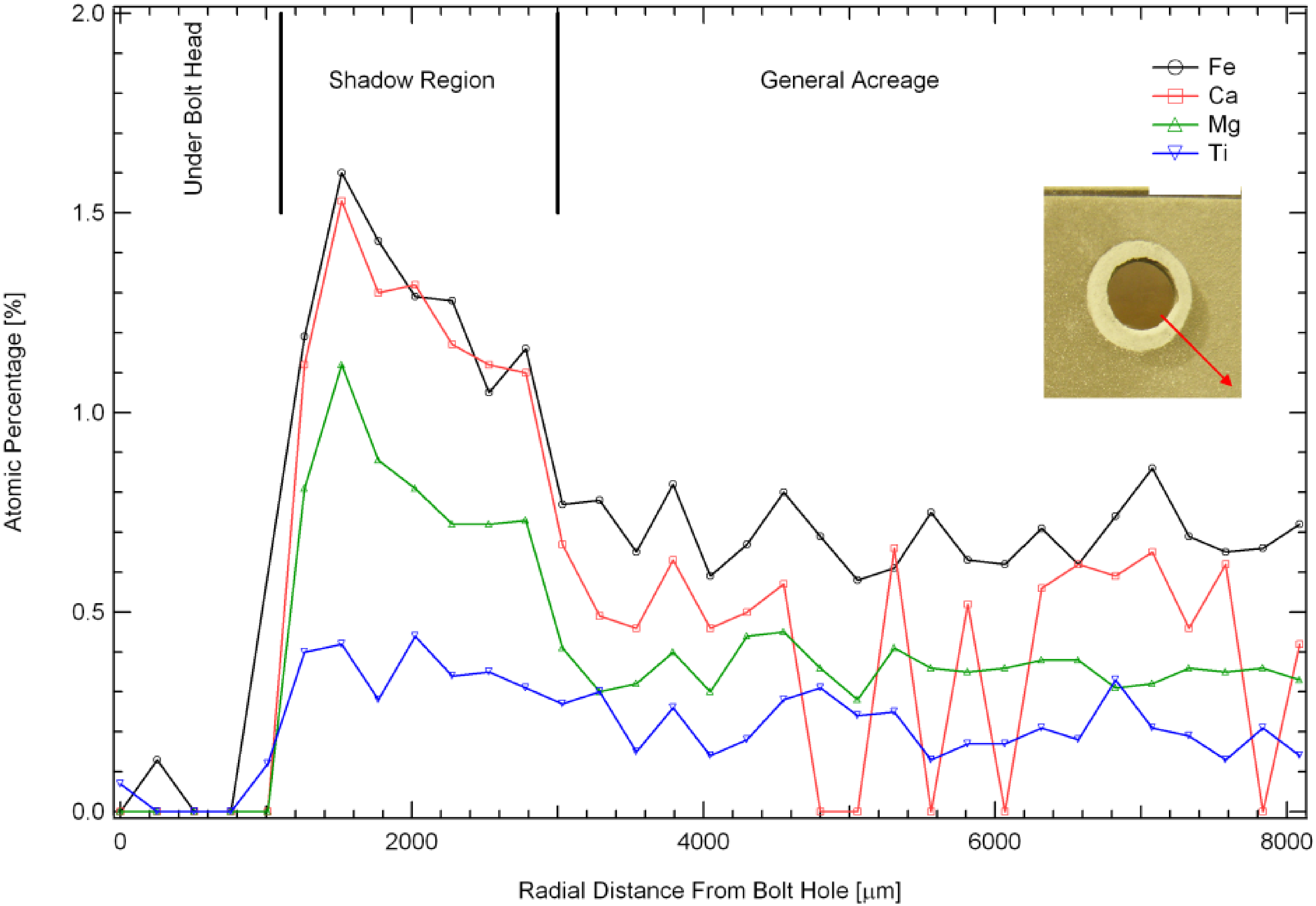
Comparison of Optical Density with Surveyor



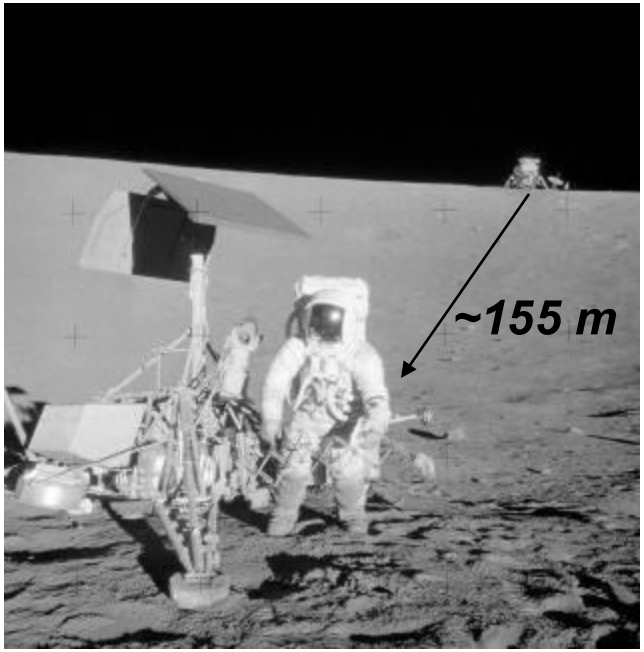
- Surveyor shows 10^3x fewer divots than if it were in main beam
- Surveyor show 34x less scouring than if it were main beam



The Shadow is Made of Dust

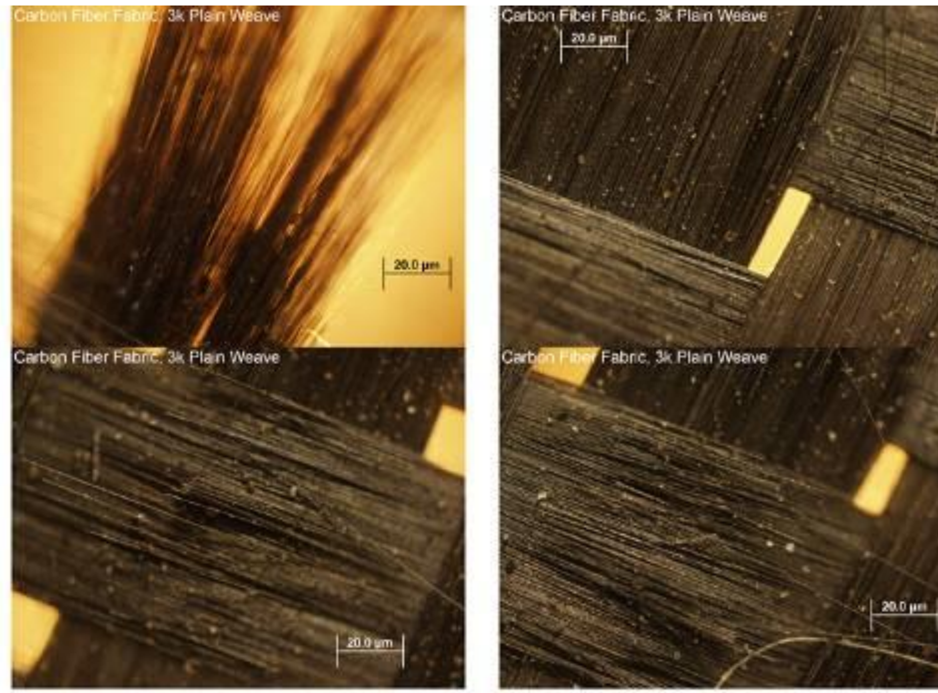


Material Damage from Blowing Particulates



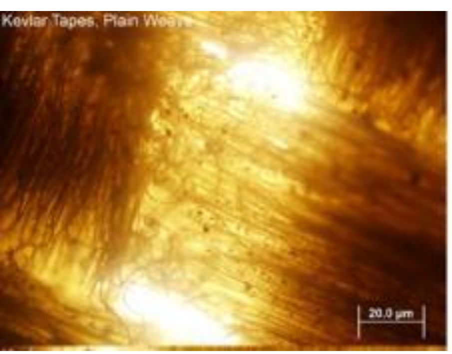
- Experiments: JSC-1A lunar soil simulant impacted onto target materials
- Particle velocities 30-80 m/s
- Far slower than lunar plume velocities
- The following slides demonstrate damage even at these lower velocities
- At 10x to 20x velocity (lunar case), particle energies will be 100x to 400x what is shown here

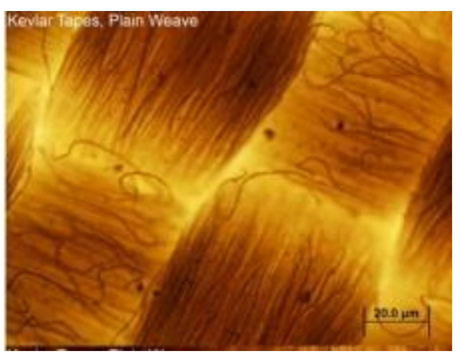
JSC-1A Impacting Carbon Fiber

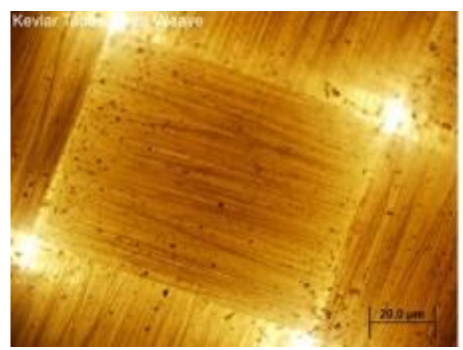


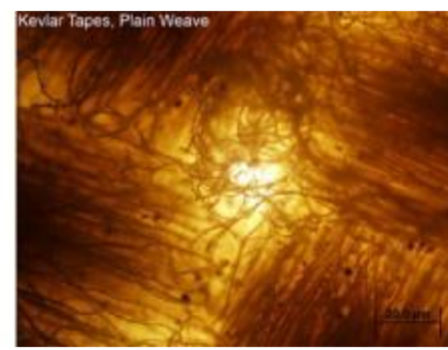
Source: Luke Roberson (NASA/KSC), Ryan Clegg (FIT)

JSC-1A Impacting Kevlar







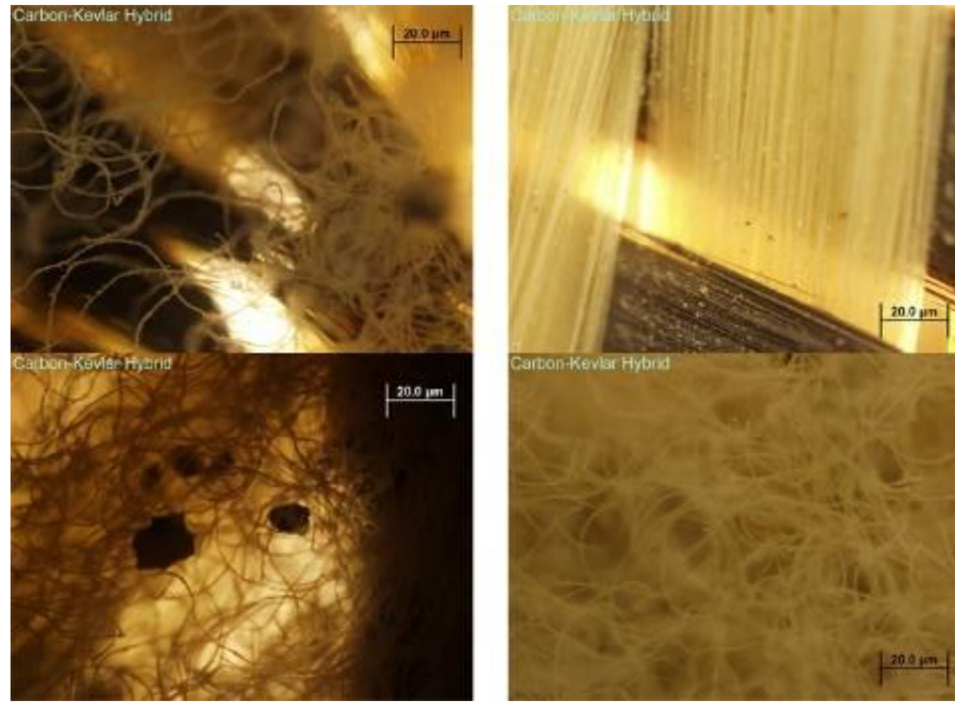


Source: Luke Roberson (NASA/KSC), Ryan Clegg (FIT)

JSC-1A Impacting Kevlar-Carbon Fiber

Before

After



Source: Luke Roberson (NASA/KSC),
Ryan Clegg (FIT)

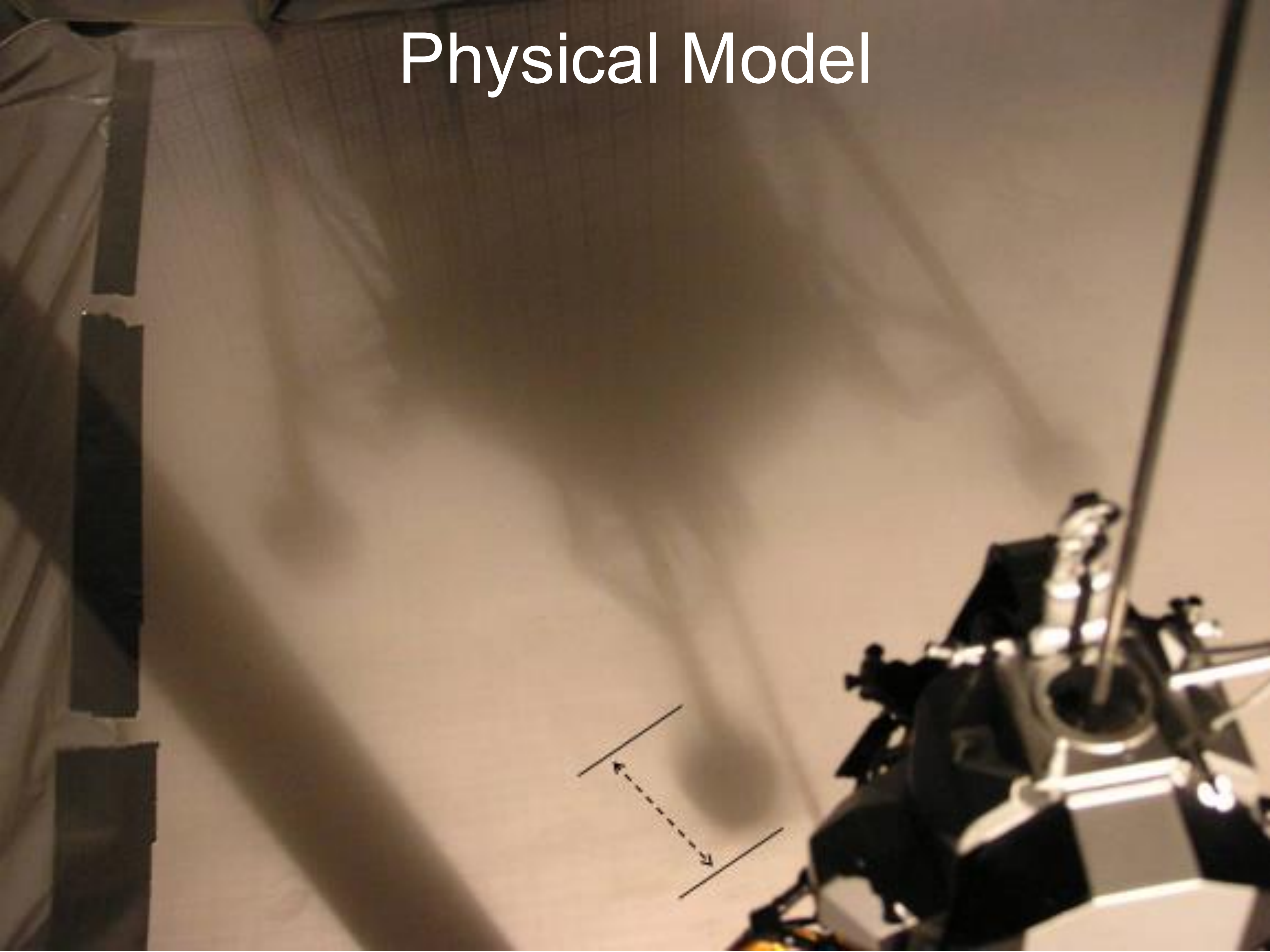
JSC-1A Impacting Glass

Source: Luke Roberson (NASA/KSC), Ryan Clegg (FIT), Philip Metzger (NASA/KSC)

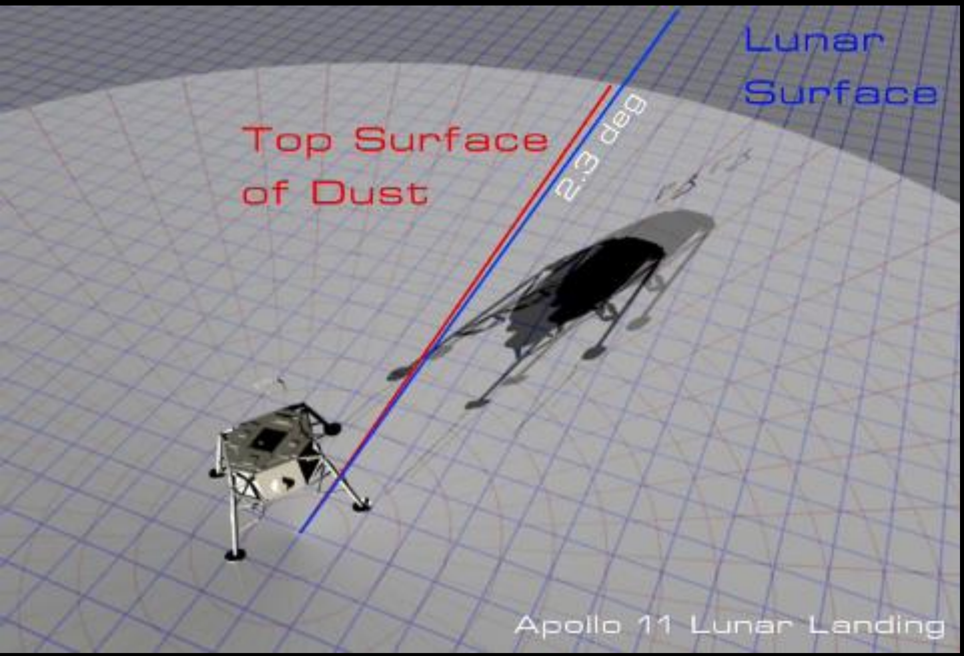
Where do the ejecta go, and how fast?

