EFFECTS OF SPACECRAFT LANDINGS ON THE MOON

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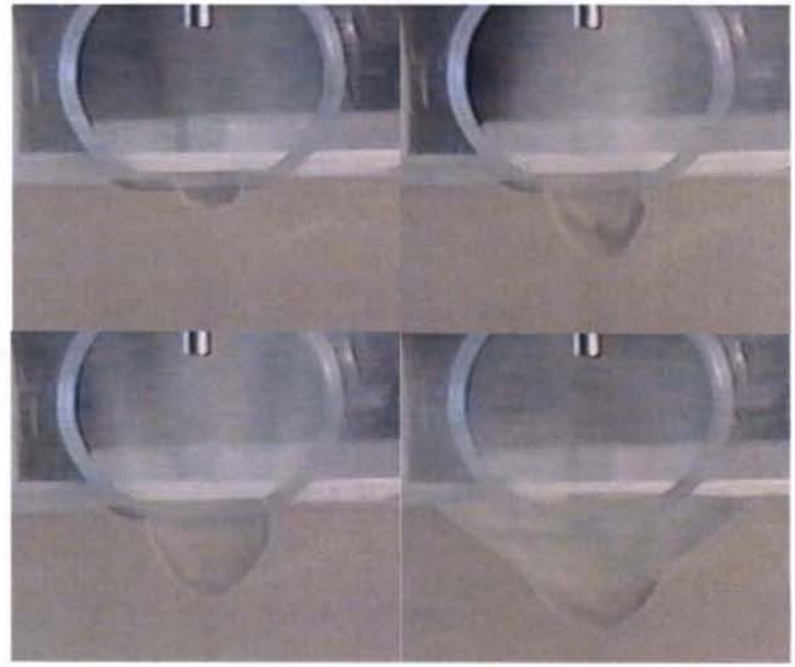
Introduction

- The rocket exhaust of spacecraft landing on the Moon causes a number of observable effects that need to be quantified, including: disturbance of the regolith and volatiles at the landing site; damage to surrounding hardware such as the historic Apollo sites through the impingement of high-velocity ejecta; and levitation of dust after engine cutoff through as-yet unconfirmed mechanisms. While often harmful, these effects also beneficially provide insight into lunar geology and physics. Some of the research results from the past 10 years is summarized and reviewed here.

- The erosion rate of lunar soil beneath a supersonic, rarefied rocket exhaust plume in lunar gravity is difficult to predict. It occurs in a spatially limited annulus that prevents saturated transport via saltation, the case most-studied for sedimentary geology.

Unsaturated Erosion Scaling Experiments

- Experiments to determine the scaling relationships for unsaturated erosion
  - Small scale, subsonic jet/soil erosion experiments in the lab
  - Similar experiments in reduced gravity aircraft
  - Similar experiments in large vacuum chambers
  - Supersonic erosion experiments in large vacuum chambers
  - Sandblasting experiments with a hypersonic gun for comparision with Surveyor III impingement damage
  - Field tests in a relevant geological setting on Mauna Kea
  - Lunar simulant optical density experiments for comparison with Apollo landing videos



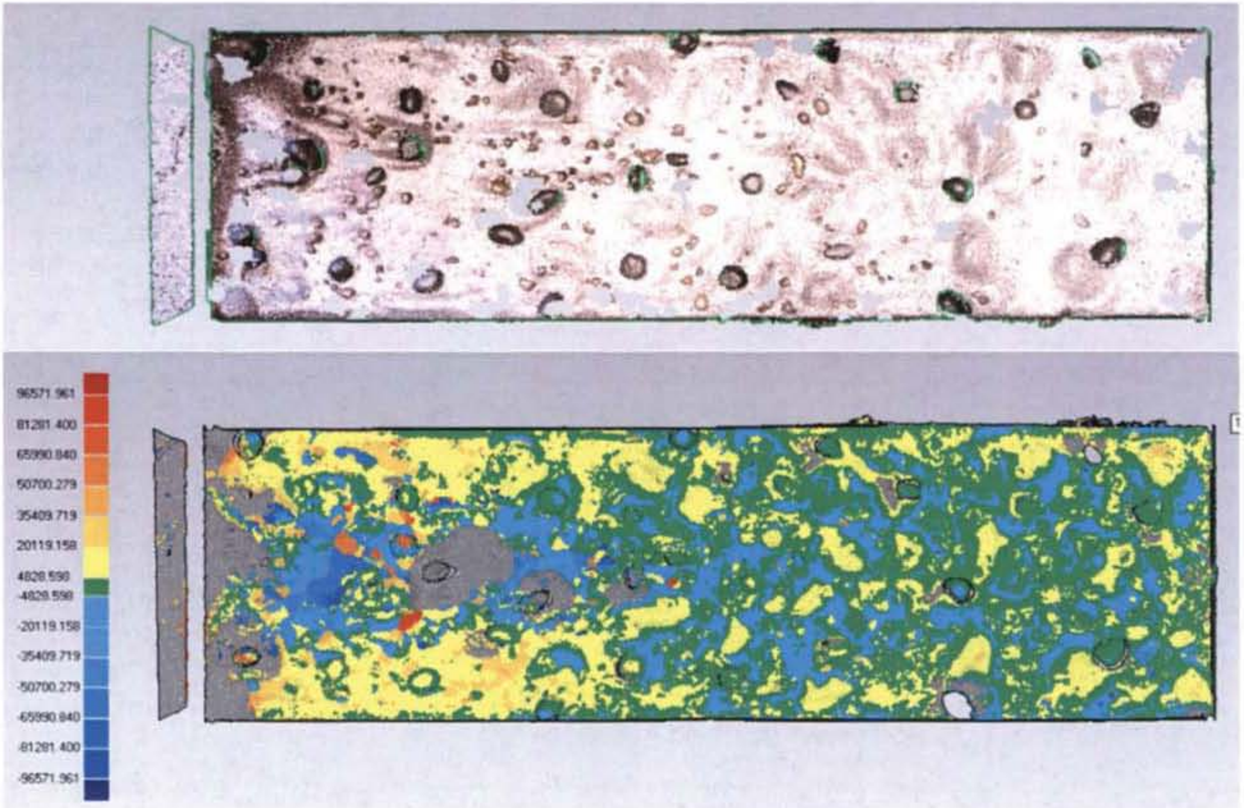
Subsonic experiments indicate unsaturated erosion scales with momentum flux, not energy flux, and as $1/(\rho D)$ where ρ is mineral density and D is average particle diameter of the soil .

