Laboratory validation of laser particle sizer for lunar-lander plume-surface interactions

N. Dhakal,[1] T. Deyo,[1] M. Gotmare,[1] J. Salano,[1] C. Kelley,[1] P. Metzger,[2] A. Dove,[1,2] C. J. Fredricksen,[3] R. E. Peale[1,3]

1 UCF
2 Florida Space Institute
3 Truventic

Abstract

We are developing an instrument that will determine lunar-lander plume particle size distribution from laser propagation decay based on images of laser light scattering. Laboratory validation experiments include imaging of laser propagation through particle suspensions in air, vacuum, or liquid.

Introduction

Lunar lander plumes entrain fine particles with high velocity that are known to damage surface assets and may also damage orbital hardware (Immer et al. 2011). Empirical particle size distributions are needed to inform models that can be used to understand and remediate the problem. We are developing a lander-mounted laser-imager system that will determine particle size distributions from wavelength-dependent laser propagation decay, which must be exponential with distance in the single-particle scattering limit. Scattered light is a measure of this intensity. Laboratory experiments for particle suspensions with independently-measured size distributions are being performed to validate our approach.

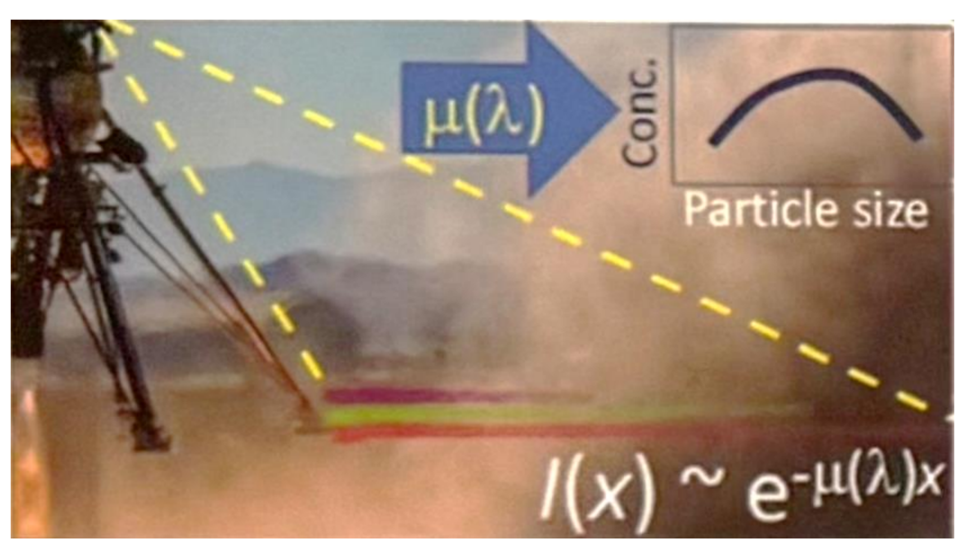

Figure 1. Schematic of lander-mounted particle sizer

Theoretical considerations

The intensity of a laser through a medium of particles is given by

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

where x is the distance along the beam. The decay constant μ is given by the linear integral equation with Mie scattering efficiency factor Q:

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

From values of $\mu(\lambda_i)$ at multiple wavelengths the integral equation may be inverted to obtain the particle size distribution N(D) as a function of particle diameter D.

Methods

Scattering media investigated include aerosols from a fog machine, suspensions of nanoparticles in liquid, and falling showers of particles in vacuum. Images are collected using a Pi camera with Raspberry Pi computer. A completed scatterometer prototype with eight laser wavelengths is currently undergoing flight testing on a tethered rocket.

Figure 2. Camera and windowed pipe to contain smoke.