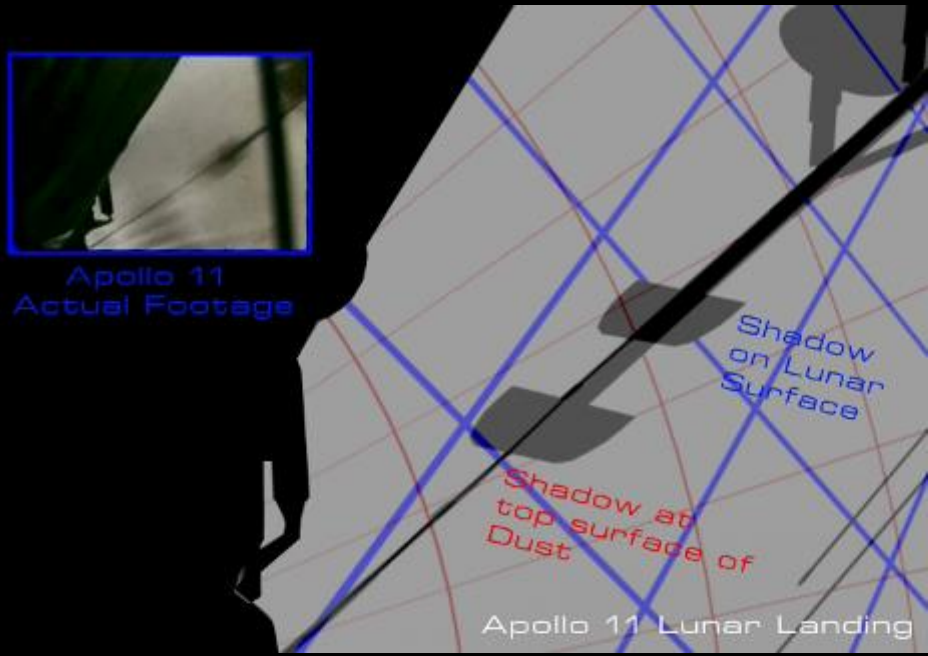
Footpad Shadow Elongation

Physical Model



Computer Simulation/Modeling



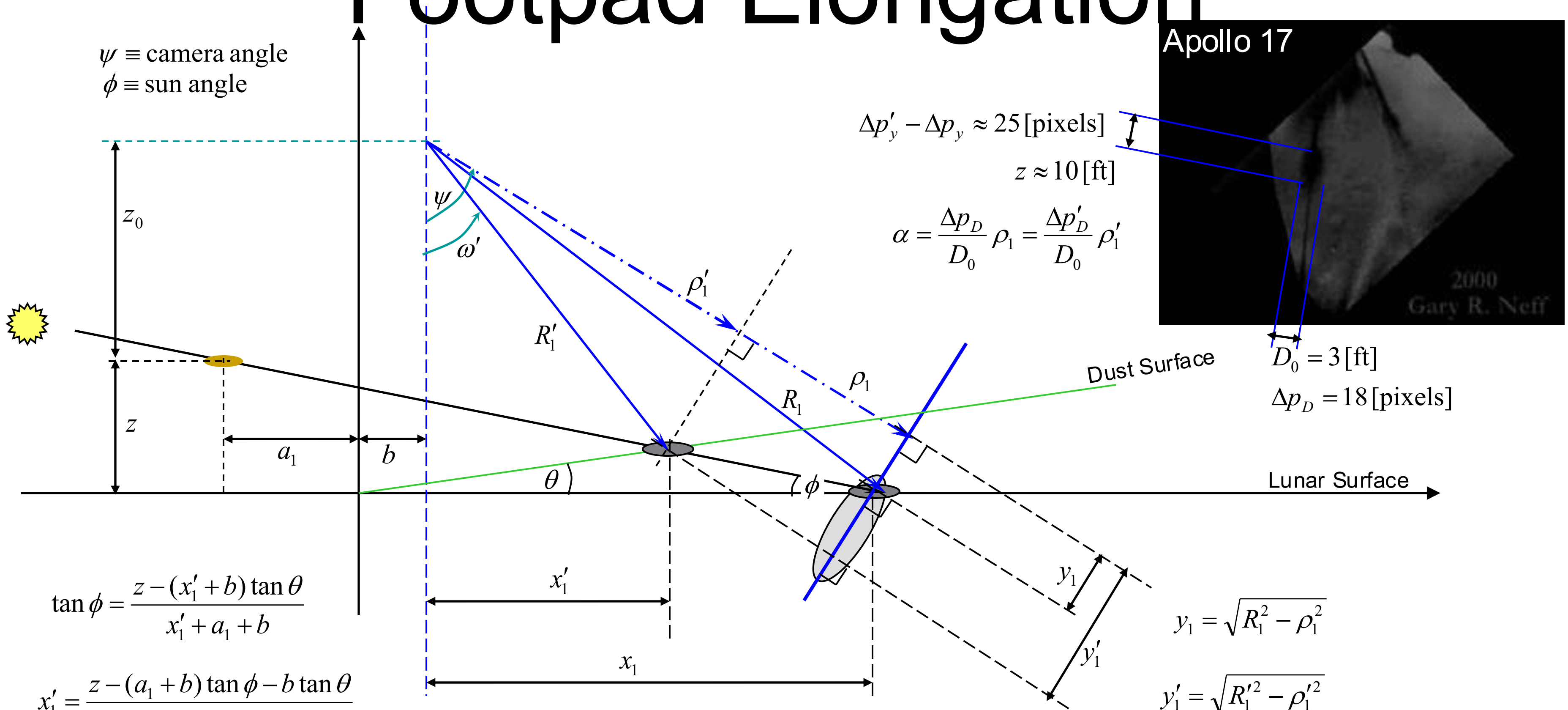


(Irving Bushnell, ASRC Aerospace put together videos)

Footpad Elongation

$\psi \equiv$ camera angle

$\phi \equiv$ sun angle



$$\alpha = \frac{\Delta p_D}{D_0}\rho_1 = \frac{\Delta p'_D}{D_0}\rho'_1$$

$$y_1 = \sqrt{R_1^2 - \rho_1^2}$$

$$y'_1 = \sqrt{R_1'^2 - \rho_1'^2}$$

$$\tan\phi = \frac{z - (x'_1 + b)\tan\theta}{x'_1 + a_1 + b}$$

$$x'_1 = \frac{z - (a_1 + b)\tan\phi - b\tan\theta}{\tan\theta + \tan\phi}$$

$$R'_1 = \sqrt{x_1'^2 + [z + z_0 - (x'_1 + b)\tan\theta]^2}$$

$$\tan\omega' = \frac{x'_1}{z + z_0 - (x'_1 + b)\tan\theta}$$

$$\rho'_1 = R'_1\cos(\psi - \omega')$$

Foot Pad Elongation: $\Delta p'_y - \Delta p_y = \alpha\left(\frac{y'_1}{\rho'_1} - \frac{y_1}{\rho_1}\right)$

3D Measurements of LM

- Video measurements calibrated on actual LM via 3D Scene Analysis
- Photogrammetry System originally developed for debris tracking analysis as part of the Columbia accident investigation

Summary of Video Analysis

	Sun Angle	Ejection Angle
11	10.8	2.3 2.3
12	5.1	-
14	10.3	2.5 2.7
15	12.2	***7.8*** ***7.2*** ***11.8***
16	11.9	1.0 1.4 1.4
17	13.0	2.0 1.6

- Dust ejection angles < 3 degrees except for Apollo 15
- Apollo 15 (*red italics*) landed on terrain with 11 degree local slope, which probably explains the higher ejection angle
- Apollo 12 shadows hard to measure due to extremely low sun angle

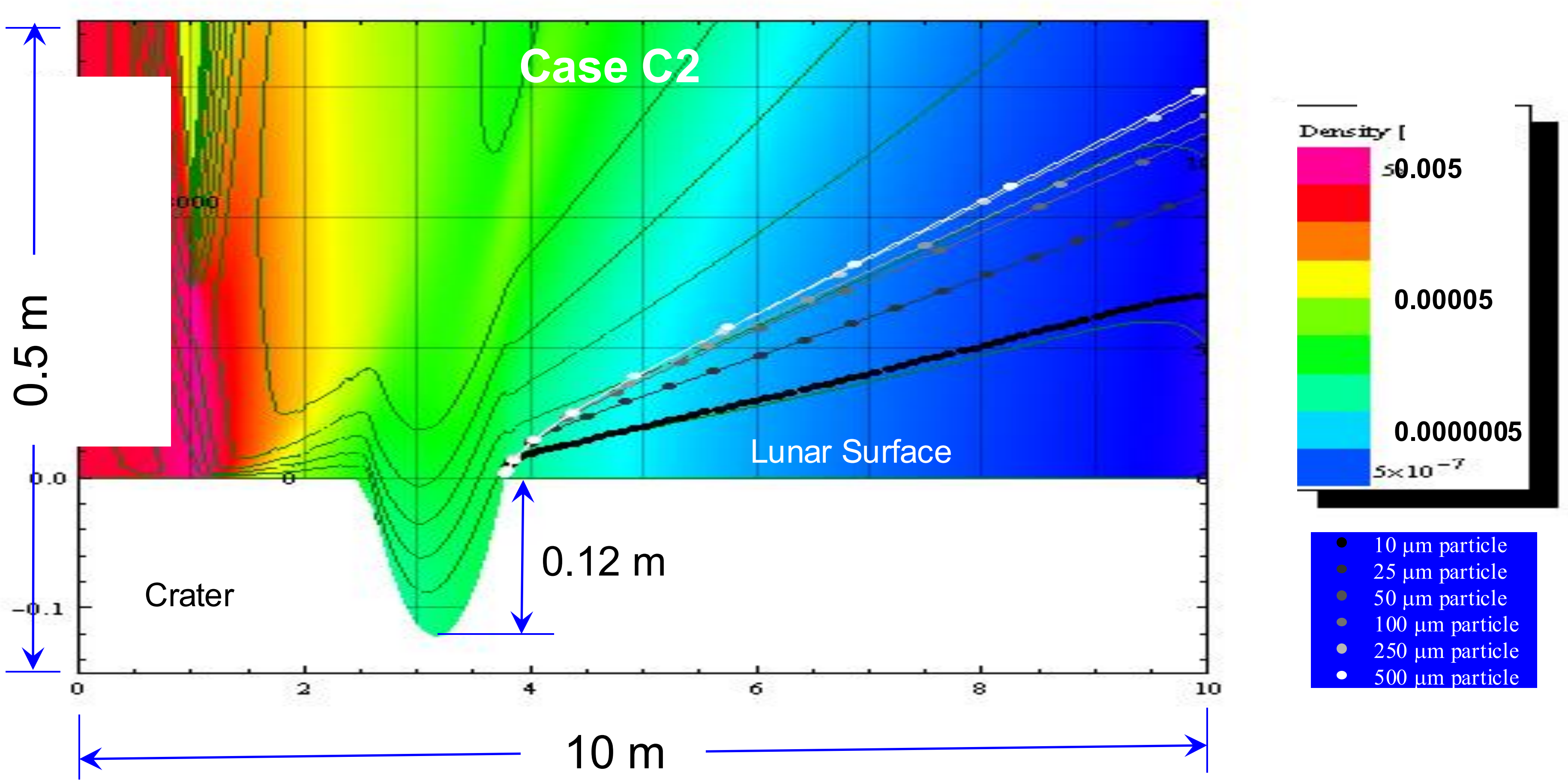
Exception: Apollo 15

Other exceptions:

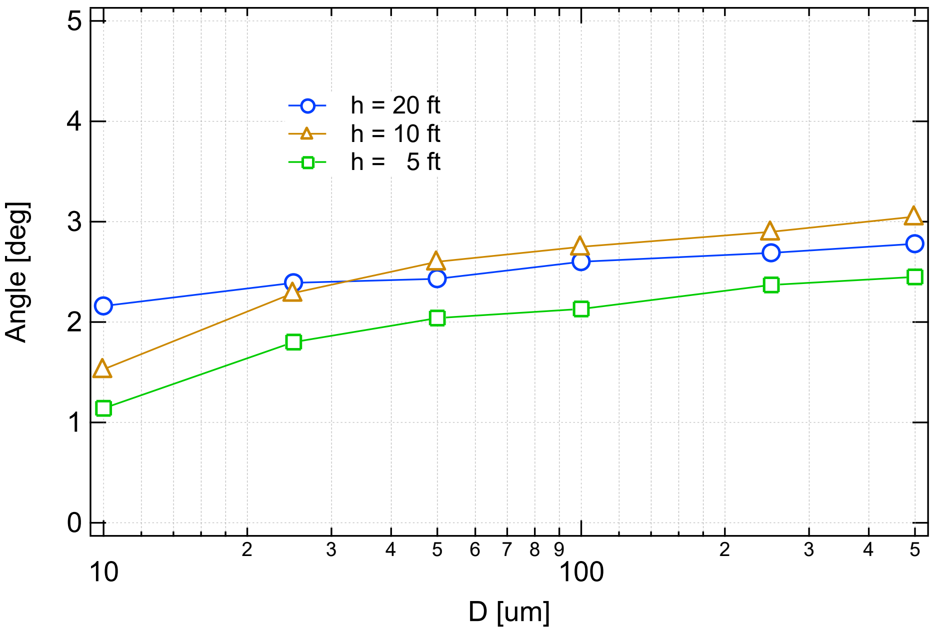
- dust streaks from small craters
- blast in terrain modification stage
- plume reflection planes for multi-engine landers

2008 Trajectory Dependence on Surface Topography

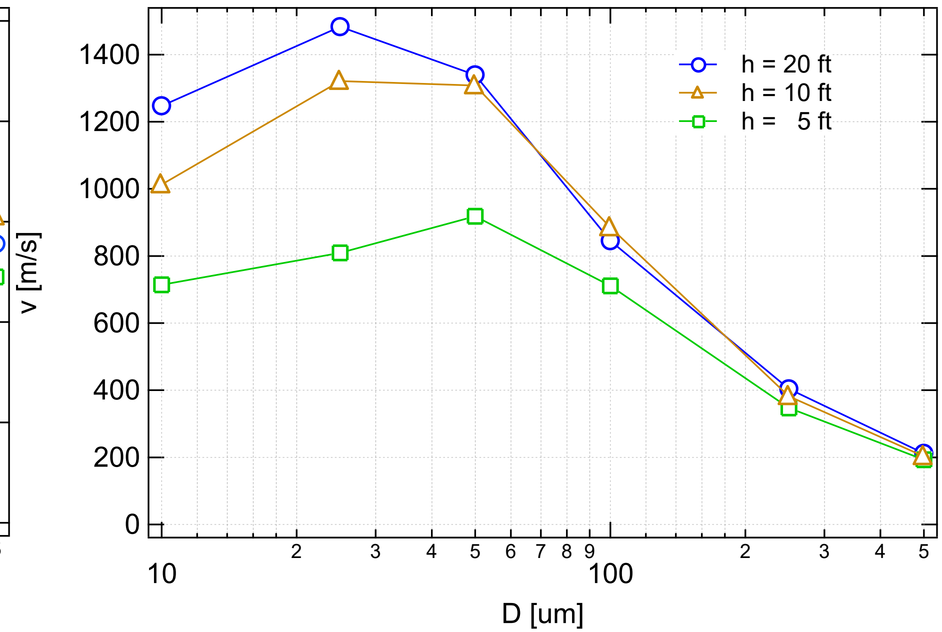
CFD Gas *Density* [kg/m^3]



2008 Estimated Dust Ejection Speed and Angle from Ballistics Simulations



Particle trajectory angles relative to ground for various particle sizes and CFD cases.



Particle speeds exiting the CFD model boundary.

Particle Size	Ejecta Speed for LM
Dust	1000 – 3000 m/s
Sand	100 – 1000 m/s
Gravel	~30 m/s
Cobbles	~10 m/s

Rock Blowing

Example: APOLLO-11

Debris #1 $D \approx 10$ cm

$v \approx 60$ mph ≈ 26 m/s

frame: 2008-2015

Apollo-11 Debris #1 frame: 2008

Apollo-11 Debris #1 frame: 2009

Apollo-11 Debris #1 frame: 2010

Apollo-11 Debris #1 frame: 2011

Apollo-11 Debris #1 frame: 2012

Apollo-11 Debris #1 frame: 2013

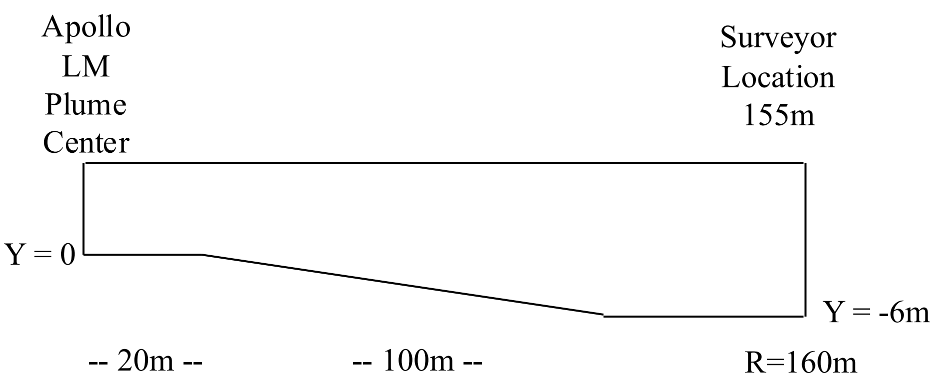
Apollo-11 Debris #1 frame: 2015

Rock Velocities

- Photogrammetry:
- D ≈ 4 cm, v ≈ 30 m/s (67 mph)
- D ≈ 10 cm, v ≈ 11 m/s (25 mph)
- D ≈ 10 cm, v ≈ 16 m/s (36 mph)
- Trajectory Simulation: (initial particle height, x = D/2; nozzle height h = 2.5 ft):
- D = 1 cm, v ≈ 31 m/s
- D = 10 cm, v ≈ 9 m/s

Demo of Lunar Plume Debris Transport

- Apollo-12 LEM Descent Engine Plume Sandblasted Surveyor-3 Spacecraft at 155m Distance
- Surface Pits Indicated Debris Particle Impact Velocities in Excess of 2000 m/s for Partial Power (Hover) Plume
- Demo Simulation With Standalone Particle Tracker Predicts 3000 m/s Debris Velocity (Simulation Was Run With Full Power LEM Plume)



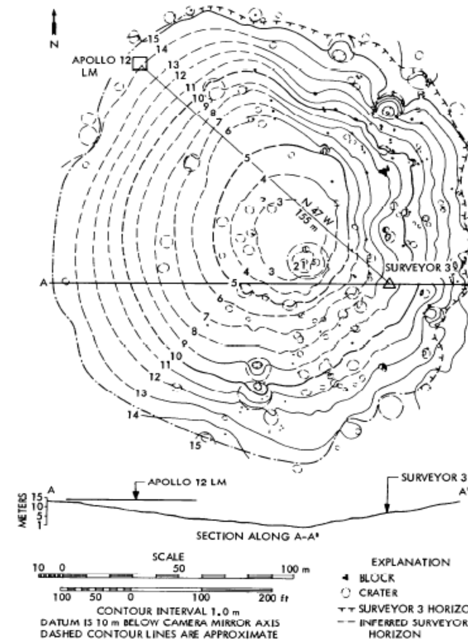
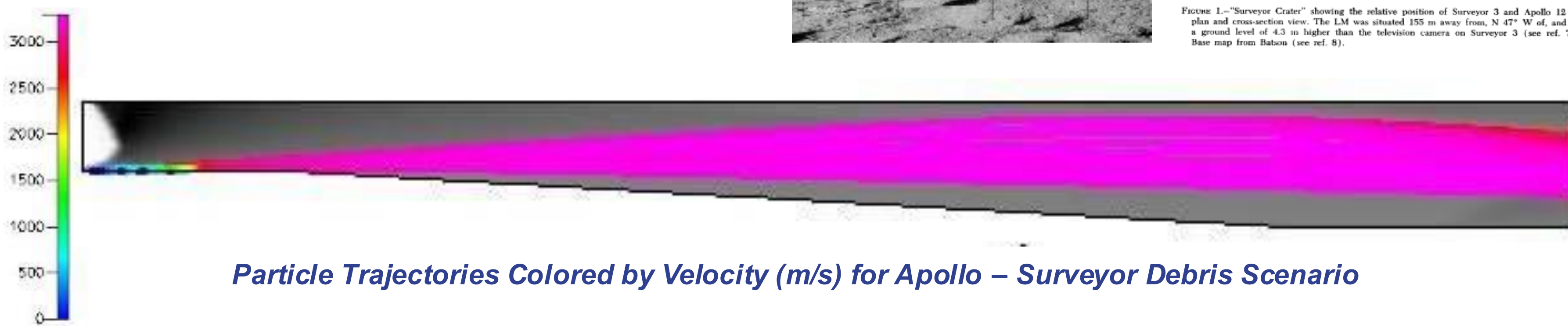


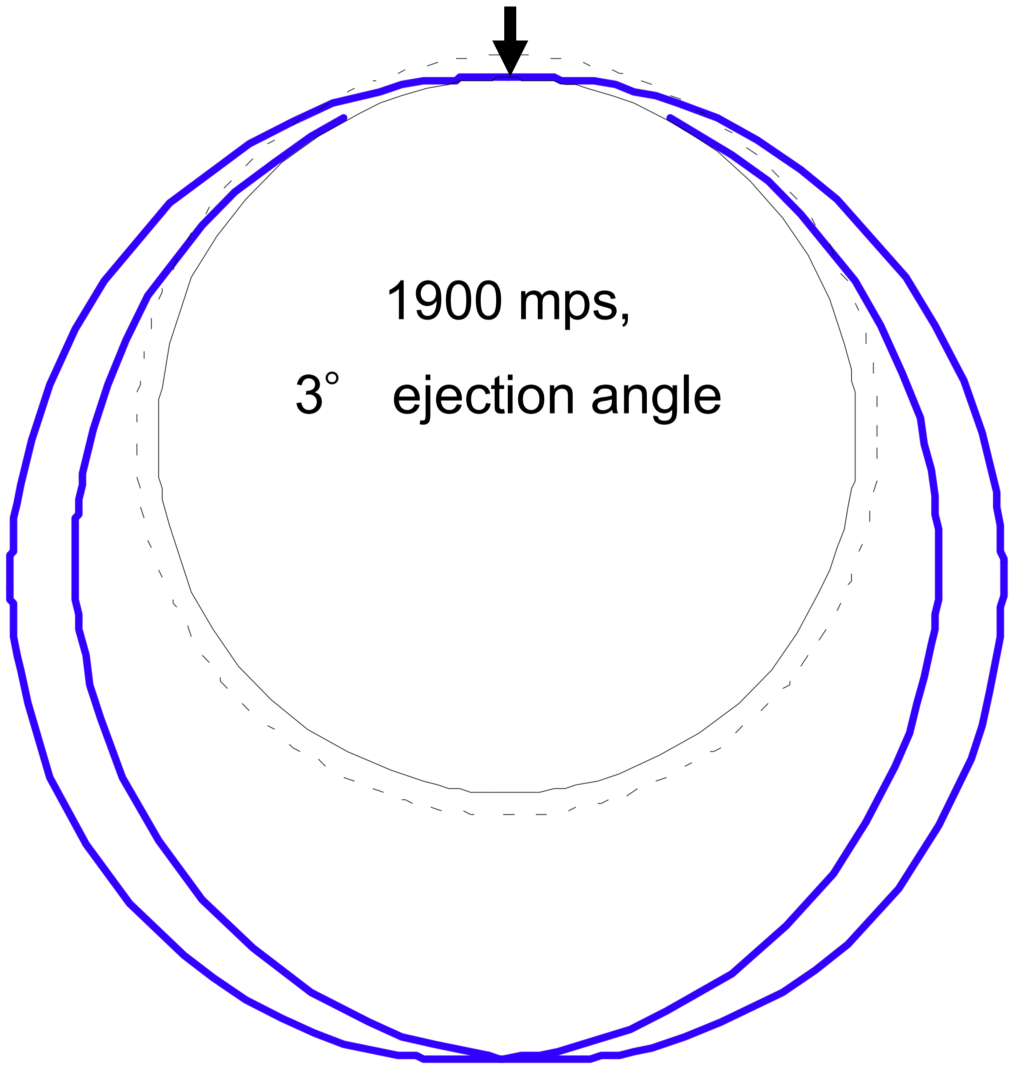
FIGURE 1.—"Surveyor Crater" showing the relative position of Surveyor 3 and Apollo 12 in plan and cross-section view. The LM was situated 155 m away from, N 47° W of, and at a ground level of 4.3 m higher than the television camera on Surveyor 3 (see ref. 7). Base map from Batson (see ref. 8).



