ROCKET PLUME IMPINGMENT ON MAUNA KEA LUNAR ANALOG SITE COMPARED WITH PHOTOGRAMMETRY OF APOLLO LUNAR LANDING VIDEOS. P. T. Metzger[1], C. D. Immer[2], J.E. Lane[3], J. Smith[4], J. W. Studak[5], B. F. Banker[5], [1]Granular Mechanics and Regolith Operations Lab, NE-S-1, NASA Kennedy Space Center, FL 32899 Philip.T.Metzger@nasa.gov, [2]ASRC-Aerospace, ASRC-15, Kennedy Space Center, FL 32899, Christopher.D.Immer@nasa.gov, [3]ASRC-Aerospace, ASRC-24, Kennedy Space Center, FL 32899, John.E.Lane@nasa.gov, [4]PISCES, University of Hawai'i at Hilo, 200 W. Kawili St., Hilo, HI 96720-4091, smith_jacob2002@yahoo.com, [5]Propulsion Systems Branch, EP-411, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, Joseph.W.Studak@nasa.gov and Brian.F.Banker@nasa.gov

Introduction: To use the resources of a planet or moon we must launch and land near the infrastructure that processed those resources and we must control the rocket exhaust plume effects to prevent damage. To better understand those effects, we have compared photogrammetric measurements of the Apollo landing videos with high speed video of rocket thruster firings performed in February 2010 upon the tephra of the PISCES lunar analog site on Mauna Kea in Hawaii.

Field Test Experiments: A cryogenic oxygen and methane thruster, designed to produce 72 N (16 lbf) thrust through a 4.4 mm diameter throat (see Fig. 1B), was fired onto the tephra (lunar regolith analog). The plume was collimated by the ambient atmosphere into a narrow jet with a high shock recovery pressure and would therefore excavate a narrow hole into the soil. To avoid this and ensure that the physics would be in the same gas/soil flow regime as during an Apollo lunar landing, we adjusted the height and angle of incidence of the thruster until its potential core no longer reached the surface. Thus, the physics would be dominated by viscous erosion, not deep cratering. Analysis of the particle size distribution [1] shows in Fig. 1A that optical density is orders of magnitude greater for the <10 micron size fraction than for the other portions of lunar soil or other dusty soil. Individual particles cannot be seen on the video unless they are larger than 2 pixels so that the bright and dark sides of the particle can be distinguished. As a result, in the field test videos we can see moving particles only <10 microns and >2 mm (with analogous limitations in the lunar landings videos). This means that the vast majority of soil is invisible when blowing and its motion can only be inferred by the release of dust, the rolling of large particles, and the cumulative changes in terrain shape.

Field Test Results: Each time the thruster was ignited, bright dust immediately became visible leaving the surface at raised terrain features such as rims of scaled "craters", as shown in Fig. 2. The raised dust immediately blew into a non-homogenous ring surrounding the impingement point, with dense streaks and billows in some areas and dust-free patches elsewhere, due to the unevenness of the terrain emitting

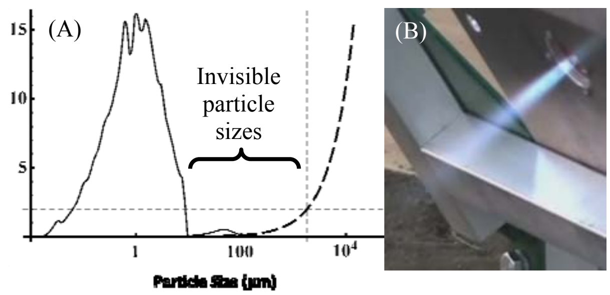

Fig. 1 (A): Solid – Surface area of blowing soil per micron particle size (arbitrary units). Heavy Dashed – camera pixels per individual particle. Light Dashed – guides to the eye at 1800 μm and 2 pixels. (B) Close-up of plume with faint Mach structure.

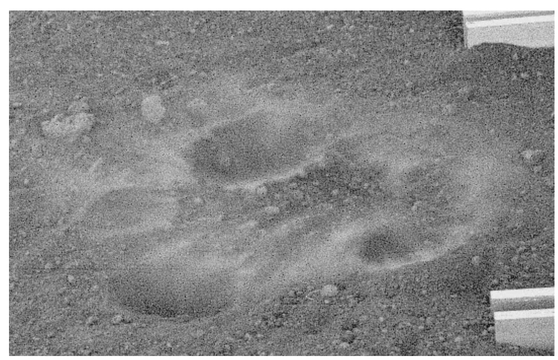

Fig. 2. Dust release indicated by the brightened surface ridges and the dust streaks leading away from them at the beginning of a thruster firing.