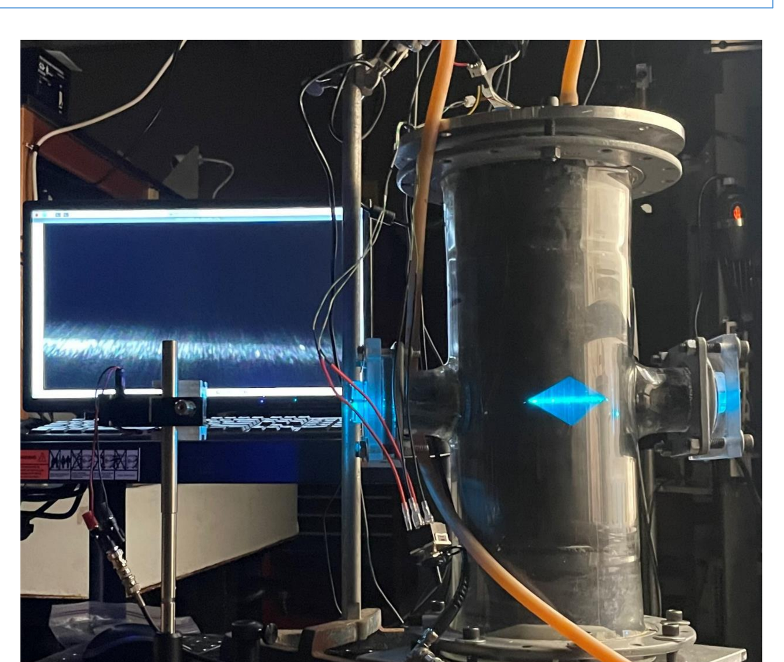

Figure 3. Shower of particles falling in vacuum.

