

# Numerically Modeling the Erosion of Lunar Soil by Rocket Exhaust Plumes

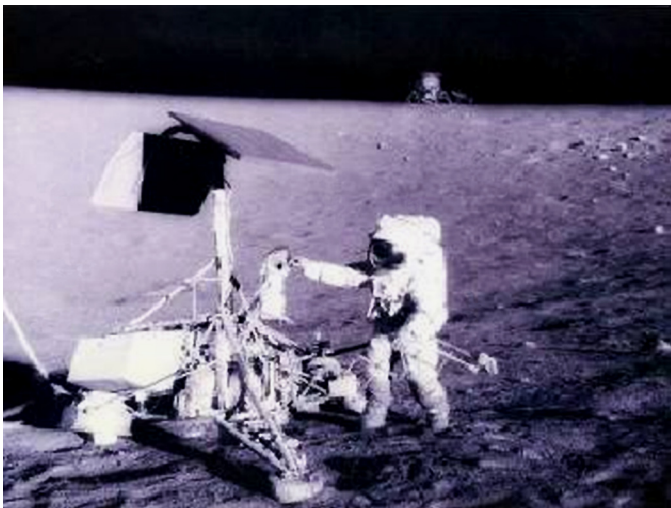
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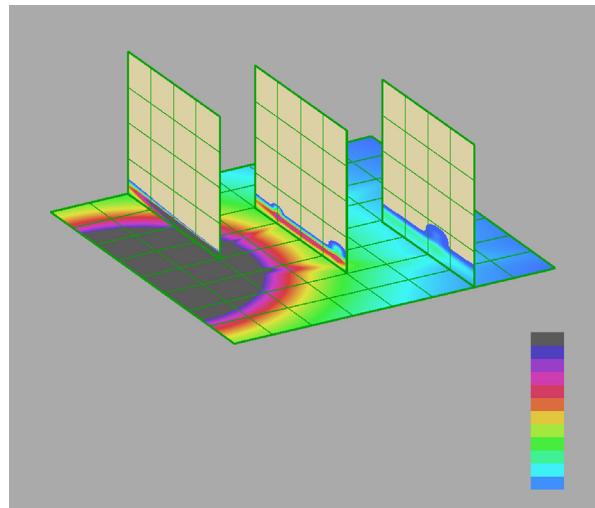
Site Preparation  
and Excavation

In preparation for the Apollo program, Leonard Roberts of the NASA Langley Research Center developed a remarkable analytical theory that predicts the blowing of lunar soil and dust beneath a rocket exhaust plume. Roberts assumed that the erosion rate was determined by the excess shear stress in the gas (the amount of shear stress greater than what causes grains to roll). The acceleration of particles to their final velocity in the gas consumes a portion of the shear stress. The erosion rate continues to increase until the excess shear stress is exactly consumed, thus determining the erosion rate. Roberts calculated the largest and smallest particles that could be eroded based on forces at the particle scale, but the erosion rate equation assumed that only one particle size existed in the soil. He assumed that particle ejection angles were determined entirely by the shape of the terrain, which acts like a ballistic ramp, with the particle aerodynamics being negligible. The predicted erosion rate and the upper limit of particle size appeared to be within an order of magnitude of small-scale terrestrial experiments but could not be tested more quantitatively at the time. The lower limit of particle size and the predictions of ejection angle were not tested.

We observed in the Apollo landing videos that the ejection angles of particles streaming out from individual craters were time-varying and correlated to the Lunar Module thrust, thus implying that particle aerodynamics dominate. We modified Roberts' theory in two ways. First, we used ad hoc the ejection angles measured in the Apollo landing videos, in lieu of developing a more sophisticated method. Second, we integrated Roberts' equations over the lunar-particle size distribution and obtained a compact expression that could be implemented in a numerical code. We also added a material damage model that predicts the number and size of divots which the impinging particles will cause in hardware surrounding the landing rocket. Then, we performed a long-range ballistics analysis for the ejected particulates.



The Apollo 12 Lunar Module landed approximately 160 m from the deactivated Surveyor III spacecraft. Blowing sand grains pitted Surveyor's surface with microscopic craters, and the blowing dust particles eroded a thin layer of material from its surface.

