Understanding the Impact of High-Velocity Dust Due to Lunar Landings

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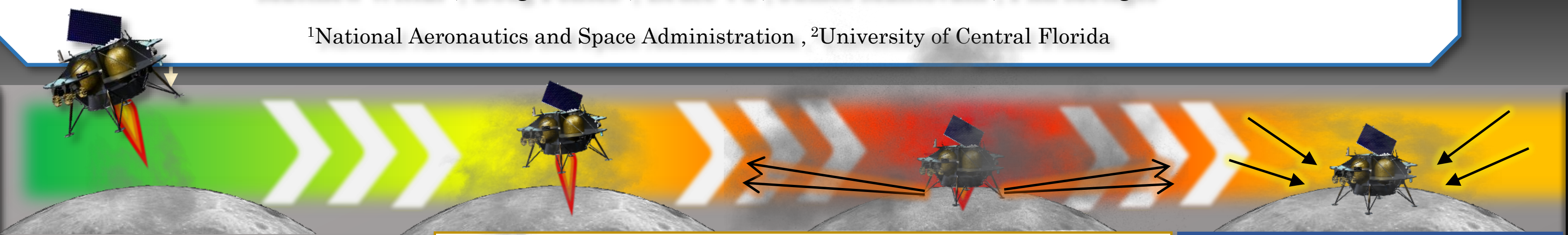
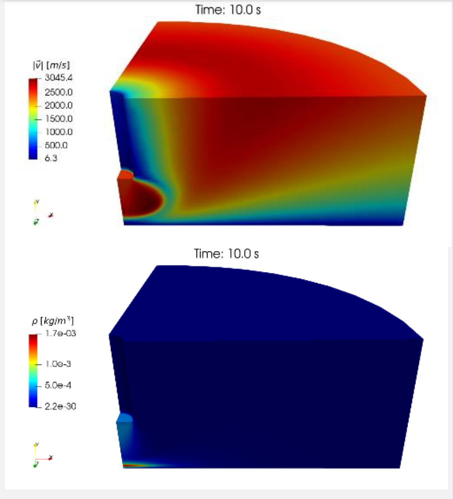


Preparing for Artemis - GMRO

The Artemis program intends to land the first woman and next man at the south pole of the moon by 2024. The Granular Mechanics and Regolith Operations (GMRO) lab has been working on understanding the physics and behavior of lunar dust. Specifically, we have an interest in both understanding the dust generated by landing plumes and finding ways to mitigate that dust to prevent damage to surface systems, orbital infrastructure, and the Apollo Heritage Sites.

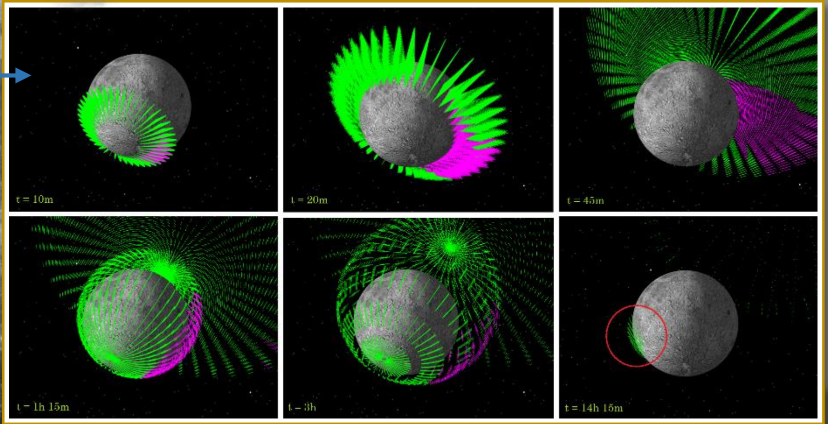
The Challenges of Lunar Dust

Unlike dust on Earth, lunar dust is especially fine and abrasive. Without an atmosphere to slow it down, dust can be accelerated to extremely high speeds both from impacts and lunar landing plumes. By combining observations of displaced regolith from Apollo and Surveyor landers with CFD simulations, we are able to mathematically describe the behavior of the dust both in terms of velocity and volume. Furthermore, the distribution of velocities can befitted to size distributions to determine the amount of mass displaced as a function of velocity, the particle size distribution of that mass, and the ultimate destination of those particles. With that completed, the next steps are to analyze the impact of this high-velocity dust and increase the fidelity of the simulations. Finally, plans exist to deploy instruments to the surface to better understand an characterize this behavior.



FreeFlyer Simulation

The software used for this simulation was a.i. Solutions' FreeFlyer. Each simulation included over 20,000 particles grouped in a formation. The purple particles are in shadow, and the red circle indicates some particles that have entered into a temporary orbit.