- Reduced gravity experiments indicate 1/g scaling for unsaturated erosion

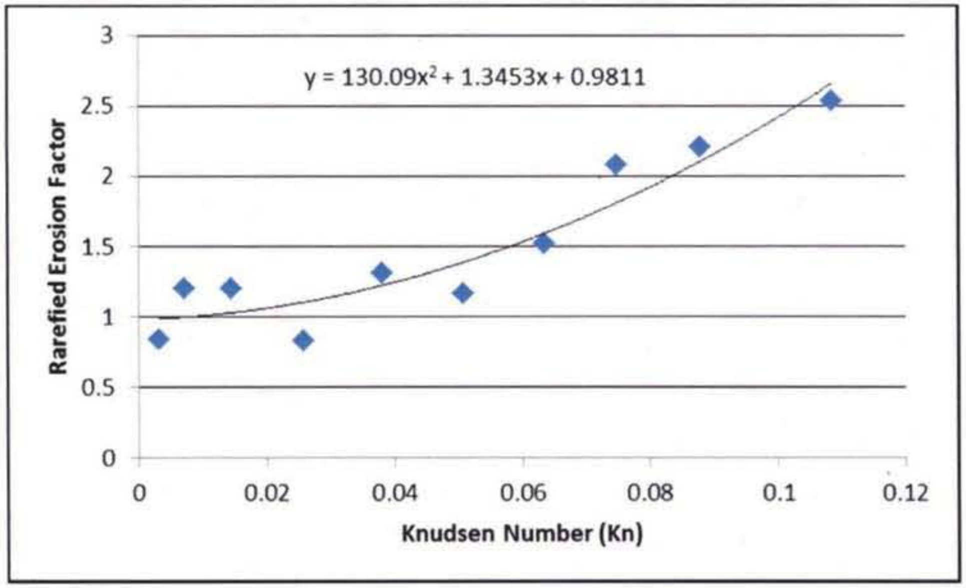
- Subsonic, rarefied erosion tests at Planetary Aeolian Lab to test dependence on Knudsen number

- Supersonic, rarefied jet flow across lunar soil simulant at Planetary Aeolian Lab to test erosion scaling with Reynolds and Knudsen numbers

- Eroded JSC-1A lunar soil simulant from supersonic, rarefied jet flow test



- Top: laser scan of eroded surface (containing rocks and gravel)
- Bottom: difference map showing how height of soil has changed before versus after erosion



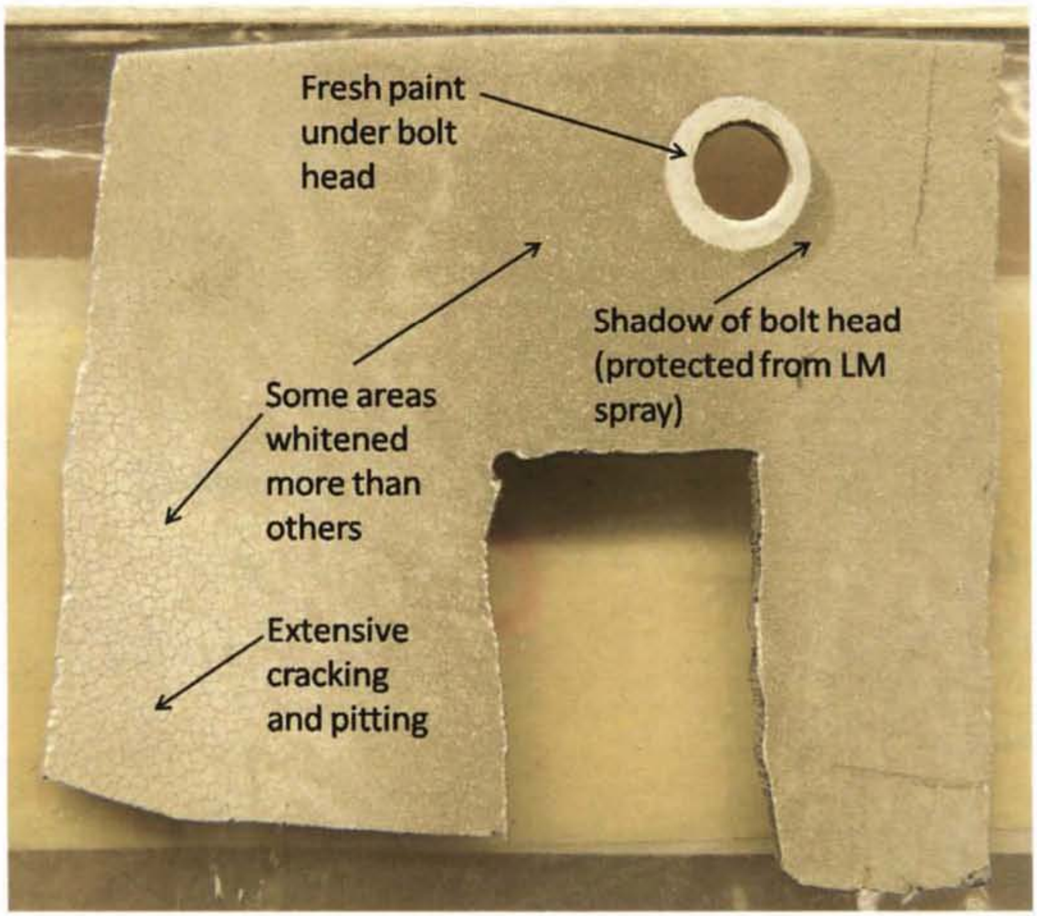
- Dependence of erosion rate of Knudsen number. Erosion rate increases above continuum predictions when flow is rarefied.
- Experiments in continuum regime obtained this equation for erosion rate ($kg/m^2/s$), where τ is shear stress of the gas and U is a constant of unknown physical meaning having the units of velocity.