Particle Trajectories Colored by Velocity (m/s) for Apollo – Surveyor Debris Scenario

Trajectories of Lunar Plume Ejecta

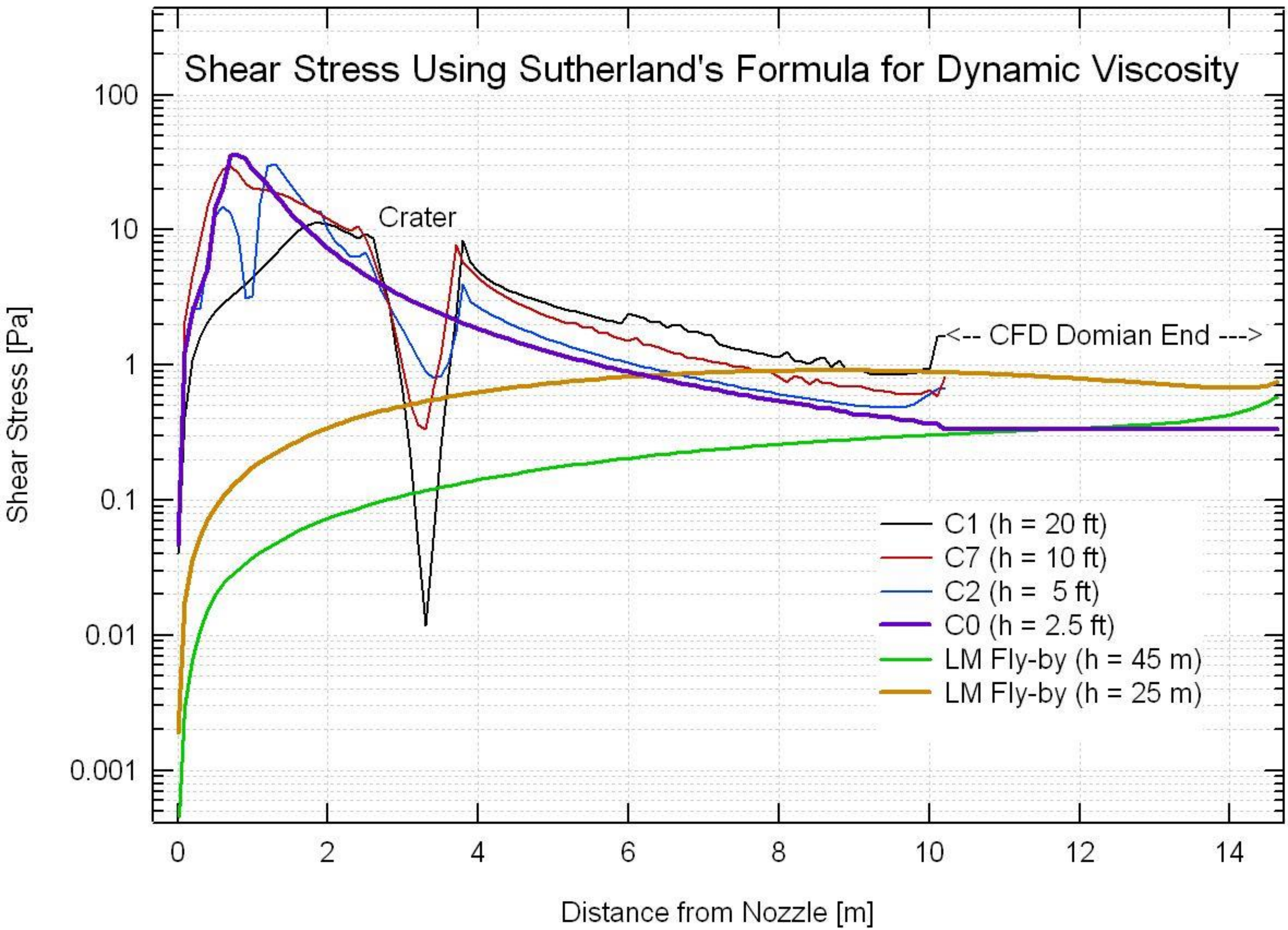
- Spray reaches orbital altitudes
- Spray encompasses the entire Moon
- At every distance on the Moon, there is a size that lands at that distance
- Significant chance of impacts if spacecraft flies through the spray
- Net velocity may be >4000 mps (hypervelocity regime)

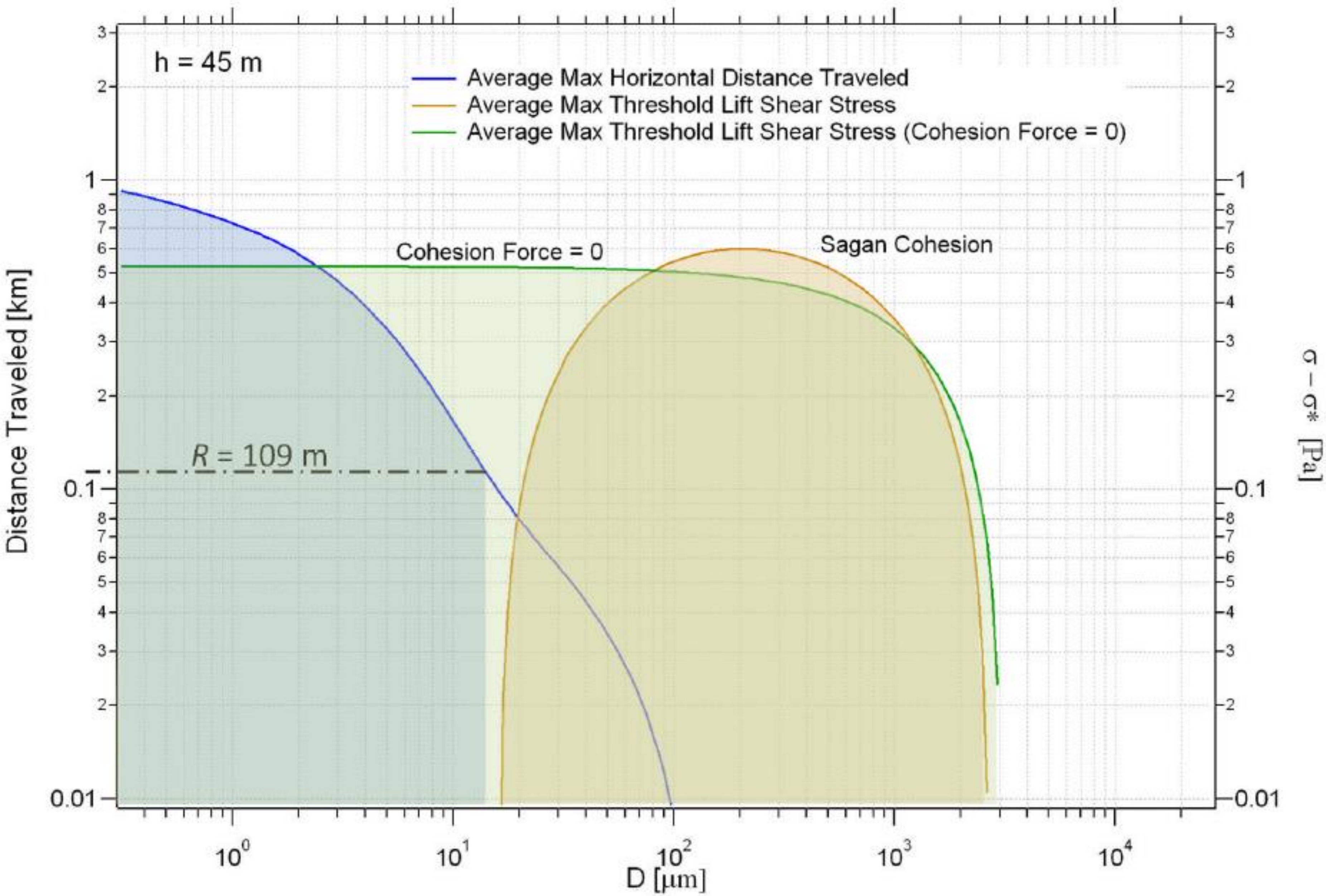


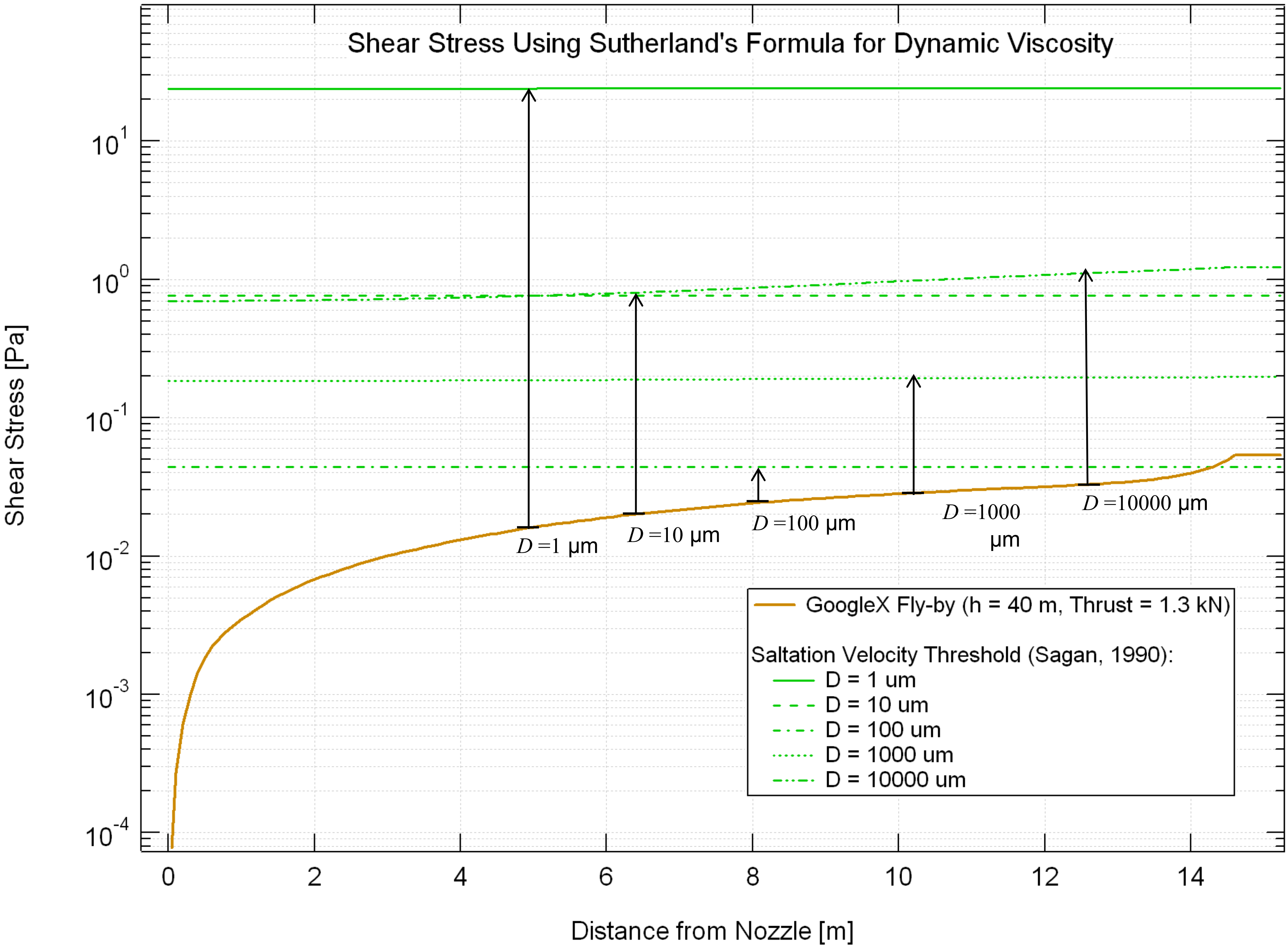
At what height does the blowing begin?

Crew Comments

- Ap11, Armstrong: "I first noticed that we were, in fact, disturbing the dust on the surface when we were at something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease."
- Ap12, Conrad: "As soon as I got the vehicle stopped in horizontal velocity at 300 feet, we picked up a tremendous amount of dust; much more so than I expected."
- Ap14, Mitchell (descent transcript): "there's some dust, Al; 110 feet. Three feet per second down. You're looking great. Six percent; there's good dust."
- Ap15, Scott: "I had a little bit of dust at 150 and completely obscured at 50 feet."
- Ap16, Duke: "It started at about 80 feet, John." Young: "Yes, 80 feet. Certainly, it started there and it got a lot worse, but you could still see the rocks all the way to the ground."
- Ap17, Cernan: "We started to get dust somewhere around 100 feet." Schmitt: "In my window, I didn't see dust until about 60 or 70 feet."


Shear Stress Using Sutherland's Formula for Dynamic Viscosity
Crater
<-- CFD Domian End --->
C1 (h = 20 ft)
C7 (h = 10 ft)
C2 (h = 5 ft)
C0 (h = 2.5 ft)
LM Fly-by (h = 45 m)
LM Fly-by (h = 25 m)
Shear Stress [Pa]
Distance from Nozzle [m]
100
10
1
0.1
0.01
0.001
0
2
4
6
8
10
12
14


h = 45 m
Average Max Horizontal Distance Traveled
Average Max Threshold Lift Shear Stress
Average Max Threshold Lift Shear Stress (Cohesion Force = 0)
Cohesion Force = 0
Sagan Cohesion
R = 109 m
Distance Traveled [km]
σ − σ* [Pa]
D [μm]

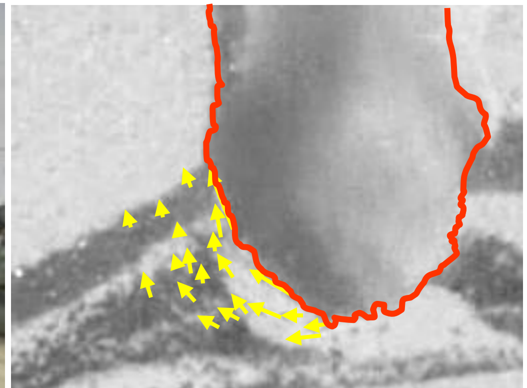


Shear Stress Using Sutherland's Formula for Dynamic Viscosity
Shear Stress [Pa]
Distance from Nozzle [m]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
2
4
6
8
10
12
14
D =1 μm
D =10 μm
D =100 μm
D =1000 μm
D =10000 μm
GoogleX Fly-by (h = 40 m, Thrust = 1.3 kN)
Saltation Velocity Threshold (Sagan, 1990):
D = 1 um
D = 10 um
D = 100 um
D = 1000 um
D = 10000 um

How much ejecta is blown?

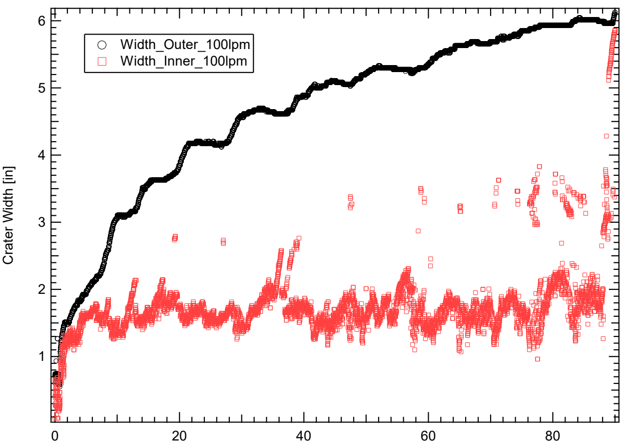
Rocket Exhaust / Soil Experiments

Reduced gravity erosion rate experiments

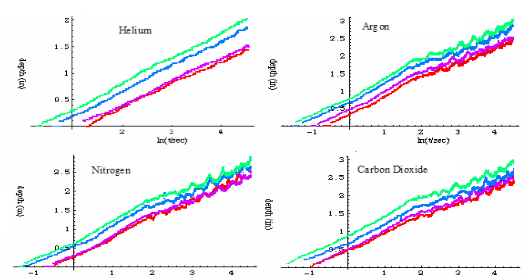


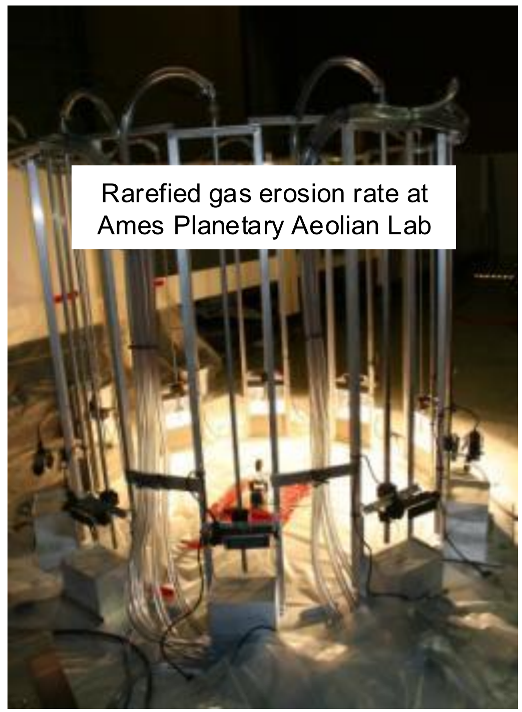
Determined physics of "Diffusion Driven Flow" which causes a bulk, tangential flow of soil (perpendicular to flow of bearing capacity failure)

Thruster firings to study phenomenology of erosion with a complex regolith



Analyzed empirical data and discovered scaling relationships for soil erosion





Rarefied gas erosion rate at Ames Planetary Aeolian Lab

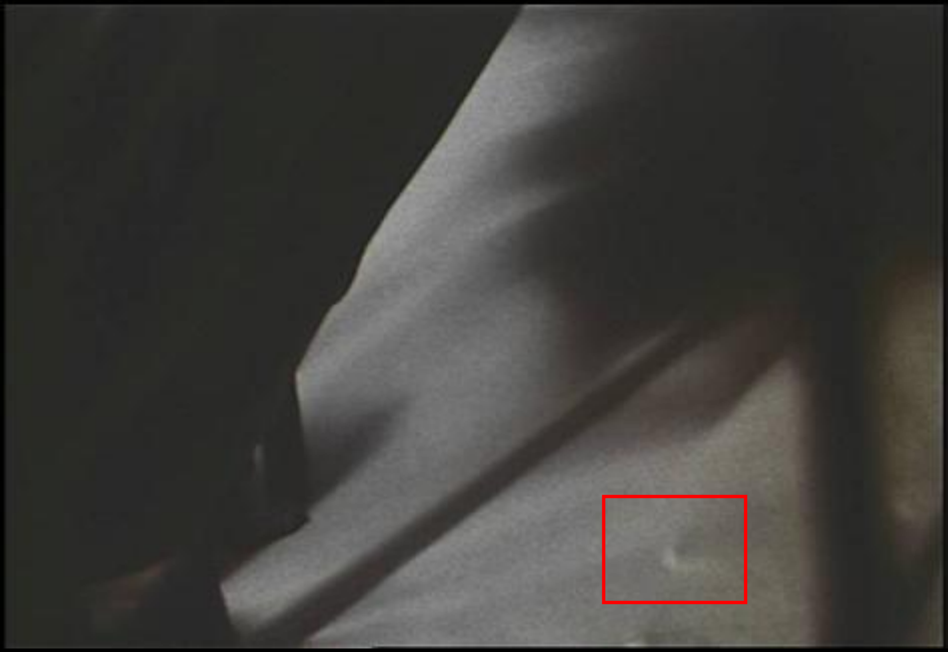
Beginning investigation with supersonic plumes

