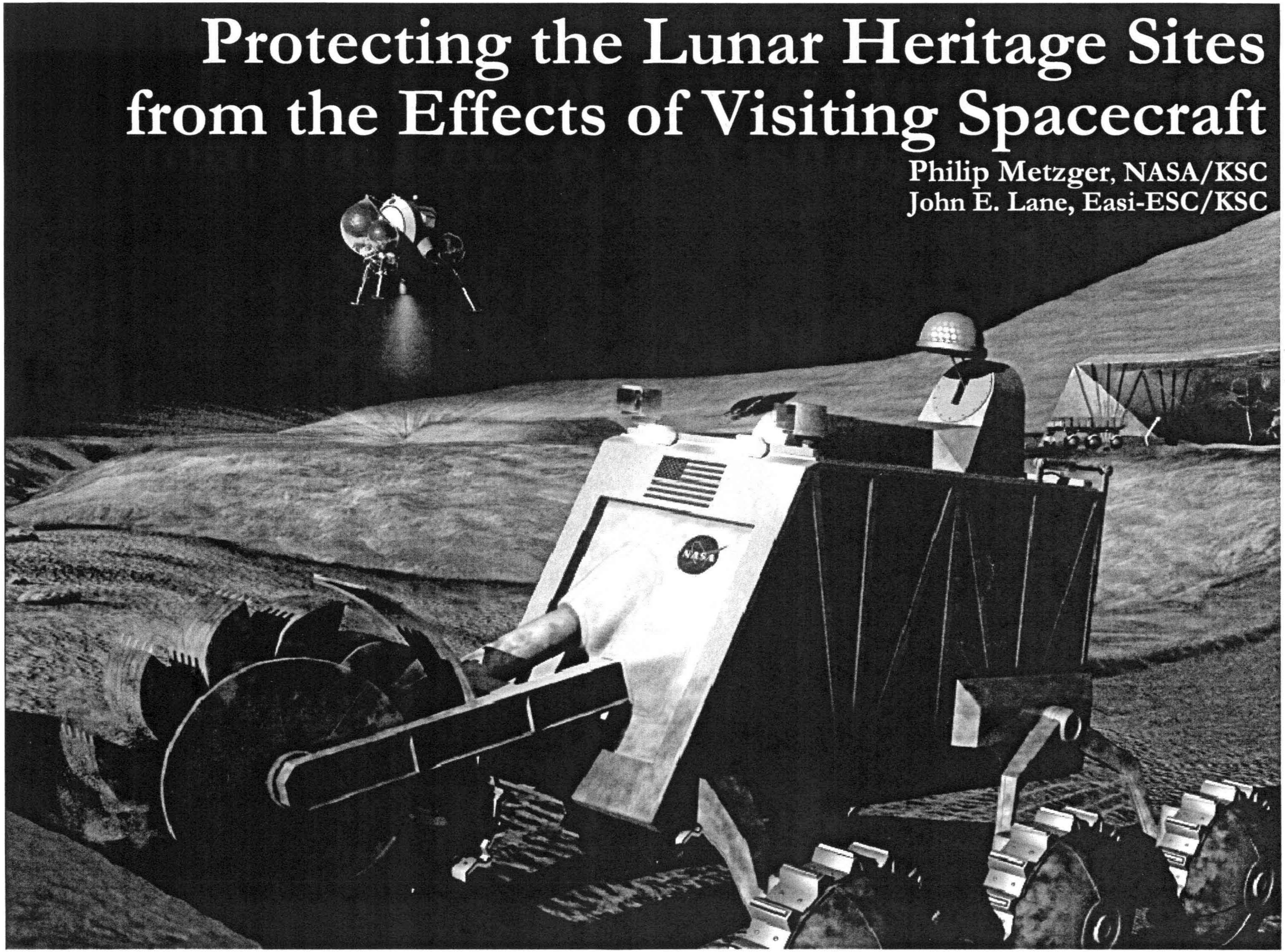
Protecting the Lunar Heritage Sites from the Effects of Visiting Spacecraft

Philip Metzger, NASA/KSC
John E. Lane, Easi-ESC/KSC



Outline

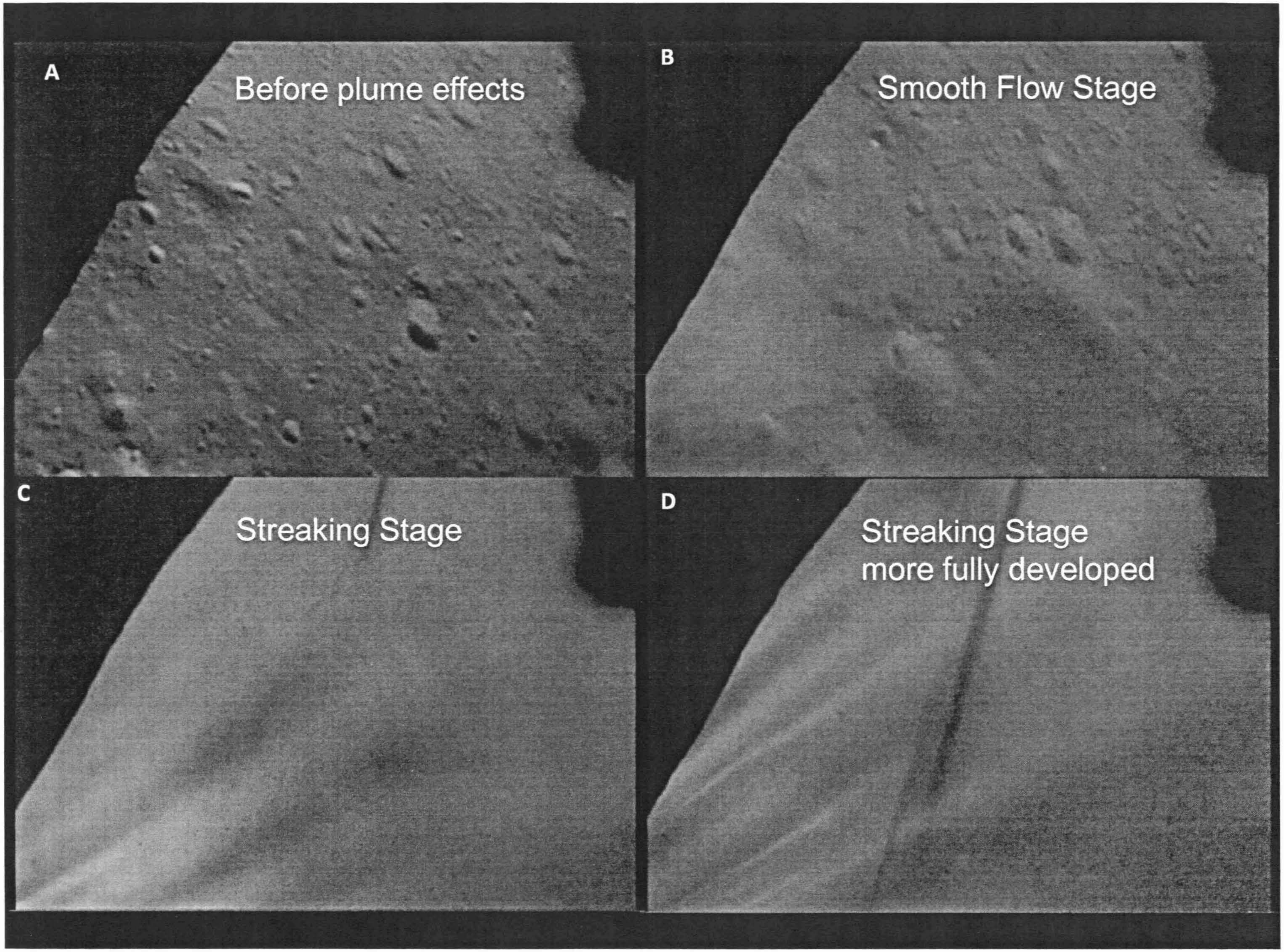
- The Problem
- Modeling of the Plume Effects
- Guidelines for Landing on the Moon
- Forward Work

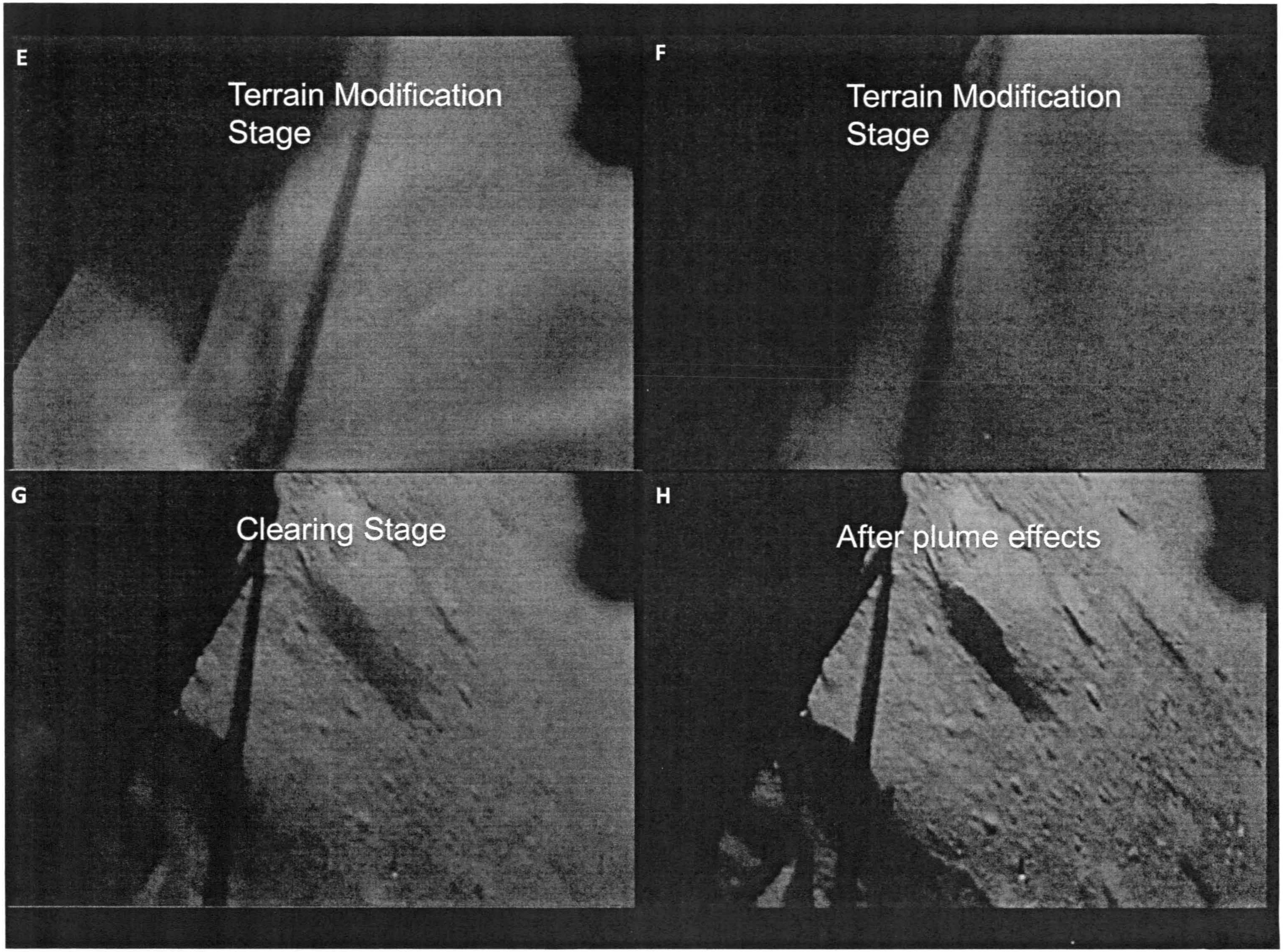
Credit:

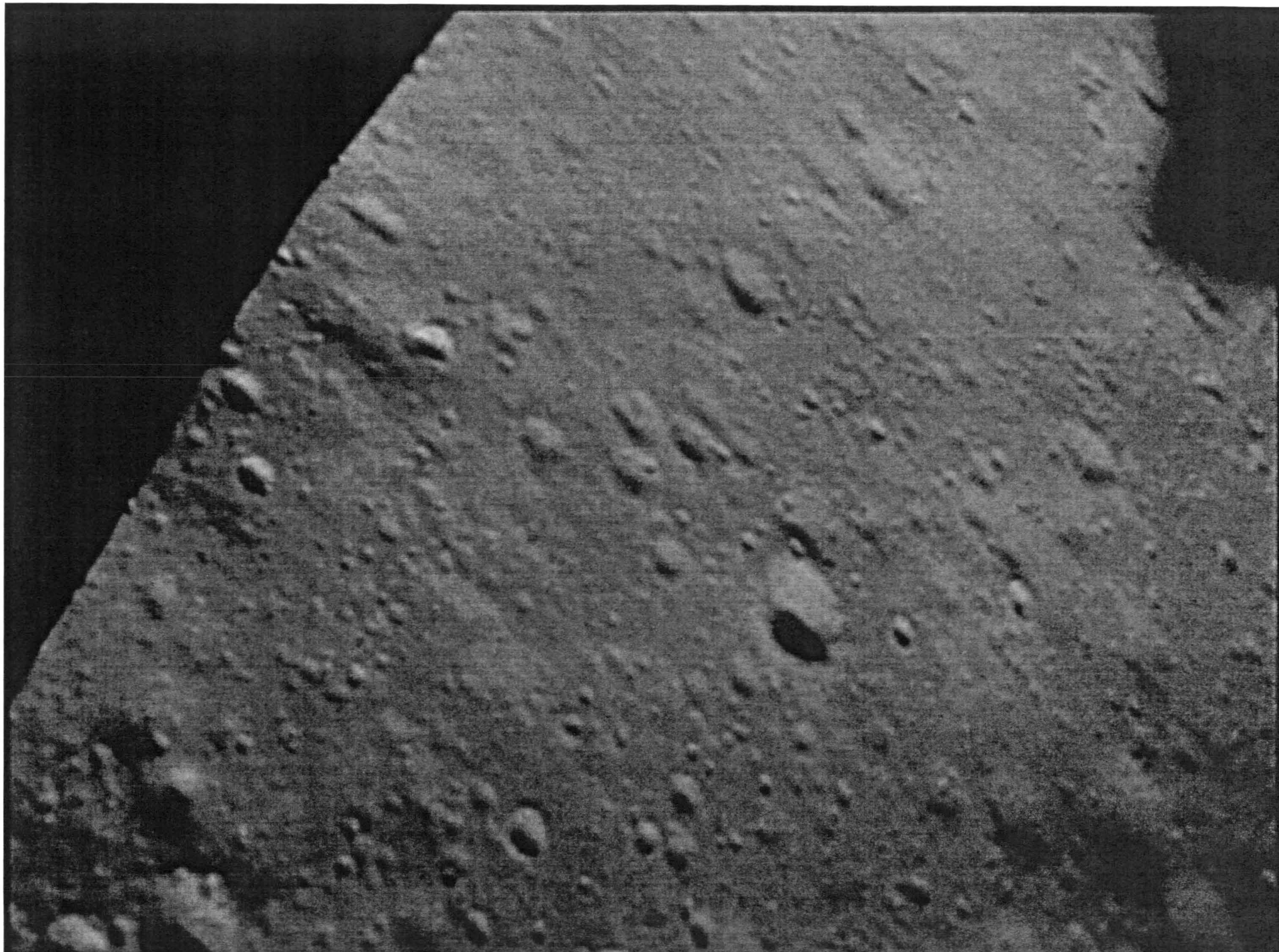
Much of the following background material was taken from "NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts." The authors of this presentation contributed the blast effects analysis to that publication, but the other content of that publication was the work of many contributors.