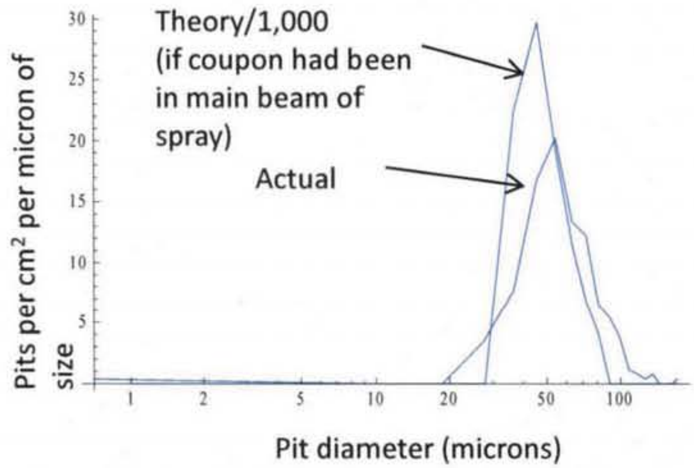
$$\dot{m} = U \frac{\rho \tau}{\rho g D + c}$$

- In the rarefied regime, the erosion rate is multipled by this function of Knudsen number Kn

$$f_R = 130\,\mathrm{Kn}^2 + 1.35\,\mathrm{Kn} + 0.97$$

- Most collisions between ejecta particle should be spatially limited to near the annulus of erosion. Analysis of Surveyor III coupons agrees with that, since flux impinging on Surveyor consisted of only the scattered particles and yet the shadows they cast had no observable penumbra implying the surface of last scattering was small and hence far away.

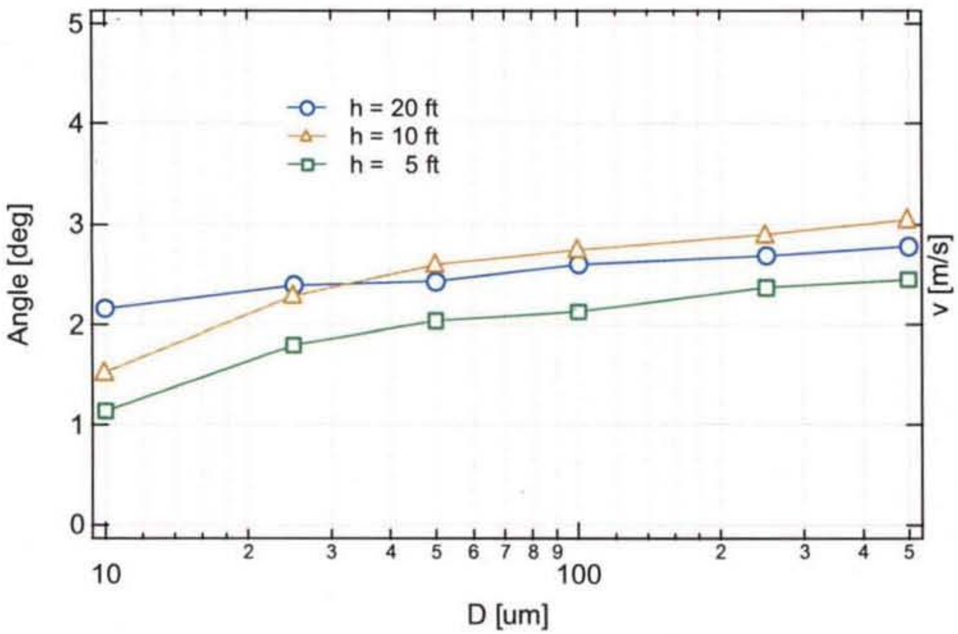




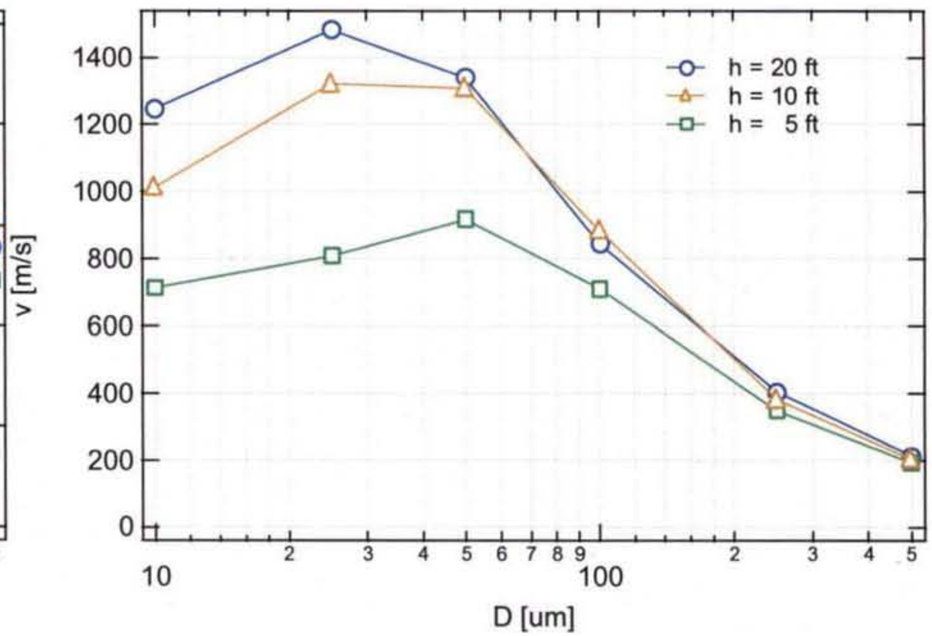
- Hence, modeling that starts particles just beyond the region of collisions should provide a first-order approximation to the trajectories of the main sheet of ejecta.