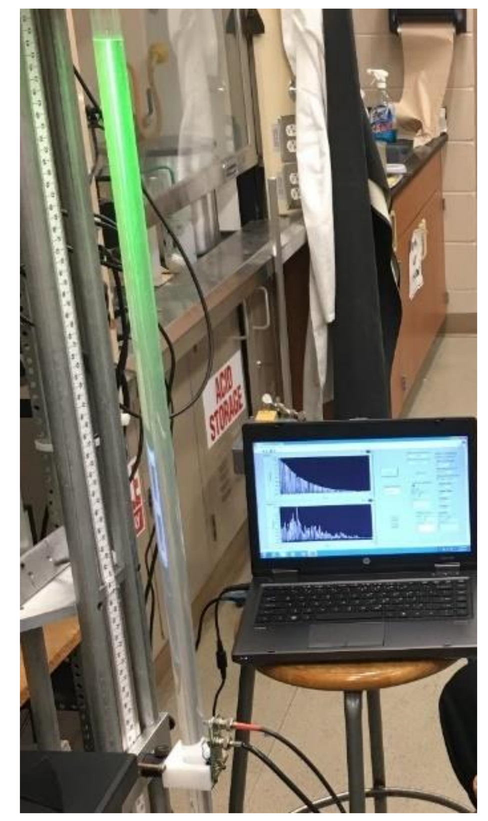

Figure 4. Nanoparticle suspension in liquid

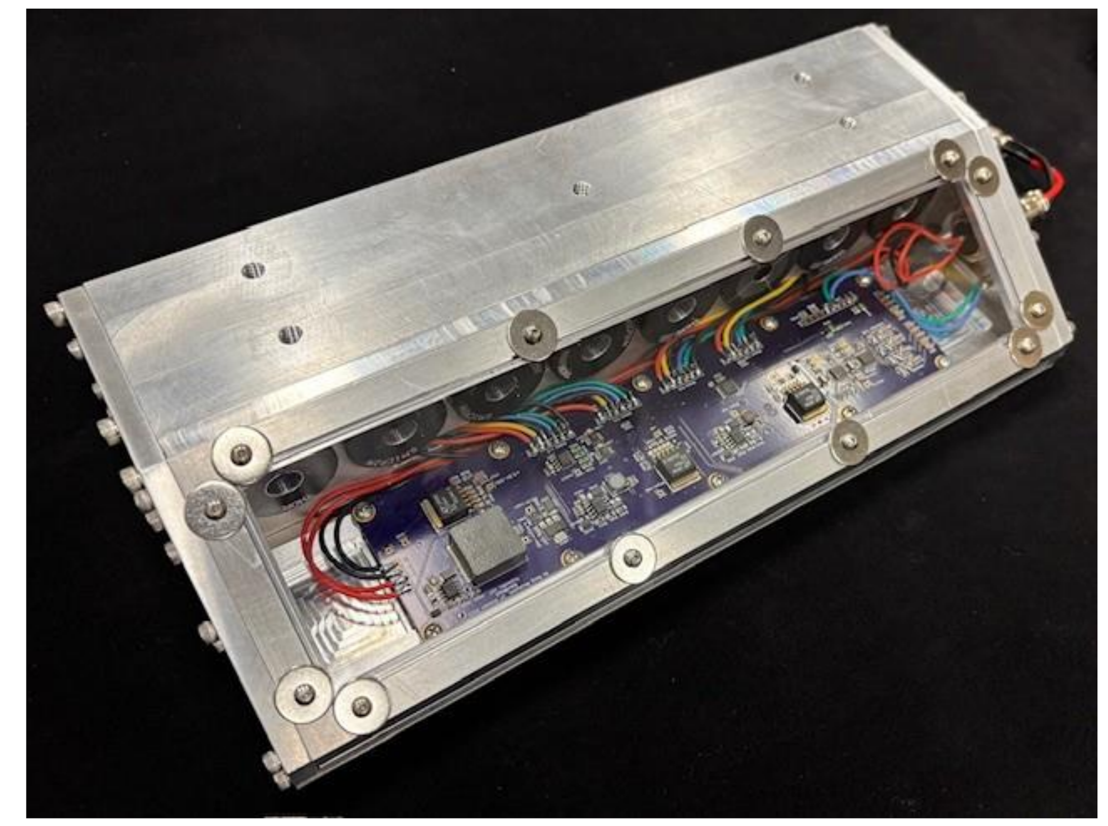

Figure 5. Eight laser prototype for rocket testing: "EjectBLAST"

Results

Figure 6 presents an image of laser propagation through aerosols generated by a fog machine. Decays were non-exponential due to concentration inhomogeneities, which were difficult to eliminate. Also, the particle size distribution was not initially known and changed with time as the aerosols evaporated.

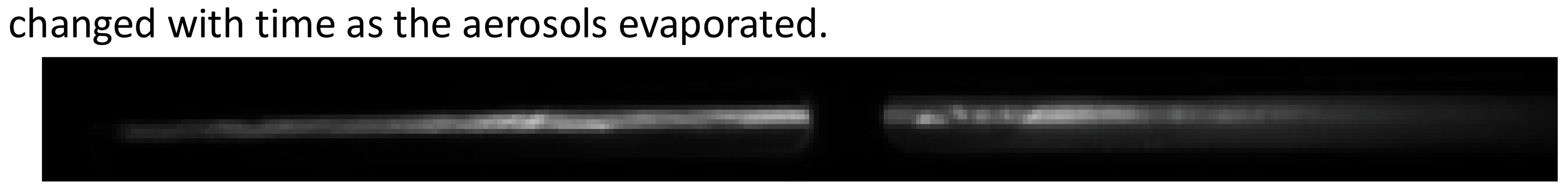

Figure 6. Non-exponential laser propagation decay in aerosol from fog machine

Figure 7 presents laser propagation decays obtained for a falling shower of particles in vacuum. This method succeeded only with particles larger than the expected submicron lunar distributions. Due to constraints in the vacuum chamber, only one laser wavelength could be used at a time, and the propagation length was limited to ~10 cm. Nevertheless, the nearly exponential decays agreed with theoretical expectations.