Scaling of Erosion Rate

$$\frac{dV}{dt} = K\,\frac{\rho v^2 A}{\rho_m g D + c?}$$

$$\frac{dV}{dt} = \sigma \cdot f(\mathrm{soil}, \mathrm{g})$$

Dust Loading (Optical Density) Calculation

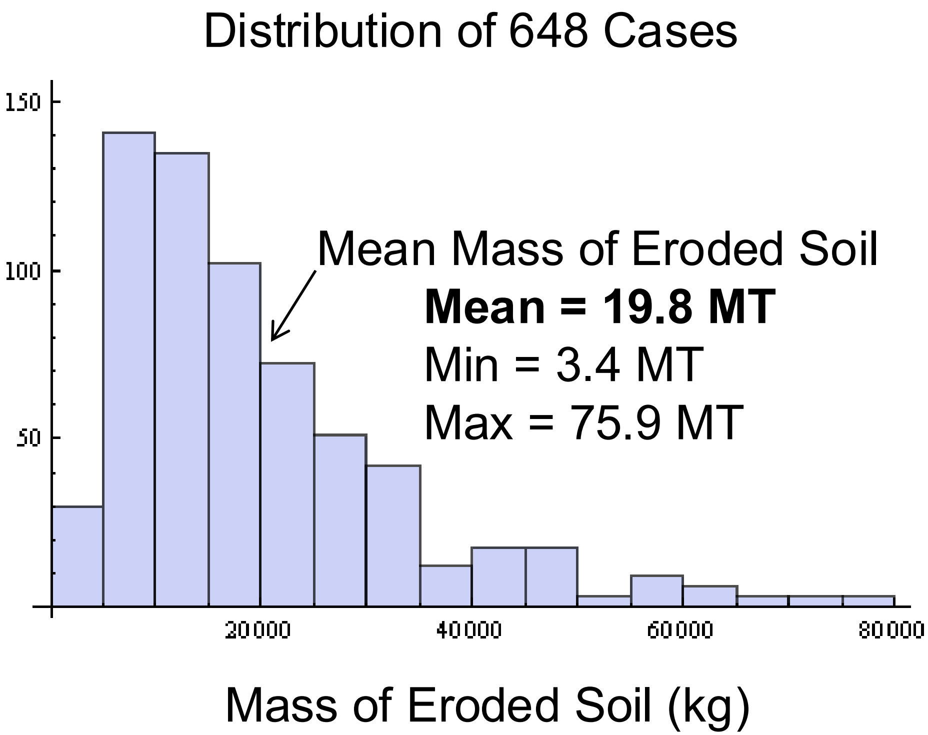


Frame 1914

Frame 1915

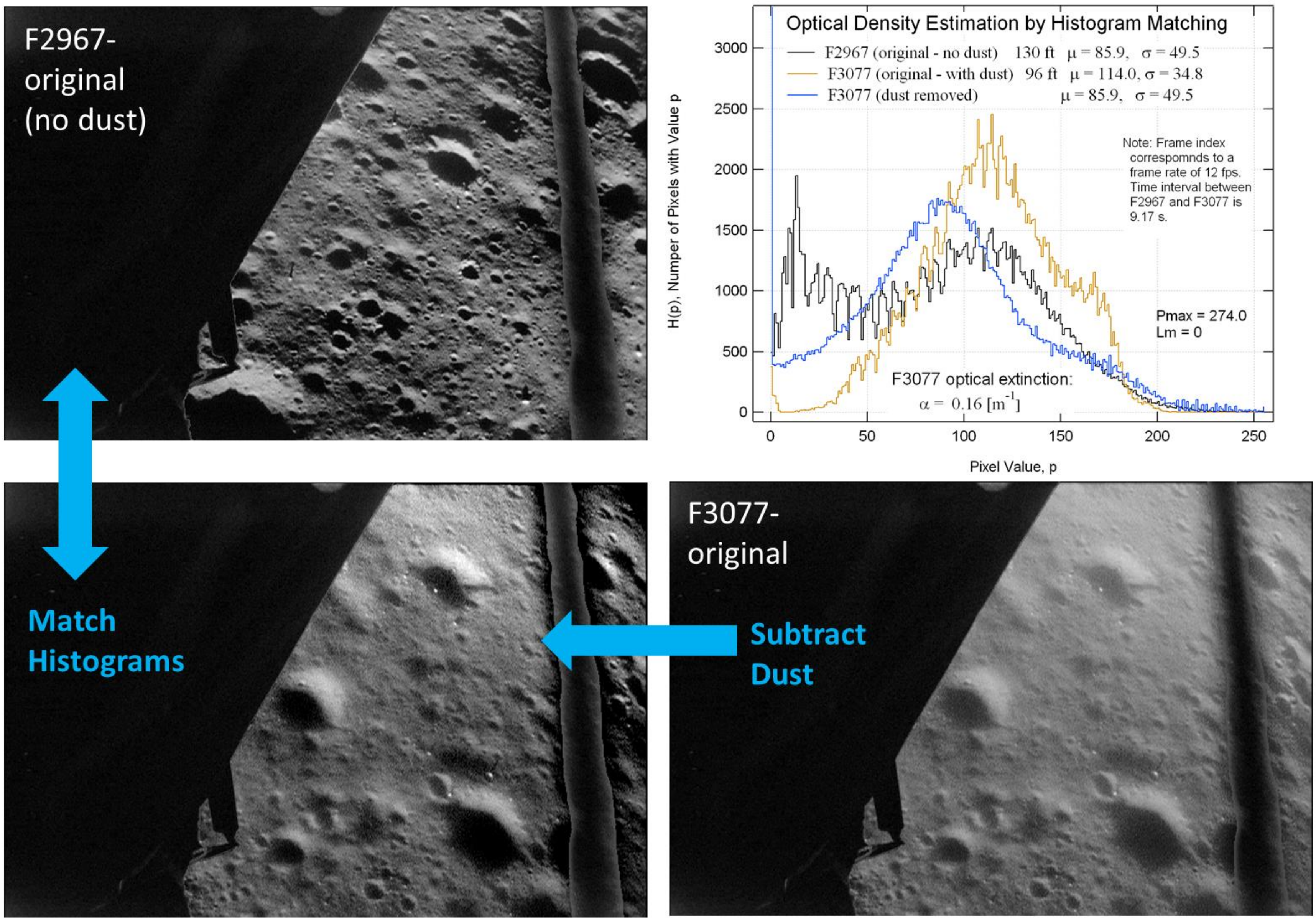
Apollo 11

Parametric Sensitivity Study

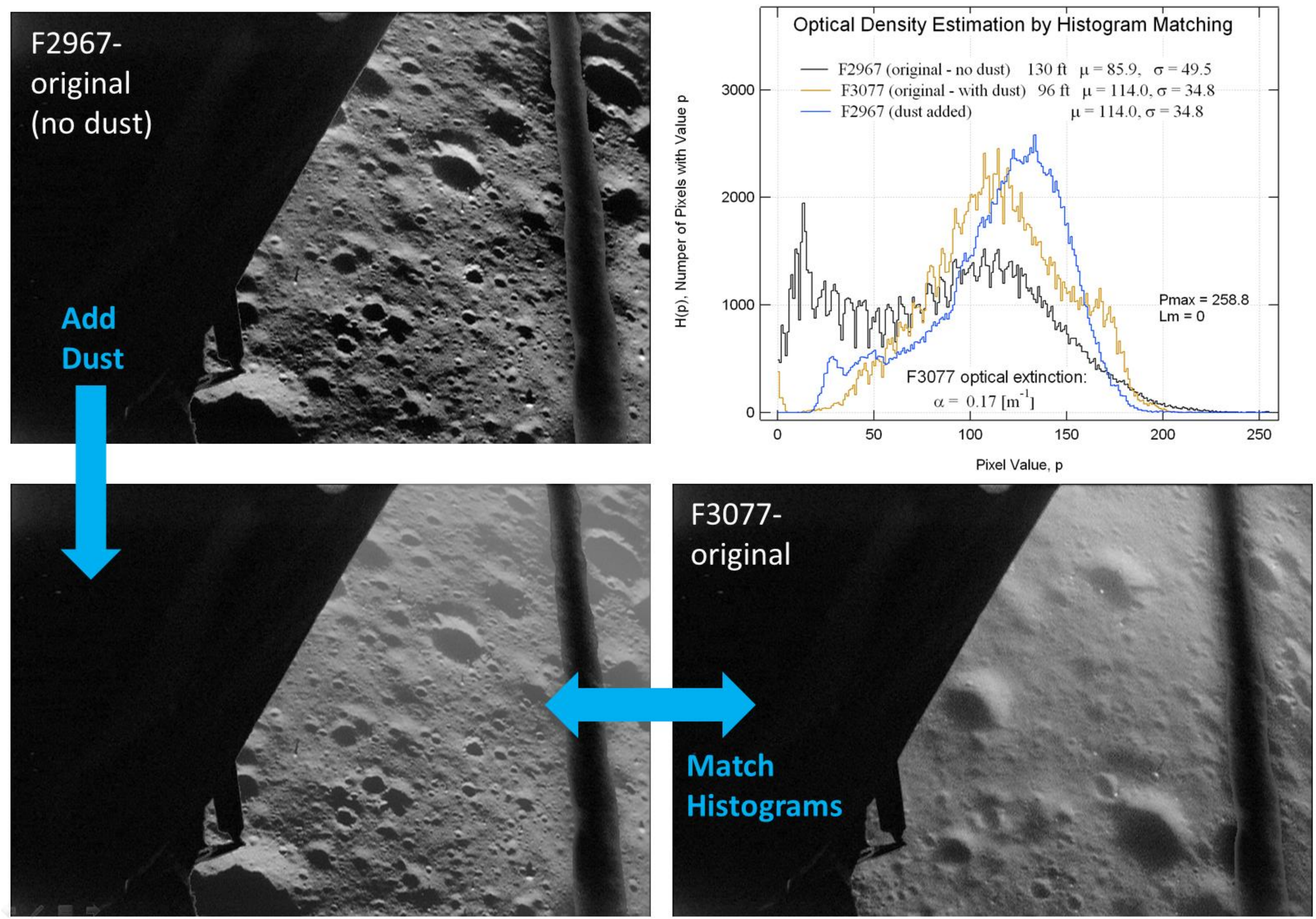


Analysis of terrain under LM indicates about 2 MT was eroded

Histogram Matching, Subtracting Dust



Histogram Matching, Adding Dust



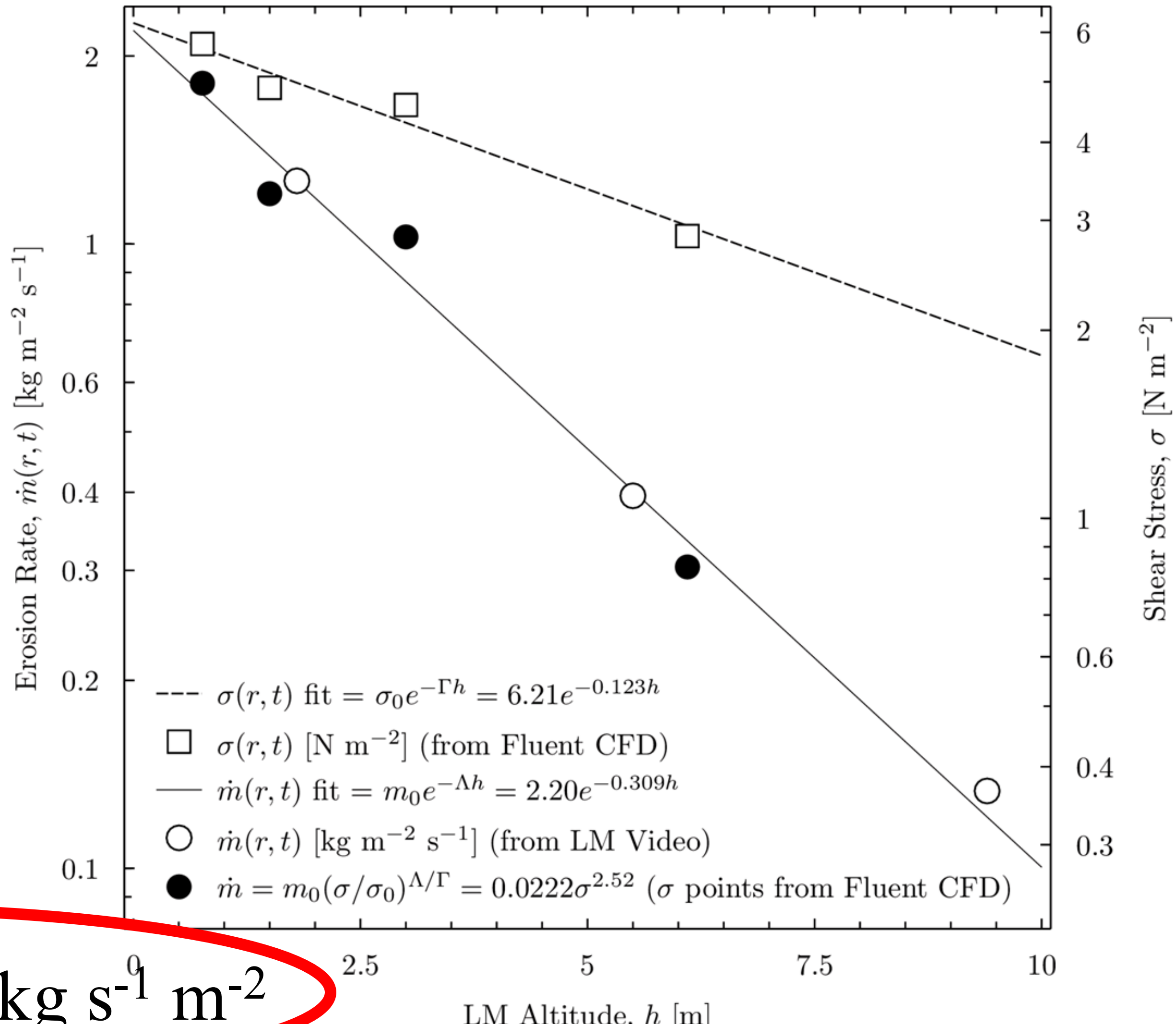
Empirical Erosion Rate Equation

Fig. 11. Averaged shear stress and mass erosion rate as a function of $h(t)$.

$$\sigma = \mu \nabla_z v_r$$
$$= \mu_0 \frac{T_0 + T_C}{(T(r,z) + T_C)} \cdot \frac{T(r,z)}{T_0} \cdot \frac{\partial v_r}{\partial z}$$

$$\overline{\sigma}(h) = \frac{2\pi \int_0^{a_0(h)} \sigma(r,h)\, r\, dr}{\pi\, a_0^2(h)}$$

$$\sigma(t) = \sigma_0 e^{-\Gamma h(t)}$$
$$\dot{m}(t) = m_0 e^{-\Lambda h(t)}$$
$$\dot{m}(t) = m_0 \left(\sigma(t)/\sigma_0\right)^{\Lambda/\Gamma}$$



$$\dot{m}(t) = 0.0222\ \sigma^{2.52}\ \text{kg s}^{-1}\ \text{m}^{-2}$$

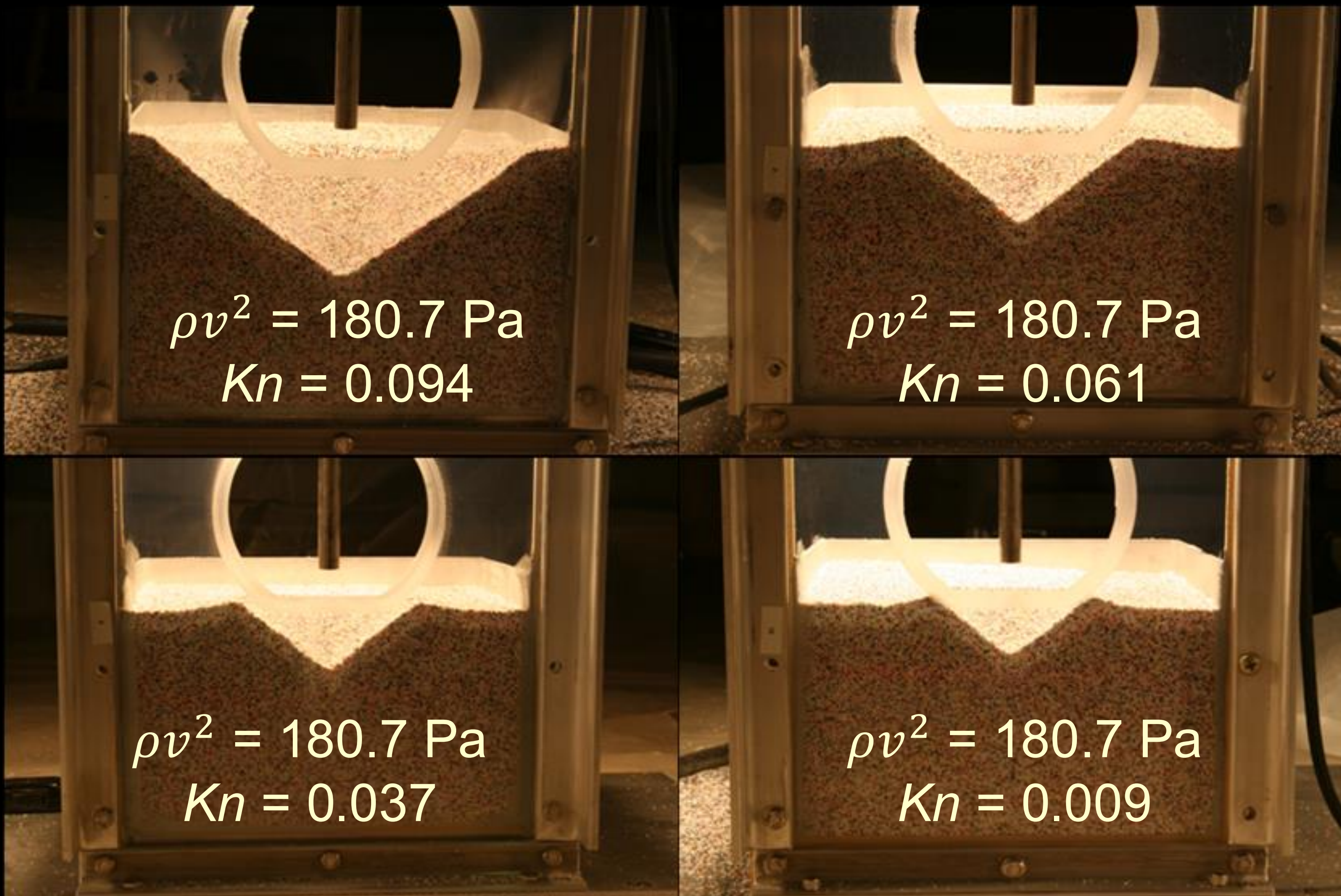
Comparison of Erosion Estimates

Reference	Apollo Mission	Total Mass Erosion [kg]
Scott (1975)*	Apollo 12	4500 to 6400
Metzger *et al*. (2008)	Apollo 12	2400
Metzger *et al*. (2010)	Apollo Average	1200
Present work: $m_T = \sum_{k=-10}^{0} \Delta m_k$	Apollo 12	2600

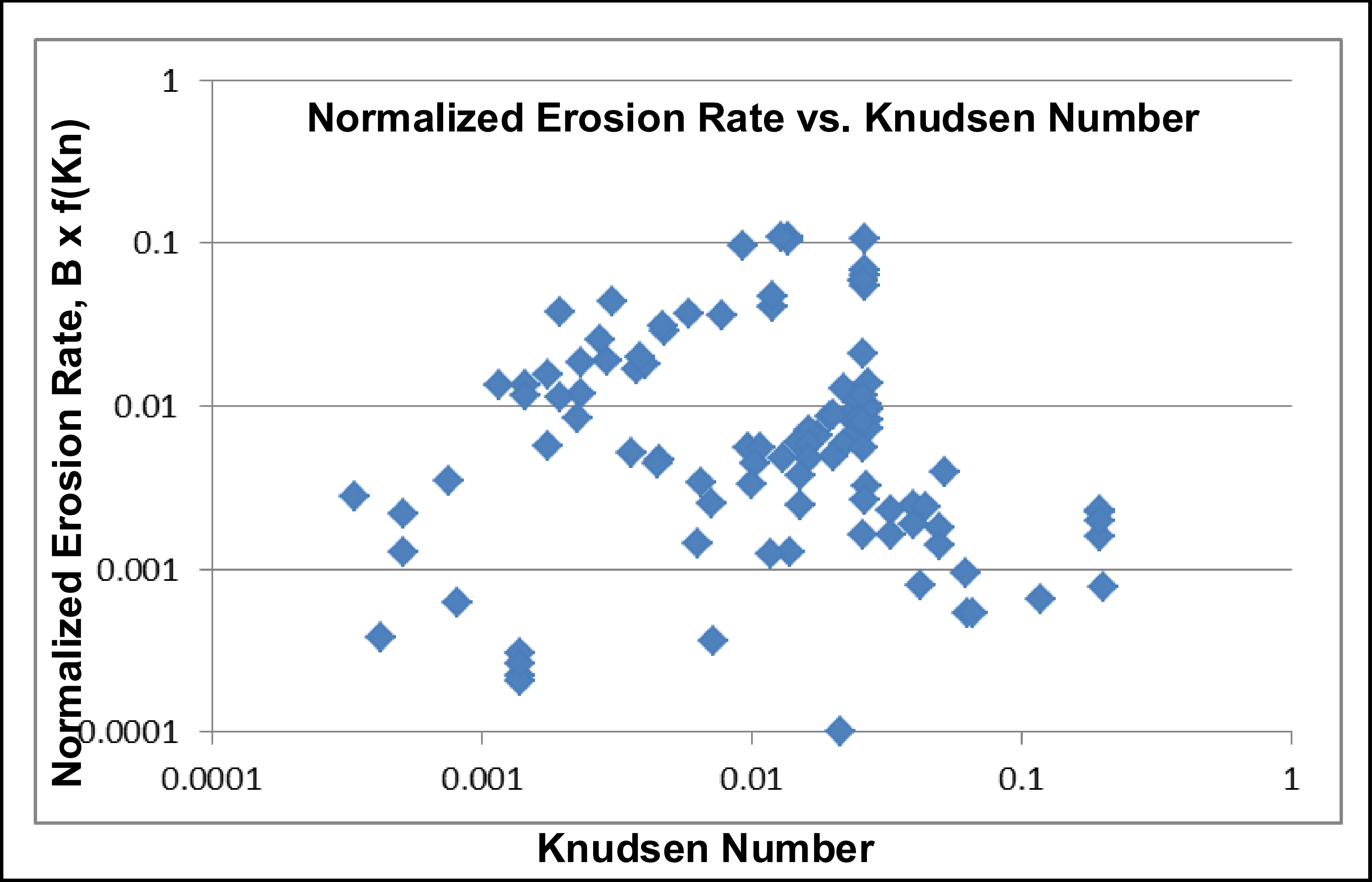
*from Metzger et al. (2011) - interpretations of data reported by Scott (1975).

