EJECTA SHEET TRACKING, OPACITY, AND REGOLITH MATURITY (EJECTA STORM): AN INSTRUMENT FOR LUNAR LANDING PLUME EFFECTS AND DUST DYNAMICS.

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Introduction: When a rocket lands on the Moon or another planetary body it blows a highly damaging cloud of high-velocity dust, sand, gravel, and rocks, which can spoof sensors, damage the lander, and damage other assets located on the planetary surface or even in orbit about the Moon. Our understanding of lunar lander plume ejecta transport has serious gaps. For example, we do not understand the science of soil erosion under such extreme conditions: supersonic flow, transitionally rarefied gas (so viscosity is breaking down, the boundary layer is affected, and the turbulence spectrum is probably affected), in low gravity, with unusually sharp and angular soil since it isn't rounded by winds or waves like desert sand [1]. In these conditions we need empirical data to guide the models and eventually to solve the soil erosion physics. NASA has been developing highly advanced flow codes to attempt making predictions of these phenomena [2], but to-date the available data sets to guide these codes are severely limited. We need to collect high-quality data from actual landings on the Moon.

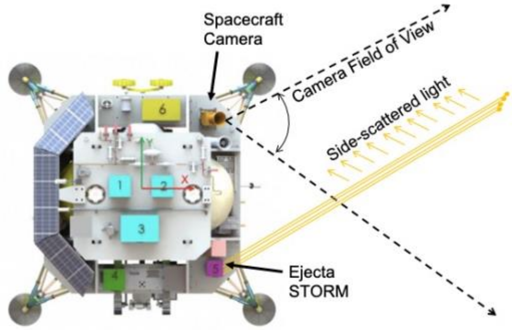

Figure 1. Ejecta STORM Concept. Lander image courtesy Orbit Beyond.

We developed the Ejecta Sheet Tracking, Opacity, and Regolith Maturity (Ejecta STORM) instrument to measure key transport phenomena to solve these open physics questions and to support development of physics-based flow codes. It consists of several lasers and cameras that record and extract information from the transmitted and back-scattered light (visible and IR).

Granular Transport Physics: It is tempting to think of the blowing dust cloud as a continuum of material (like air or water) that can be measured simply using descent imagery cameras, microwaves, passive infrared, or another bulk-detection method. However, the clouds are a mixture of particle sizes traveling between each other at different velocities correlated to their sizes [3], scattering with size-dependence [4], which results in size segregation that determines the local sizes and concentration of entrained particulates and the local momentum transfer between the particles and the gas. Ultimately, this particle-scale behavior governs the ejecta transport. The Ejecta STORM sensor makes measurements, including particle-scale measurements, with fine spatial and temporal resolution.

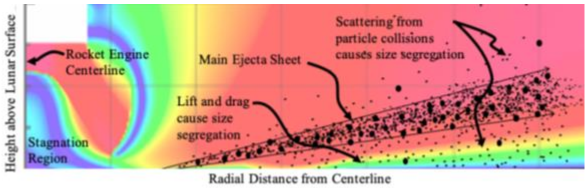

Figure 2. Schematic of ejecta sheet blown by lander.

Measurements: Ejecta STORM measures the amplitude of light transmitted down the beam then backscattered at each point along the beam. Starting from the top of the beam and working down it is possible to determine the extinction coefficient $k(\lambda)$ at each point along the beam, where λ is the wavelength of the laser. If the particle size distribution $P(D)$ is known at each point, the particle number density N in the cloud can be determined from:

$$k(\lambda) = \int_0^\infty \pi \frac{D^2}{4} C_E\big(D, m(\lambda)\big) P(D)\, \mathrm{d}D \qquad (1)$$

where $C_E(\alpha)$ is the single particle scattering coefficient and $m(\lambda)$ is the index of refraction of the mineral particles [25]. This defines an inverse problem: given $k(\lambda)$ and C_E, solve $P(D)$. In practice these functions are discretized, $D \in D_i$ and $\lambda \in \lambda_j$, so the matrix form of the above equation becomes $k_i = A_{ij} P_j$ where A_{ij} is a collection of terms from the integrand. With as few as four lasers, it is possible to measure some transport segregation of the particle sizes in the cloud, but with more lasers it is possible to invert the matrix equation and solve the entire $P(D)$. It is a tradeoff for how much accuracy is desired in $P(D)$ versus the mass and power requirements for the instrument. We are developing two versions of the instrument: one that uses four lasers to constrain only the finest fraction in the cloud, and another with more lasers from visible to longwave IR to constrain the entire $P(D)$.