The Problem:

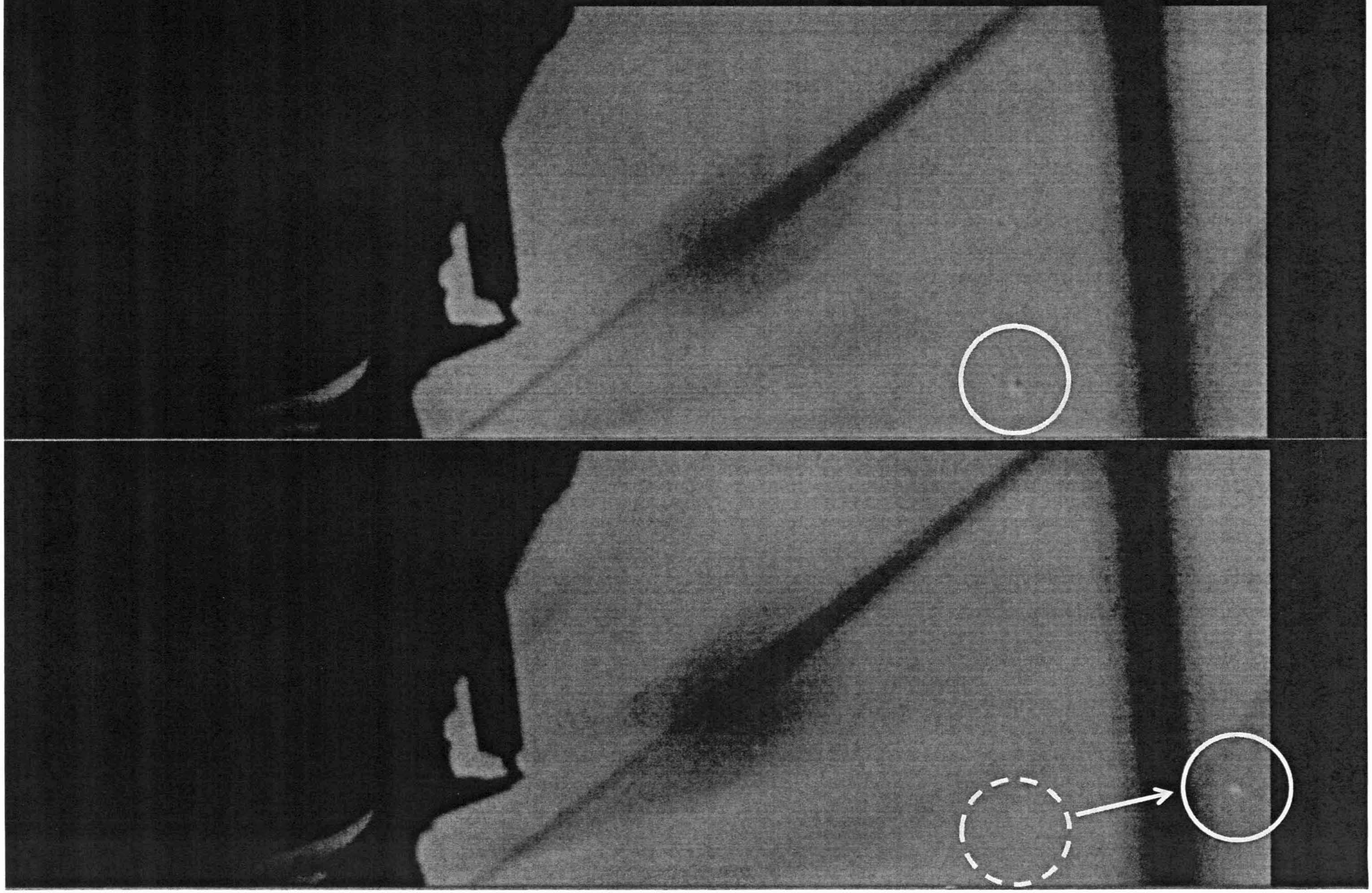
Rocket exhaust blows soil and rocks over vast distances at velocities upwards of 1 to 3 km/s, and this will be highly abrasive and damaging if it impacts the valuable lunar heritage sites.


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

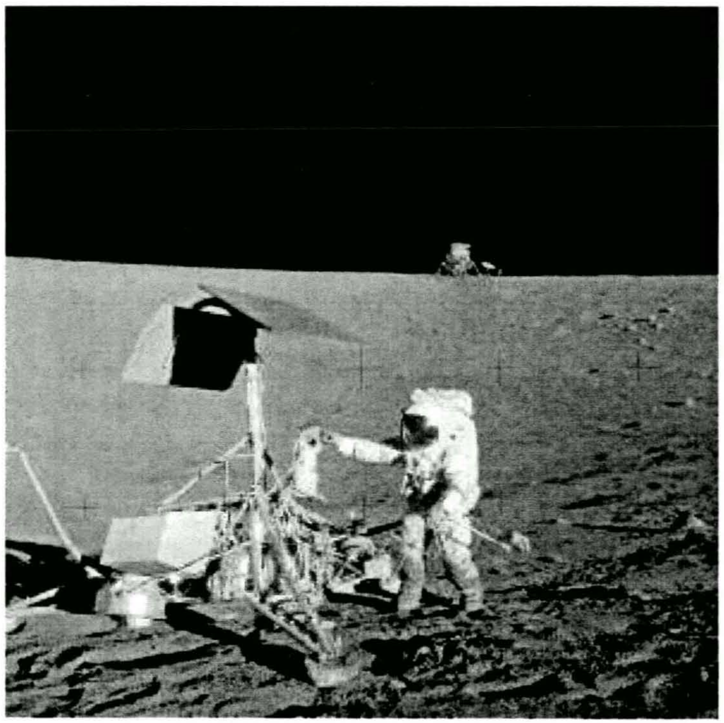

E
Terrain Modification Stage
F
Terrain Modification Stage
G
Clearing Stage
H
After plume effects

