



Laser-Propagation Image Analysis to Obtain Lunar Plume Particle Size Distributions

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Abstract

We are developing an instrument to determine particle size distributions in lander plumes. The method measures propagation decay in images of scattered laser beams. We present a means of extracting intensity vs propagation distance in pixel units corrected for lens distortion.

Introduction

Lunar lander exhaust plumes entrain fine surface particles that can damage both surface and orbital assets, yet the particle-size distributions and resulting dynamics remain poorly constrained [1]. Empirical determination of these distributions is essential for validating and improving predictive models. To address this, we are developing a lander-mounted laser-imager system ("EjectaBLAST") that derives particle-size distributions from wavelength-dependent laser propagation decay. The raw data are images, from which intensity vs distance curves must be extracted. These curves must be corrected for a number of instrumental and environmental artifacts before their analysis. This presentation considers the first of these: lens distortion.

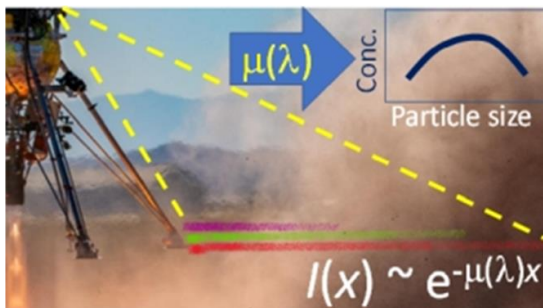


Figure 1. Schematic of EjectaBLAST operation.

Theoretical Considerations

The intensity of a laser beam in a scattering medium decays exponentially with distance x for uniform distributions in the single-particle scattering limit according to [2]

$$I(x) = I_0 \exp(-\mu x)$$

The decay constant μ for a given wavelength λ is

$$\mu(\lambda) = \int_0^\infty \frac{\pi D^2}{4} Q(D, m, \lambda) N(D) dD = \int_0^\infty K(D, \lambda) N(D) dD$$

where the kernel K for a given refractive index m is the scattering cross section for spherical particles of diameter D , and Q is the scattering efficiency factor from Mie theory. Elsewhere [3,4] we discuss the inversion to obtain a vector of concentration values $N(D_i)$ from a vector of measured decay constants at a number of discrete wavelengths $\mu(\lambda_i)$. A first step is to obtain accurate values for those decay constants.

Methods

EjectaBLAST's laser module (Figure 1, left) comprises eight laser wavelengths. In nm these are 404 (violet), 435 (indigo), 491 (blue), 517 (green), 662 (red), 782 (near-IR), 825 (near-IR), and 967 (near-IR). The EjectaBLAST's monochrome camera (Figure 1, right) collects images of beams propagating through the scattering medium. The image is 1920 x 1200 pixels, with the long axis aligned to the beam propagation. Raw images I_{pq} are corrected for lens distortion using OpenCV-based pixel remapping derived from calibration images. Instead of correcting full frames, laser decay curves are extracted from vertical slices across the bent beam images (Figure 3), where each slice corresponds to an integer column index p . For each slice, the intensity I_{pq} is plotted versus integer row index q and fitted with a Gaussian to determine the centroid $\langle q \rangle$, background B_i , and integrated area $A_p = \sum_q I_{pq} - B_p$. The corrected beam coordinates (ξ, η) are obtained from $(p, \langle q \rangle)$. Then propagation distances in pixel units are computed as

$$r = \sqrt{(\xi - \xi_0)^2 + (\eta - \eta_0)^2}$$

Plotting A_p versus r yields the decay curve $I(r)$.



Figure 2. EjectaBLAST Laser and camera modules.

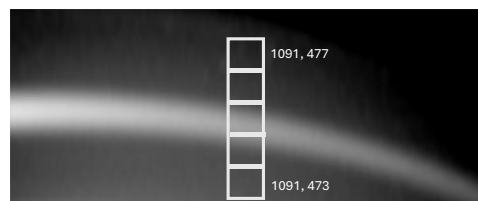
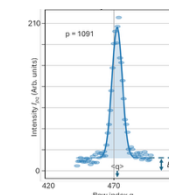


Figure 3. (left) Schematic of vertical slide through uncorrected beam image with five numbered pixels (not to scale). (right) actual slice intensity data with Gaussian fit.



Results

Figure 4 presents uncorrected and corrected images of laser beams propagating through ~100 nm TiO₂ particles suspended water. The lasers enter from the left, with wavelength increasing from top to bottom. Water absorption strongly attenuates the longest IR beam. While uncorrected beams curve downward, the corrected images appear straight but variably stretched or compressed.

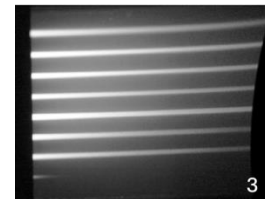
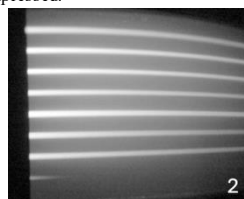


Figure 2. (left) Portion of uncorrected image of eight laser beams propagating in a suspension of TiO₂ particles in water. (right) Same portion after correction.

Figures 3 (left) presents uncorrected $(p, \langle q \rangle)$ and corrected (ξ, η) beam position data from nine image slices. The corrected positions lie on a line with random variations due to finite signal to noise ratio, which worsens with distance.

Figure 4 (right) plots the beam intensity from the image as a function of distance in pixel units. The curve is approximately exponential decay, but the semi-log inset reveals slight curvature due to system and environmental artifacts other than lens distortion. After all corrections for these additional artifacts, the curve should be pure exponential, allowing a determination of accurate propagation-decay constants.

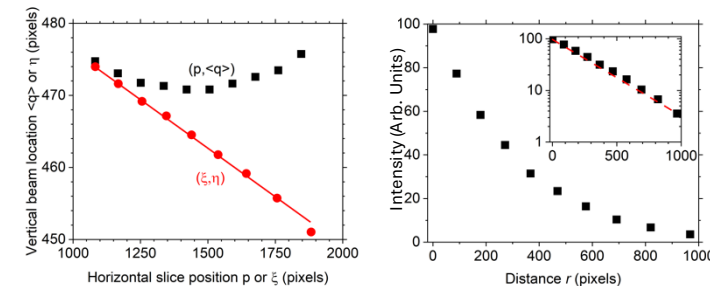


Figure 4. (left) Uncorrected and corrected beam positions for nine slices through an image of one beam. (right) Beam intensity vs distance in pixel units. The inset indicates non-exponentiality due to system and environmental artifacts other than lens distortion.

Discussion and summary

EjectaBLAST is a lunar-lander mounted instrument to obtain empirical particle size distribution. This presentation demonstrated a means of real-time data reduction and lens-error correction. Remaining challenges include conversion from pixel units to real-space dimensions, followed by correction for foreshortening, perspective, angle dependence of scattering and window transmittance, and environmental artifacts.

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