- Surveyor III coupon

Estimated Dust Ejection Speed and Angle from Ballistics Simulations

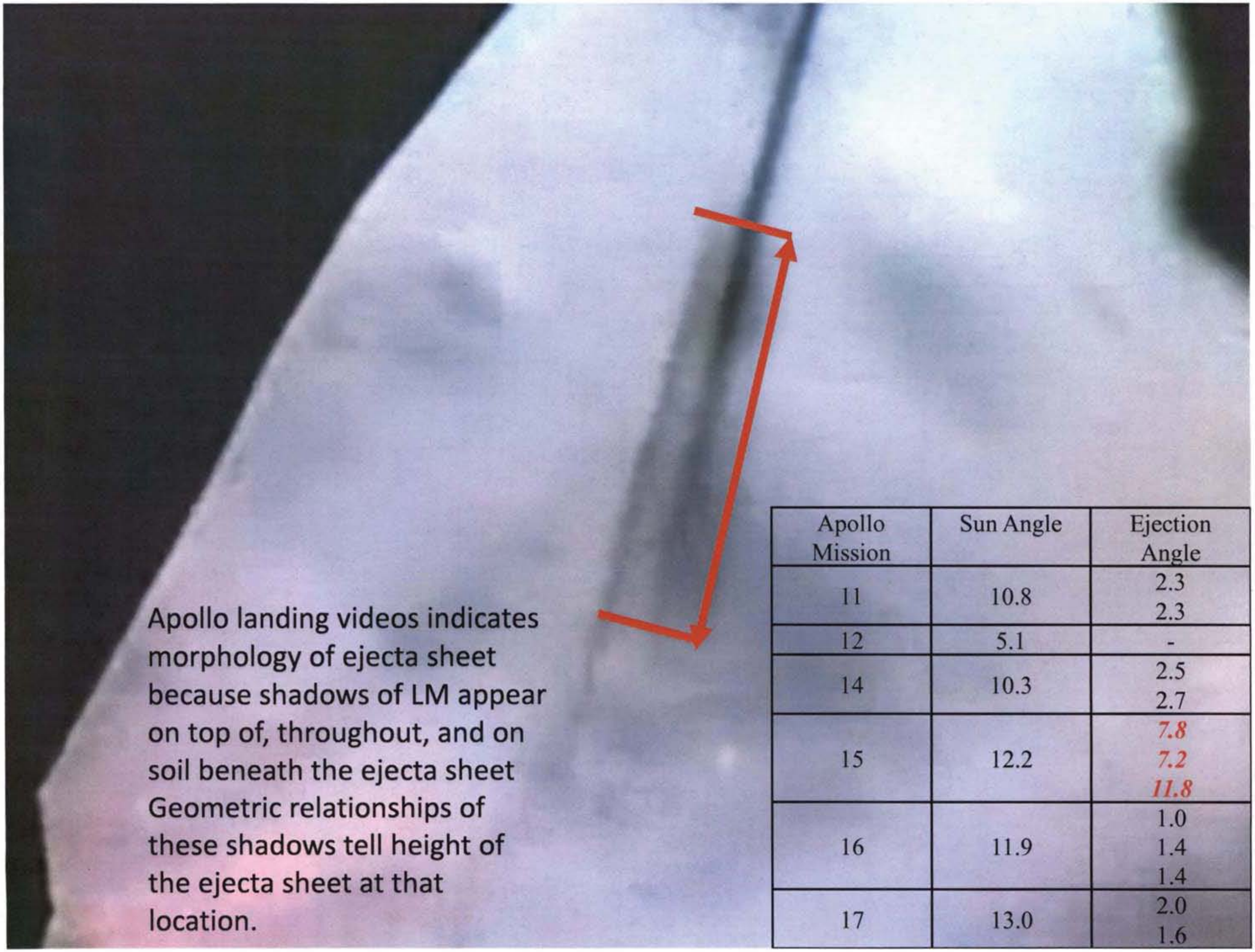


Particle trajectory angles relative to ground for various particle sizes and CFD cases.



Particle speeds exiting the CFD model boundary.

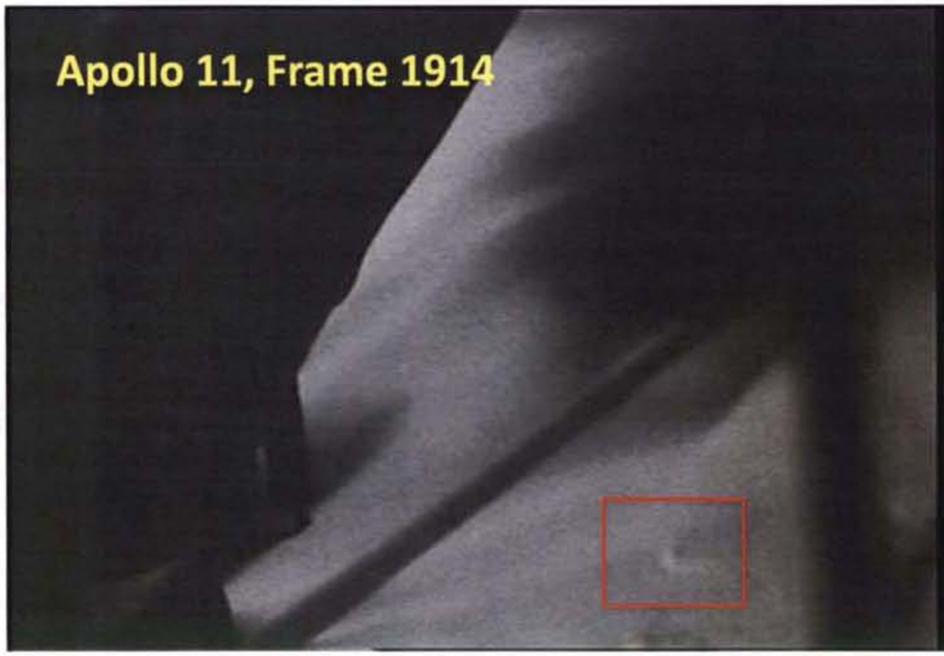
Predicted speeds are highly dependent on a number of parameters that are not yet well understood