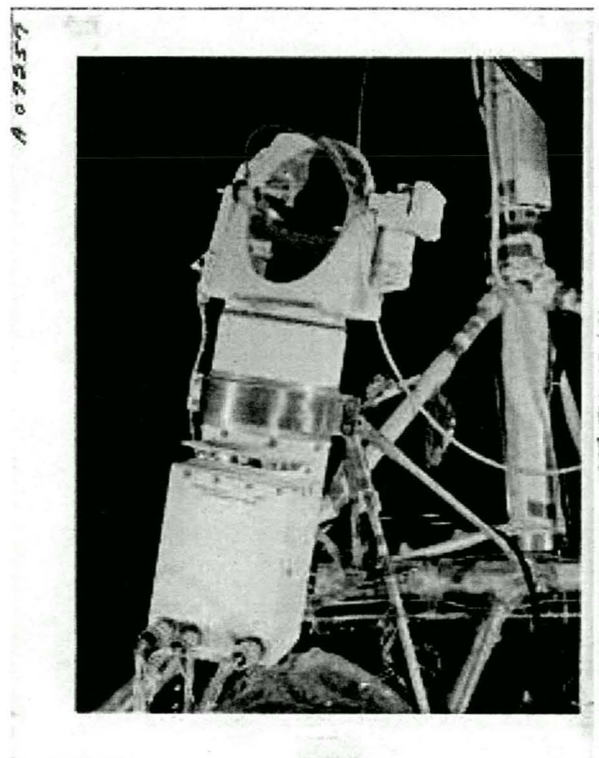


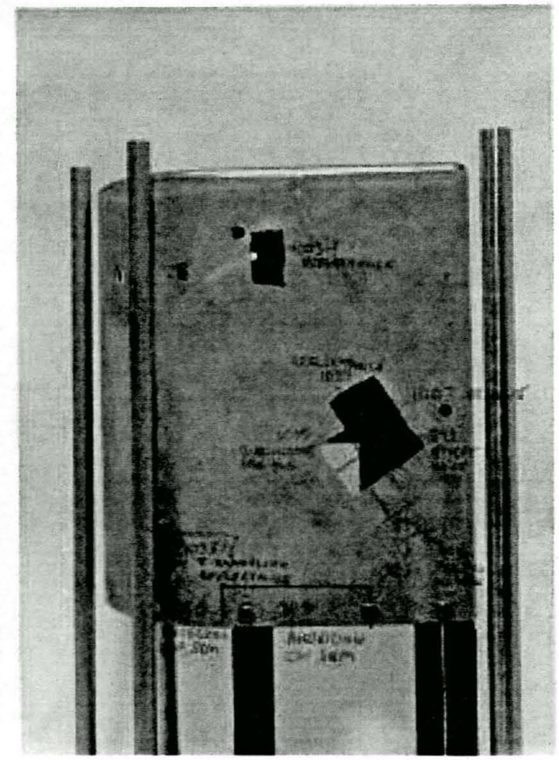
Rocks Blowing



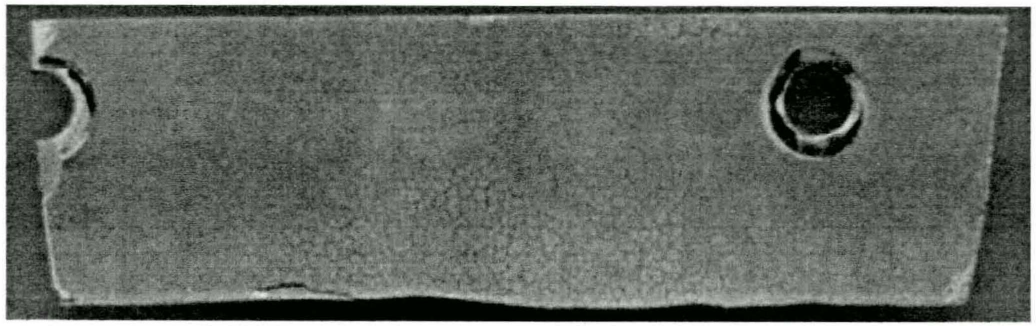
Surveyor III Coupons

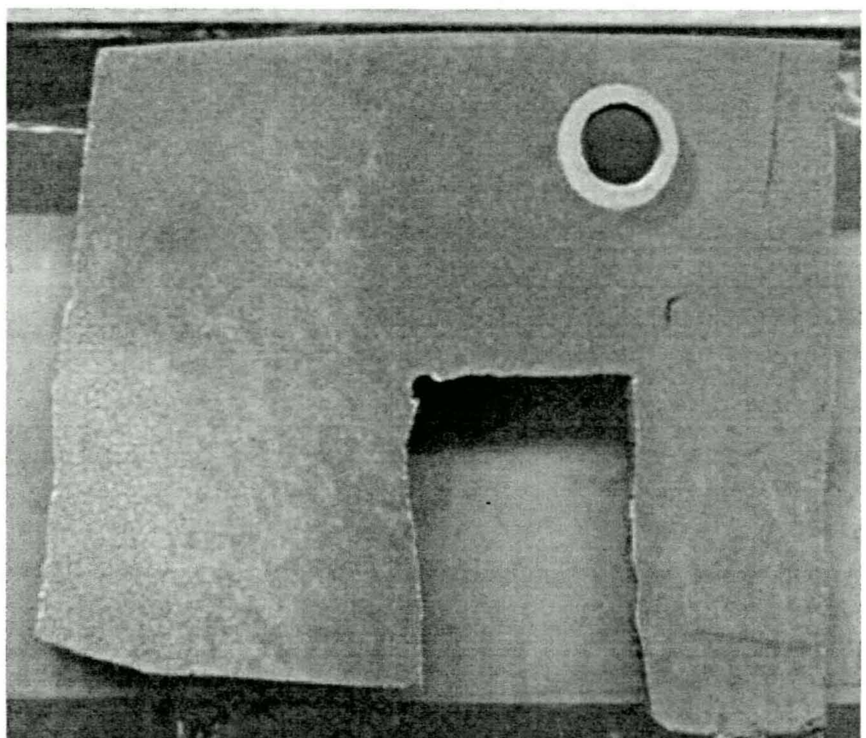




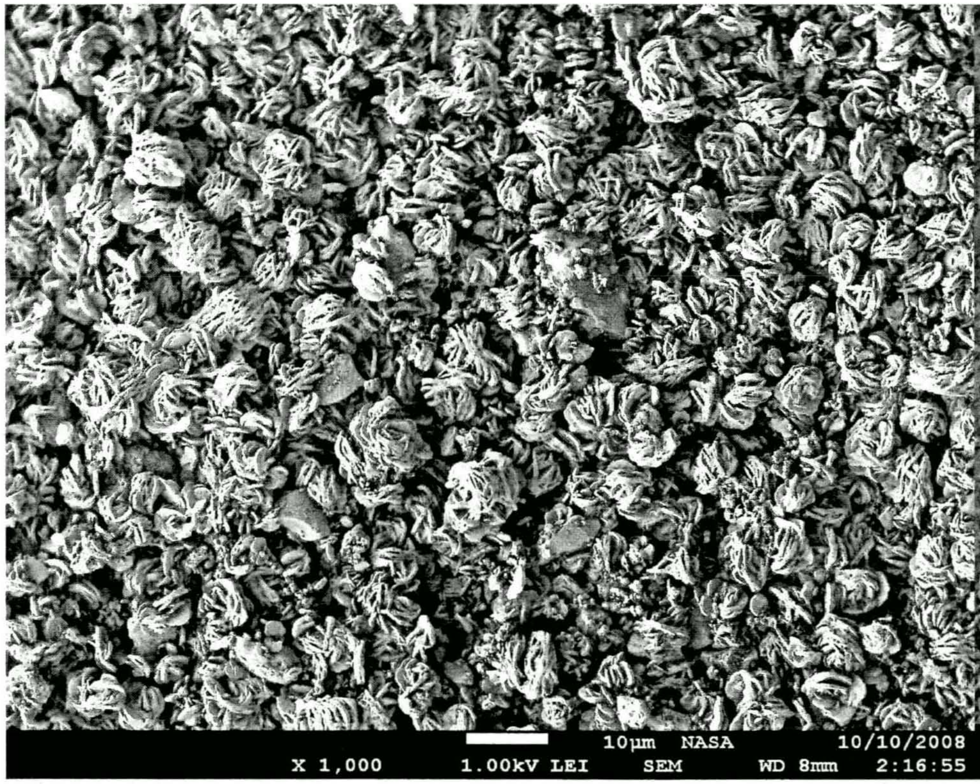


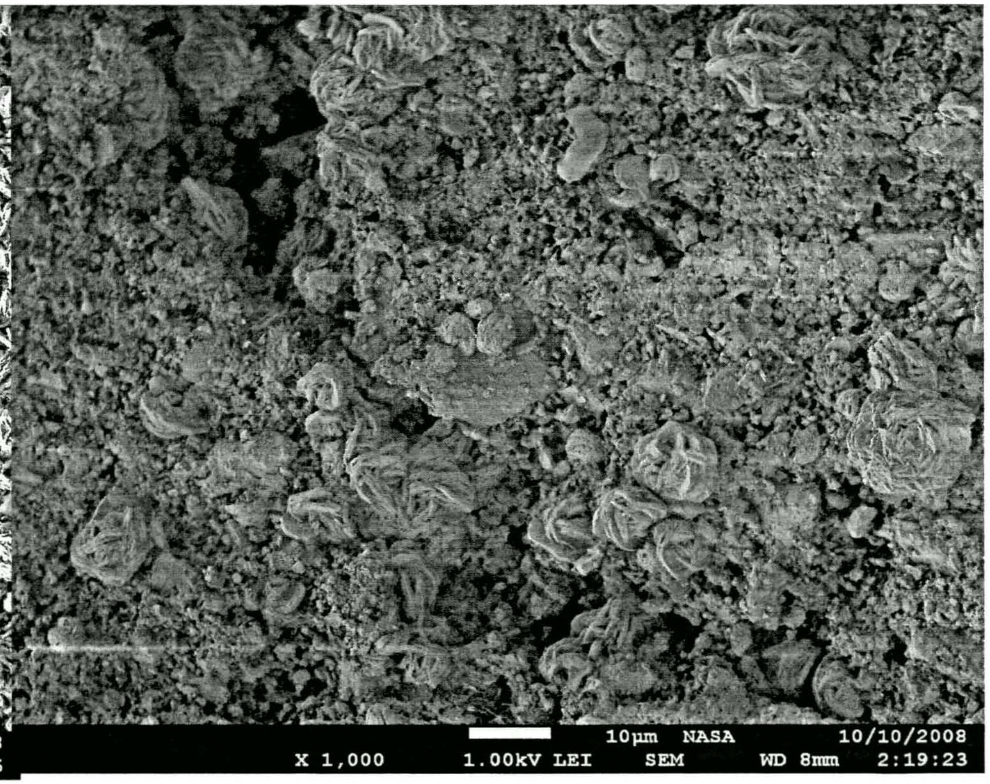
Surveyor III Coupons



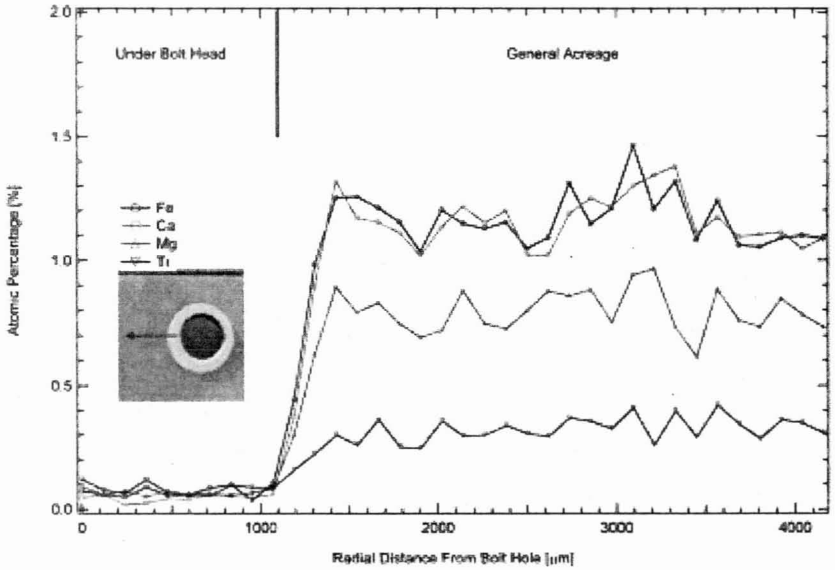


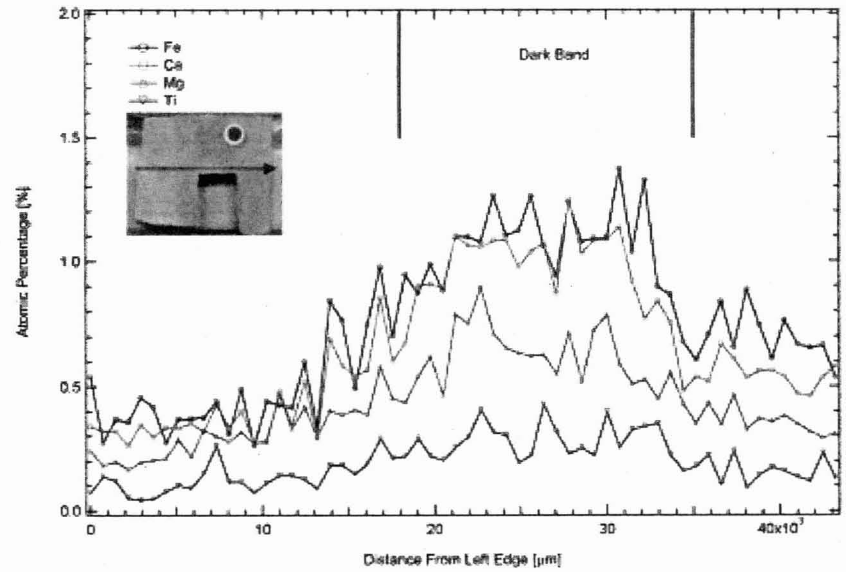
SEM Imagery

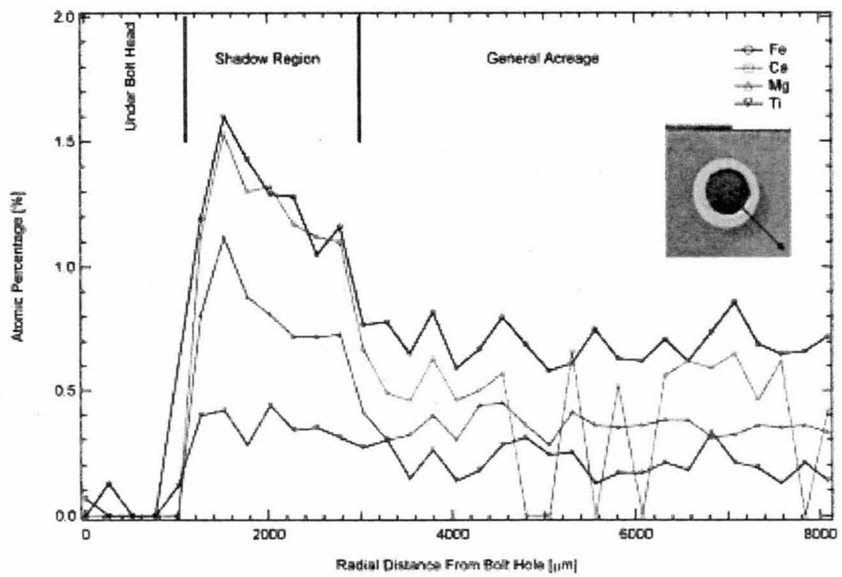

10µm NASA 10/10/2008
X 1,000 1.00kV LEI SEM WD 8mm 2:16:55


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

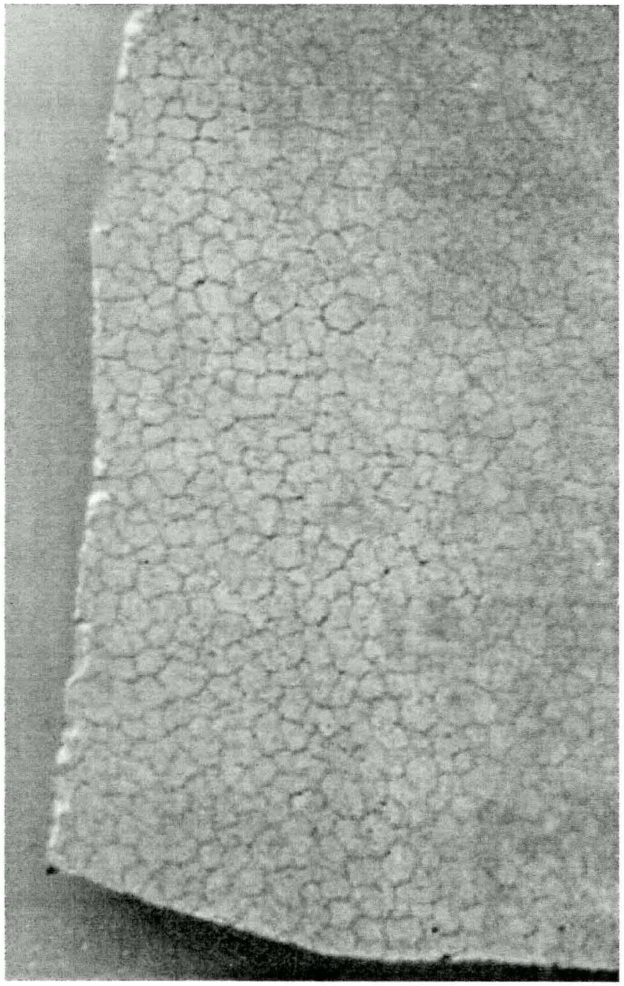
Energy Dispersive X-ray Spectroscopy

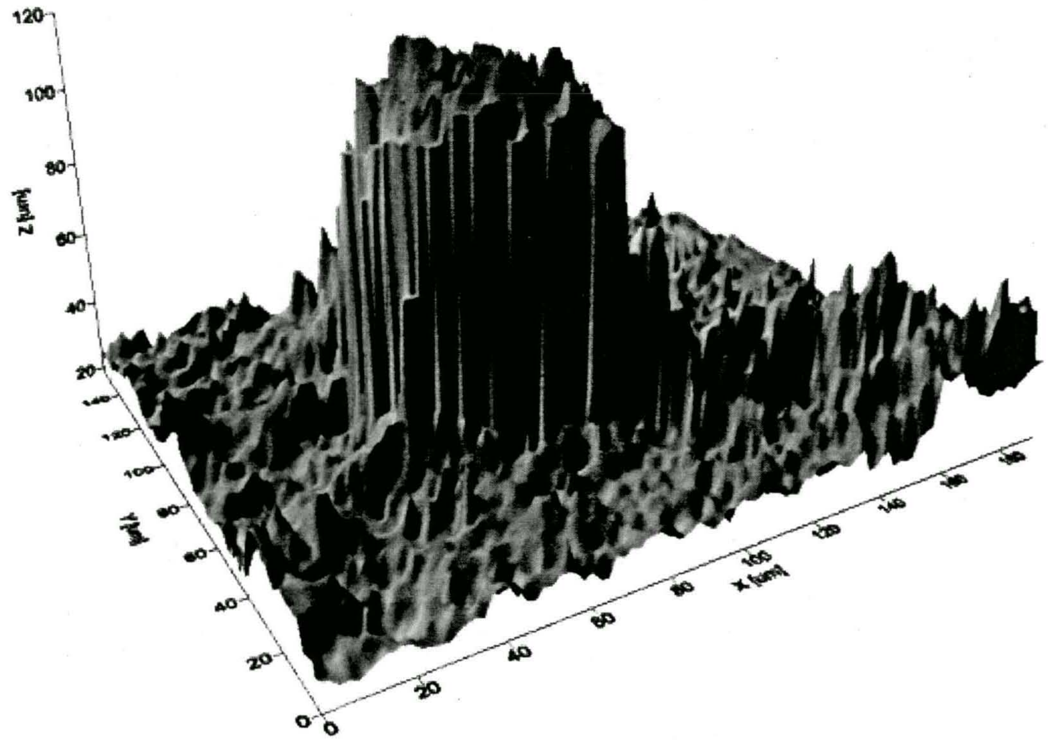






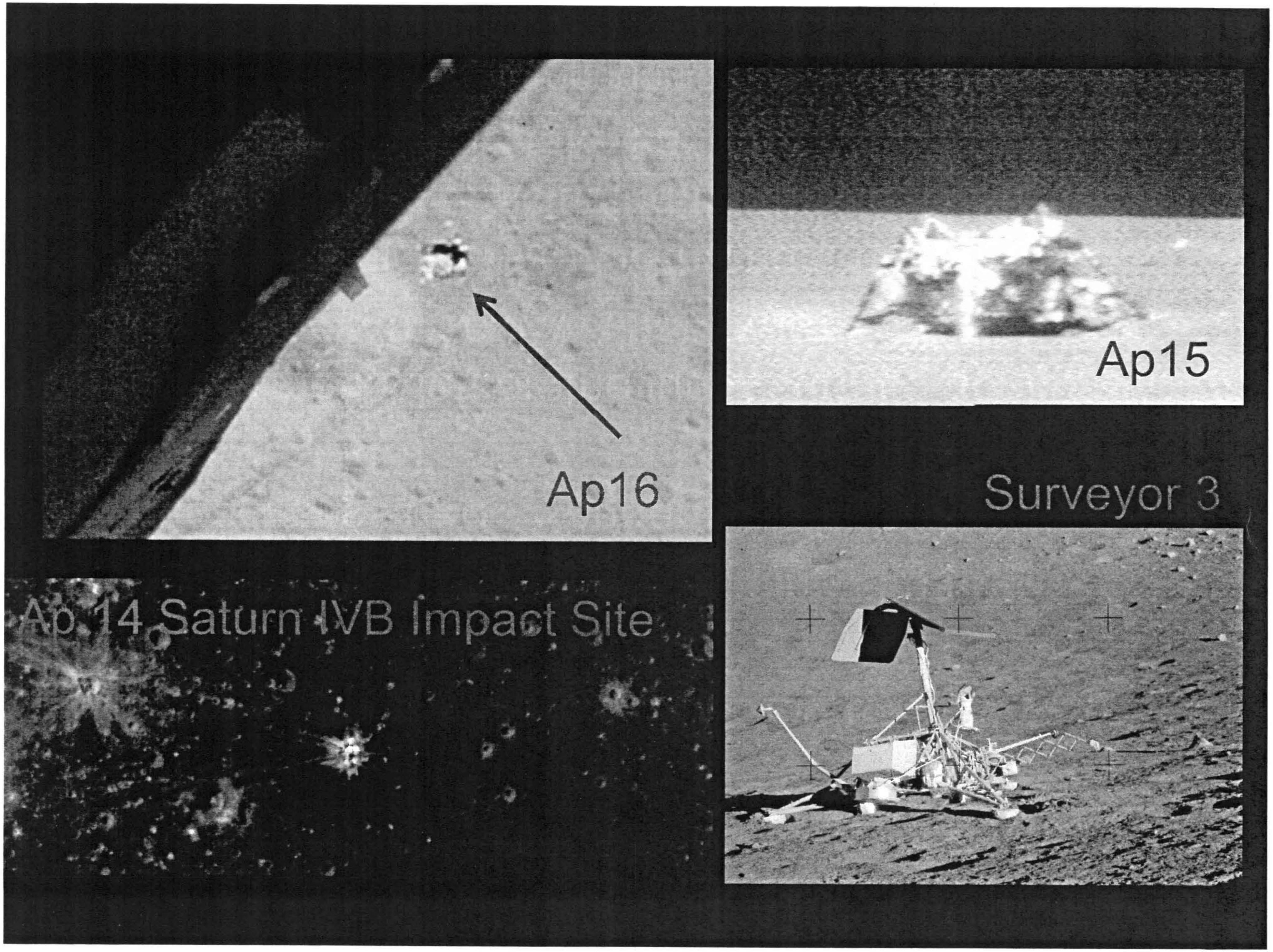
Pits and Cracks





Value of the Heritage Sites

- Scientific Value
  - Witness plates of the lunar environment
    - Dust transport, micrometeoroids, cosmic ray flux, solar wind implantation, etc.
  - Revisit to answer questions left from Apollo missions
- Engineering Value
  - How did various materials hold up?
- Archaeological Value
  - "Space Archaeologists" consider the Apollo sites to be the most important archaeological sites in the human "world"
- Historic Value
- National Value
- *Commercial Value*
  - visiting these sites may help commercial space companies establish their business; hence the Google Lunar X-Prize


Ap16
Ap15
Surveyor 3
Ap 14 Saturn IVB Impact Site

US Artifacts on the Moon

- Apollo lunar surface landing and roving hardware
- Unmanned lunar surface landing sites
- Impact sites (e.g., Ranger, S-IVB, LCROSS, LM ascent stage)
- Experiments left on the lunar surface, tools, equipment, misc. EVA hardware
- Specific indicators of US human, human-robotic lunar presence, including footprints, rover tracks, rocks fractured to take samples, etc.
  - NOTE: not all anthropogenic indicators are protected as identified in the recommendations