- This erosion law predicts ~ 20 kg blown by Chinese Chang'e 3 and 4 landers.
- Analysis of Chang'e landing video showed ~19 kg was blown.

Visual Results

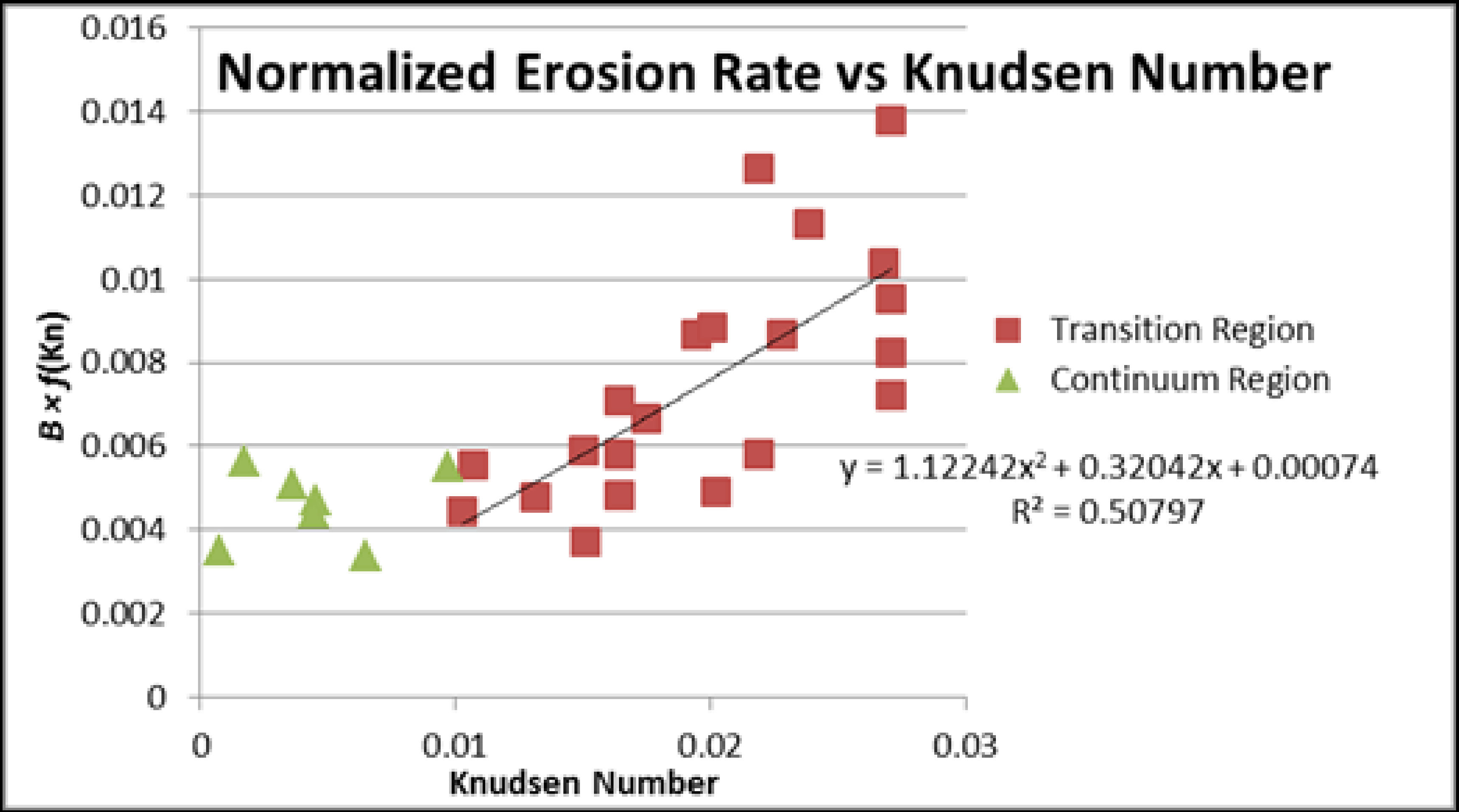


All Data

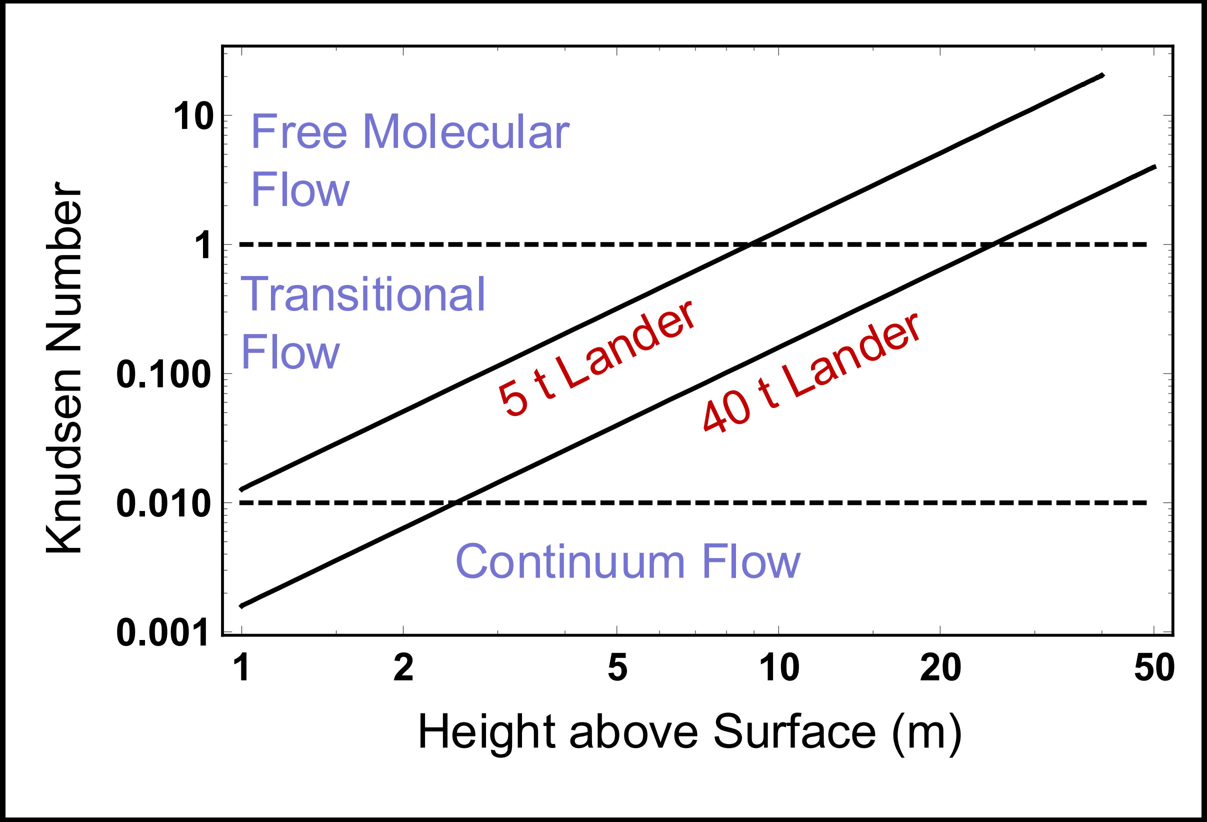


Normalized Erosion Rate vs. Knudsen Number
Normalized Erosion Rate, B x f(Kn)
1
0.1
0.01
0.001
0.0001
0.0001
0.001
0.01
0.1
1
Knudsen Number

All "Play Sand" Results

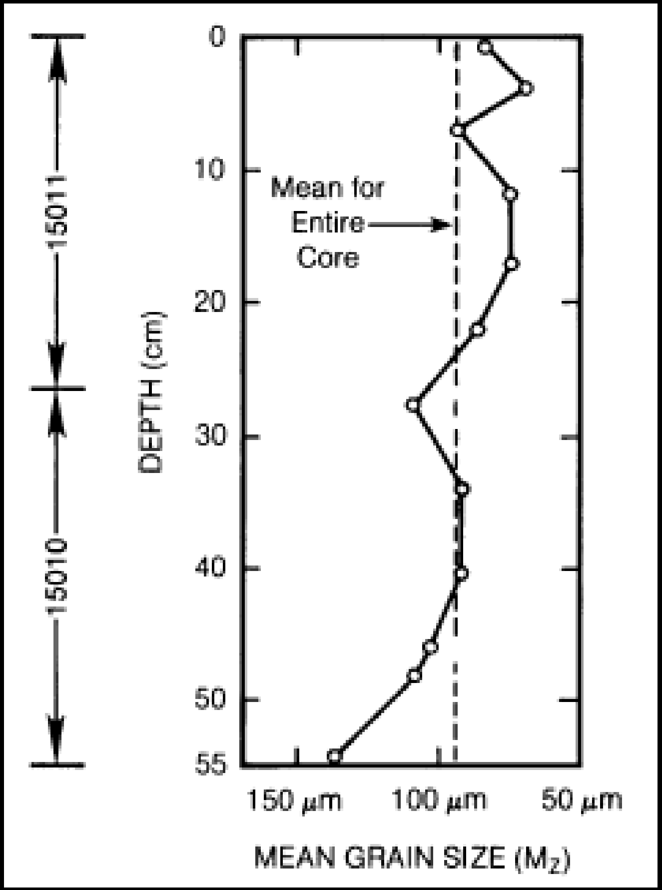


Different Erosion Law in Last 2.5 m?

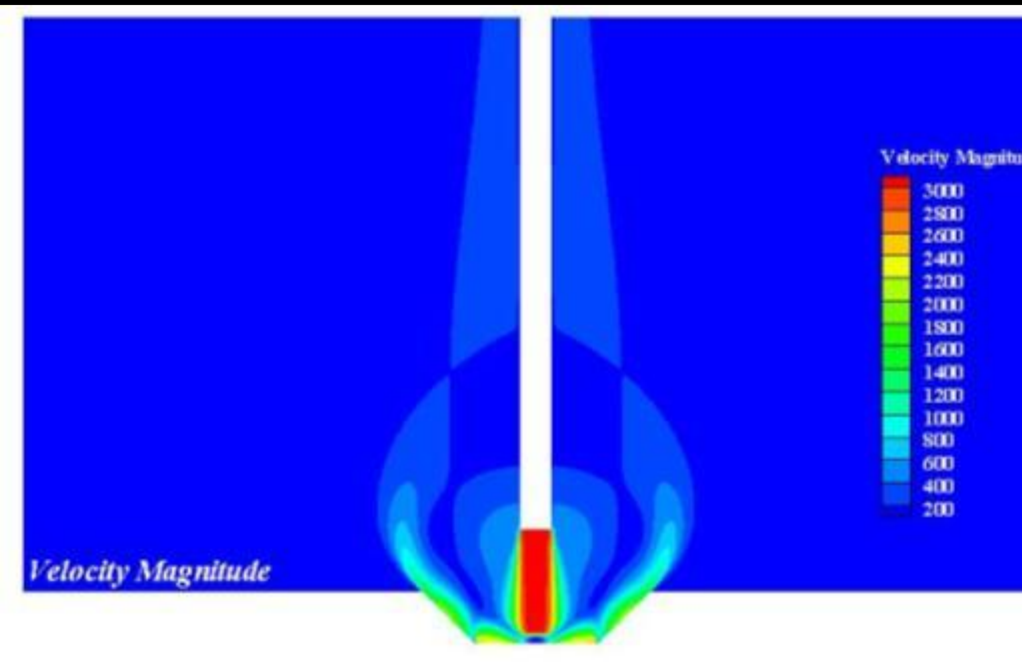


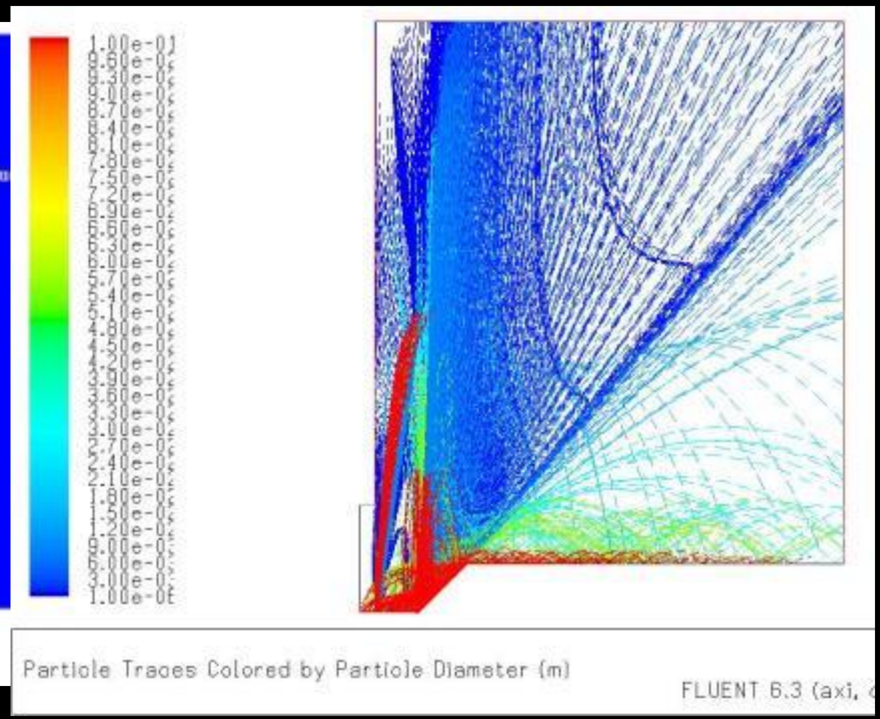
Lunar Soil Changes with Depth

Relative Density (%)	Description
0 – 15	Very loose
15 – 35	Loose
35 – 65	Medium
65 – 85	Dense
85 – 100	Very dense



Deep Erosion Changes the Ejecta Angles



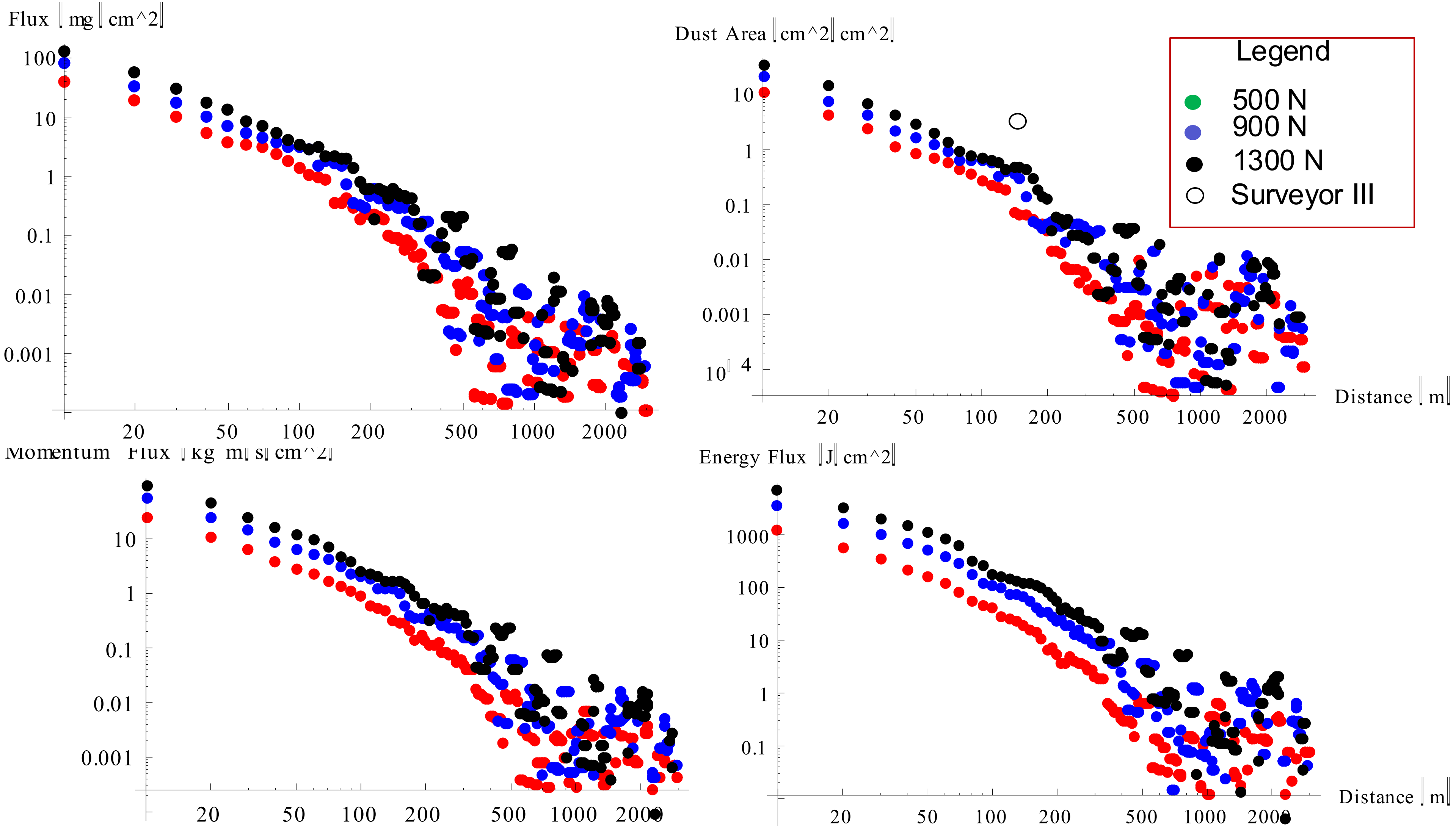


Lagrangian discrete phase model

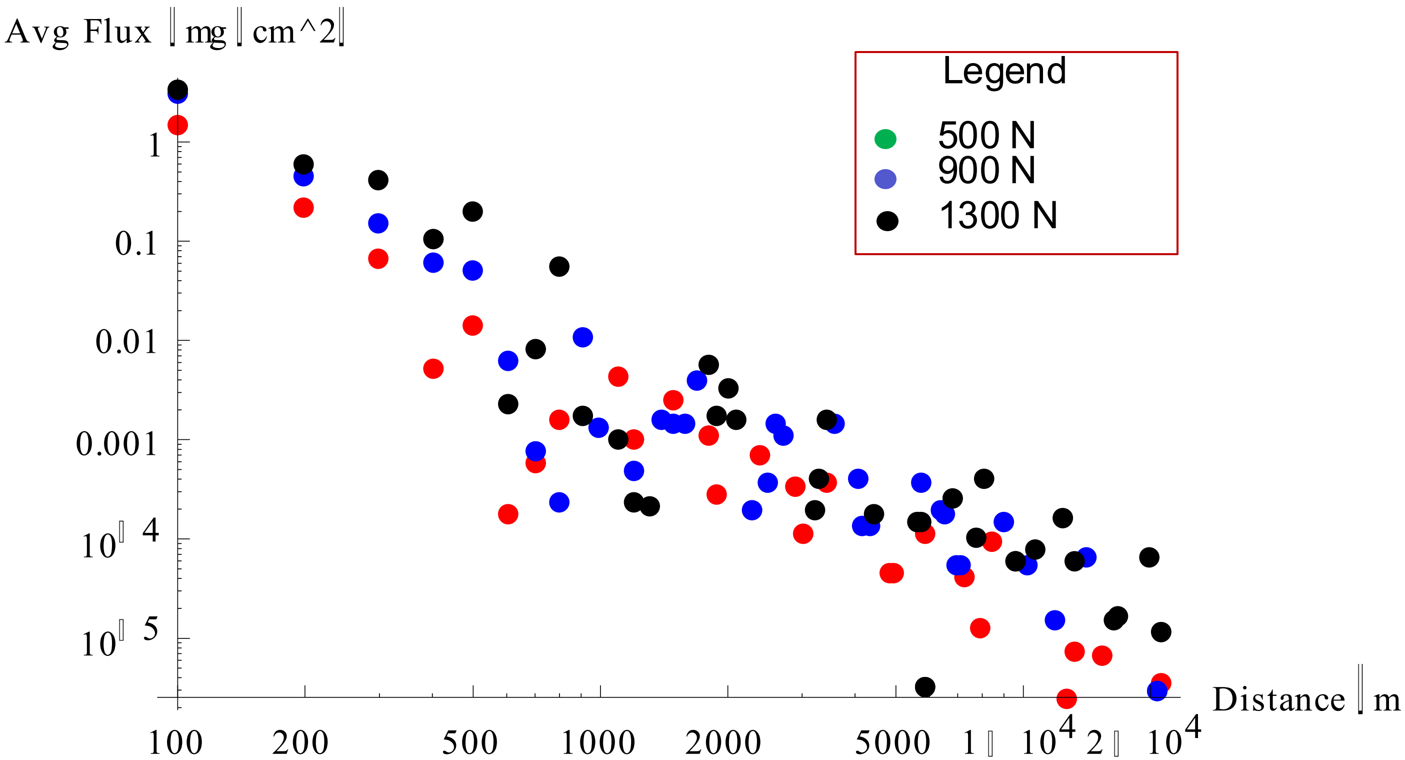
- **discrete phase inertia**
- **hydrodynamic drag**
- **force of gravity**

Dnozzle=1.2m	Depth (m)	Width (m)
Case 1	15.4	4.88
Case 2	2	4.88
Case 3	**2**	**4.88 (45 degree)**
Case 4	2	4.88 (60 degree)