Initial Conditions

Based on data obtained from Apollo and Surveyor missions in addition to CFD work performed both at KSC and UCF, the initial conditions of the particles were constrained to between 1 and 3 degrees above the horizontal at the impingement point and a velocity range of between 1.5 and 2.7 km/s.

Calculating Mass & Velocity

Building on the work of Housen & Holsapple (2011), Lane & Metzger (2016), and Metzger (2020), three parameters were combined to provide a global estimate of displaced mass as a function of lander mass, particle size as a function of velocity, and total Mass exceeding a given velocity. Given these metrics, Wittal et al (2020) was able to determine the number and size of dust particles estimated to be found at any given position and time following a lunar landing.

Apollo 11 Heritage Site

Assuming a featureless surface, there exists no point on the moon which would completely eliminate all impacts at the Apollo 11 site. However, because most dust is constrained as described above, it was found that the vast majority of dust does not reimpact near the Apollo 11 site when landing near the south pole.

Core Assumptions

The following assumptions were made in order to constrain and simplify the problem:

- The moon is approximated as an oblate spheroid with no surface features
- Considered only Sun, Earth, and Moon gravity.
- Particles are approximated as spheres with uniform density
- Particle density was approximated as 1500 kg ·m^-3
- Particle collisions were not considered

More details & animation at:

https://www.youtube.com/watch?v=lV-gWDzNWew&t=14s

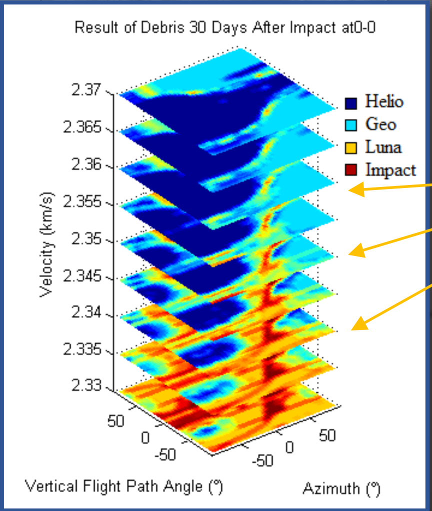
Charged Lunar Environment

The lunar environment experiences electromagnetic forces from a variety of sources. Constraining all of these forces proved to be difficult due to the dynamic nature of the problem. This problem was simplified by assuming a constant solar flux and Earth magnetotail. Particles were assumed to have a charge of 1 µC·m^-2.

The charge dynamics in this simulation include:

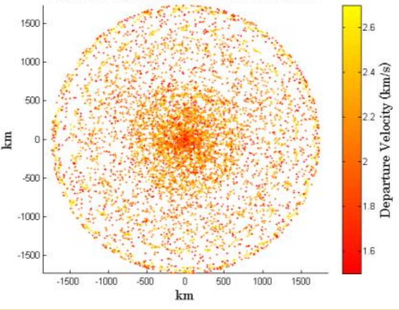
- Particle charges
- Surface charge
- Solar wind
- Earth's magnetotail

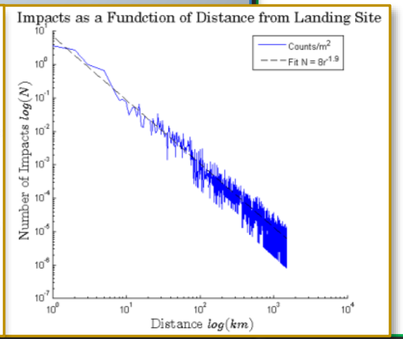
These charges vary over time and space, making study of these phenomena and their interaction with dust challenging.



Reimpacting Dust

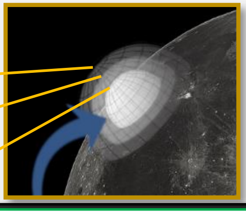
It was found that dust that reimpacts the surface after completing at least one orbit does so preferentially close to the landing site (below, left), with a chance of reimpact following a power law (below, right).





Ejecta and Dust in Orbit

The slice plots represent domes of constant velocity, where each slice maps the surface of a hemisphere of debris trajectories at a given velocity to their corresponding destination. Prior work has shown that a significant amount of debris may end up in orbit, depending on initial conditions



Results & Future Work

After running many simulations, it became clear that the risk of damage to the Gateway was negligible, with only ~18 particles for any give 1000 cubic kilometers during the first perilune passage after a south pole landing.

However, the frequency of reimpacts near the landing site was considerable and depends on the mass of the lander as follows:

$$L_I(r) = (-0.00085M_{\text{Lander}}^2 + 0.39M_{\text{Lander}} + 3.9)r^{-1.9}$$

based on simulation data M_{Lander} is the lander mass and r is the distance from the landing site. For example, as many as 8 impacts per sq. km. should be expected 1km away from the landing sight for a 40t Artemis lander.