Representative Artifacts

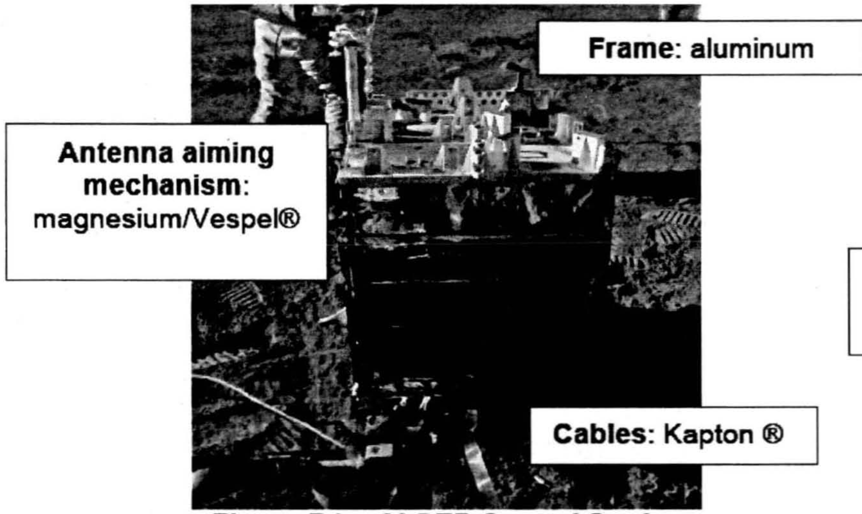


Figure B1 – ALSEP Central Station

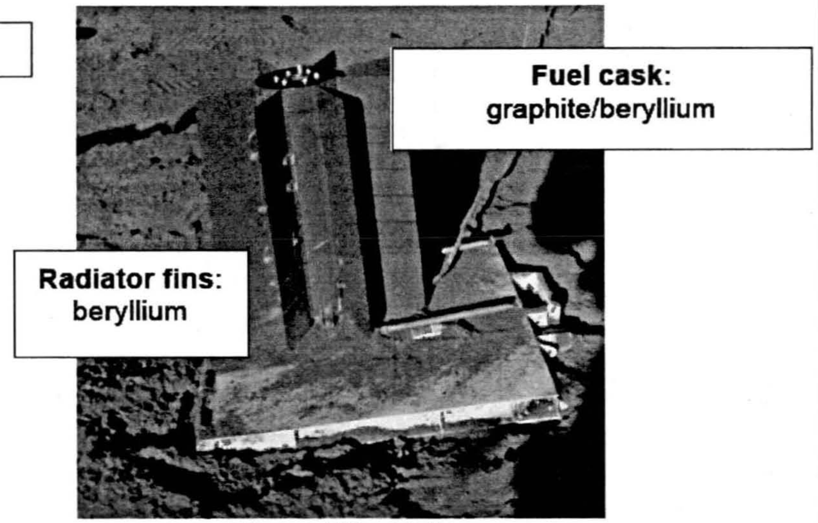


Figure B2 – RTG

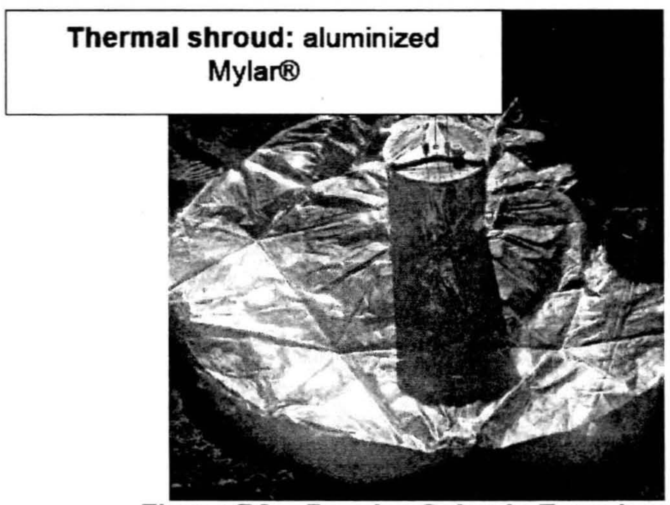


Figure B3 – Passive Seismic Experiment

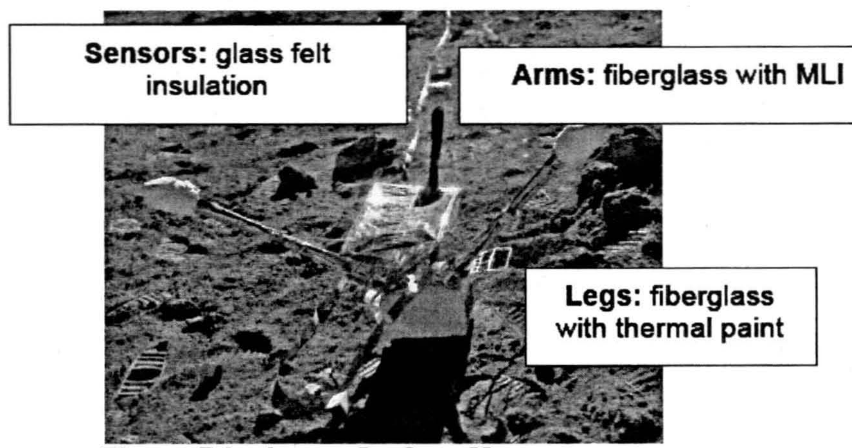


Figure B4 – Lunar Surface Magnetometer

Representative Artifacts

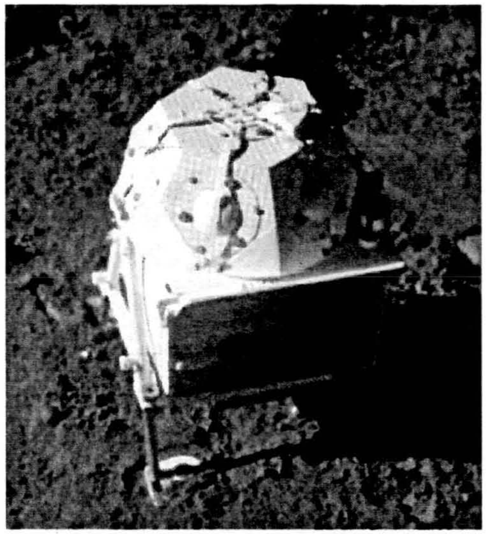


Figure B5 – Solar Wind Spectrometer

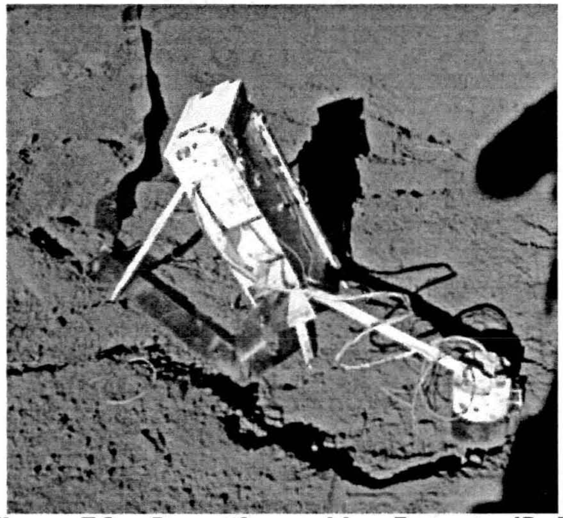


Figure B6 – Suprathermal Ion Detector/Cold Cathode Ion Gage

Probes: epoxy-fiberglass

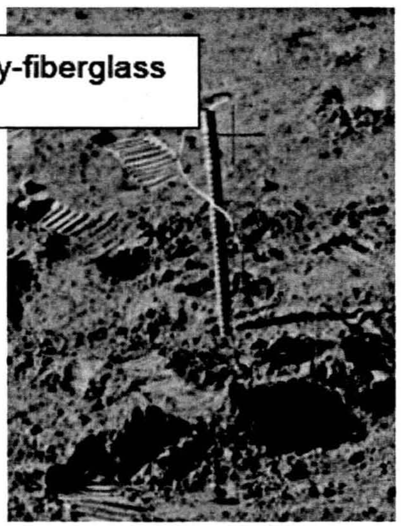


Figure B7 – Heat Flow Experiment

Reflectors: fused silica glass

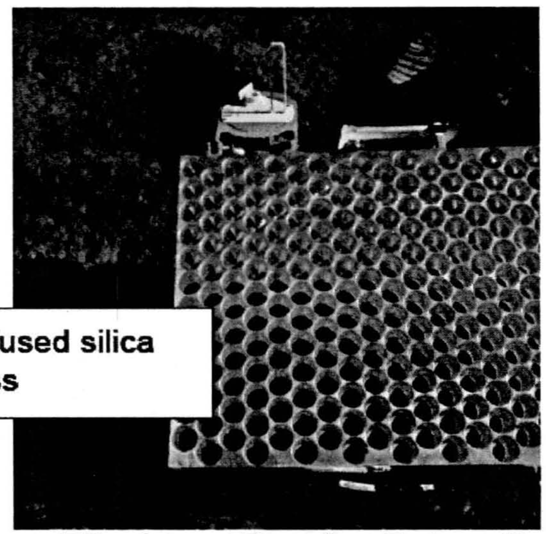


Figure B8 – Laser Ranging Retroreflector

Representative Artifacts

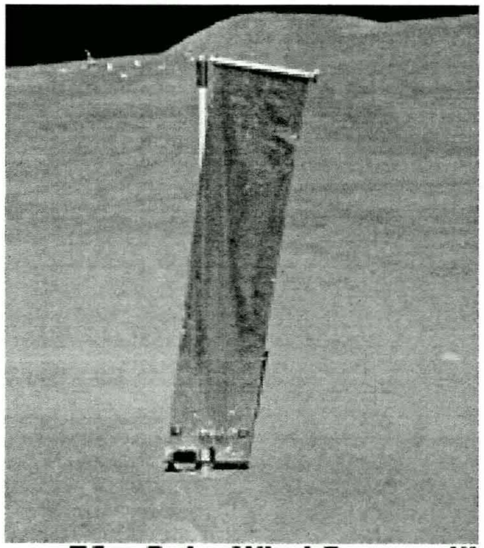


Figure B9 – Solar Wind Composition Experiment (Only Support Pole Remained on Moon)