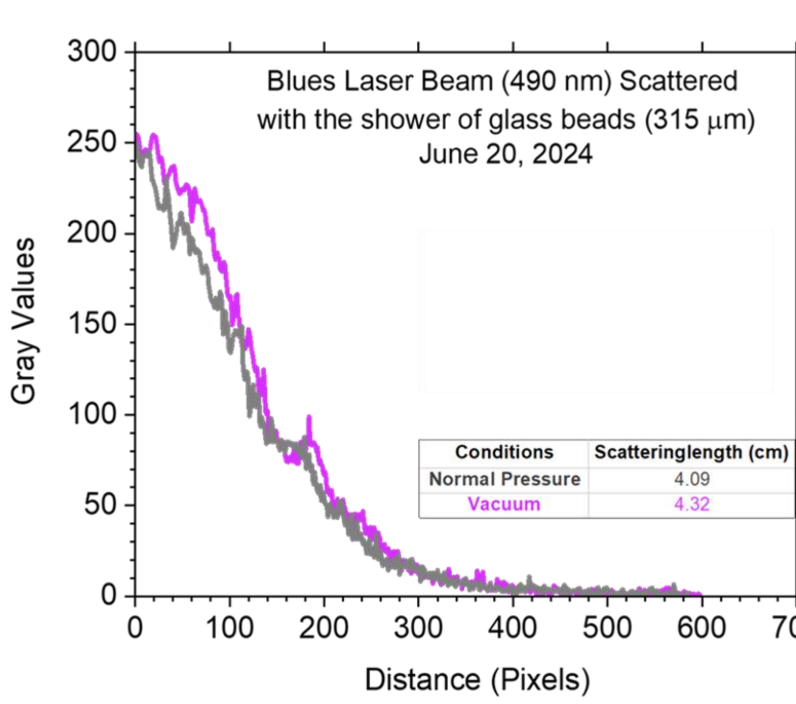

Figure 7. Laser propagation decays for falling particles in vacuum chamber

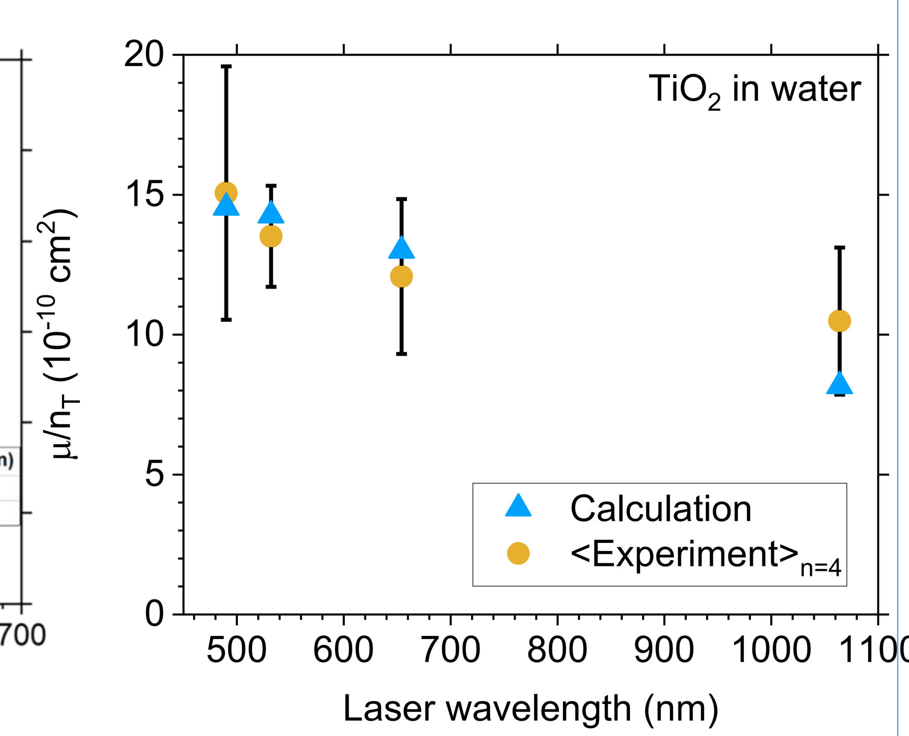

Figure 8. Comparison of theory and experiment for decay constants of laser propagation in liquid particle suspension

Figure 8 presents a comparison of measured and calculated decay constants for suspensions of submicron TiO_2 particles in water. The particle size distribution was independently known. Agreement is good. For micron-sized particles and larger, more viscous liquids such as glycerin were found necessary to sustain the suspension.

Figure 9 presents a photograph of the EjectaBLAST system mounted on a tethered rocket for first flight tests with Exos Aerospace. Similar tests are also ongoing with Astrobotic.

