Measuring Plume Effects of Lunar Landing and Launch: Ejecta Sheet Tracking, Opacity, and Regolith Maturity (Ejecta STORM)

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Problem Statement: Rockets operating on the airless Moon will blow a high velocity ejecta sheet of dust, sand, gravel, and rocks, which can be highly damaging to surrounding assets including spacecraft orbiting the Moon. Much of the physics is still unsolved [1], although great progress has been made in a new generation of flow codes [2]. For more progress we need datasets measured with high spatio-temporal-resolution during actual lunar landings.

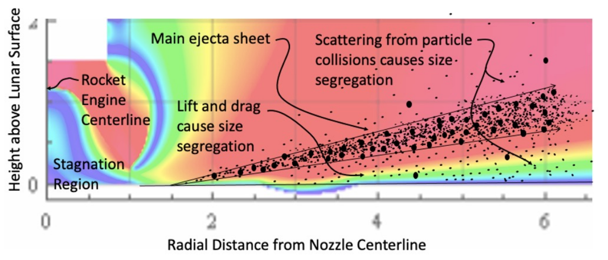


Diagram of flow of rocket exhaust and eroding regolith (side view from centerline of rocket).

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.

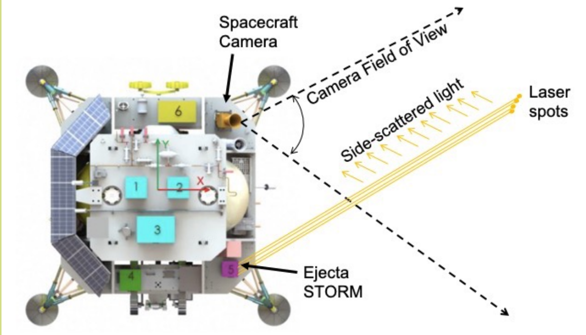


Diagram of sensor lasers and camera installation on a lunar lander (top view). Lander image courtesy Orbit Beyond.

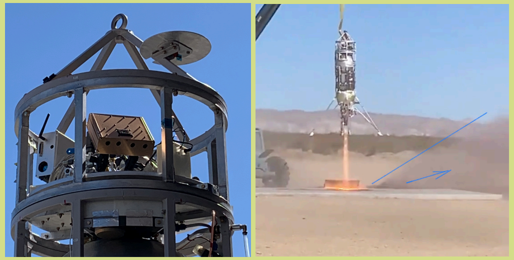
Measurements: Ejecta STORM measures the amplitude of scattered light at each point along the lengths of multiple laser beams. With this dataset we calculate the extinction coefficient $k(\lambda)$ at each point along the beam, where λ is the wavelength of the laser. The particle number density N at each point along the beam can be determined from:

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

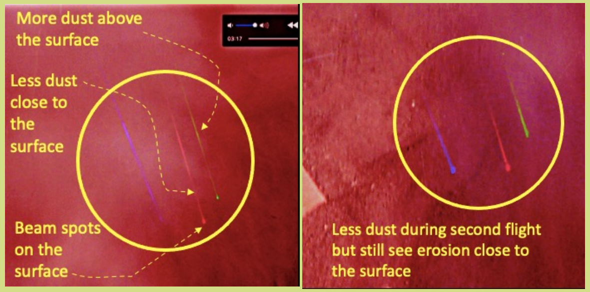
where $C_E(\alpha)$ is the single particle scattering coefficient at a given point along the beam, $m(\lambda)$ is the index of refraction of the mineral particles at the landing site, and $P(D)$ is the particle size distribution at that point along the beam. This defines an inverse problem: given $k(\lambda)$ and C_E, solve N and $P(D)$. These functions are discretized, $D \in D_i$ and $\lambda \in \lambda_j$, so the matrix form of the equation is $k_i = N A_{ij} P_j$ where A_{ij} is a collection of terms from the integrand.

The sensor uses multiple laser wavelengths to determine maturity of the lunar soil and to provide additional constraint on the particle size distribution.

Flight Testing: The prototype has been installed on the Masten Space Systems Xodiac rocket and completed four test flights using lunar soil simulant spread on and around the launch/landing pad. The flight achieved TRL-5 and demonstrates the sensor concept measures dust density as a function of high above the lunar surface.



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



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

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References: [1] Metzger P.T. (2020) Workshop on the Effects of Dust to Human Lunar Exploration, Houston, Feb. 11-13, 2020. [2] Liever P.A. et al. (2018) Earth and Space 2018. [3] Lane J.E. et al. (2010) Earth and Space 2010. [4] Anand A. et al. (2013) Phys Rev E 87, 022205.