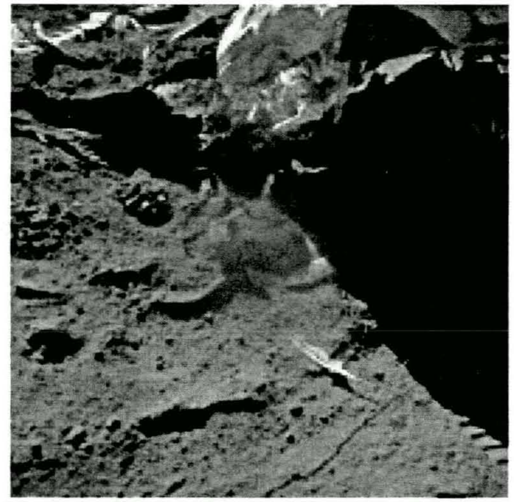


Figure B10 – Hammer and Feather Demonstration

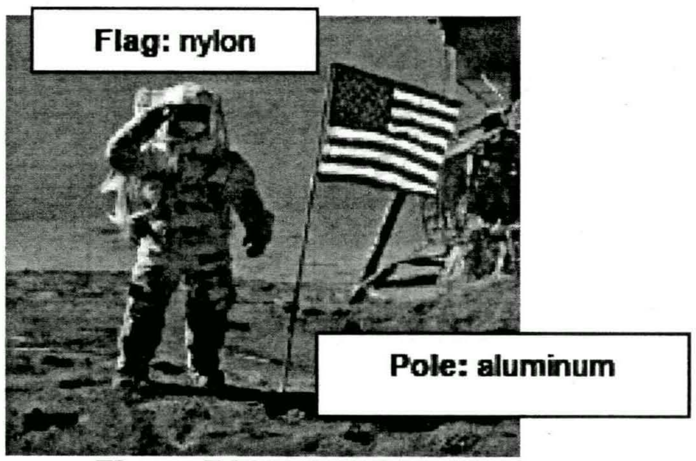


Figure B11 – U.S. Flag

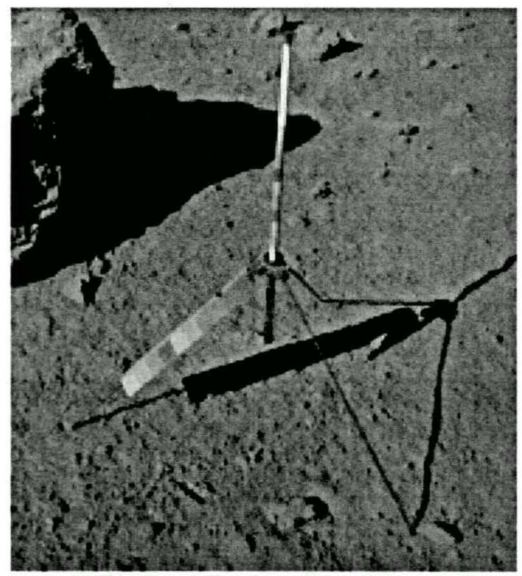


Figure B12 – Gnomon

Representative Artifacts

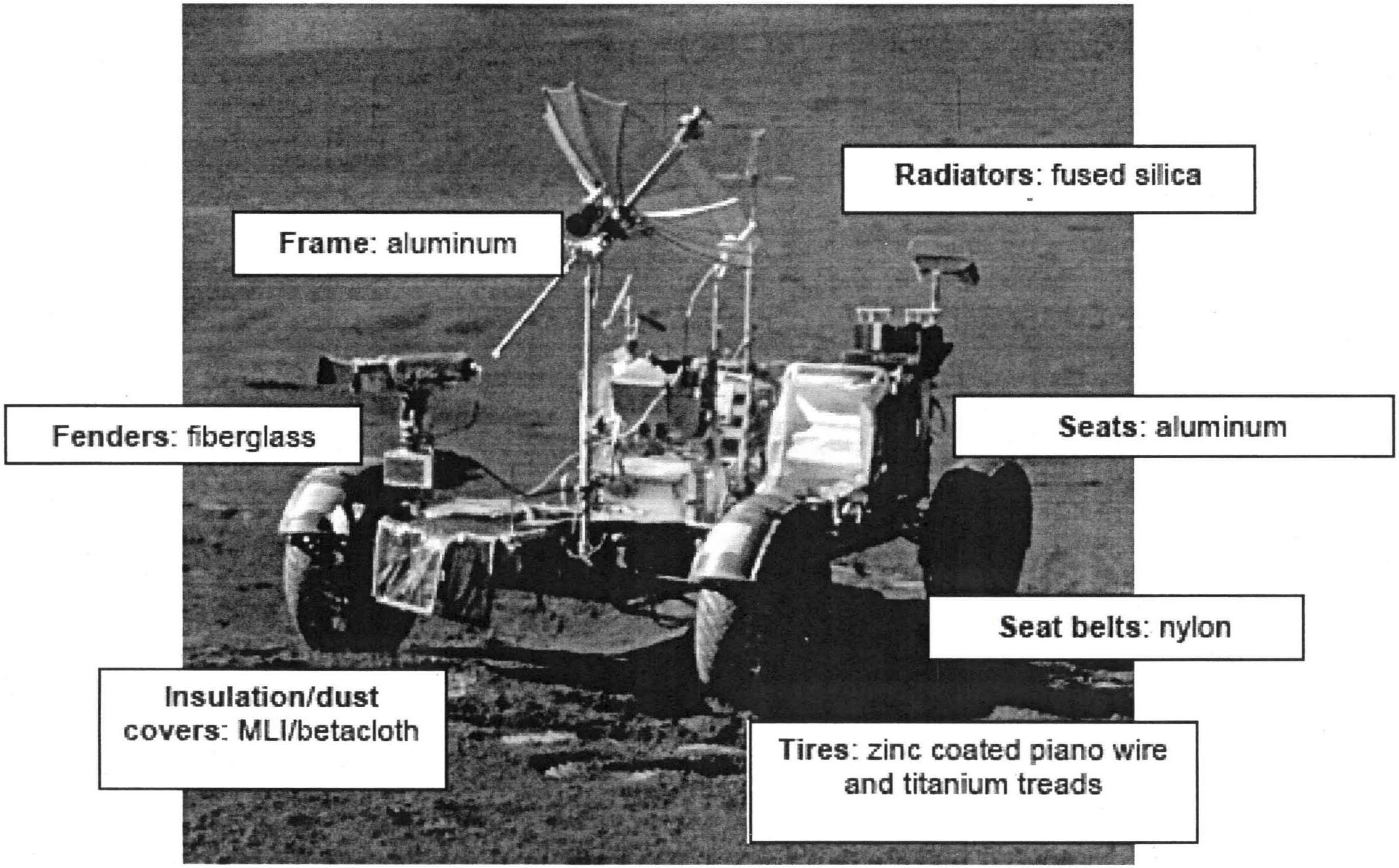


Figure B13 – Lunar Roving Vehicle

Representative Artifacts

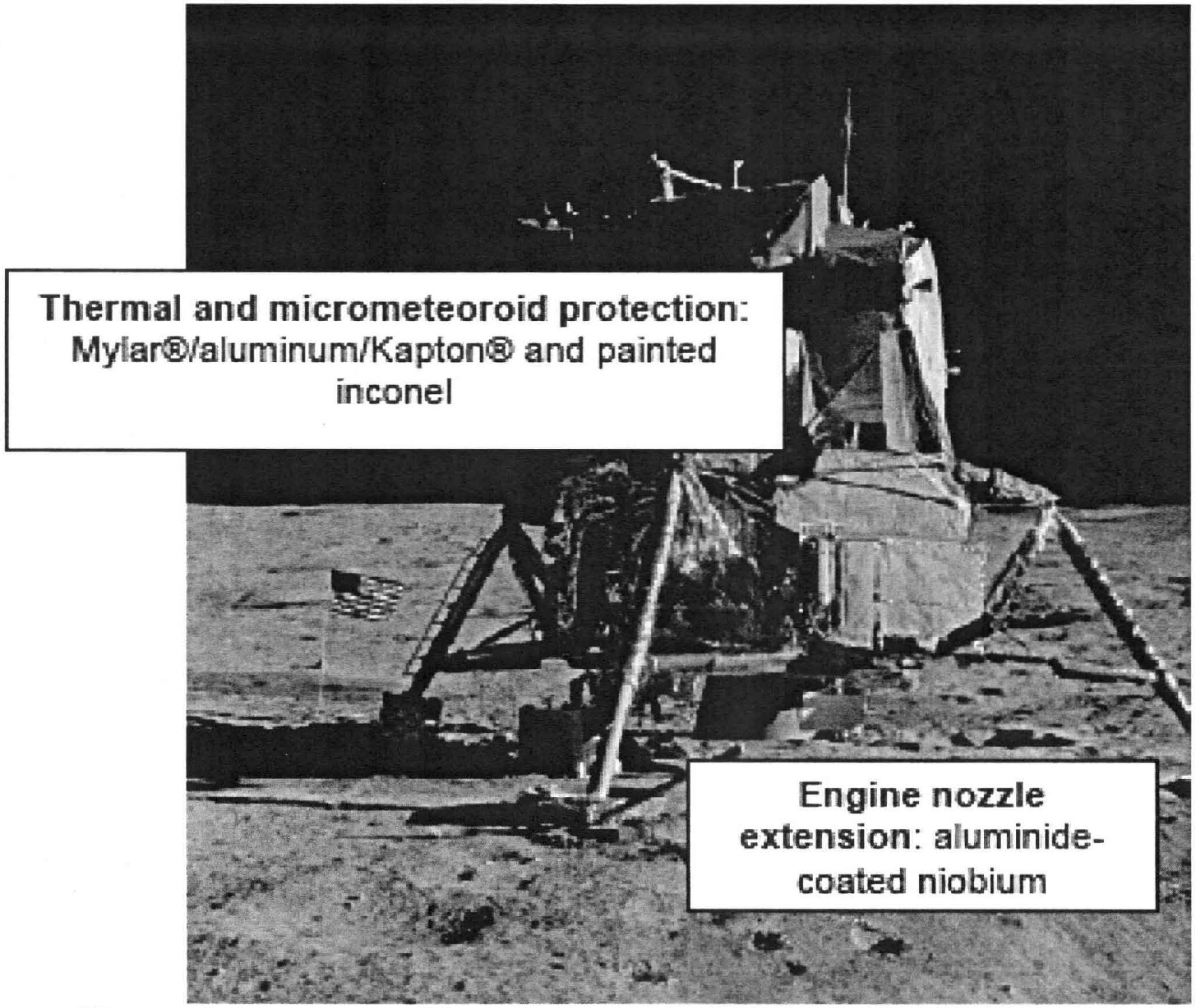
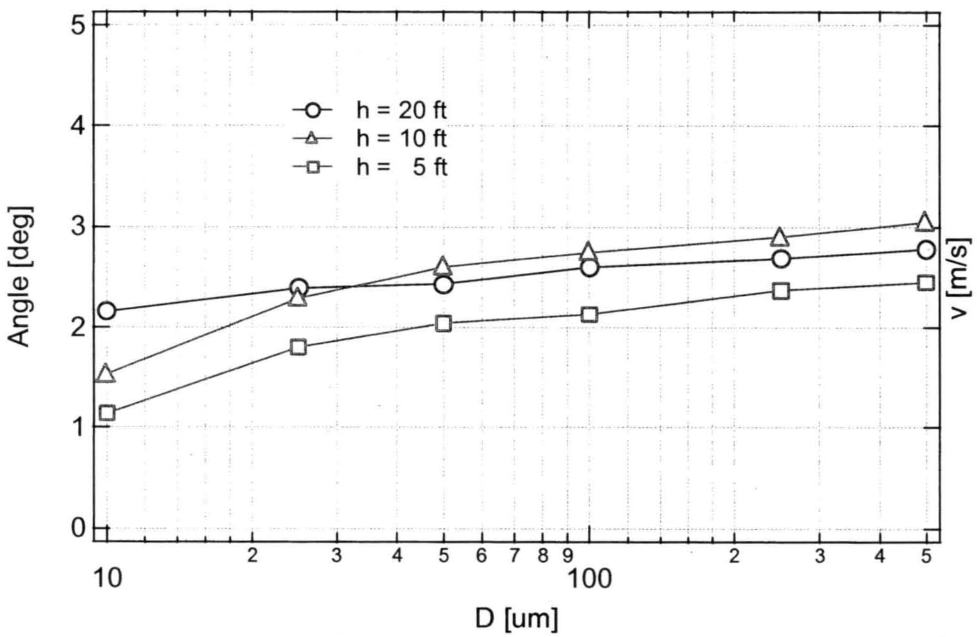


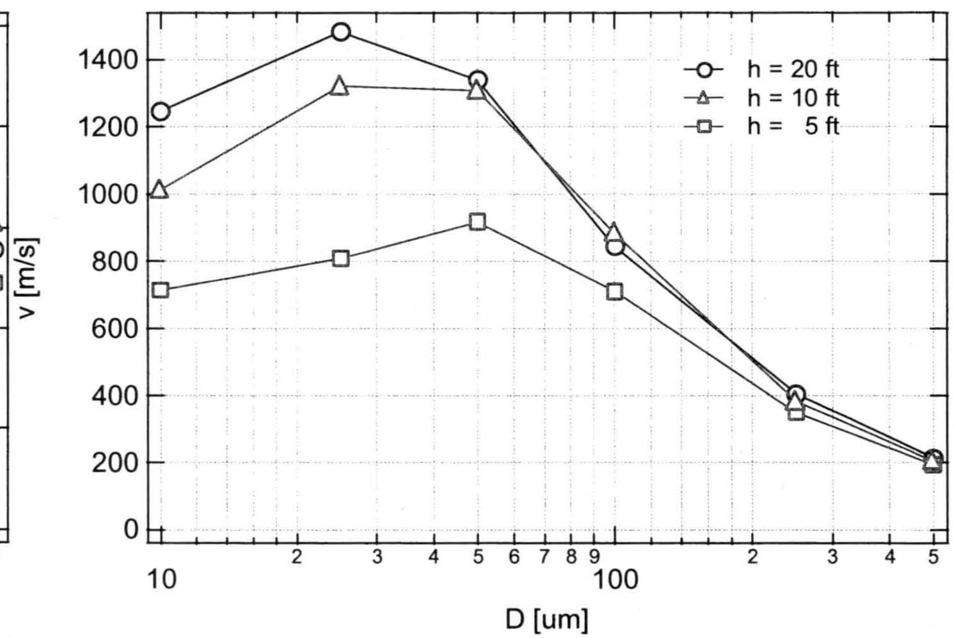
Figure B14 – Lunar Module Descent Stage (Shown with Ascent Stage)

Modeling the Plume Effects

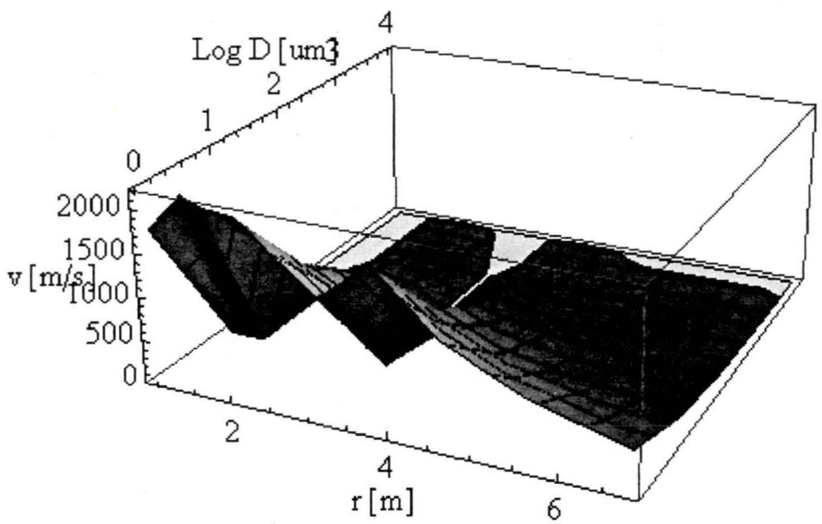
2008 Estimated Dust Ejection Speed and Angle from Ballistics Simulations



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

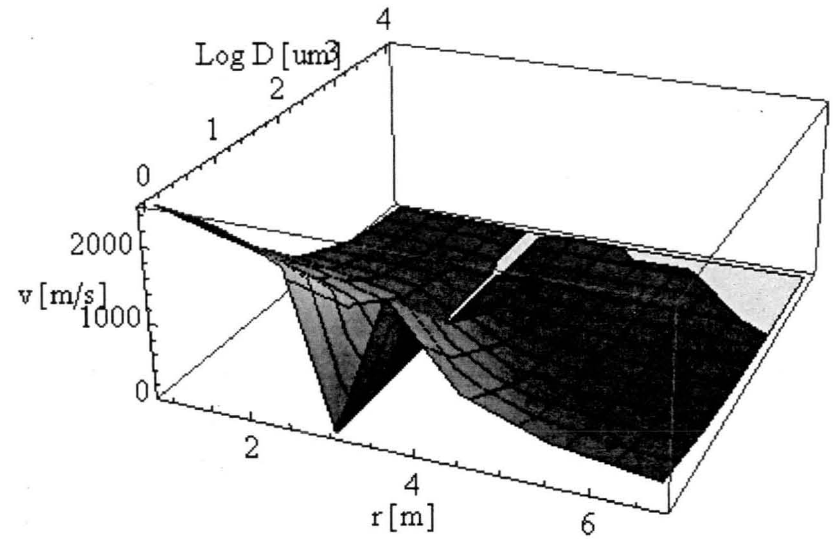


Particle speeds exiting the CFD model boundary.



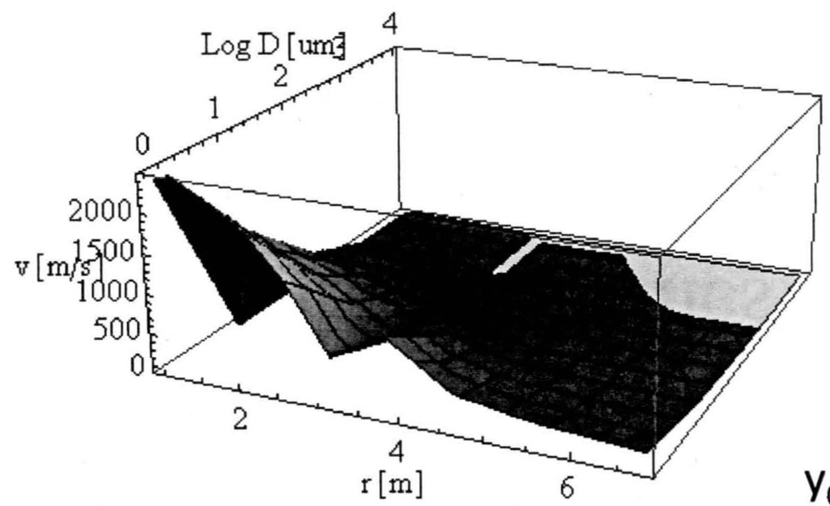
CFD Case 1 (h = 20 ft)

y_0 = 0.10 m   Thrust = 33 kN



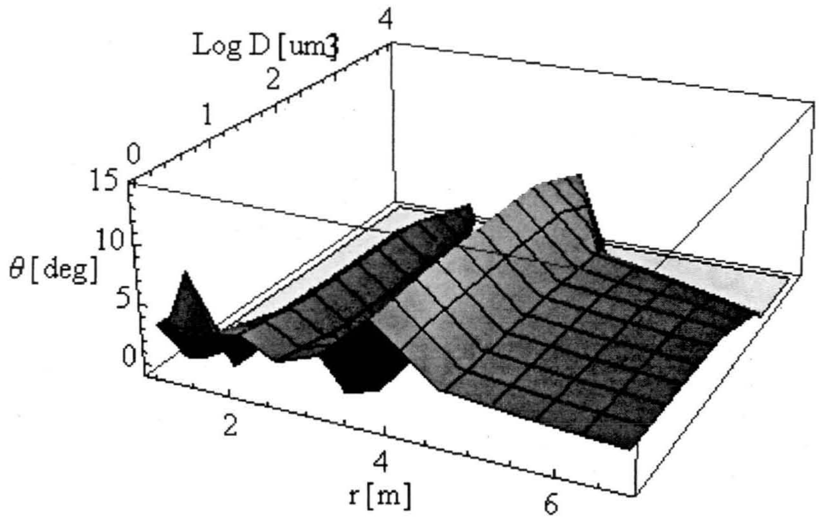
CFD Case 7 (h = 10 ft)

y_0 = 0.10 m   Thrust = 33 kN

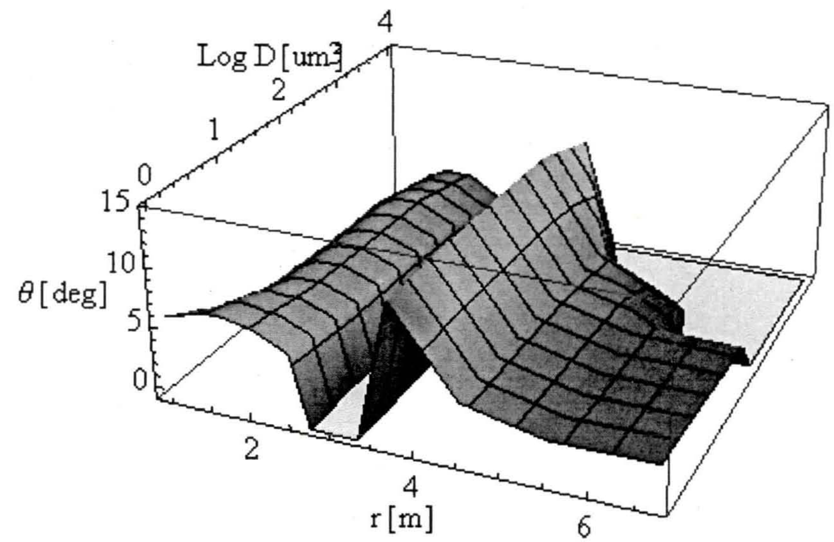


CFD Case 2 (h = 5 ft)