GLXP-Sized Landers

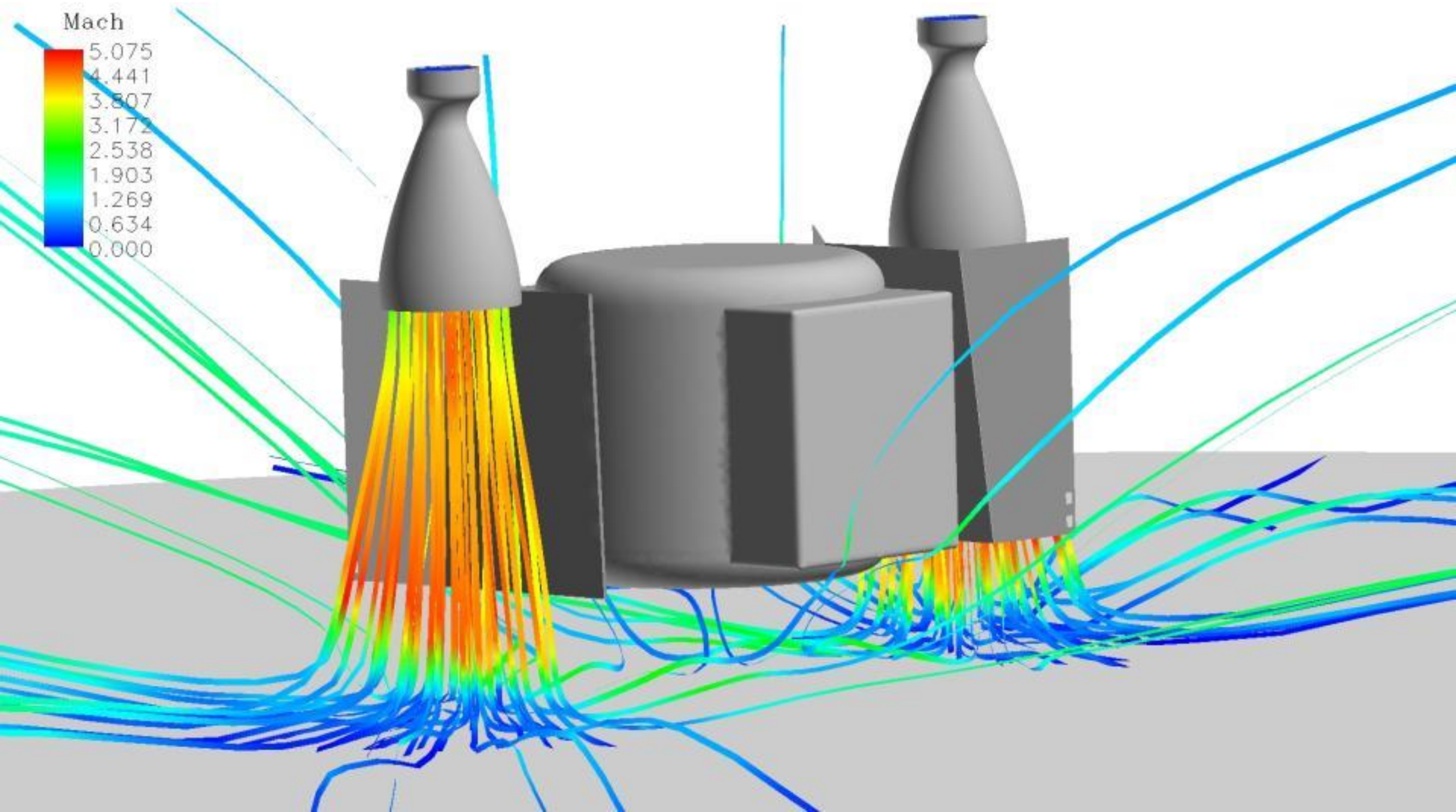


Tail-Off Continues >20 km

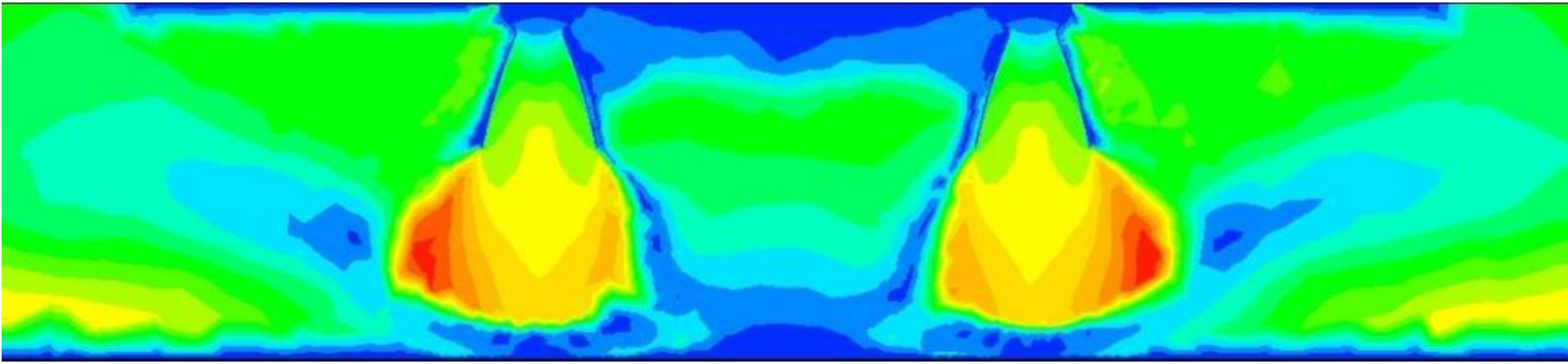


Multiple Engines

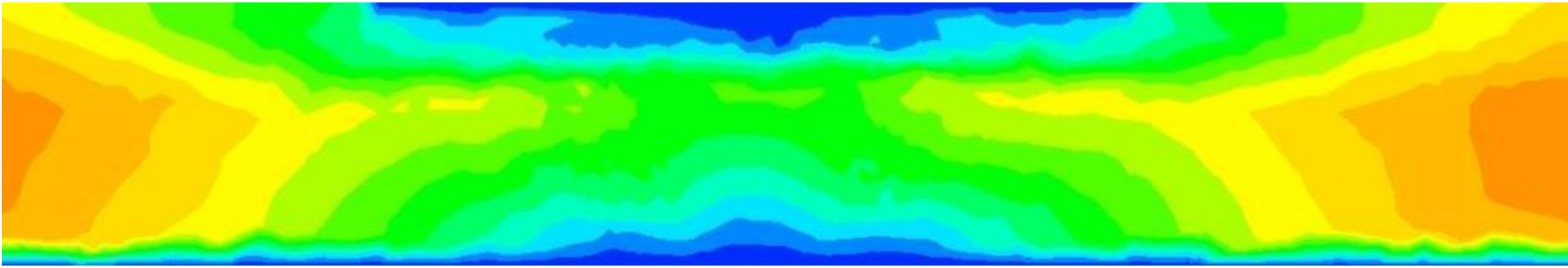
Multi-engine effects



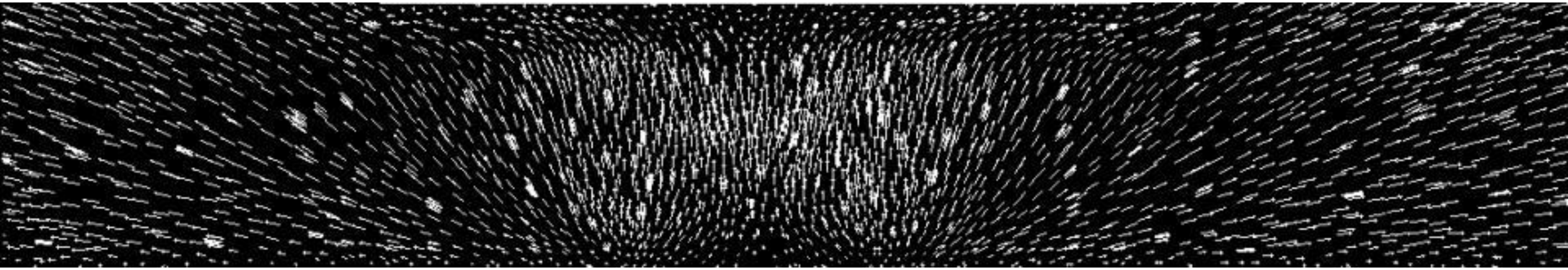
Multi-engine effects



Gas speed on the plane through the engines



Gas speed on the plane between engines



Gas direction on the plane between engines

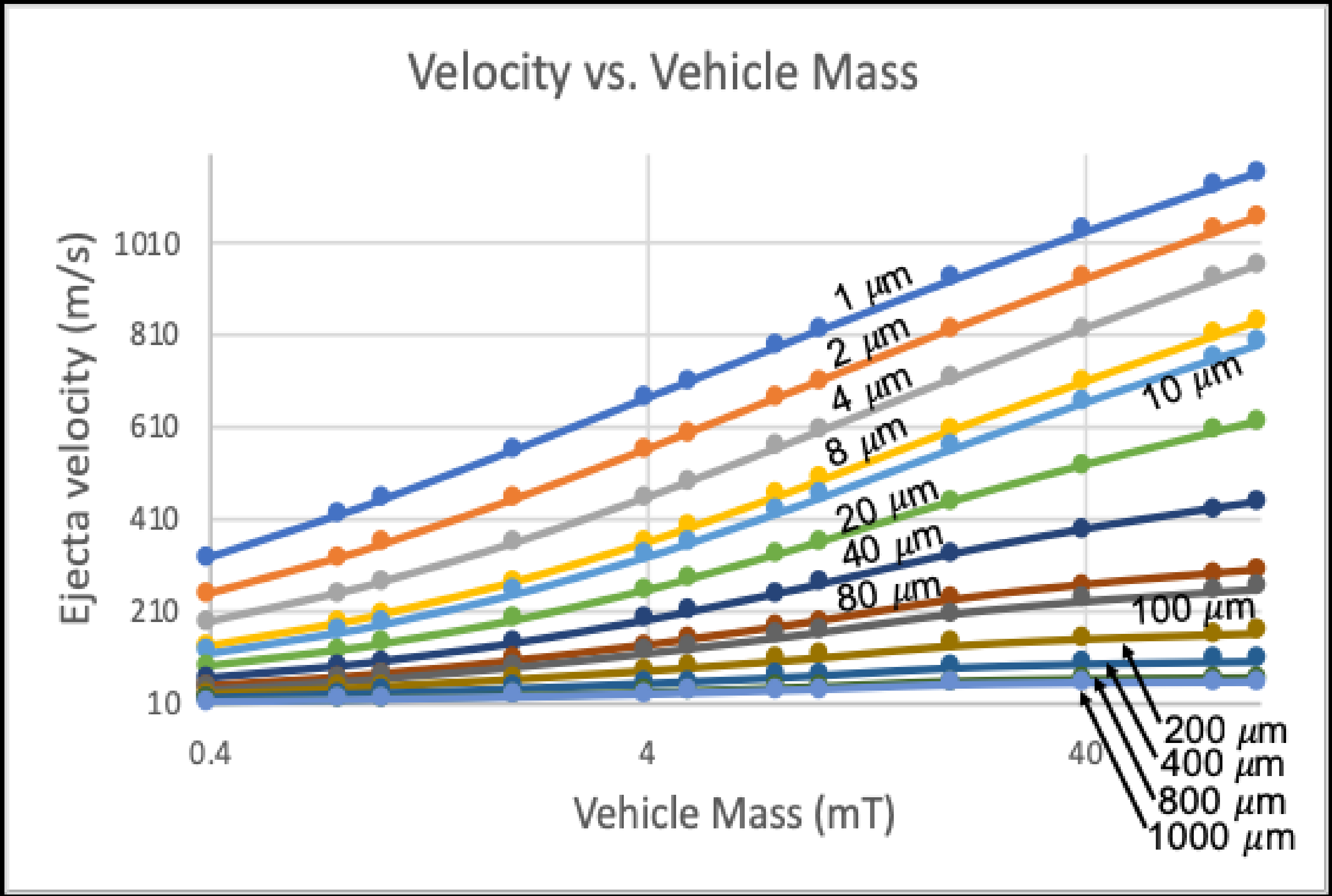
Recent Results

How Fast Will Ejecta Travel?

Effect of denser plume gas

This is for only one case of vehicle height and starting location of the particle.

This provides insight into scaling but it is NOT the worst-case.



How Fast Will Ejecta Travel?

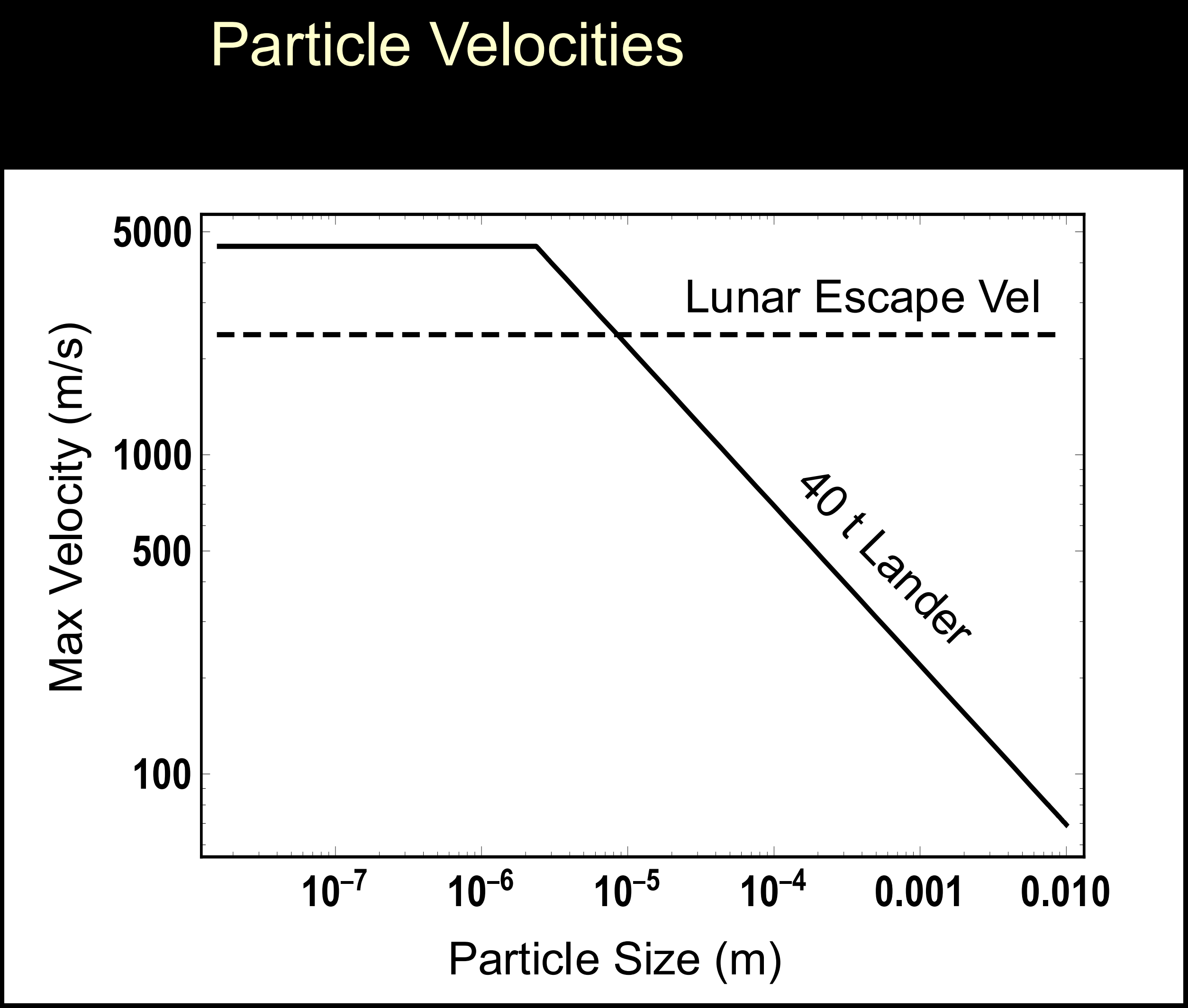
- Effect of higher specific impulse propellant

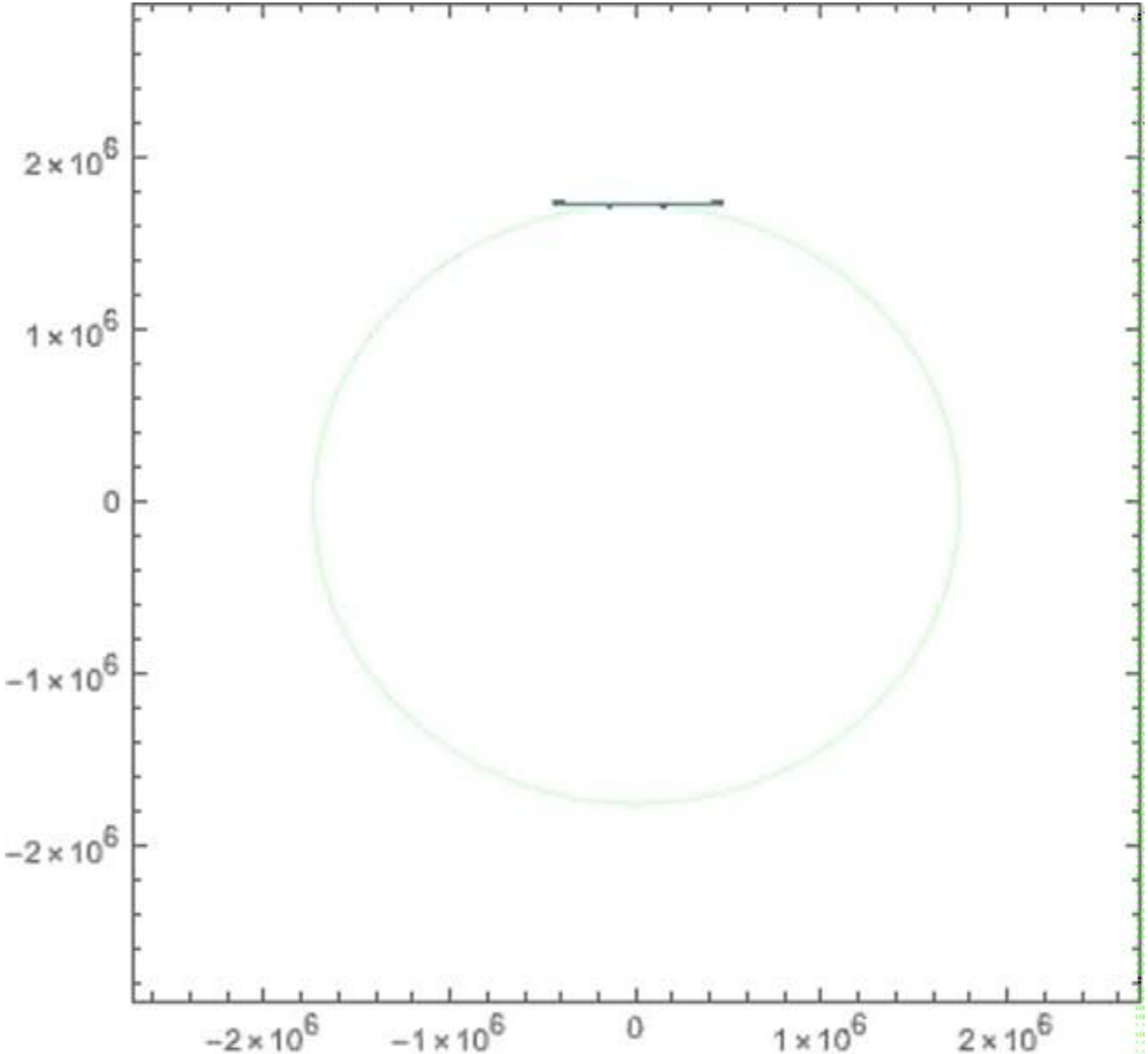
Lunar escape velocity	2.4 km/s
Aerozone/N_2O_4	3.1 km/s
CH_4/LOX	3.8 km/s
H_2/LOX	4.5 km/s

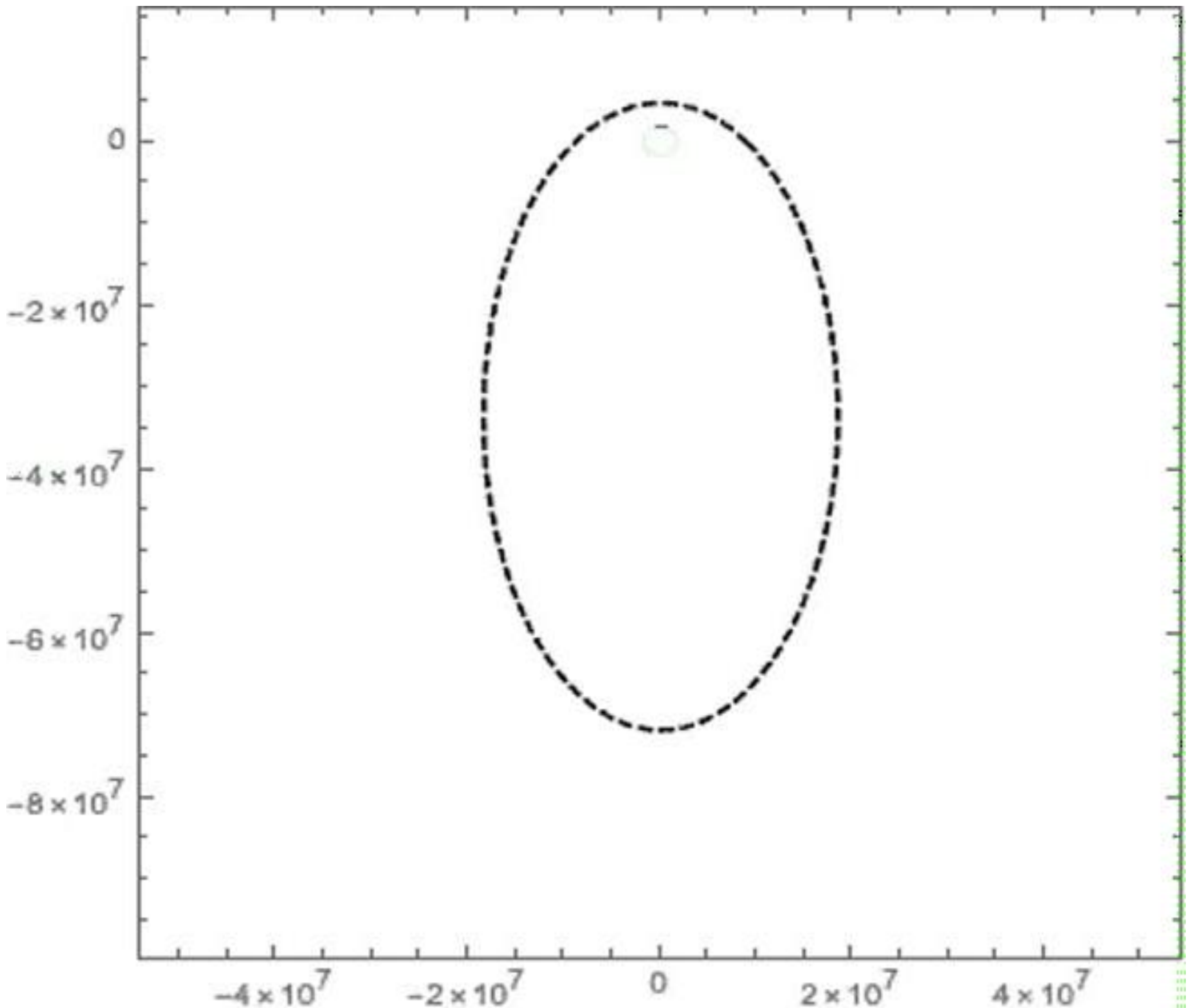
How Fast Will Ejecta Travel?