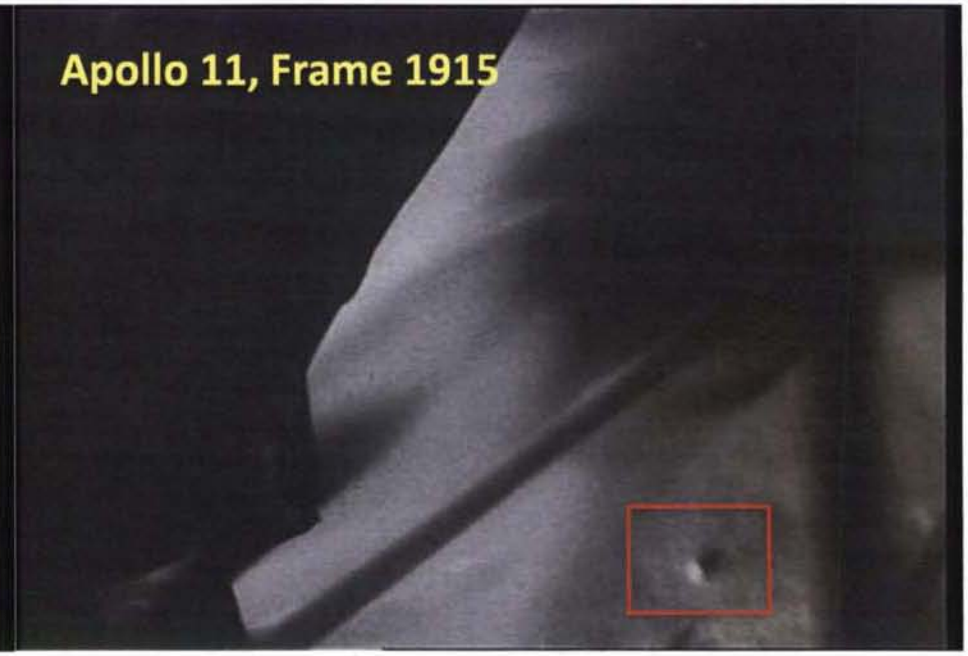


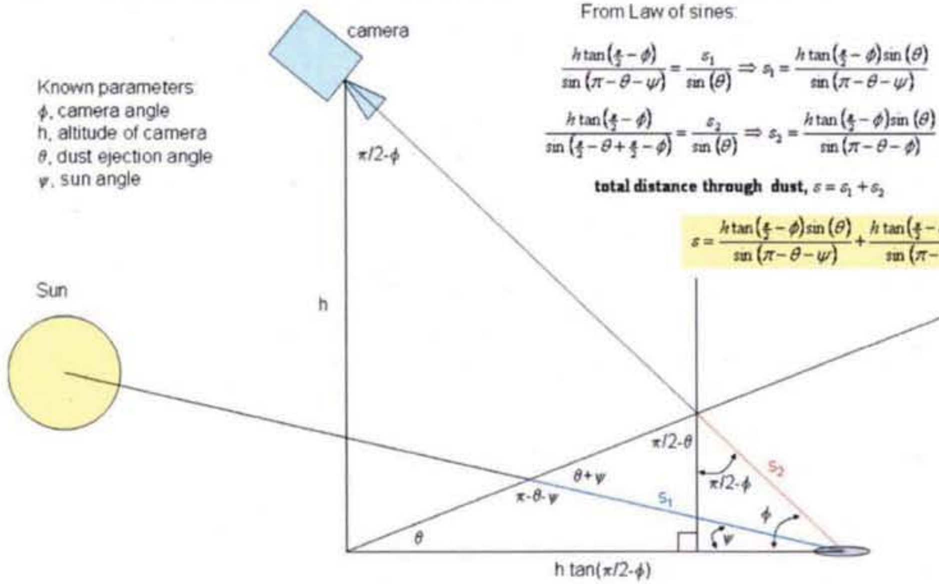
Apollo landing videos indicates morphology of ejecta sheet because shadows of LM appear on top of, throughout, and on soil beneath the ejecta sheet Geometric relationships of these shadows tell height of the ejecta sheet at that location.

Apollo Mission	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 Loading (Optical Density) Calculation







From Law of sines:

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

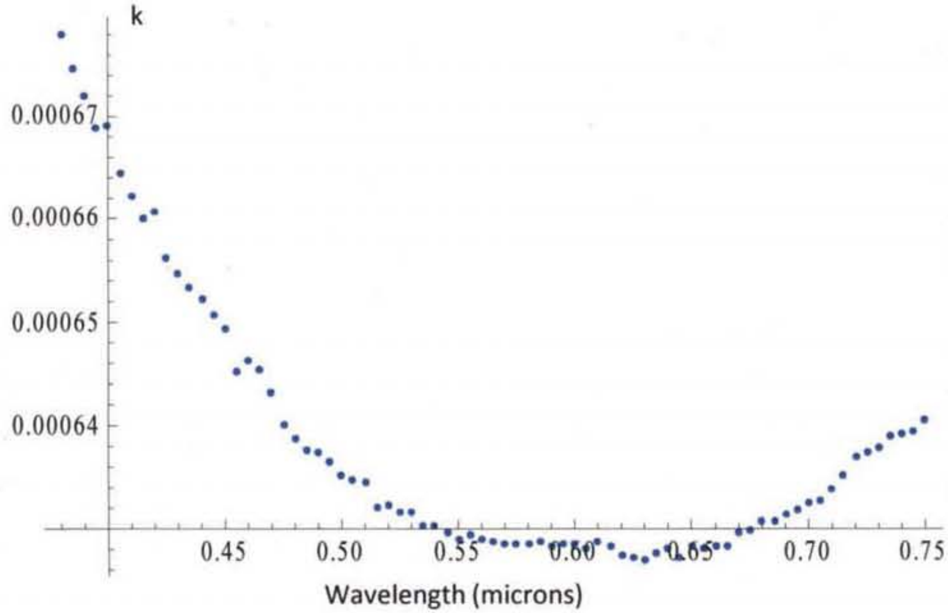
$$\frac{h\tan\left(\frac{\pi}{2}-\phi\right)}{\sin\left(\frac{\pi}{2}-\theta+\frac{\pi}{2}-\phi\right)}=\frac{s_2}{\sin\left(\theta\right)}\Rightarrow s_2=\frac{h\tan\left(\frac{\pi}{2}-\phi\right)\sin\left(\theta\right)}{\sin\left(\pi-\theta-\phi\right)}$$

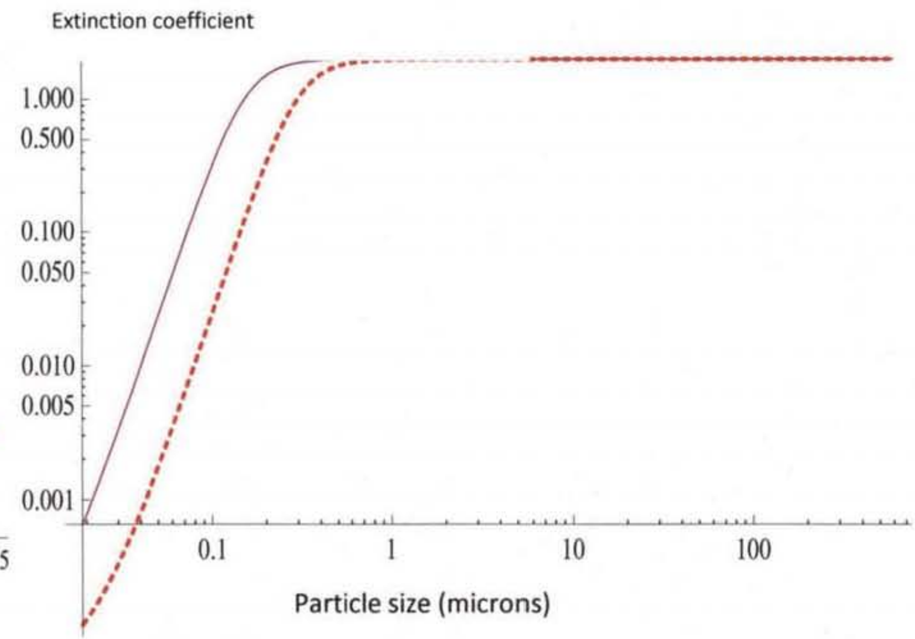
total distance through dust, $s=s_1+s_2$

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

Optical Properties of Lunar Soil

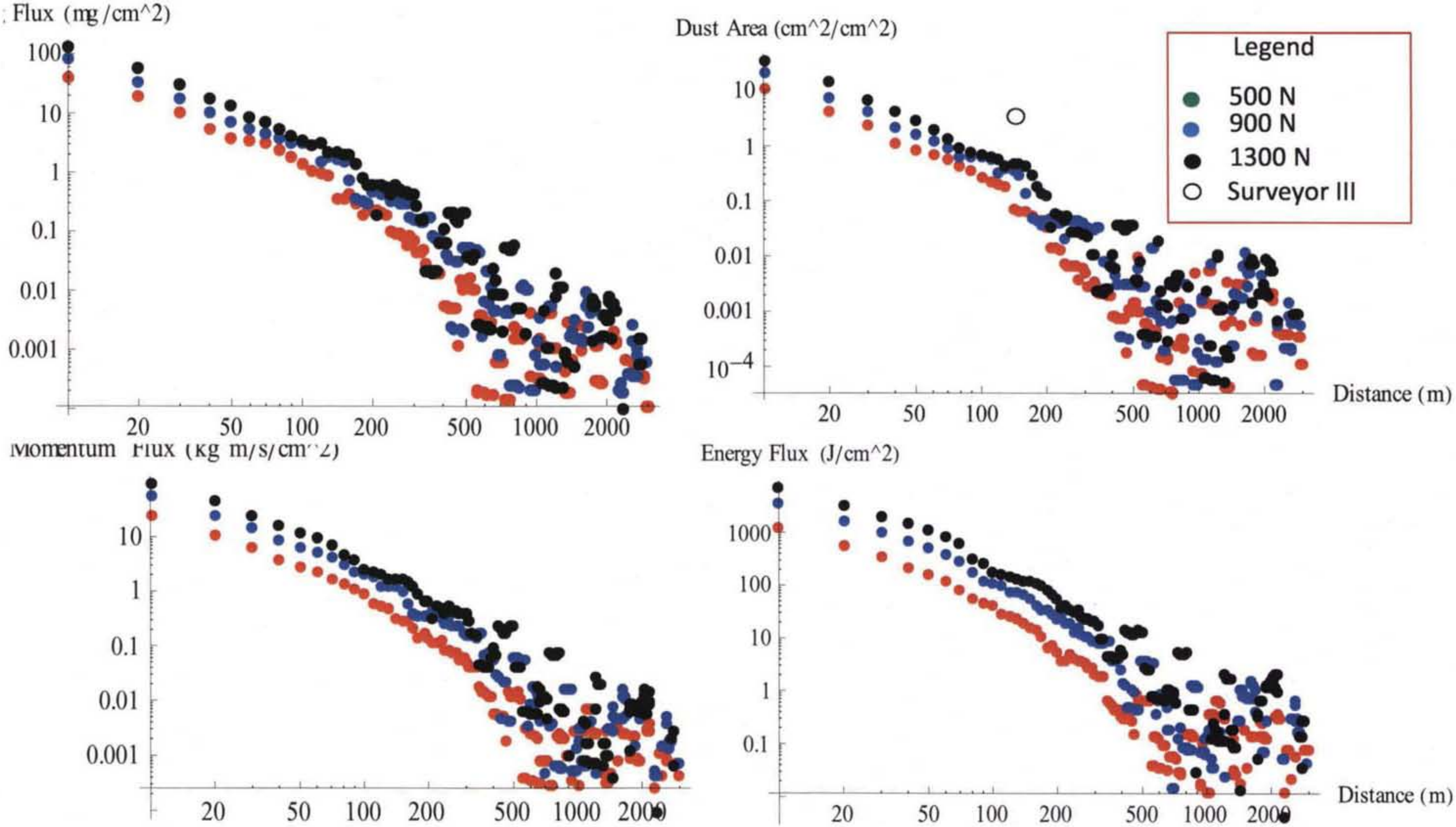
$$C_E = \begin{cases} 4\alpha \,\mathrm{Im}\left[\dfrac{(n-ik(\lambda))^2-1}{((n-ik(\lambda))+2)^2}\right]+\dfrac{8}{3}\alpha^4\,\mathrm{Re}\left[\dfrac{(n-ik(\lambda))^2-1}{((n-ik(\lambda))+2)^2}\right] & , \quad \alpha \text{ small} \\ 2 & , \quad \alpha \text{ big} \end{cases}$$