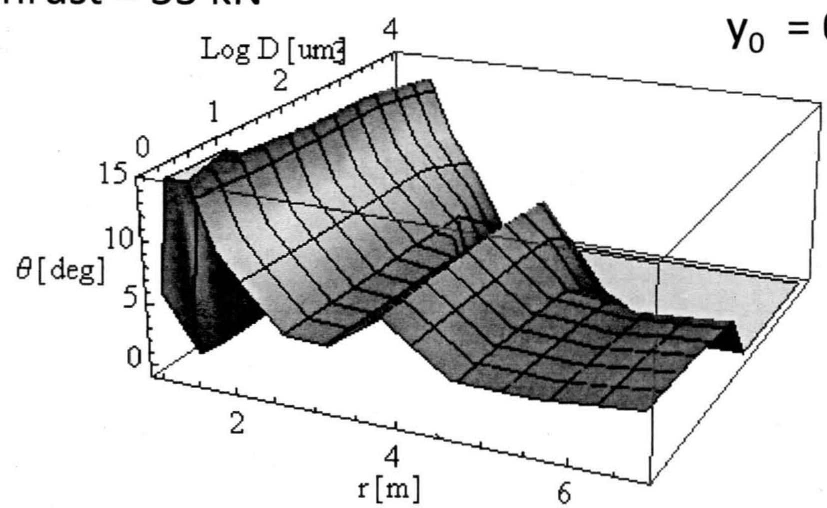
y_0 = 0.10 m   Thrust = 33 kN



CFD Case 1 (h = 20 ft)
y_0 = 0.10 m Thrust = 33 kN



CFD Case 7 (h = 10 ft)
y_0 = 0.10 m Thrust = 33 kN



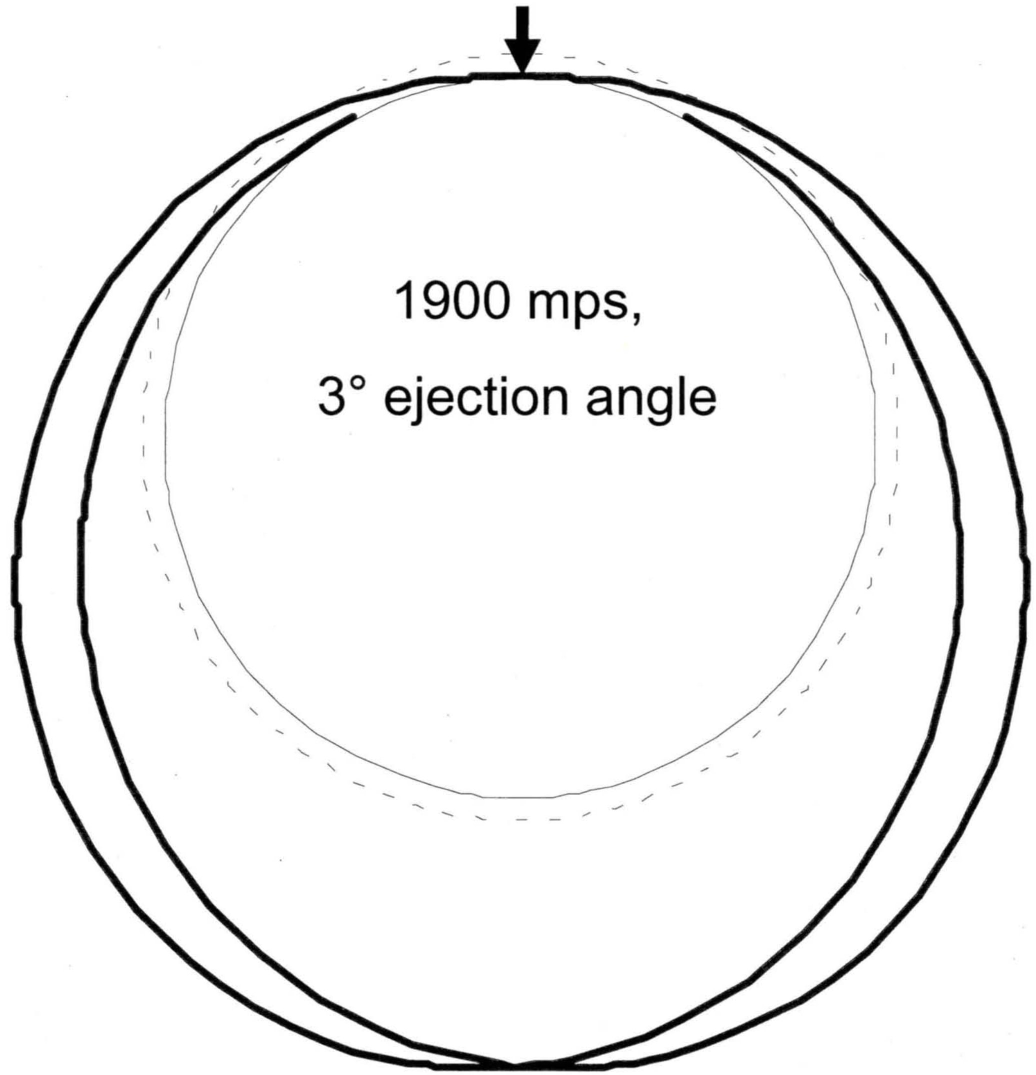
CFD Case 2 (h = 5 ft)
y_0 = 0.10 m Thrust = 33 kN

Rock Velocities

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

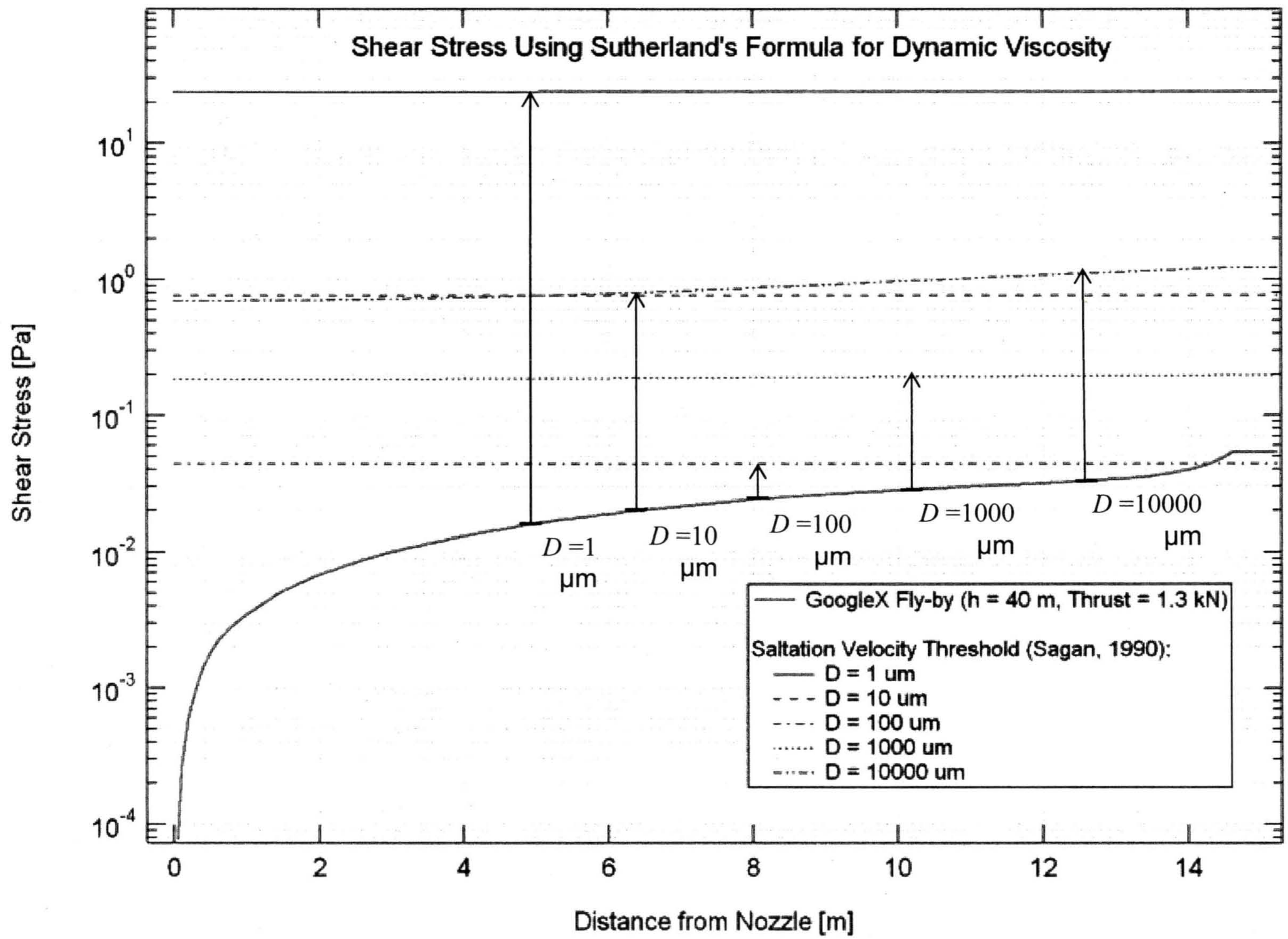
Trajectories of Lunar Plume Ejecta

- 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)



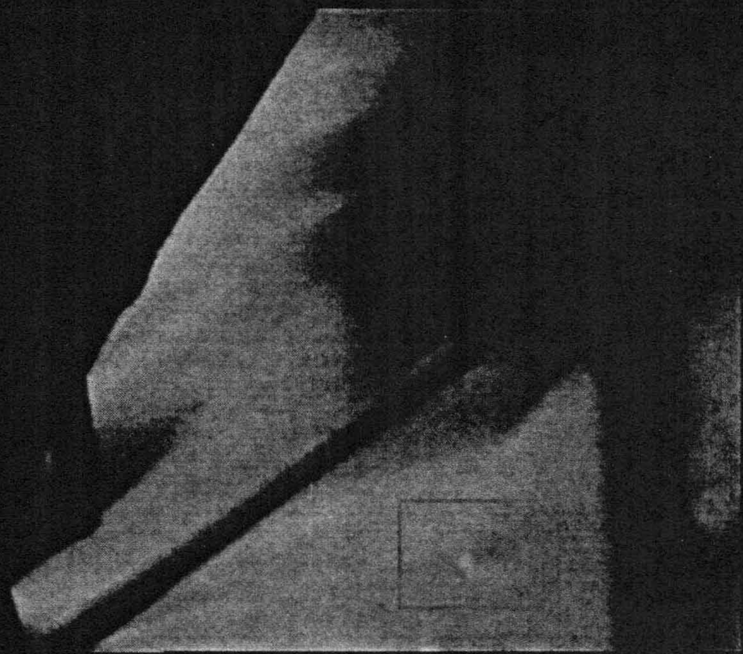
Height of Incipient Erosion

- Crew comments: typically it became visible at 24-30 m
- Thrust dependence implies it will start at lower altitudes for smaller vehicles
  - Must keep any particle size from blowing or saltation will cause all particle sizes to blow
  - Multi-engine effects have not been assessed
  - Pulsed-engine effects have not been assessed

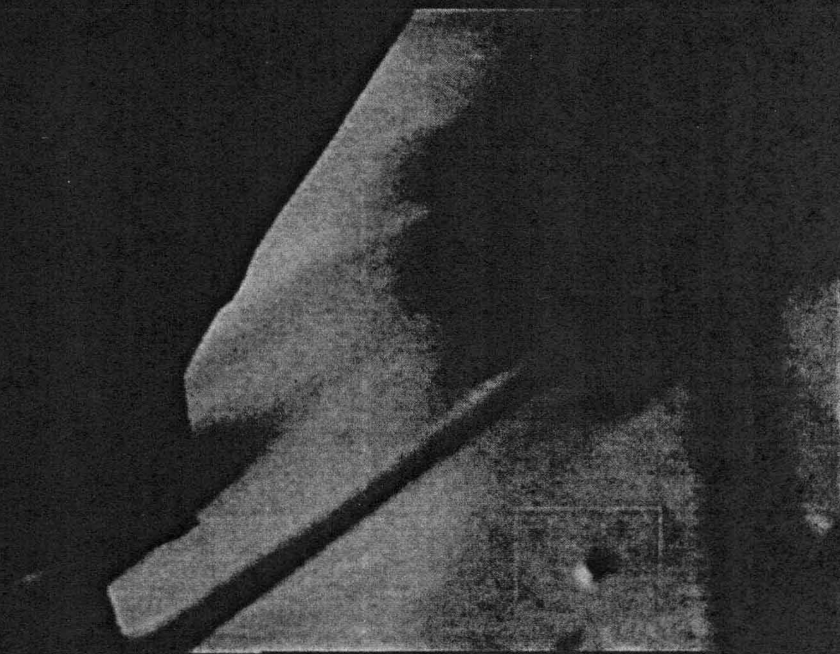


Below 40 m is a reasonable estimate for GLXP-class vehicles

Dust Loading (Optical Density) Calculation



Frame 1914

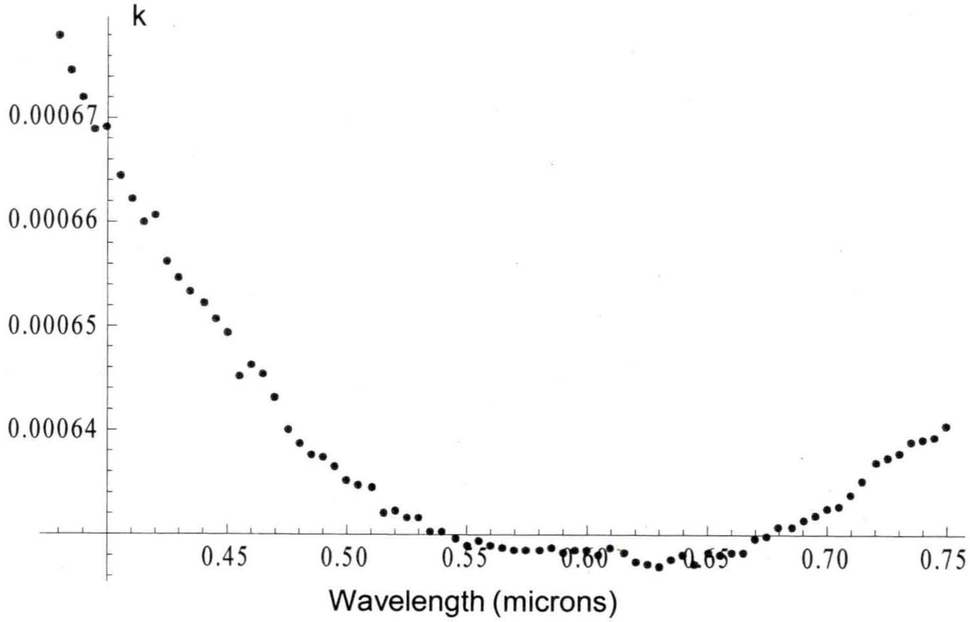


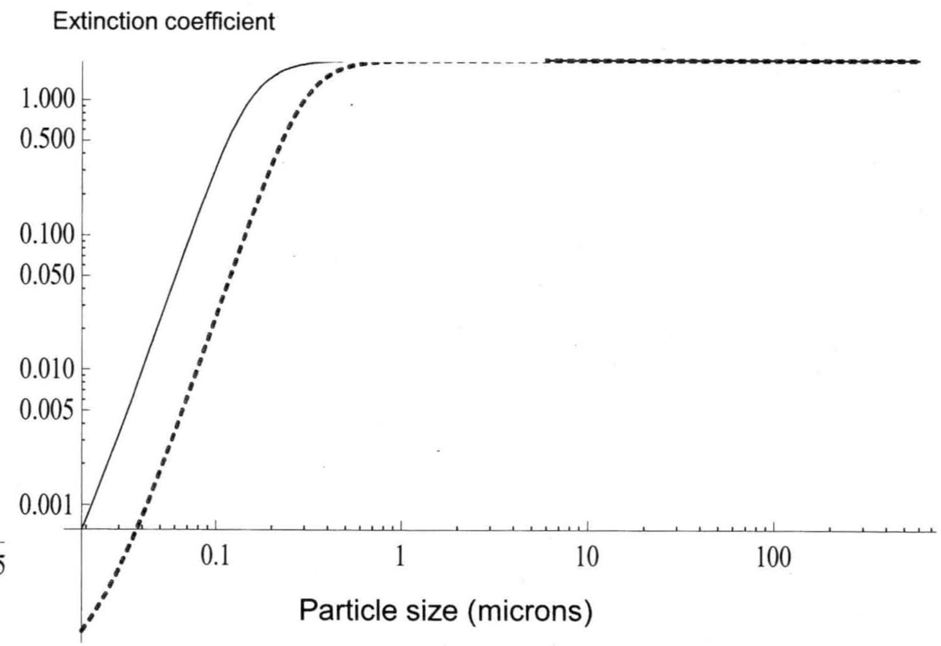
Frame 1915

Apollo 11

Optical Properties of Lunar Soil

$$C_E = \begin{cases} 4\alpha \,\mathrm{Im}\left[\dfrac{(n-ik(\lambda))^2-1}{((n-ik(\lambda))+2)^2}\right] + \dfrac{8}{3}\alpha^4 \,\mathrm{Re}\left[\dfrac{(n-ik(\lambda))^2-1}{((n-ik(\lambda))+2)^2}\right] & , \quad \alpha \text{ small} \\ 2 & , \quad \alpha \text{ big} \end{cases}$$





