APOLLO VIDEO PHOTOGRAMMETRY ESTIMATION OF PLUME IMPINGEMENT EFFECTS

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INTRODUCTION

Each of the six Apollo mission landers touched down at unique sites on the lunar surface. Aside from the Apollo 12 landing site located 180 meters from the Surveyor III lander, plume impingement effects on ground hardware during the landings were largely not an issue. The Constellation Project's planned return to the moon requires numerous landings at the same site. Since the top few centimeters are loosely packed regolith, plume impingement from the lander ejects the granular material at high velocities. With high vacuum conditions on the moon (10^{-14} to 10^{-12} torr), motion of all particles is completely ballistic. Estimates from damage to the Surveyor III show that the ejected regolith particles to be anywhere 400 m/s to 2500 m/s. It is imperative to understand the physics of plume impingement to safely design landing sites for the Constellation Program.

RESULTS AND DISCUSSION

Digitized versions of the film taken during the six lunar surface landings allow unprecedented analysis with modern photogrammetry techniques. Quantitative estimates of phenomena in the field of view of the landing cameras have been calculated.

Using the sun angle, the altitude of the lander, the angle of the camera with respect to the ground, and the elongation of the shadows of the lander on the surface, the regolith ejection angle for each mission has been estimated and is shown in Table 1. These effect/results have been corroborated with both physical modeling and 3D Cad model reconstruction. In general the ejection angle with respect to the surface is 1-3 degrees, but Apollo 15 landed on an inclined surface of about 11 degrees. Additionally, immediately preceding touchdown, Apollo 15 had a "blow out" with very high dust ejection angle, likely greater than 22 degrees.

Table 1 Dust ejection angle for Apollo Missions derived from video photogrametry.

Apollo Mission	Dust Angle [deg]
11	2.6
14	2.4
15	8.1
16	1.4
17	2.0
avg	3.3

The common belief during the Apollo program was that the plume impingement

Figure 1 Two consective frames at T-8.5 sec from Apollo 12 Landing. Note the change in streak angle, likely due to change in thrust.

would result in excavation of regolith of size on the order of 1 millimeter and smaller. For the Apollo 14 landing at about T-3.2 seconds (prior to touchdown), the plume exhumes two rocks on a crater rim in the central field of view. Shortly after, they are lofted by the exhaust plume. Using the altitude of the lander, the magnification of the camera, and the effective the pixel size, the authors estimate the rocks to be about 10-15 cm in diameter.

Leonard Roberts' model of plume impingement assumes that crater wall angle is the primary factor in determining regolith ejection angle. While the "roughness" of the lunar surface certainly contributes to regolith excavation, there are several cases where ejection angle changes with engine thrust. Figure 1 shows an example of a "jump" in dust streaks between two consecutive frames; likely as a result of thrust change.

Finally, the density of the lofted regolith has been estimated using the extinction coefficient of lunar regolith, the camera height, the sun angle, the camera angle, the dust ejection angle, and comparisons of a bright object during momentary clearings of the dust. Estimates for these events from Apollo 11 and 16 result in particle densities from 10^9-10^{13} particles/m^3: a few orders of magnitude larger than that predicted by Roberts' model.