the dust. The dust ring expanded outwardly through radial convection as more dust was continually generated at the original radius of the ring and beyond. Simultaneous was the first motion of gravel-sized particles, and probably sand because the removal of bulk sand would be needed to ensure a continuous supply of new dust. The dust particles were in suspension while the gravel-sized particles were rolling along the surface as bed load. It is not known how the sand-sized particles moved, whether through rolling, saltation, or sustained aerodynamic flight in the high velocity gas, because they were not visible. In all directions the rolling bed load moved at much lower velocity than the suspended dust. For the visible material, convection was primarily downstream away from the jet with only a little back-flow along the ground toward the test rig. Thus, canting the nozzle was effective to control the direction of the ejecta. Next, as the soil eroded around gravel cobbles, persistent dust streaks formed in their wake. When they were sufficiently exhumed, they were torqued up from their resting places and rolled away by the gas, leaving a hole in the soil behind them. The holes rapidly disappeared because they were filled by sand deposition and/or the surface around them was lowered by erosion. After thruster shut-off, the terrain at and around the impingement point was left visibly brighter with a light yellow appearance relative to the darker gray of the bulk tephra, as shown in Fig. 3.

Fig. 3. Brightening of impingement zone (contrast enhanced).

This bright color was found to be a thin layer of dust, which would immediately go into suspension when disturbed by kicking, leaving the ground the original gray color. If this dust layer was not mechanically disturbed it would persist as long as we continued to observe it (i.e. it would not go into suspension through nominal wind at the test site). We infer that erosion rates are not the same for each particle size and therefore some become more concentrated than others in the top layer of soil during the initial erosion process. These surface concentrations reach steady state when the resulting size distribution is equal to the original size distribution in the bulk divided by the erosion rate as a function of particle size. Thus, after the initial transient, the size distribution of the *blowing* material matches the natural distribution of the bulk material (beneath the surface layer), a condition that must be true else some sizes would concentrate to infinity. The brightened zone therefore implies that the dust-sized particles were eroded at a slower rate than other particle sizes, which is counter-intuitive. Finally, as shown in Fig. 3, gravel was rolled away from the brightened zone, forming a gravel-rich band at the extent of bed load transport.

Apollo Landings: Several of the observed field test phenomena are analogs to phenomena observed in the Apollo landings, and thus help to interpret the Apollo landings. First, a sheet of dust was observed blowing away from the lunar lander's plume impingement point. We measured the shape of the dust sheet using photogrammetric methods taking advantage of the Lunar Module shadows [2] and found that its angular thickness above the horizontal was only about 3 degrees. This sheet was very non-homogeneous, containing streaks and time-varying features. We interpret this as the result of terrain feature such as rocks and craters, which are changing beneath the lander partly by translation of the lander and partly by erosion moving the features. For example, in Apollo 14 after touchdown there was a single, rapidly shifting dust streak until engine cutoff, which implies the throttled-down plume was still changing the terrain beneath the lander. Second, because dust generation is continuous in the landings, we infer that not only the dust but also the bulk of the soil, which would be invisible in the videos, is blowing. Analysis of the optical density of the blowing dust fraction [1] shows that by proportionality of the invisible particle sizes there must have been about 10 cm (20 MT) of soil blown from a broad region. Third, we have seen what appear to be rocks being exhumed and becoming greatly elongated before they are blown out from the field of view [2]. Some colleagues have wondered whether these could be friable dirt clods falling apart in the plume. However, the Mauna Kea tests shows that rocks form dust tails as they are exhumed, and this would appear as elongation of the rocks in the low-resolution Apollo videos. The coarser particles of a disintegrating dirt clod would have been invisible. Our simulations show that rocks should indeed be blown by Lunar Module plumes [3]. Fourth, a brightening of the soil was observed around the Apollo landing sites. We do not know if this was caused by the same mechanism seen on Mauna Kea, but if it was, then the diameter of the brightened region indicates the diameter over which erosion occurred. Fifth, photographs under the Lunar Modules after landing show swept-clean surfaces with no loose material and all cobbles partially embedded. All the loose material must have been either blown or rolled away from beneath the lander. This implies that a concentration of rocks exists at some radius around the landing sites, moved outwardly to the extent of bed load transport.

References: [1] Metzger P.T. et al. (2010) *Earth & Space 2010*. [2] Immer C.D. et al. (2008) *Earth & Space 2008*. [3] Lane J.E. et al. (2008) *Earth & Space 2008*.