Courtesy Paul Lecy (U. Hawaii-Manoa)

Dust Optical Path

Known parameters:

ϕ, camera angle
h, altitude of camera
θ, dust ejection angle
ψ, sun angle

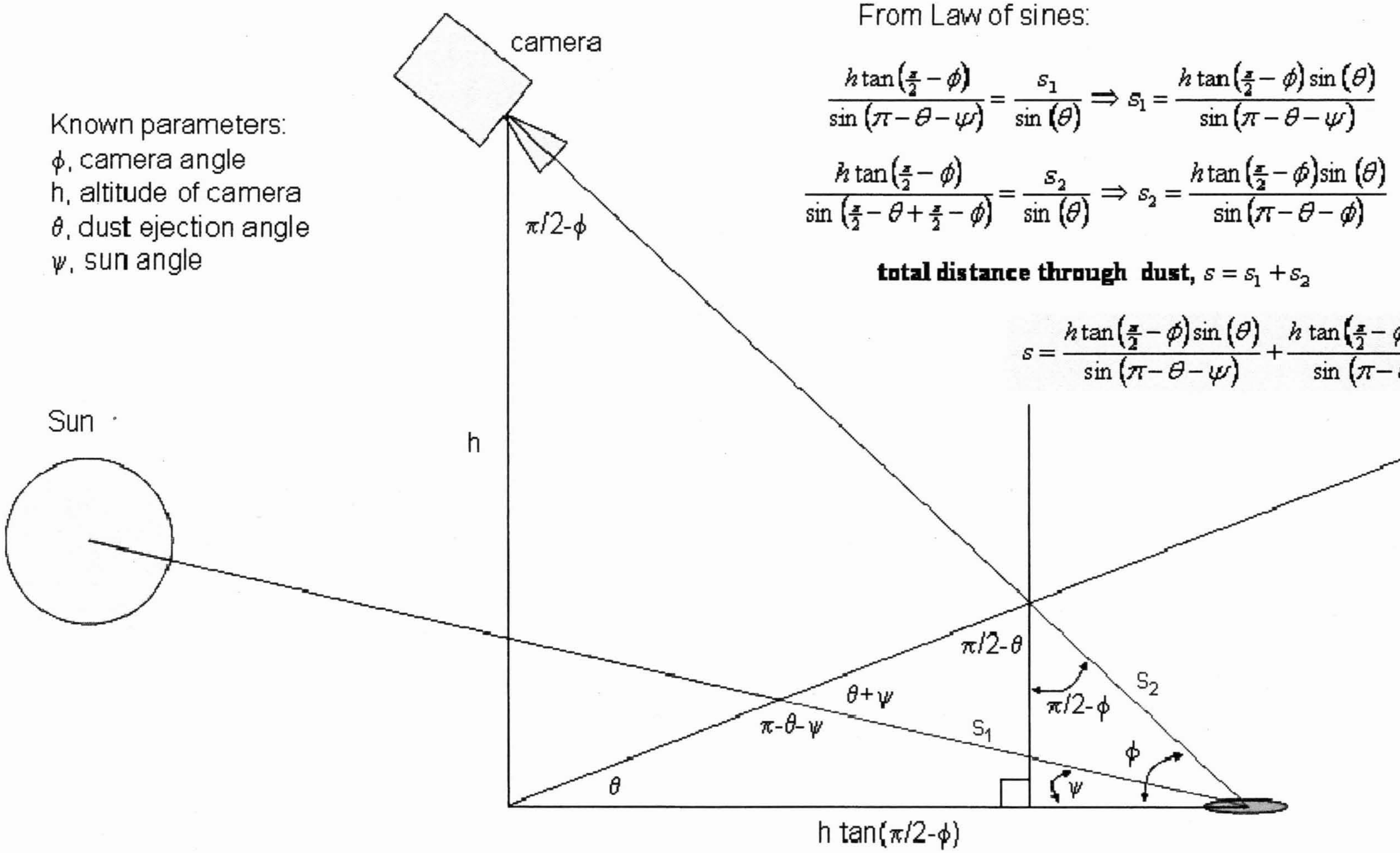
From Law of sines:

$$\frac{h\tan\left(\frac{\pi}{2}-\phi\right)}{\sin\left(\pi-\theta-\psi\right)}=\frac{s_1}{\sin\left(\theta\right)}\Rightarrow s_1=\frac{h\tan\left(\frac{\pi}{2}-\phi\right)\sin\left(\theta\right)}{\sin\left(\pi-\theta-\psi\right)}$$

$$\frac{h\tan\left(\frac{\pi}{2}-\phi\right)}{\sin\left(\frac{\pi}{2}-\theta+\frac{\pi}{2}-\phi\right)}=\frac{s_2}{\sin\left(\theta\right)}\Rightarrow s_2=\frac{h\tan\left(\frac{\pi}{2}-\phi\right)\sin\left(\theta\right)}{\sin\left(\pi-\theta-\phi\right)}$$

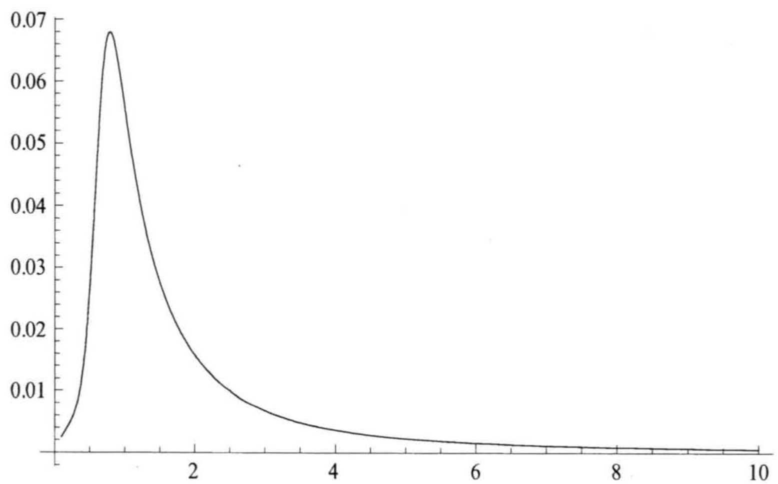
total distance through dust, $s=s_1+s_2$

$$s=\frac{h\tan\left(\frac{\pi}{2}-\phi\right)\sin\left(\theta\right)}{\sin\left(\pi-\theta-\psi\right)}+\frac{h\tan\left(\frac{\pi}{2}-\phi\right)\sin\left(\theta\right)}{\sin\left(\pi-\theta-\phi\right)}$$

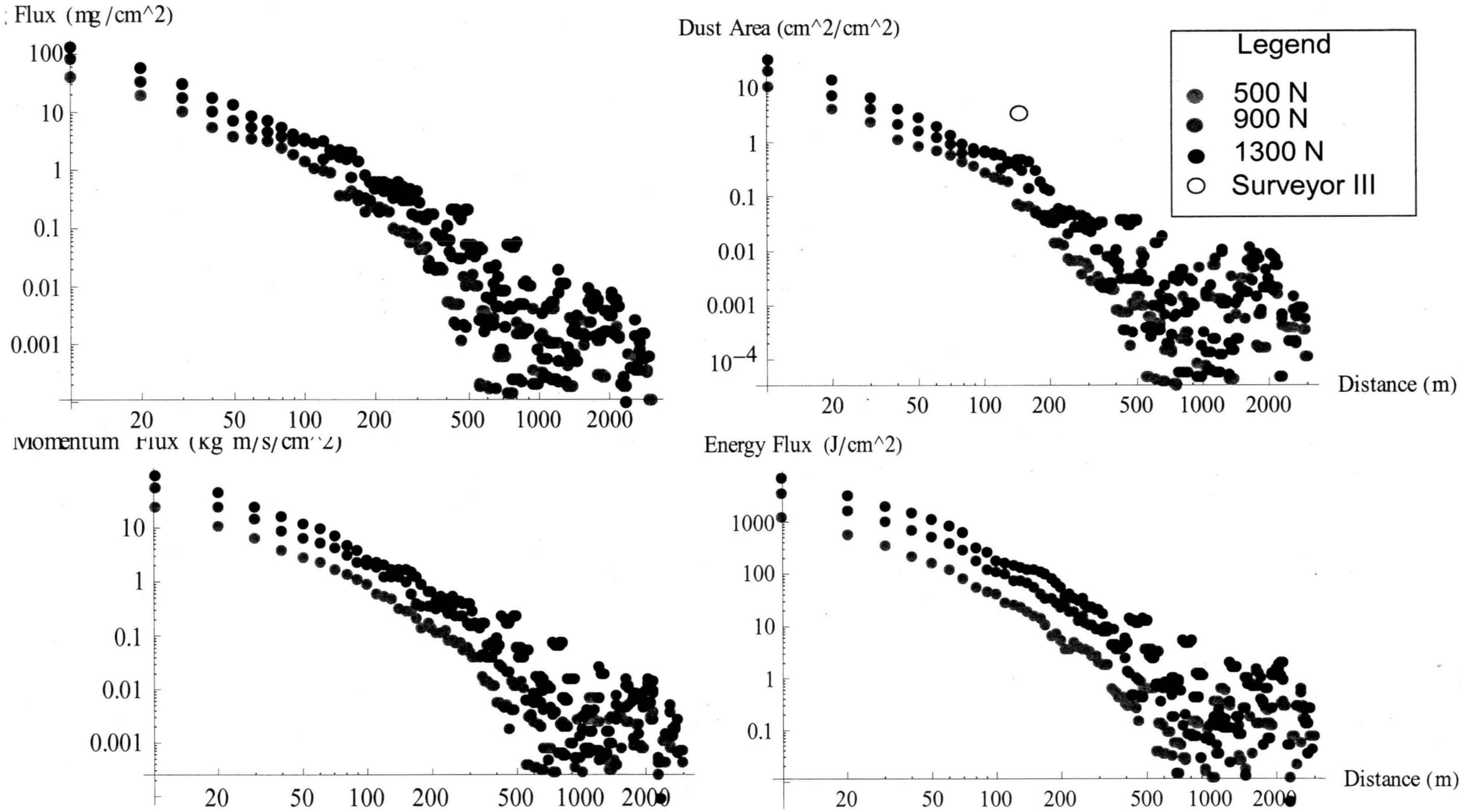


Total Eroded Soil

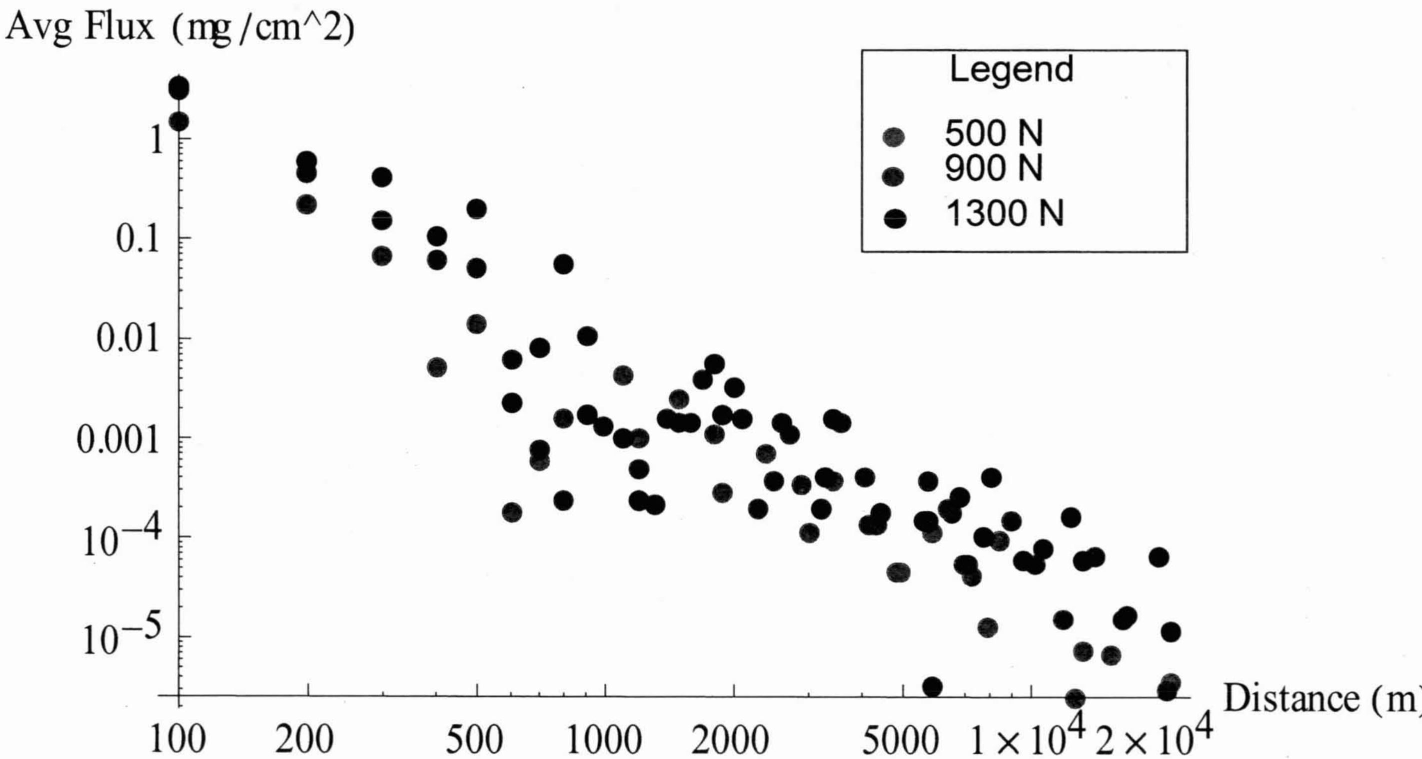
- Integrating optical density measurement of the flux over time and space:
  - Most likely 2 to 8 MT were eroded
- Terrain under LM indicates about 1 MT (order of magnitude) was eroded