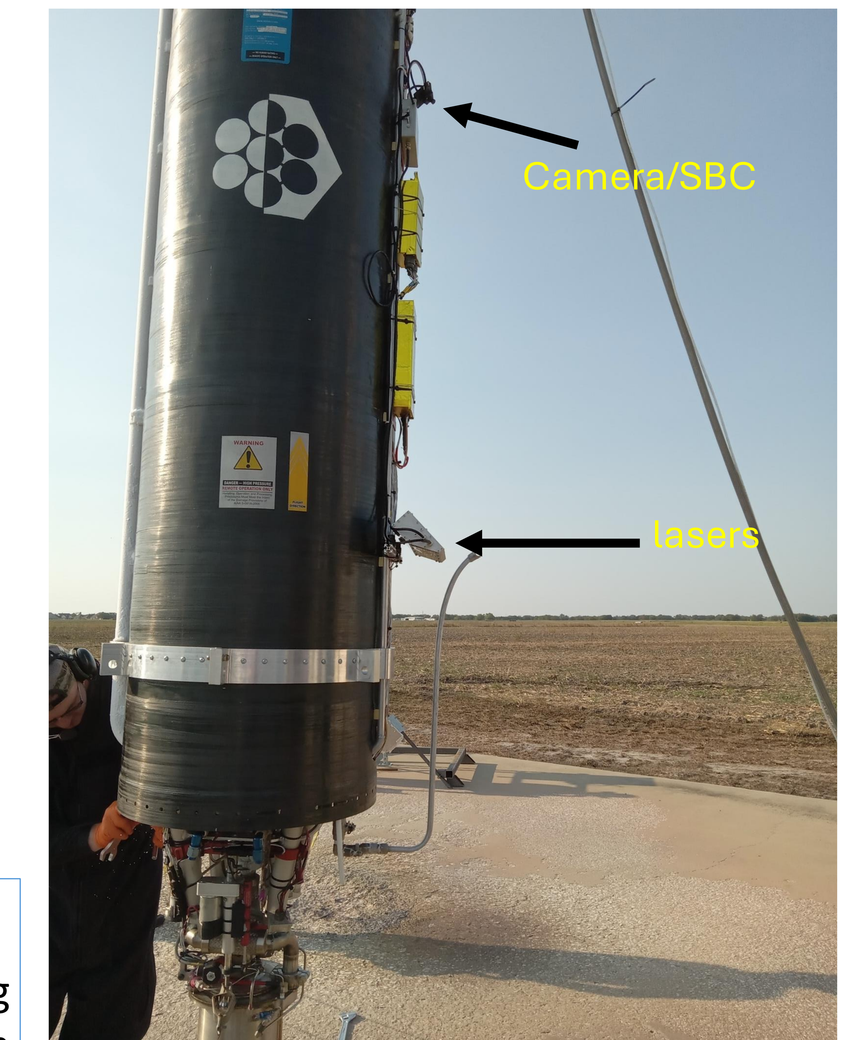

Figure 9. Ejectra-blast mounted on Exos Aerospace tethered rocket

Discussion and Summary

Suspensions of particles in liquid appear to be the best laboratory scattering medium for validating the multi-wavelength particle sizer. Several image artifacts and challenges must to be addressed to obtain accurate exponential decays. The images of the beams are not straight due to aberration in the camera lens. The images of the beams are usually not along a single row of pixels, making pixel counting non-trivial. The beam intensity needs to be integrated across slices perpendicular to the beam propagation to improve the signal to noise ratio (SNR) in the desired data. The beams are not parallel due to pointing uncertainties. Foreshortening makes the relationship between pixel number and physical distance non-linear. Foreshortening causes each length element of beam integrated by a pixel to increase with distance. Perspective causes parallel beams to converge in the image as distance increases. Perspective causes the beam to appear narrower with distance from the source. The actual beam width increases with propagation distance due to diffraction. Scattering also causes the beam to spread. The received intensity of scattered light from a given length element decreases as inverse distance squared. The scattered intensity is polarization dependent. The received intensity depends on the angle the scattered light makes with the beam direction. The angle dependence of scattering depends on the particle size distribution and polarization. The camera's dynamic range needs to be adjusted to avoid saturation yet remain sensitive to weak signals. The camera's dynamic range may need to be adjusted in real time due to changing scattering conditions. The camera's responsivity is wavelength dependent. The individual lasers at different wavelengths have different optical powers. The raw data comprises a large number of high resolution files of large size, while the desired information to be extracted comprises files of much smaller size. All of these challenges are solvable with the aid of laboratory experimentation and flight testing. In Summary, our laboratory validation studies are supporting the feasibility of an instrument to image laser propagation decay and to obtain decay constants at multiple wavelengths in lunar-lander dust plumes. Results of lander-mounted EjectaBLAST will provide particle size distributions to inform modeling of the plume-surface interactions on the Moon

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Reference: Immer, C. D., Metzger, P., Hintze, P., Nick, A., and Horan, R. "Apollo 12 Lunar Module Exhaust Plume Impingement on Lunar Surveyor III." Icarus 211, 1089 (2011).