

# Trajectory Model of Lunar Dust Particles



Site Preparation  
and Excavation

The goal of this work was to predict the trajectories of blowing lunar regolith (soil) particles when a spacecraft lands on or launches from the Moon. The blown regolith is known to travel at very high velocity and to damage any hardware located nearby on the Moon. It is important to understand the trajectories so we can develop technologies to mitigate the blast effects for the launch and landing zones at a lunar outpost. A mathematical model was implemented in software to predict the trajectory of a single spherical mass acted on by the gas jet from the nozzle of a lunar lander. As initial conditions, the trajectory calculation uses the particle diameter  $D$  and initial position of the particle  $r_0 = (x_0, y_0, z_0)$ , where the vertical direction  $x$  is positive up and equal to zero at the surface. Typically, the user sets the particle's starting position above the surface as  $x_0 = D/2$ .

The model uses an input file that contains data for the forces created by high-velocity gas flow. The model can use data in either of the following formats:

**Two-dimensional:** Based on cylindrical symmetry, in this format, the problem is set up to be independent of the azimuth angle. The two-dimensional data used in this project was created by computational fluid dynamics (CFD) software.

**Three-dimensional:** The full three-dimensional case makes no assumption of symmetries. Three-dimensional data was created with Direct Simulation Monte Carlo (DSMC) software, which uses probabilistic simulation to solve the Boltzmann equation for fluid flows. Individual molecules are moved through a simulation of physical space in a realistic manner that is directly coupled to physical time such that unsteady flow characteristics can be modeled. Intermolecular collisions and molecule-surface collisions are calculated by means of probabilistic, phenomenological models. The DSMC method assumes that the molecular movement and collision phases can be decoupled over periods shorter than the mean collision time. Figures 1 and 2 show simulation model geometry on the lunar surface with corresponding simulated craters.

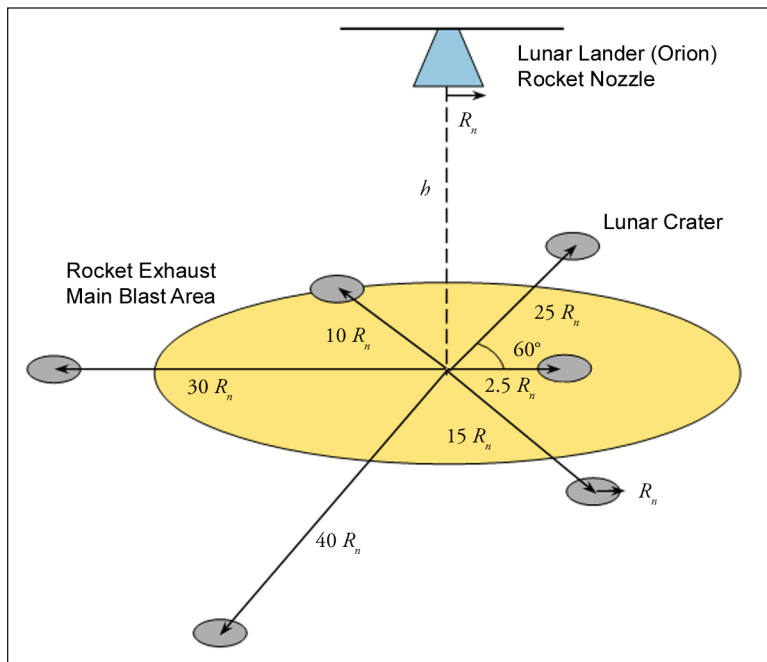


Figure 1. Three-dimensional simulation geometry with equal-size craters at varying distances from the rocket blast center.

For a particle of diameter  $D$  and mass  $m$ , the trajectory from drag can be estimated by a Taylor series expansion about time point  $k$ , resulting in a set of discrete-difference equations for position and velocity, using constant lunar gravity  $g_L$  and lunar soil particle density  $\rho_L$ . The CFD/DSMC output provides estimates of gas density  $\rho(\mathbf{r})$  and gas velocity  $\mathbf{u}(\mathbf{r})$ . These values are interpolated from the CFD/DSMC grid by the identification of the nearest grid neighbors around the  $k$ th trajectory point and the application of an N-dimensional interpolation algorithm. See Figure 3.

