MODIFICATION OF ROBERTS' THEORY FOR ROCKET EXHAUST PLUMES ERODING LUNAR SOIL

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BACKGROUND TO ROBERTS' THEORY

In preparation for the Apollo program, Leonard Roberts 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 is 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 consumed 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. He calculated the largest and smallest particles that could be eroded based on forces at the particle scale, but the erosion rate equation assumes that only one particle size exists in the soil. He assumed that particle ejection angles are determined entirely by the shape of the terrain, which acts like a ballistic ramp, the particle aerodynamics being negligible. The predicted erosion rate and particle upper size limit 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 particle size limit and ejection angle predictions were not tested.

MODIFICATIONS TO ROBERTS' THEORY

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

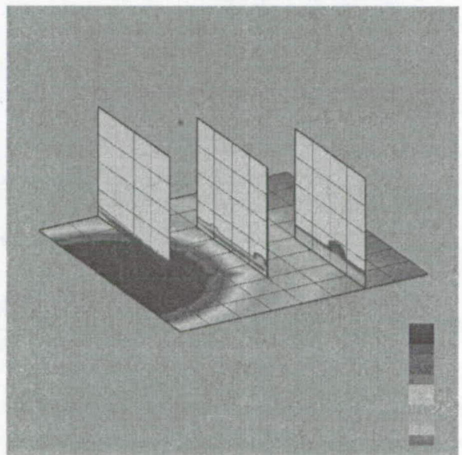

Figure 1. Output of modified Roberts model showing mass flux in a 3D map. Inhomogeneities are due to surface craters ejecting particle at higher angles

NUMERICAL RESULTS

We have compared the model's predictions with the divots observed in the Surveyor III hardware returned by the Apollo 12 astronauts. The model predicts ~3 divots/cm^2. Between 0.5 and 5 divots/cm^2 were measured on the Surveyor. We have 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/m^3 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 particle size limit. 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 on-going work we are correcting the cohesive force and lower particle size limit, coupling the model to modern gas flow codes, including particle collisions in the erosion rate equation, and making other necessary improvements.

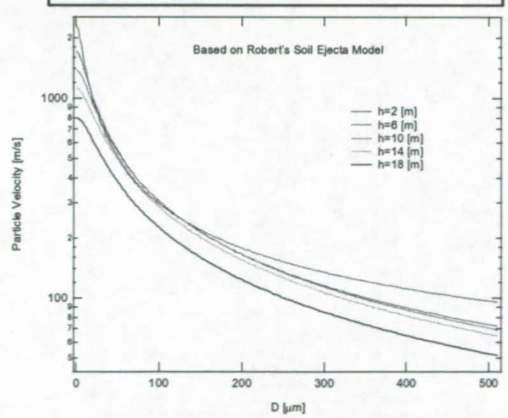

Figure 2: Predicted particle velocities as a function of particle diameter and lander height