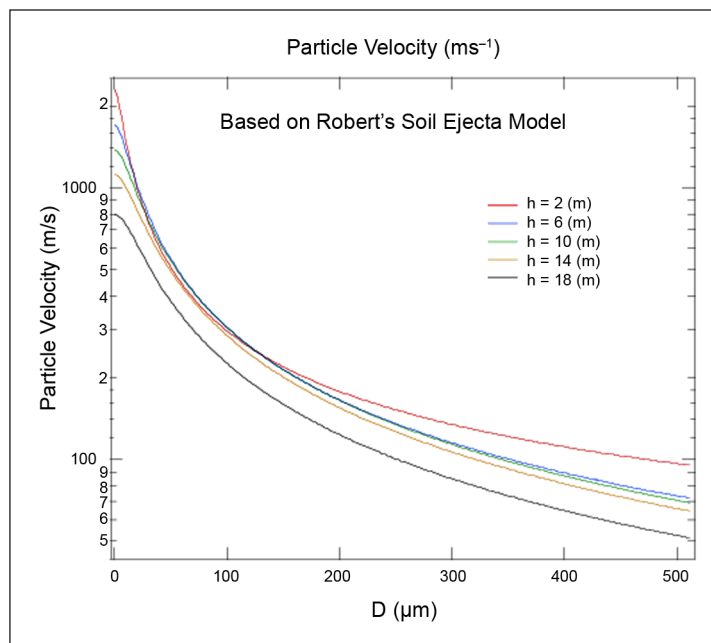


Output of modified Roberts' model showing mass flux in a 3-D map. Particles ejected from surface craters at higher angles create inhomogeneities.

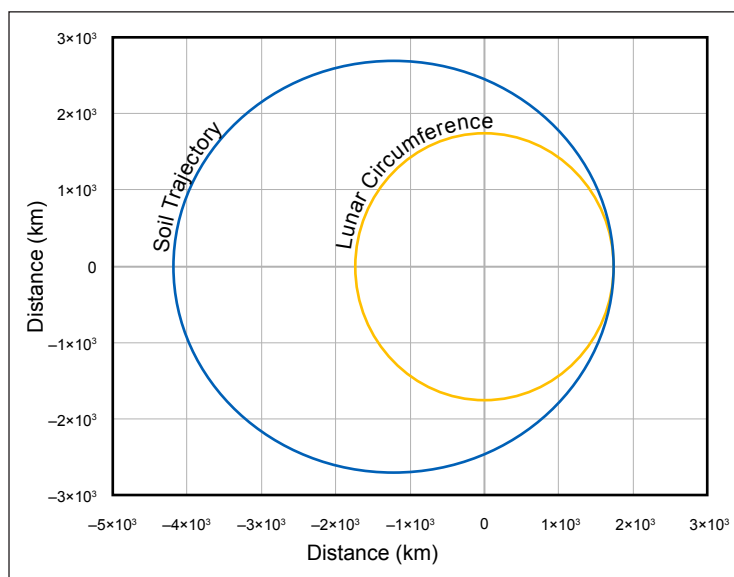
We compared the model's predictions with the divots observed in the Surveyor III hardware returned by the Apollo 12 astronauts. The model predicted about three divots per square centimeter compared to the one-half to five divots per square centimeter measured on the Surveyor. We compared the model's predictions for entrained-particle concentration with the concentration implied by the optical density in the Apollo landing videos. The model predicts  $10^6$  particles per cubic meter in the dust cloud. The Apollo landing videos indicate the true number was closer to  $10^8$ . This large error is almost certainly due to the form of Roberts' cohesion force equation, which apparently overestimates the lower limit of particle size. The ballistics indicate that the particles travel the circumference of the Moon, nearly reaching escape velocity, although Roberts' model may be overestimating the velocities. In ongoing work, we are correcting the cohesive force and lower limit of particle size, coupling the model to modern gas flow codes, including particle collisions in the erosion rate equation, and making other necessary improvements.

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Predicted particle velocities as a function of particle diameter and lander height.



Ballistic trajectory for particles traveling at predicted velocities transverse nearly the circumference of the Moon.