GLXP-Sized Landers



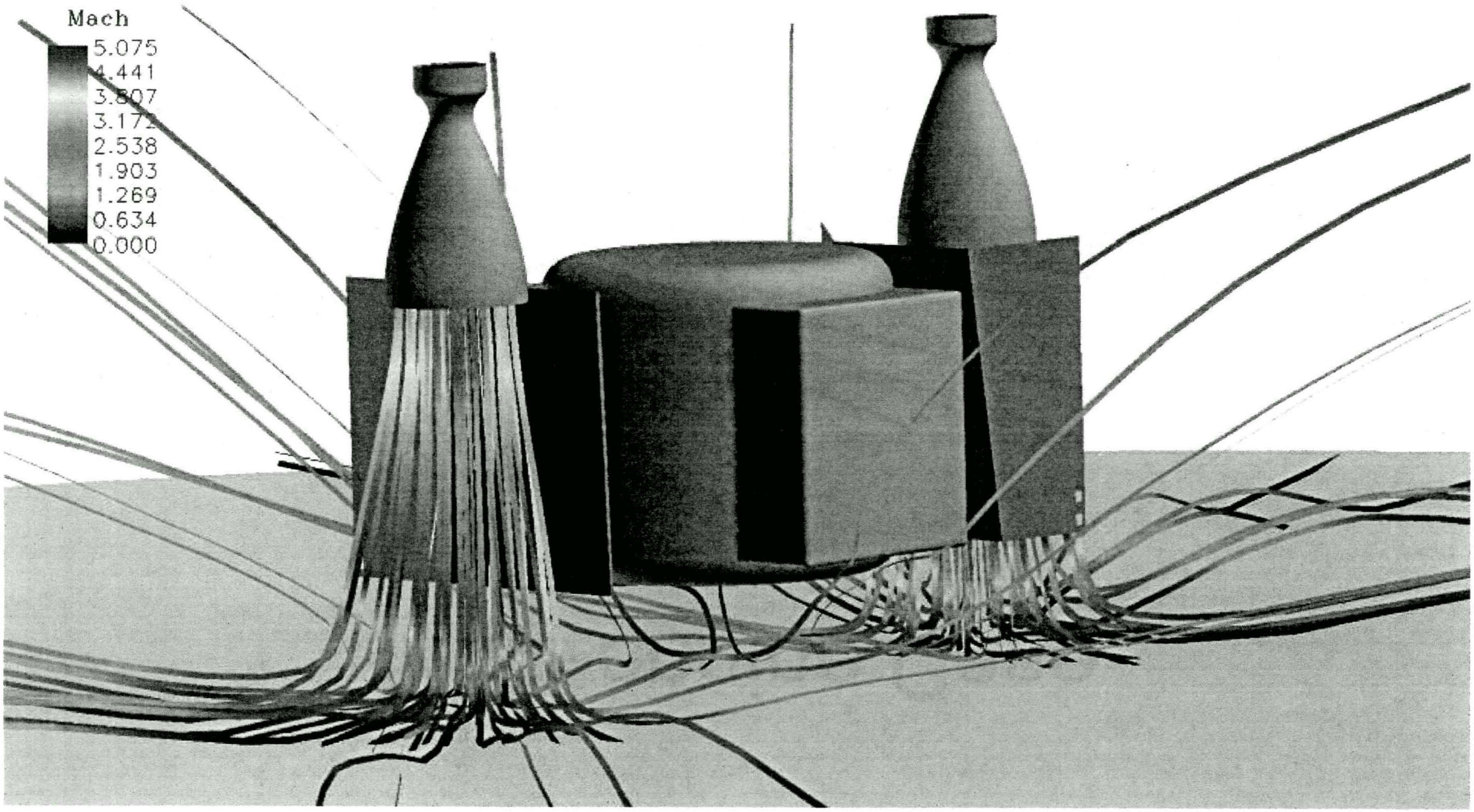
Tail-Off Continues >20 km



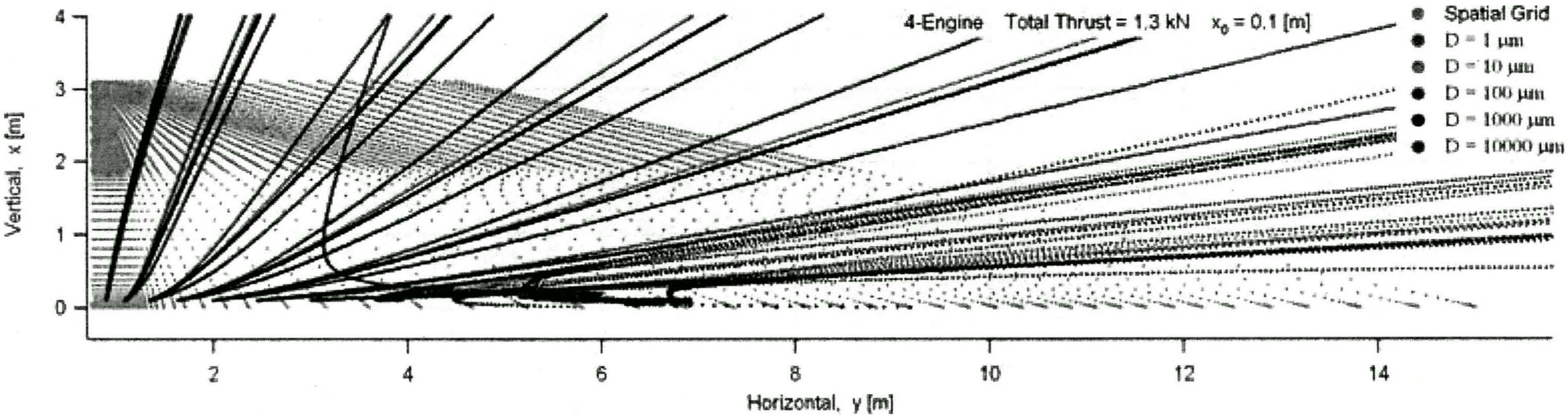
What is missing in this analysis?

- *Very crude estimate* of about 2 tons for LM
- Depends on the environment heavily
  - Turbulent Kinetic Energy not "usual" due to rarefaction of plume
  - Lunar soil and gravity
  - Soil cohesion not well understood
  - No instrument has ever measured this in the correct environment
- Our estimate depends on particle velocities and comes from few optical density data points
- We know how to improve this, but need funds

Multi-engine effects



Multi-engine Case



Shock Effects

- Shock impingement due to engine ignition
- Relevance: “Hopper” spacecraft and engines that throttle via pulsing
- Creates higher stress on soil
  - Higher erosion rate
  - Possible “splash” effects
  - Possible higher ejection angles
- Expected to cause worse damage to surrounding hardware

Summary of Modeling

- Focused research for a decade has presented a compelling picture of the *main* physics of lunar plume effects
  - Variety of data sources in substantial agreement regarding the orders-of-magnitude
- These effects are more severe than we previously realized
  - Terrestrial "common sense" does not expect the extreme sandblasting of dust in vacuum
  - Surveyor III under-represents the effects, since it was in a crater beneath the spray
  - Prior literature from the Apollo-era uses pre-computer methods that we now know are not accurate; do not use those methods or equations
- The basic understanding is adequate *for now* to protect historic sites
- Much more research is needed to
  - Quantify the physics
  - Develop physics-based computer models to predict the effects
  - This is high value research to support future spaceflight objectives

Guidelines for Landing on the Moon

Landing Distance

- Land 2 km away on a tangential approach path

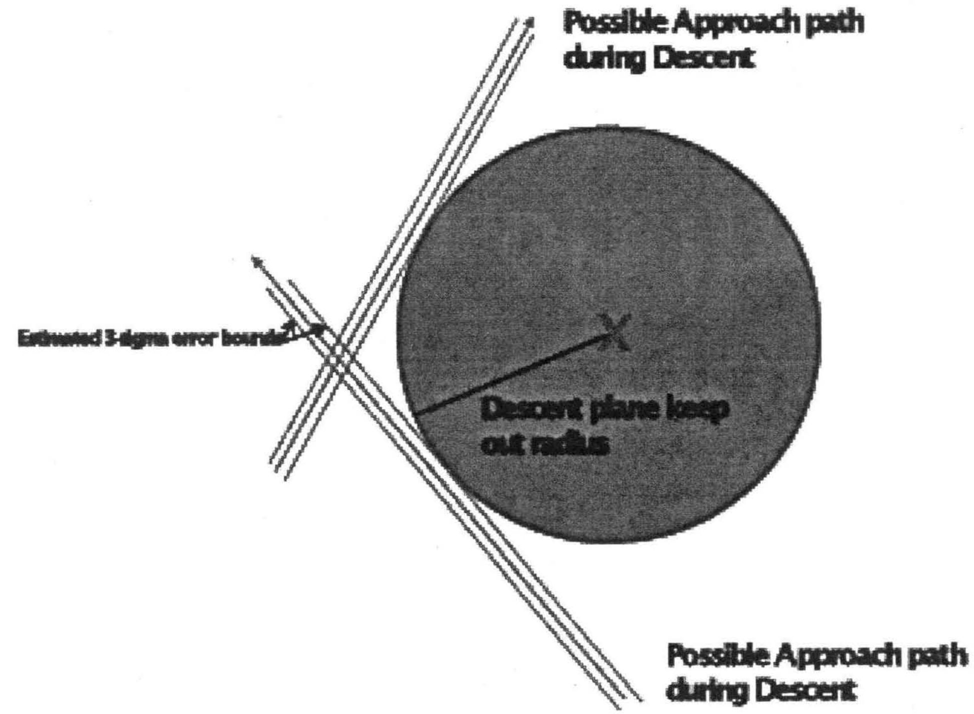


Figure 1: Possible Approach Path Scenarios

Lander Orientation

- Keep plume reflection planes pointed away from the artifacts, since enhance erosion rates and higher ejecta angles occur on those planes

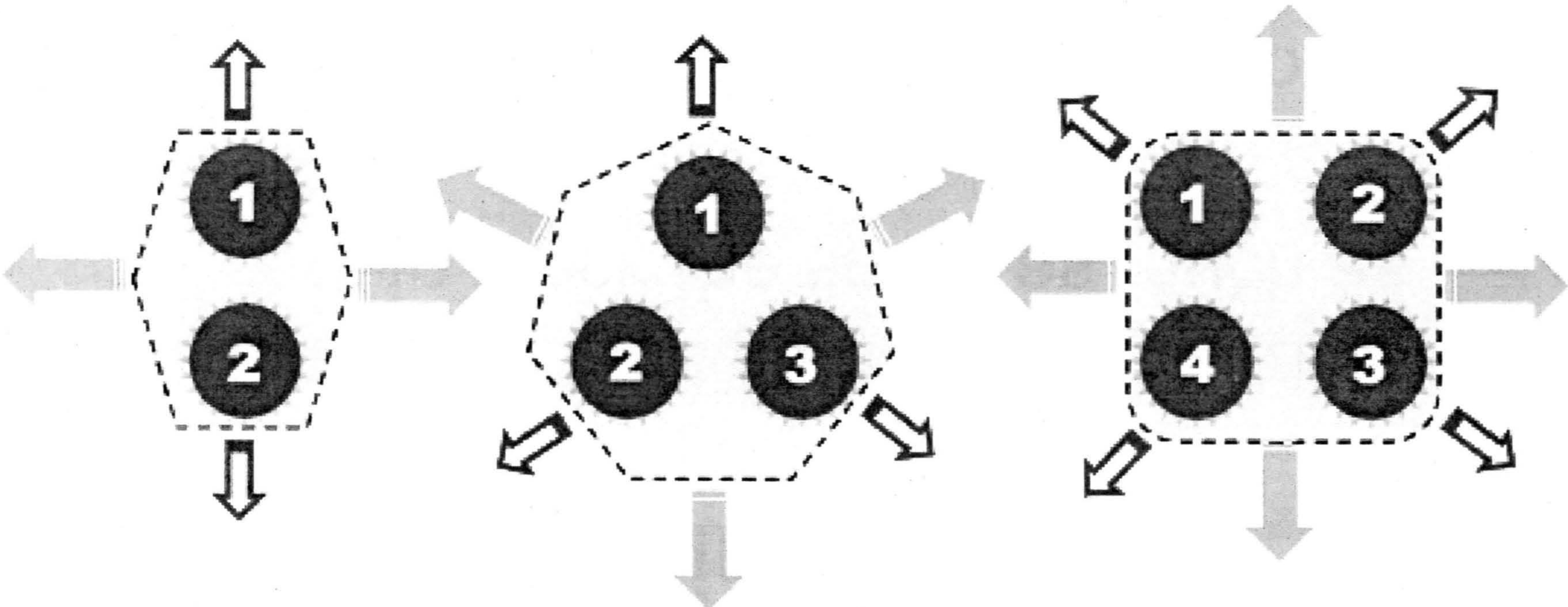


Figure 3: Diagram of multiple engine spacecraft ejecta paths – orange (solid) arrow denotes direction of maximum ejecta flux 'rooster tail' along plume reflection planes. Open (green) arrow identifies direction of minimum ejecta flux.

Terrain Barriers

- Recommend landing behind natural terrain barriers to block the spray as much as possible
- 2 km distance reduces but does not eliminate damage
- Damage is cumulative with each visiting spacecraft
- Terrain barriers are for ALARA principle
  - As Low As Reasonably Achievable

Low Altitude Flyby

- Hoppers translating within 2 km should remain higher than 40 m
  - Ensure no dust motion
- Hoppers never get within a 45 degree cone of artifact boundary
  - Ensure no propellant droplets deposited on artifacts

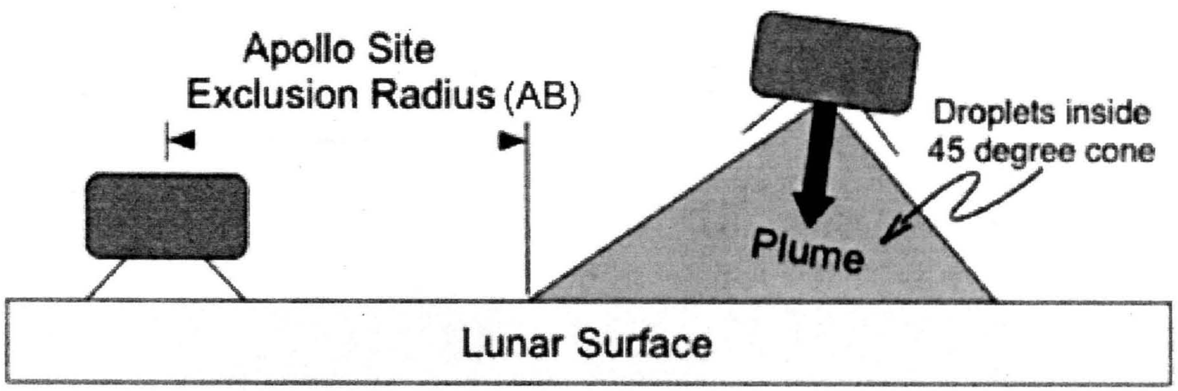


Figure 8: Illustration of plume droplet cone.

COLA Windows

- Collision Avoidance (COLA) Windows should be assessed to protect orbiting spacecraft, too
- Ejecta travels higher than orbital altitudes
- Impact velocities will be relative to spacecraft motion, putting it into the hypervelocity impact regime
- Can expect multiple impacts if spacecraft is at trajectory node same time as ejecta

Other Recommendations

- Other recommendations (not addressed here) include
  - Rover keepout zones, varying for each site
  - Linear wheel speed of rovers
  - Use direct approach and backtrack to avoid excessive disturbance of soil

Forward Work

Forward Work

- Particle Impact Tests at WSTF
- Run models on ARC supercomputers for a wider variety of conditions and with higher fidelity
- Coordinate data collection of a GLXP lander with LADEE observations
- Place a look-down sensor on a GLXP lander, preferrably during the LADEE mission
- Use above results to improve models
- Reassess guidelines and update

Questions?