Another estimate of $P(D)$ for the local landing site is obtained from the optical maturity parameter [5] and/or the spectopolarization index [6] that measure the redness of the blowing soil's albedo. These indices are correlated to maturity which can also be correlated to the evolution of typical particle size distributions in lunar soil [7]. Four wavelengths in Ejecta STORM were selected to facilitate measuring those two indices in addition to the other measurements.

A third version of Ejecta STORM is planned to also measure velocities of the particles at each length along the beams using a volumetric Bragg grating on one camera as a doppler filter to compare with an unfiltered camera. This method was previously developed by Metzger et al. under the name Particle Ejection and Levitation Tracker [8].

Flight Opportunity Test: The NASA Flight Opportunities Program funded flight tests of Ejecta STORM on a Masten Space Systems Xodiac rocket. This enabled realistic integration with flight cameras, flight dynamics, and plume-induced ejecta. The experiment used a crushed basalt simulant for lunar soil. The laser assembly was located on the top of the rocket (Figure 3); a GoPro camera was mounted near the top on the opposite size of the rocket's circumference, and a high-resolution camcorder was mounted near the bottom of the rocket directly beneath the lasers. Three tests flights were performed, including two that were tethered and one that flew from point-to-point. After each of the first two flights, camera and laser pointing angles were adjusted, and camera settings including zoom were adjusted to improve data capture.

Figure 3. Left: Ejecta STORM on the top of the Xodiac rocket. Right: Flight test blowing simulated lunar soil while Ejecta STORM takes measurements.

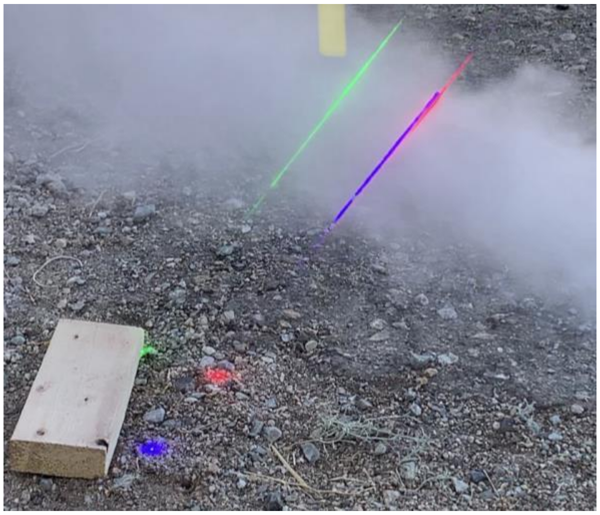

Figure 4. Pre-flight check. Bright backscatter along the beams shown in a cloud of lunar simulant blown in a jet, with beam spots on the ground beneath.

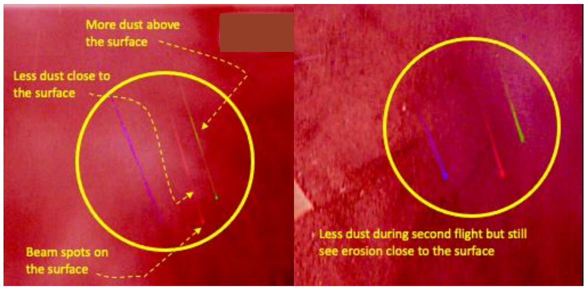

Figure 5. Imagery during flight tests of laser side scatter and transitted beam spots through simulated lunar dust.

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