Lunar Levitation Dust Instrument for a Lander: Investigating Electrostatic Dust Transport on the Moon

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Introduction: Dust levitation on the lunar surface, first observed by Surveyor 6 as horizon glow at the terminator (see Fig. 1), remains a significant challenge in understanding electrostatic dust transport mechanisms. The study of lunar dust is critical due to its potential hazards for surface operations, including optical degradation of scientific instruments, lunar based astronomy, increased wear on mechanical components, and risks to astronaut health [1]. Furthermore, understanding dust dynamics is essential for the success of future lunar exploration missions, including the Artemis program and the establishment of long-term lunar bases.

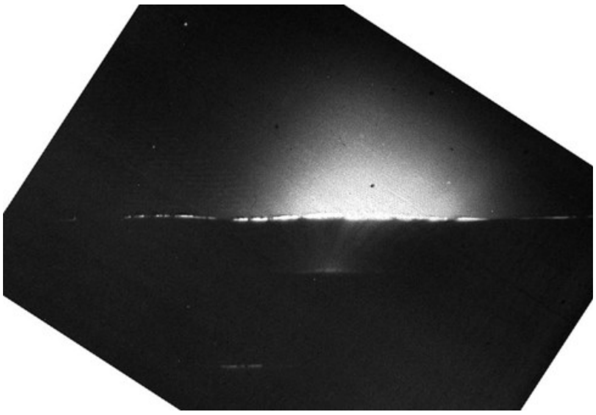

Figure 1: Surveyor 6 image showing a glow on the western lunar horizon after sunset. This phenomenon is caused by sunlight forward scattering at dust paricle clouds, known as "Horizon Glow" [2].

This research presents the theoretical framework, instrument development, and initial experimental validation of a dedicated lunar dust levitation detection system designed for deployment on a lunar lander. The instrument utilizes a 532 nm pulsed laser in conjunction with a stereo camera system to detect and characterize levitated dust particles within distances of up to 10 m. The targeted particle size range extends from 1 to 20 µm, with the potential to detect larger particles. The theoretical framework incorporates electrostatic charging, which is mainly by local plasma environment, photoemission of electrons due to solar Ultraviolet (UV) and X-rays, and lofting mechanismsas well as particle dynamics to model the size distribution and motion of dust in the Moon's near-surface plasma environment. The generated electrostatic surface potential accelerate dust particles of certian size which are then lofted above the surface and launched into sheat the region with upward velocity, as described in the dynamic fountain model of lunar dust [3]. Following to the work, we calculate the maximum height (Z_{max}) (see Fig. 2) reached by dust particles of micron range (1-10 µm) and the exit velocity at the top of the sheath (V_{exit}) (see Fig. 3) for the cases of fast and slow solar streams [7]. It is observed that only under fast solar streams the particles gain the required electrostatic potential to escape the sheath.

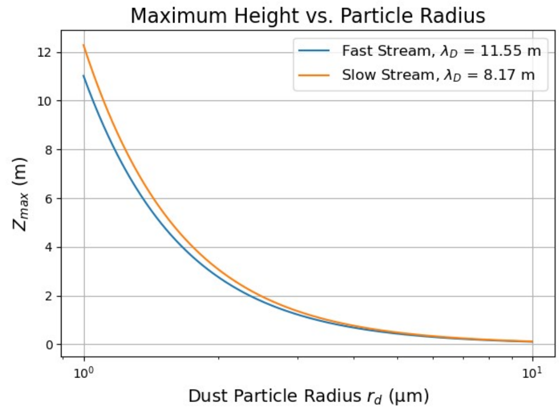

Figure 2: *: Maximum height dust particles travel while following the ballistic trajectory. Calculated for the cases of Fast and Slow Solar stream. Smaller particles go higher as they posses higher charge-to-mass ratio. λ_D is the Debye length in meter.*

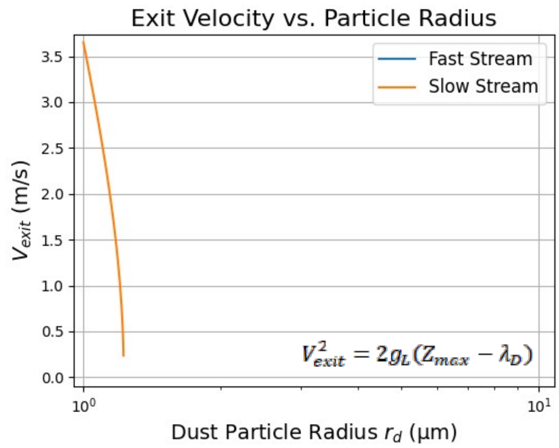

Figure 3: *: Exit velocity at the top of the sheath region. Only particles that follow the condition $Z_{max}>\lambda_D$ have been plotted.*

Supporting calculations predict the expected trajectories and distribution of levitated dust under varying surface conditions and solar zenith angles [3]. Signal-to-noise ratio (SNR) estimates indicate that reliable detection of particles larger than 1 µm is feasible at distances of up to 5 with an SNR of larger than 10 (see Fig. 4).