For each size lander, there is a particle size that will be blown completely off the Moon

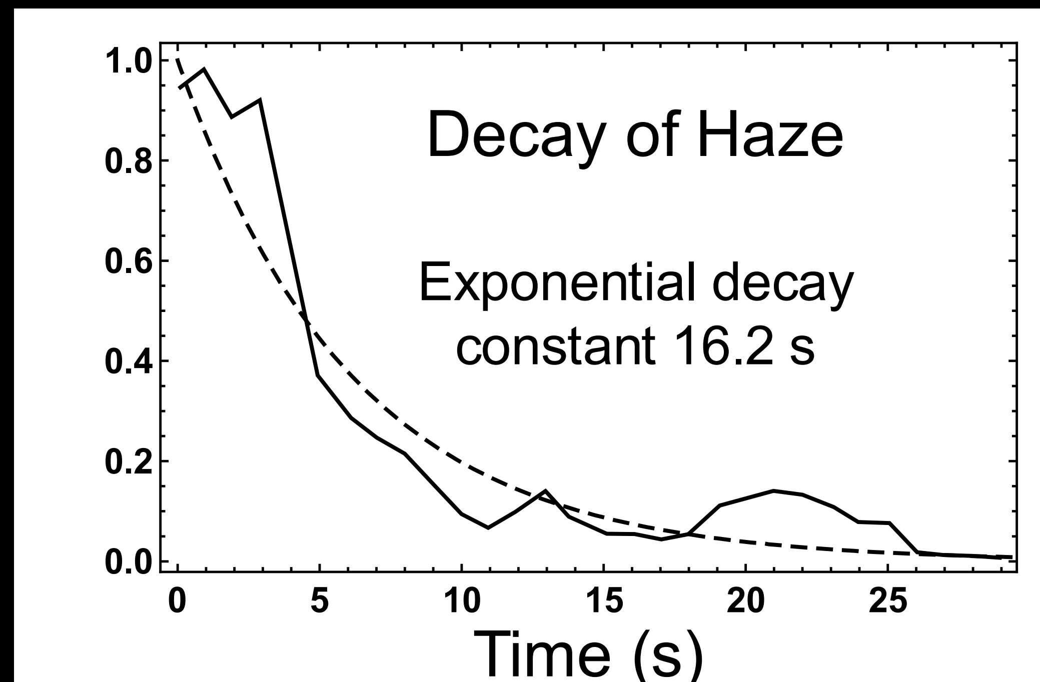
For a 40 t lander, it is particles $\leq 10\mu m$

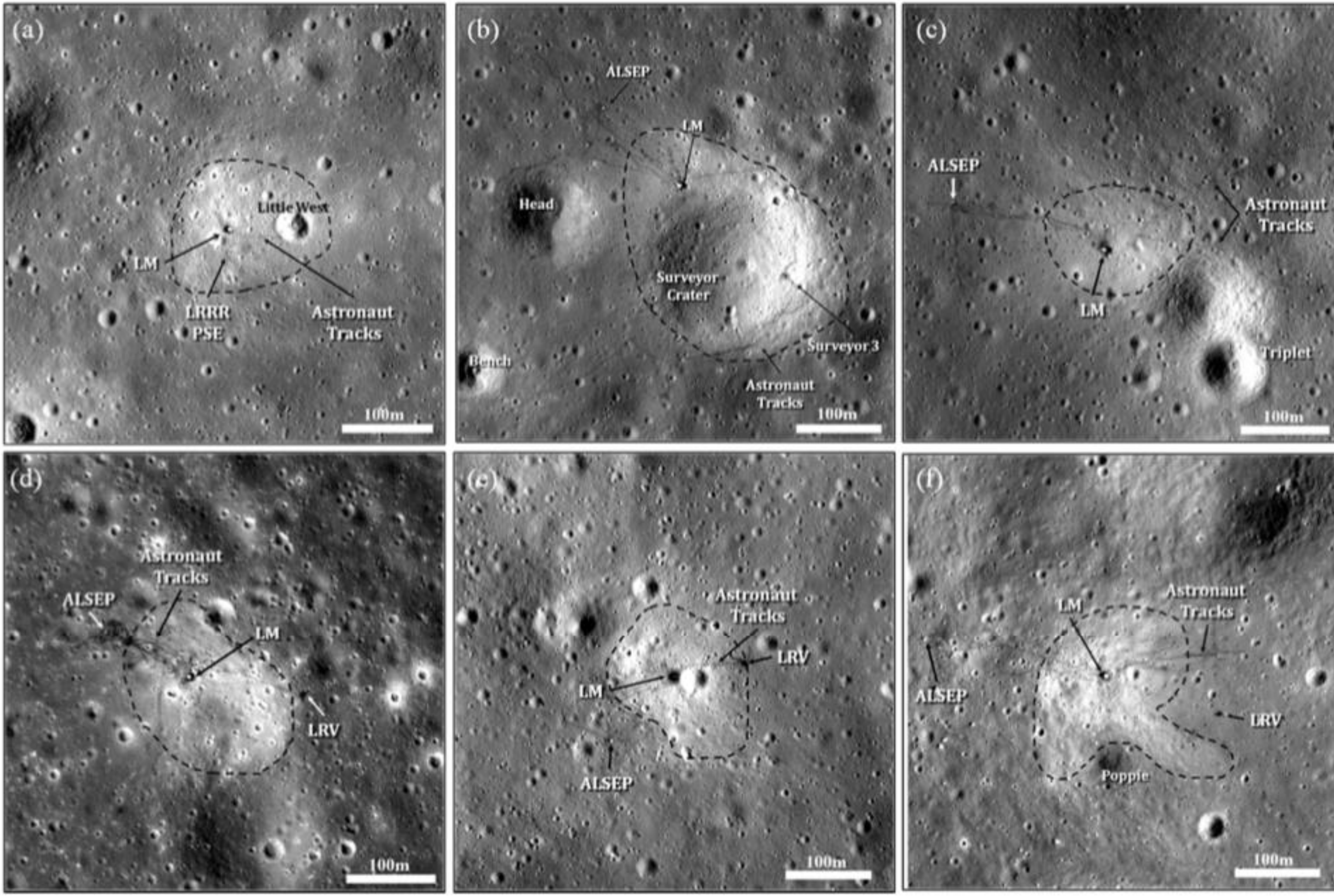



2×10^6
1×10^6
0
−1×10^6
−2×10^6
−2×10^6
−1×10^6
0
1×10^6
2×10^6

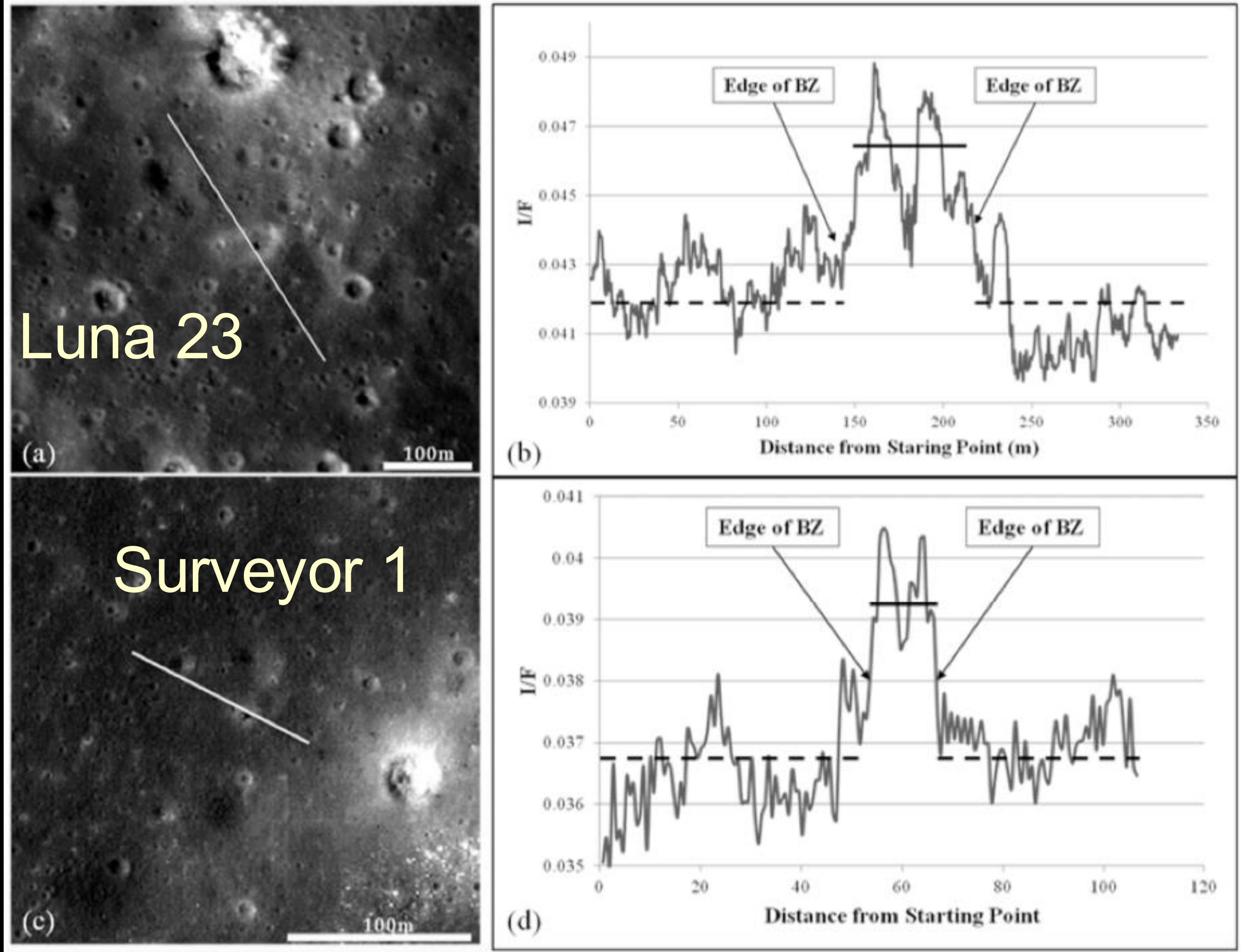

0
−2 × 10^7
−4 × 10^7
−6 × 10^7
−8 × 10^7
−4 × 10^7
−2 × 10^7
0
2 × 10^7
4 × 10^7

Slow Decay of Haze Post-Landing

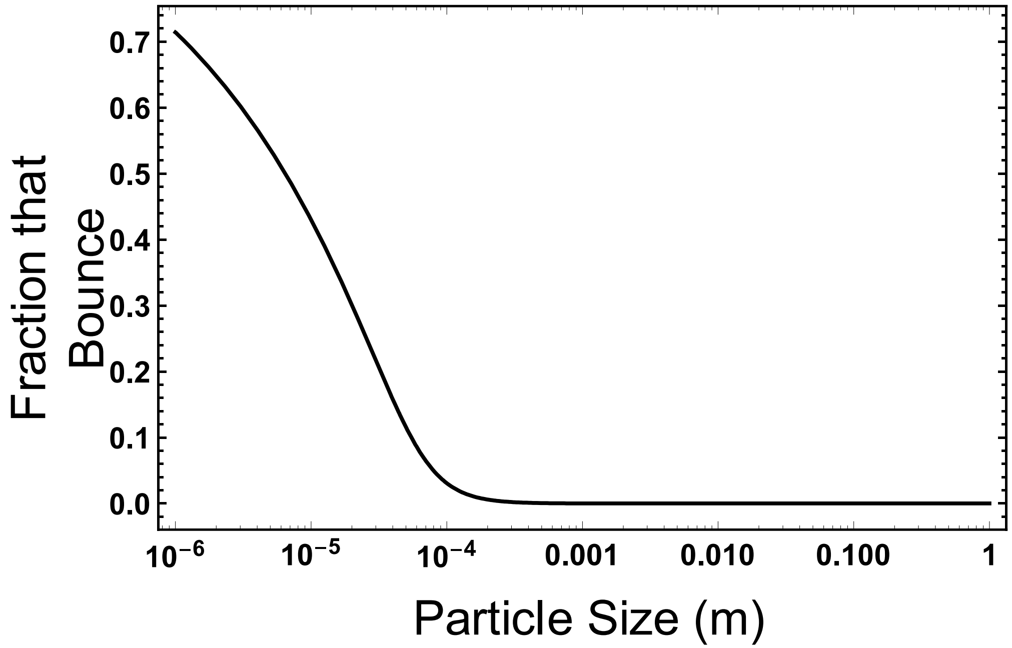




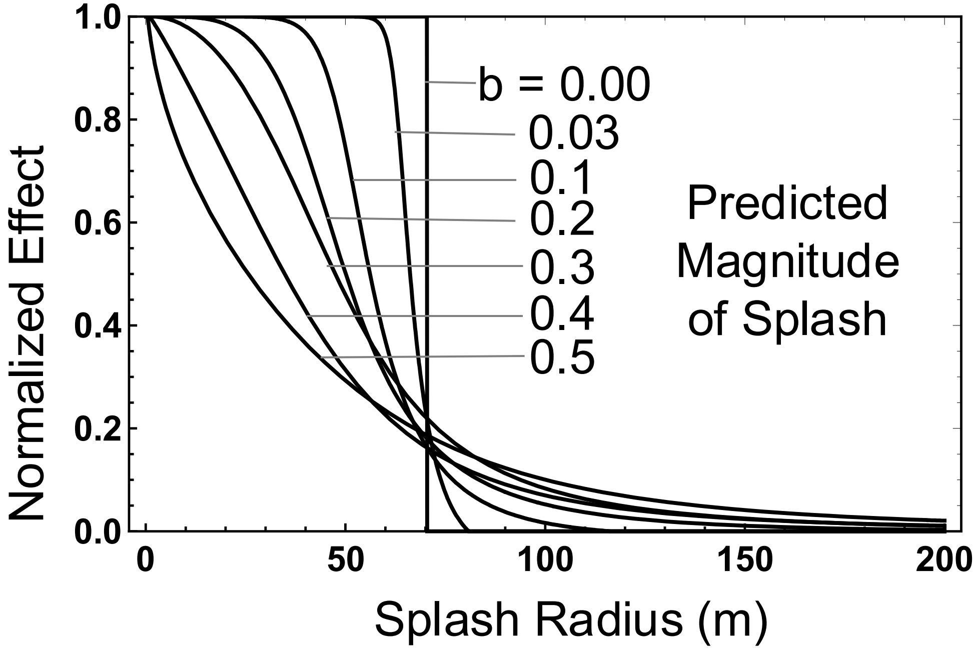
From: Clegg [Watkins], Ryan N. "Photometric Investigations of Lunar Landing Sites and Silicic Regions using LRO Narrow Angle Camera Images." (2015). Arts & Sciences Electronic Theses and Dissertations. 460. https://openscholarship.wustl.edu/art_sci_etds/460

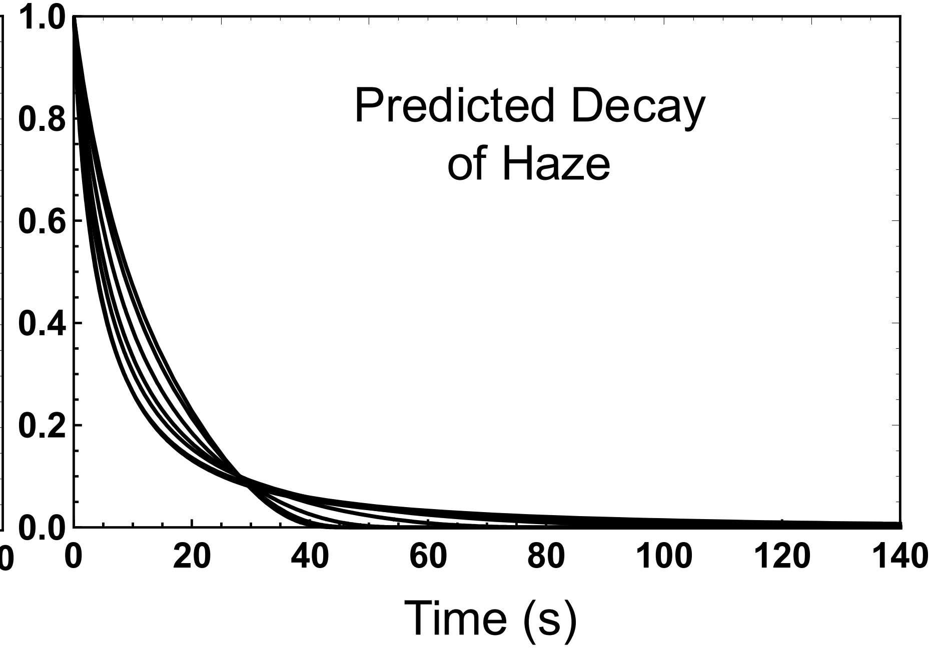


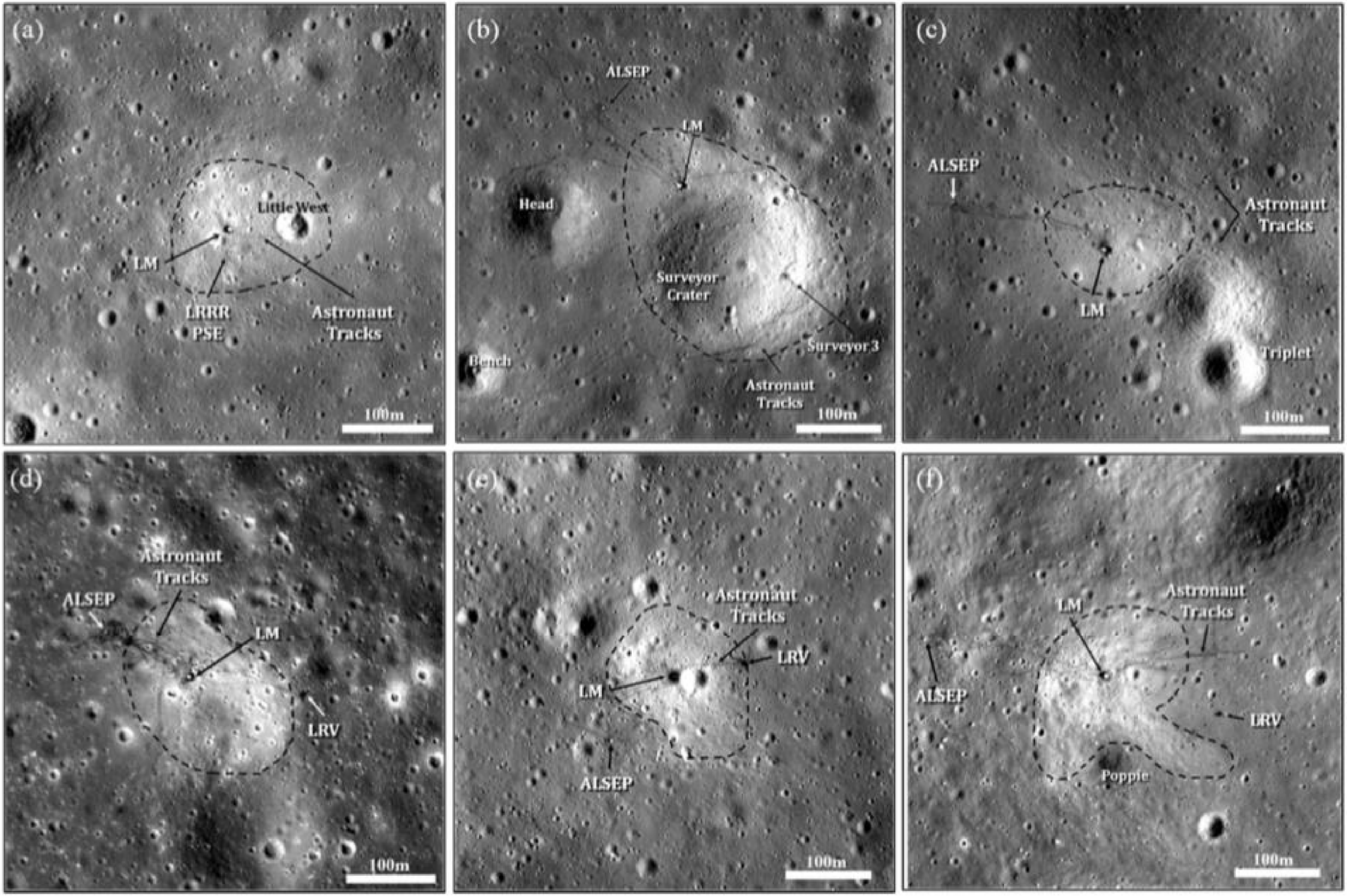
From: Clegg [Watkins], Ryan N. "Photometric Investigations of Lunar Landing Sites and Silicic Regions using LRO Narrow Angle Camera Images." (2015). Arts & Sciences Electronic Theses and Dissertations. 460.