The coefficient of drag,  $C_D$ , is a function of the computed Reynolds number,  $R_e$ . Lift acceleration caused by the vertical gradient of the horizontal component of gas flow is also computed, with the use of an estimated coefficient of lift,  $C_L$ . Since particle lift and drag coefficients (especially lift) are unknown at these high Mach and rarefied flow

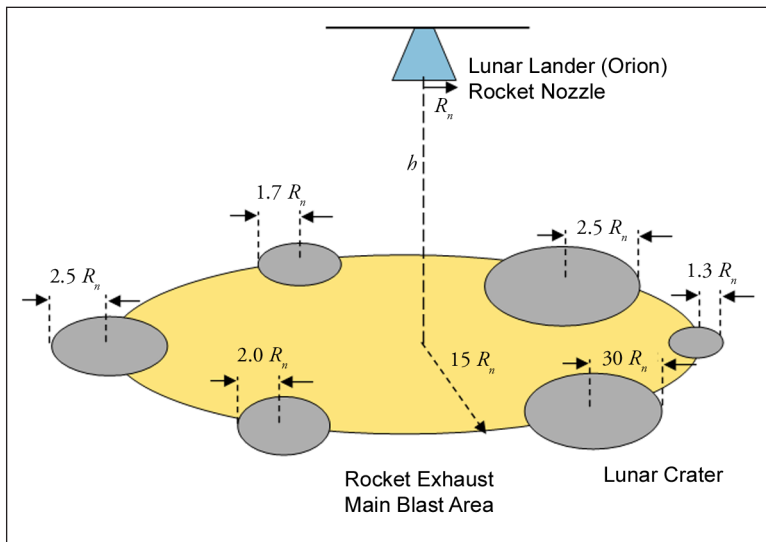


Figure 2. Three-dimensional simulation geometry with varying crater sizes at equal distances from the rocket blast center.

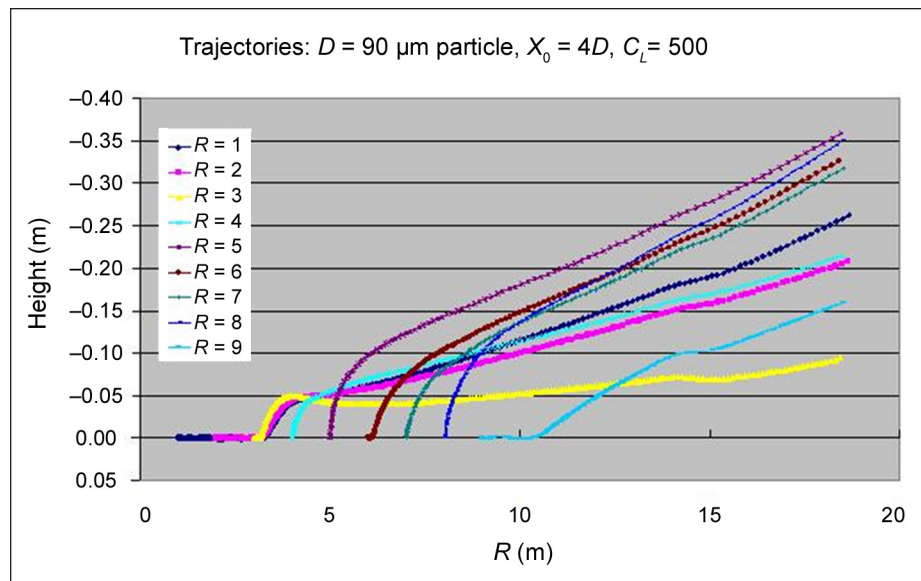


Figure 3. Trajectory plots of 90- $\mu\text{m}$  lunar dust particles initialized to varying distances from the rocket blast center.

conditions, the simulation results for various particle sizes and trajectory angles are adjusted ad hoc to match Apollo video photogrammetry.

The gas properties, density, velocity vector, and temperature predicted by the CFD/DSMC simulations allow us to compute the forces on a single particle of regolith. Once these forces are known, the trajectory path and velocity of the particle are computed. Note that all calculations of trajectory assume that the duration of particle flight is much shorter than the change in gas properties. In other words, the particle trajectory calculations take into account the spatial variation of the gas jet, but not the temporal variation. This is a reasonable first-order assumption.

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