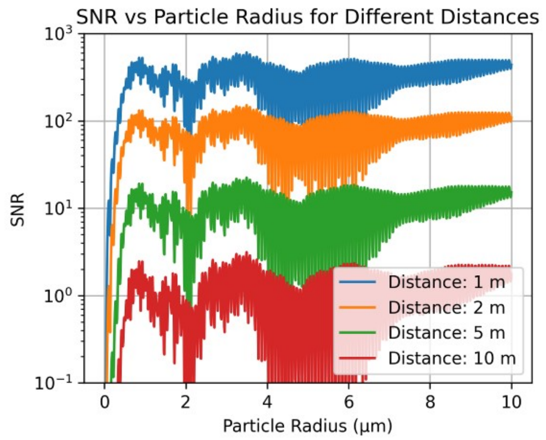

***Figure 4**: Calculated SNR for different distances between instrument and particle using a 532 nm laser beam, 1 mJ, 34 mrad and a 40 mm aperture objective lens. The complex refractive index of the particles is assumed to be 1.56-0.01j [5].*

Experimental Setup: The experimental setup comprises a commercial diode-pumped solid-state (DPSS) laser operating at 532 nm with a pulse energy of 1 mJ and a pulse length of 1 ns. The laser beam is expanded to a diameter of 10 mm with a divergence of 34 mrad. The detection system employs a Thorlabs CMOS camera with a 3.5 µm pixel pitch, coupled with an objective lens featuring a variable F/# to test different depths of fields. To determine the three-dimensional position of dust particles, a novel four-mirror-assisted single-detector stereo vision system is implemented [4]. Laser and camera are synchronized by a signal generator which triggers both units. The camera operates in global shutter mode at frame rates of 35 fps (full sensor) and of up to 800 fps for regions of interest (ROI). The experimental validation of the breadboard concept is performed under controlled conditions, demonstrating the feasibility of laser-stereo imaging for tracking levitated dust particles.

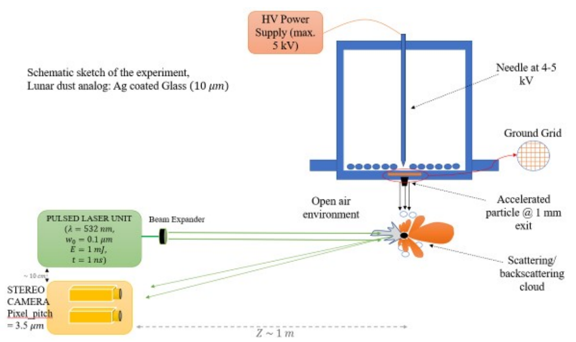

***Figure 5**: Schematic of the experimental setup for dust particle detection. The green laser is sent out, scattered at the particles and captured by a stereo camera for determination of the position in space*

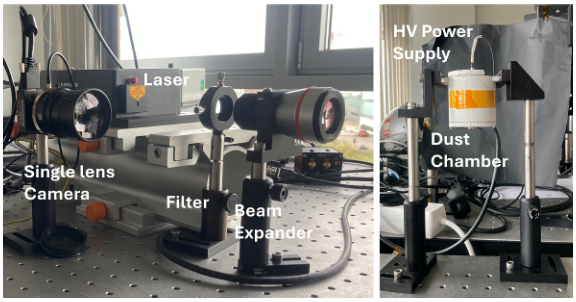

***Figure 6**: Experiential Lab-setup with a single lens camera and pulsed laser unit on the left side and 3D-printed dust chamber with dust source inside kept on elevation from surface on righ side, ~1 m distanced from Laser. Dust Chamber is connected to a 5 kV High-Volatge DC Supply. The Signal Generator connected to Laser power source is placed behind the camera.*

A dust source provided by the University of Stuttgart generates defined particle streams composed of 10 µm Ag-coated SiO_2 spheres. Planned experiments incorporate particles of varying sizes and materials [6]. Initial results confirm the successful detection of micron-scale particles and validate the technical feasibility of the instrument concept. The data collected will be used to refine the detection algorithms and improve the accuracy of dust characterization in future tests. The schematic setup of the experiment is shown in Fig 5. and actual setup is shown in Fig. 6.

Summary and Conclusions: Future work will focus on enhancing the detection algorithms for the particles in the images, tracking particle movement, optimizing data processing techniques, and adapting the instrument for integration into a compact 1-2U payload for lunar deployment on a landed platform. This research contributes to a deeper understanding of lunar dust transport phenomena, with implications for the design of landers, surface operations, planetary exploration, and the development of mitigation strategies to protect future missions from dust-related hazards.

References: [1] Horányi M. et al. (2024) Phil.Trans. R. Soc. A 382: 20230075. [2] Colwell et al. (2009) ASCE 0893-1321. [3] Stubbs et al. (2005) j.asr.2005.04.048. [4] H. Luo et al. (2021) Measurement 186, 110083. [5] Davis, S. et al. (2013) PSS 90 (2014) 28–36. [6] Li, Yanwei et al. (2023) Appl. Sci. 2023, 13, 4441. [7] T.J. Stubbs et al. (2014) PSS 10-27