$$v = 0.03 \times \frac{2.01}{D^b} \frac{(10^{-6})^b}{(10^{-6})^{0.5}}$$







From: Clegg [Watkins], Ryan N. "Photometric Investigations of Lunar Landing Sites and Silicic Regions using LRO Narrow Angle Camera Images." (2015). Arts & Sciences Electronic Theses and Dissertations. 460. https://openscholarship.wustl.edu/art_sci_etds/460

Surveyor Off-Nominal Landing

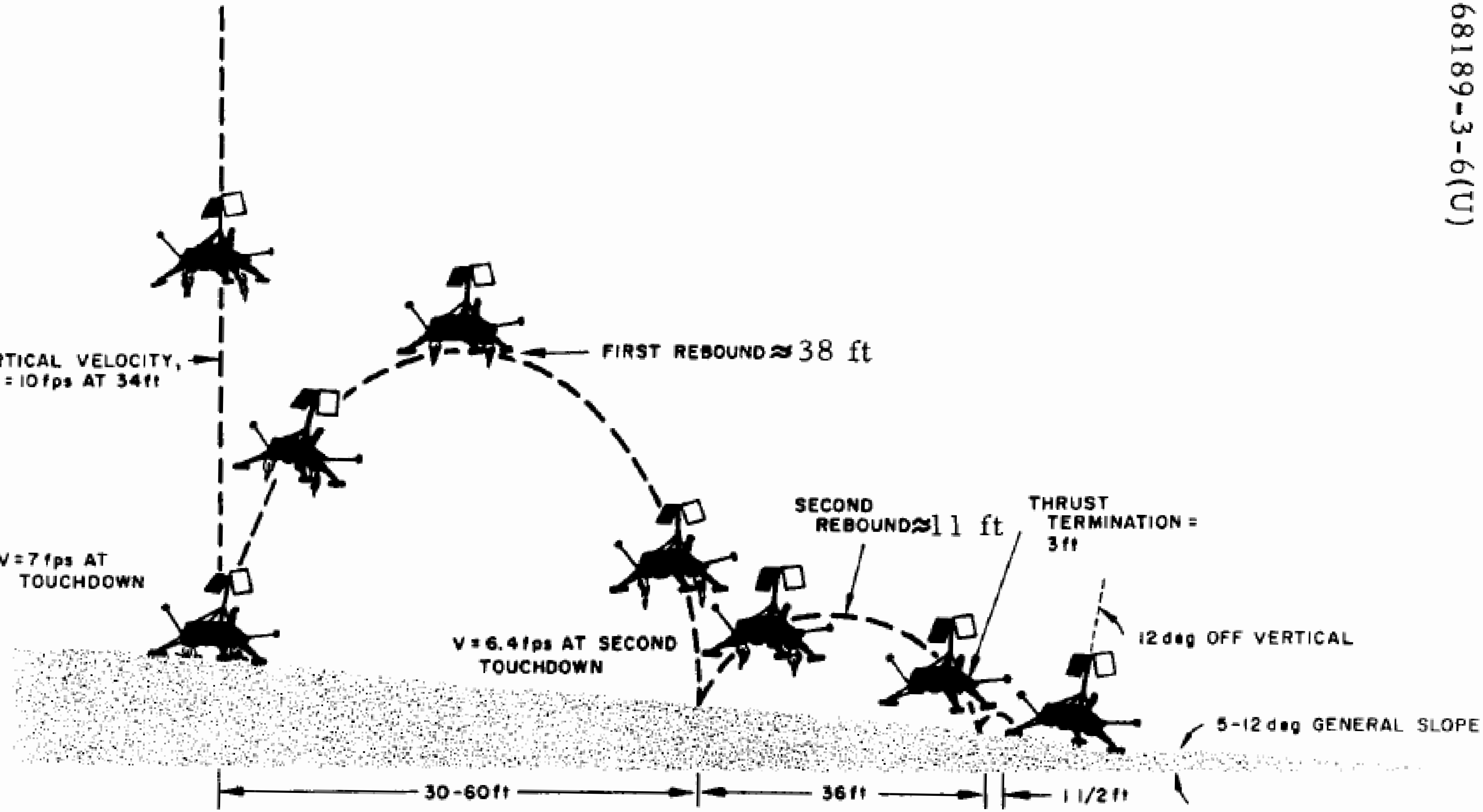
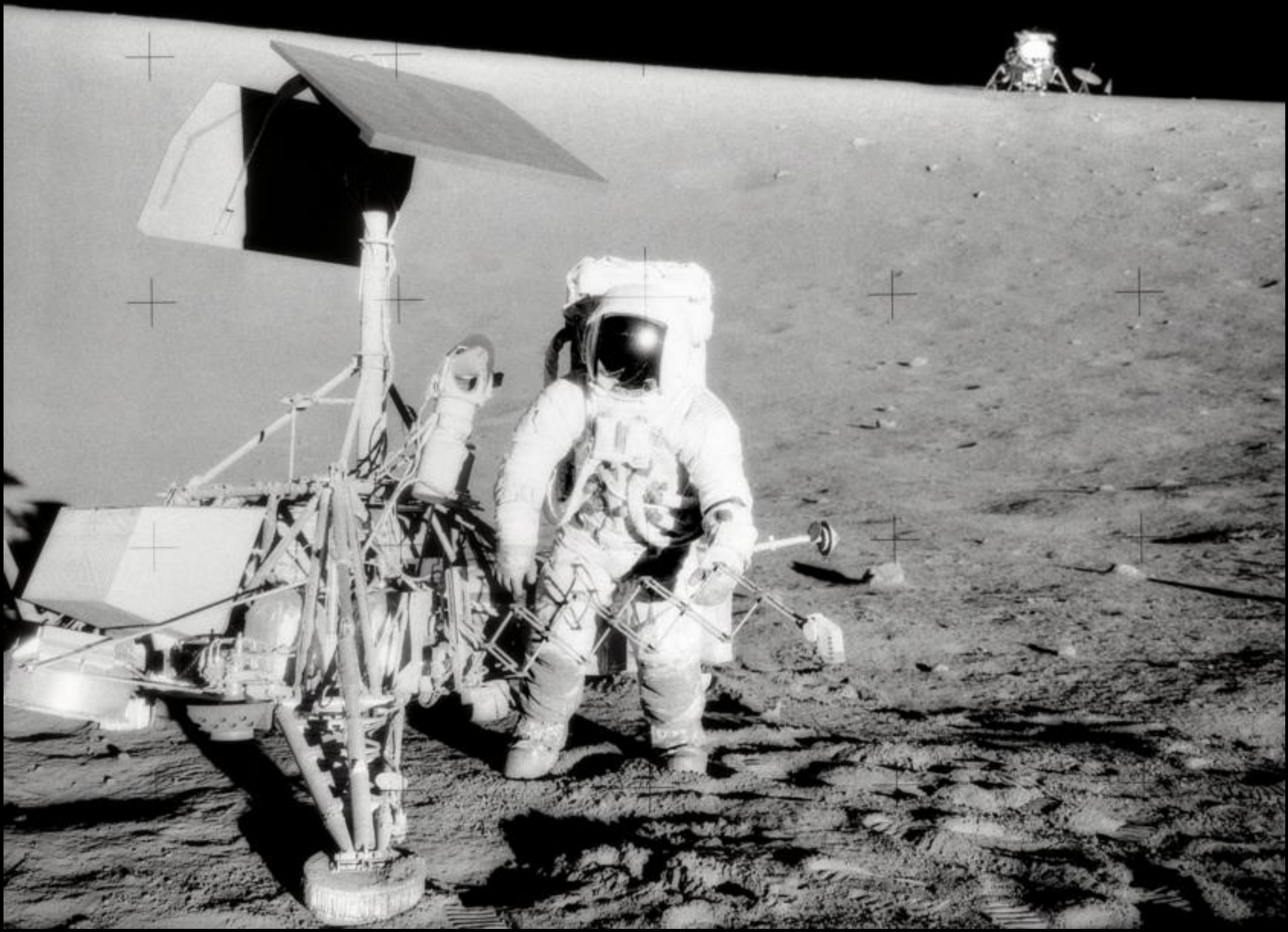
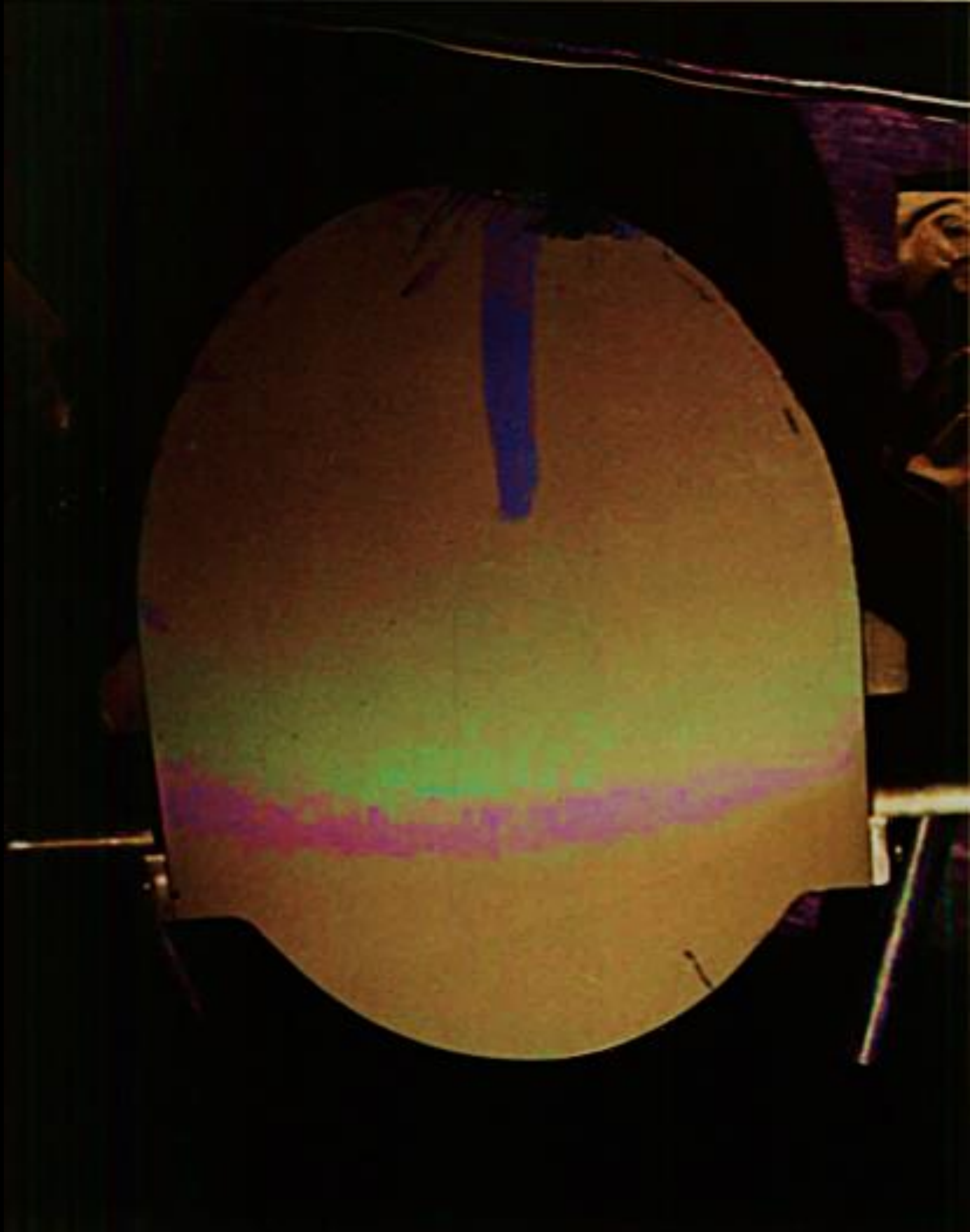
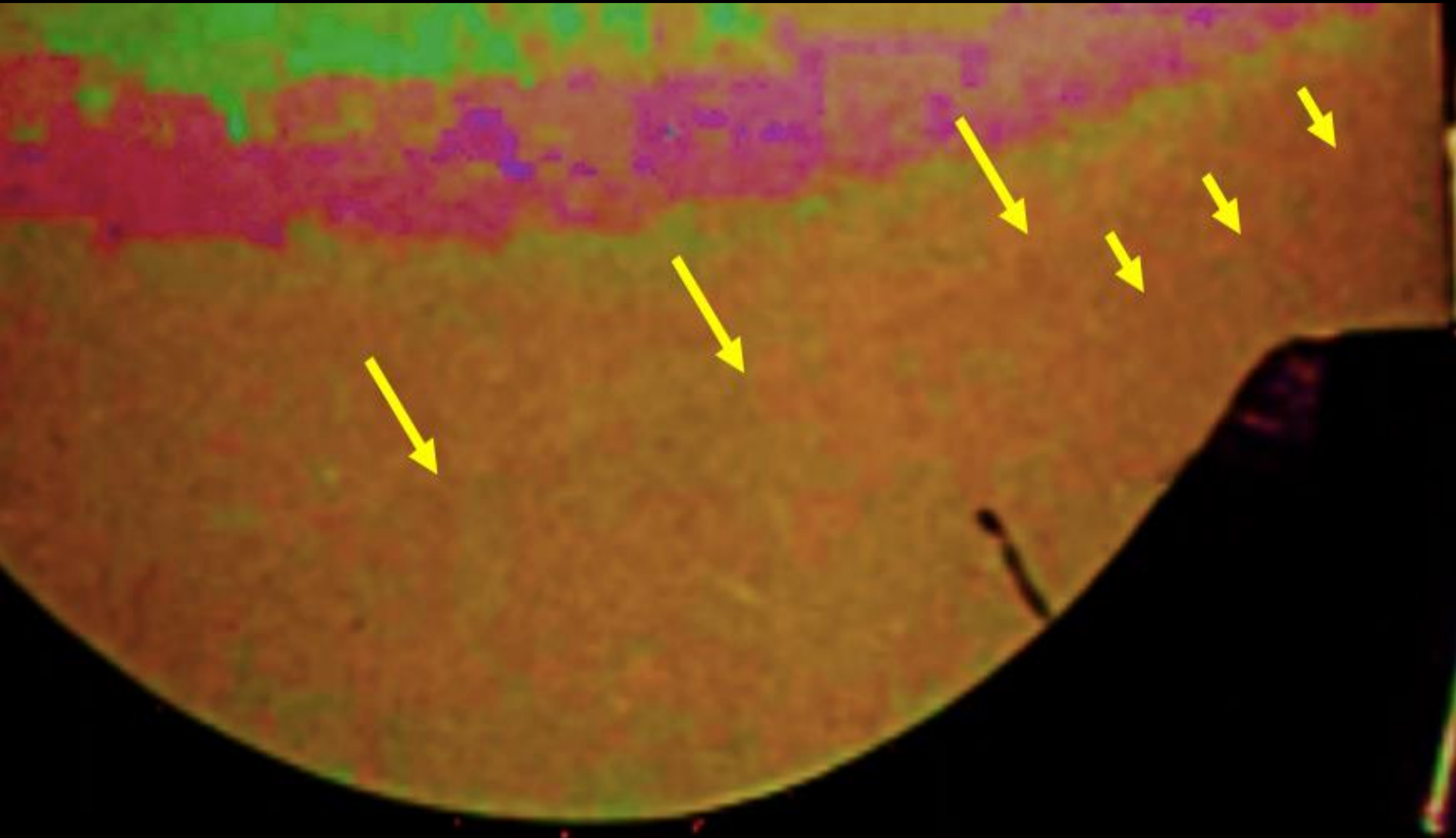
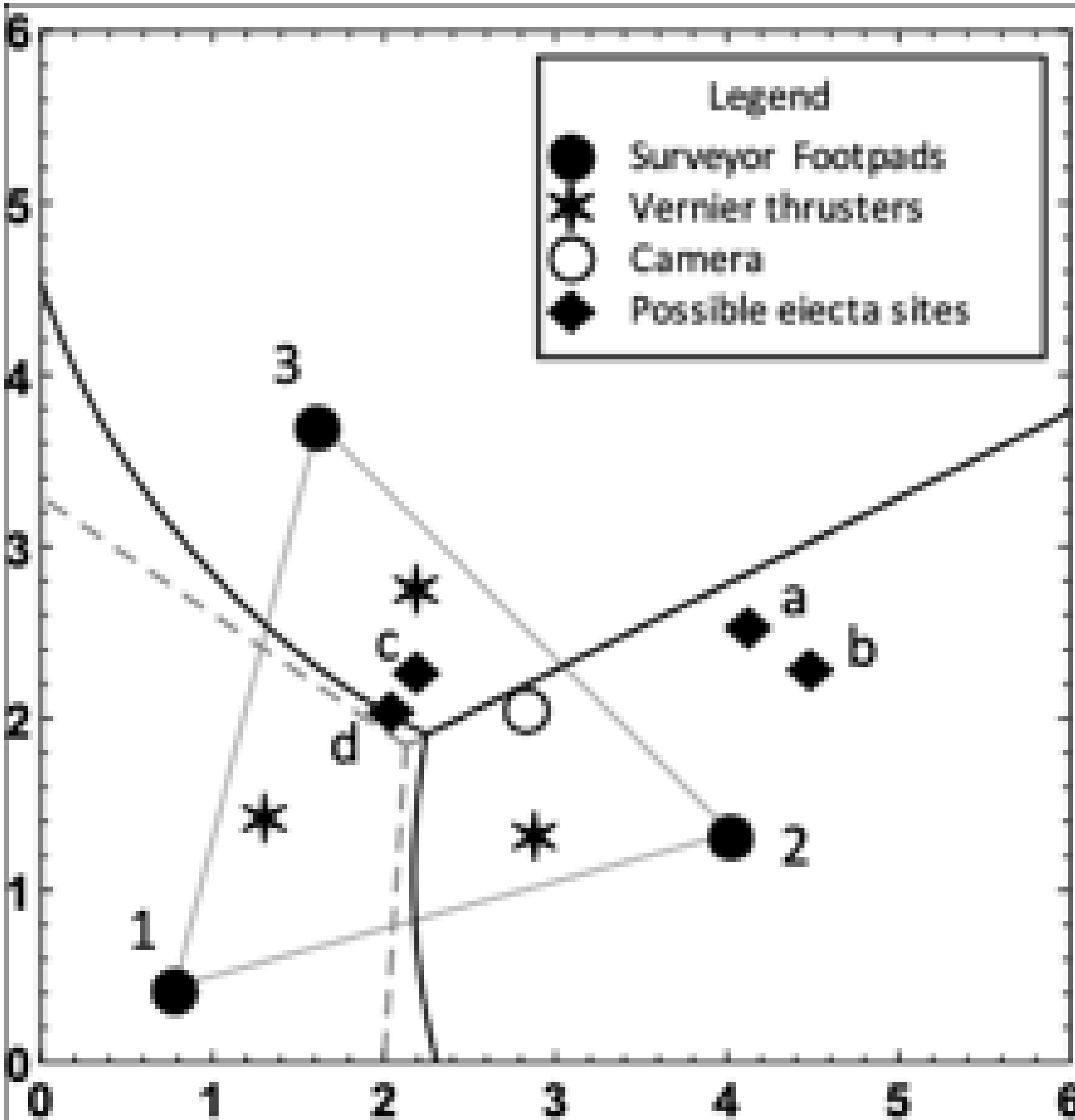


Figure 4-6. Surveyor III Landing Profile








Legend
Surveyor Footpads
Vernier thrusters
Camera
Possible electa sites
1
2
3
a
b
c
d
0
1
2
3
4
5
6
0
1
2
3
4
5
6