Courtesy Paul Lecy (U. Hawaii-Manoa)

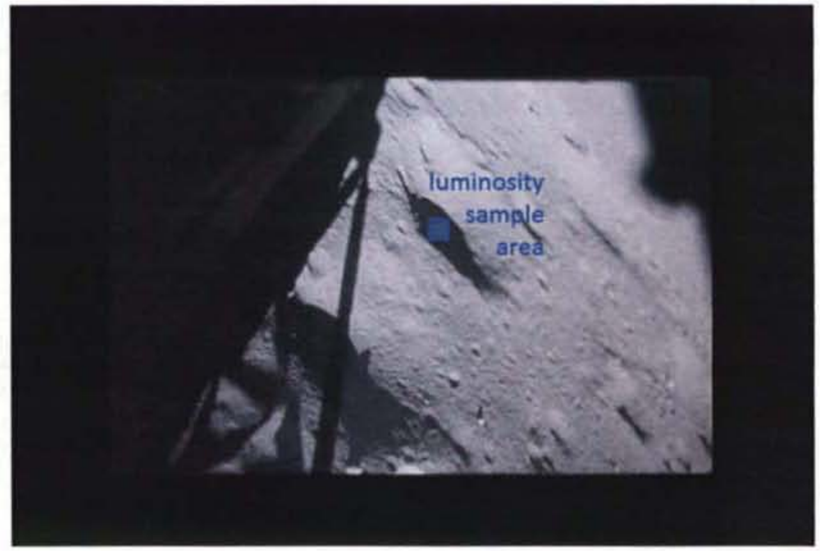
GLXP-Sized Landers



Dust Lofting long after plume is gone

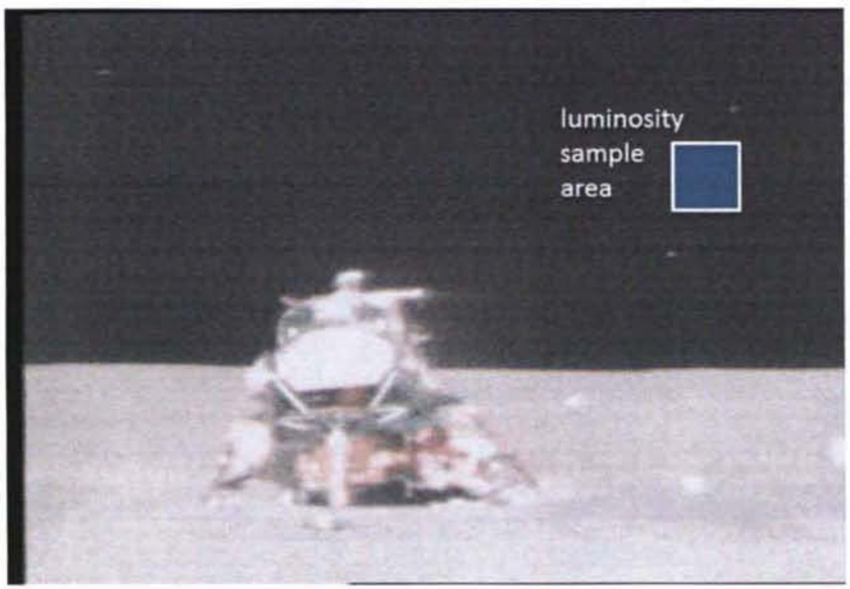
Apollo 15: Descent

Apollo 15: Descent

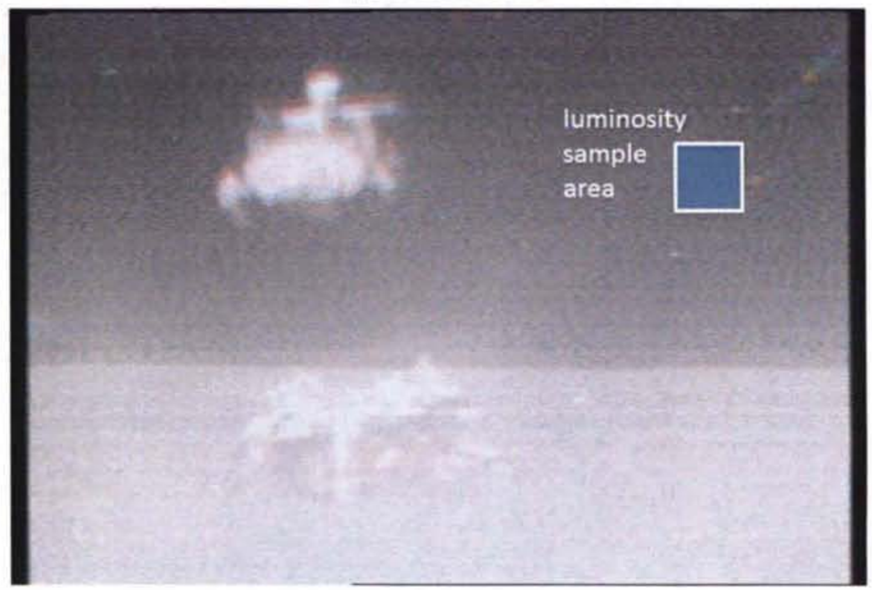


View from Apollo 15 after engine cutoff. (Left) Immediately after engine cutoff. (Right) Long time (>30 sec) after engine cutoff.

Apollo 15: Ascent

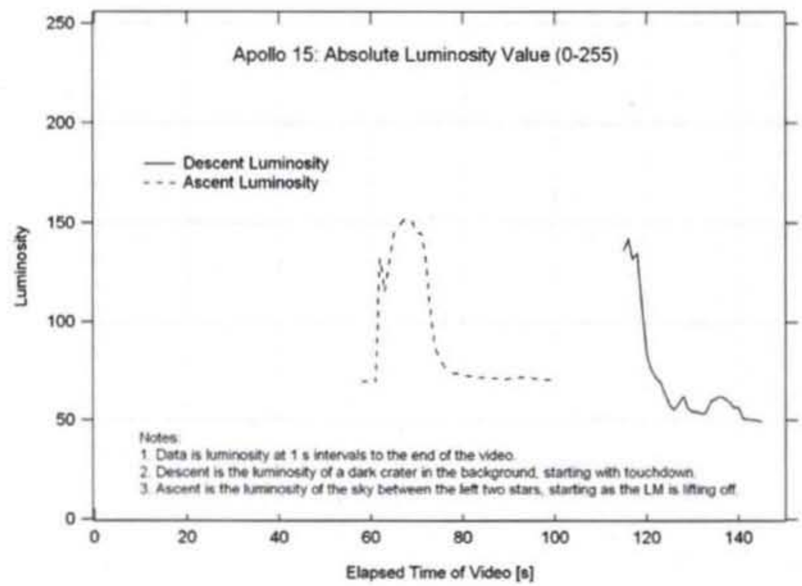


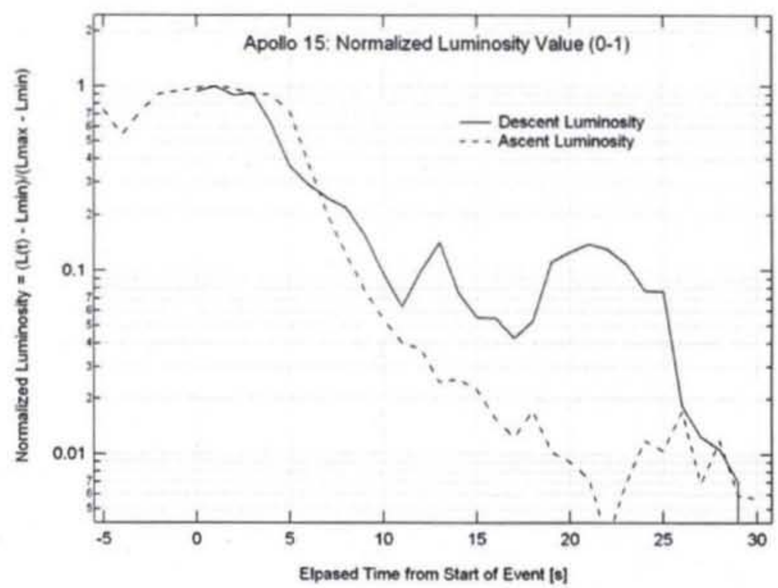
Apollo 15: Ascent



View from Apollo 15 Lunar Rover Vehicle. (Left) Before LM engine ignition. (Right) After LM engine ignition.

Dust clearing in Apollo 15 ascent compared to descent.





Geological Strata Stripped by Plume

- Images of the regolith under the Lunar Modules show that the soil was stripped away by the plume in well-defined layers, possibly the geological strata. This implies that there are mechanical discontinuities at the strata boundaries. We hypothesize that these are due to micrometeoroid gardenting, penetrating to a depth of only 1 or 2 mm to form a skin that resists the plume, while the strata themselves are on the order of 1 or 2 cm thick with less resistance to the plume.

Apollo 11 surface. Arrows show the contact between the upper soil layer and the sub layer. Area A has numerous radial erosional remnants, each headed by gravel. Area B has a set of short longitudinal features in the form of downward steps from the impingement point. Trench C was caused by the soil contact probe during landing. The engine nozzle is visible at the top. (Detail from NASA photograph AS11-40-5921HR.)

Summary

- Progress has been made in modeling the plume effects from landing spacecraft on the Moon
- More work is needed to understand and model the effects of soil particle collisions in the gas flow and the effects of turbulence in the rarefied gas
- Lofting of dust long after plume is gone is possibly electrostatic but this has not been confirmed
- Plume effects provide an additional probe of the geology of the lunar soil