Ejecta Assessment for Optimizing Natural Landing Pad Selection

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Background

As more permanent infrastructure and presence are established in pursuit of lunar resources, we must develop strategies to acquire and maintain access to regions of interest (ROI), including priority landing sites. Plume Surface Interaction (PSI) presents a challenge regarding safety near natural landing sites (sites with no constructed landing pad). Regolith particles, primarily less than a millimeter in diameter, traveling at high speeds (possibly exceeding lunar escape velocity) can directly impact and damage nearby terrain and existing infrastructure.

Historically, this phenomenon occurred when regolith ejected from the Apollo 12 lander resulted in significant pitting and erosion of the Surveyor III lander, approximately 155m away [1]. Figures 1 and 2 show the resulting damage to Surveyor III.

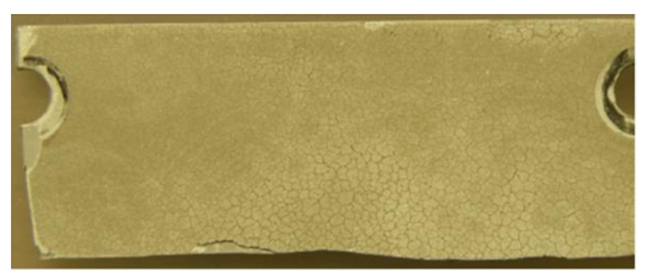

Figure 1. Pitting and cracking shown in color differences in returned portions of Surveyor 3 [1]

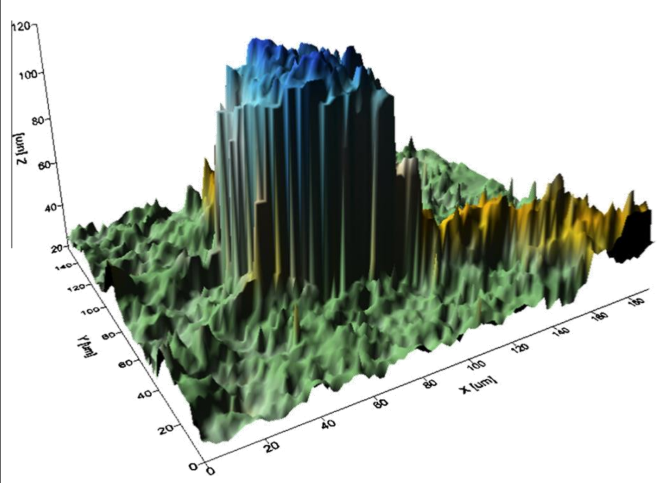

Figure 2. An example pit modeled from returned portion of Surveyor 3 [1].

This project aims to develop a tool that will provide a safety index in the product form of an aerial map overlay. Given a landing location, the overlay will show the comparative risk from a lander within a given radius of the landing site. Inversely, if we have a location we wish to protect, the overlay can show all landing locations that minimize the ejecta risk within a given radius of the protected site.

In the absence of constructed landing pads to mitigate ejecta, this tool would allow for the optimization of natural landing pad selection as well as the selection of sites for planned infrastructure development.

Initial Model Setup: Digital Terrain Model & 2D Cross-Section

Using the Apollo 12 landing scenario as a proof of concept for our index tool, we acquire the high-resolution Digital Terrain Model (DTM) of the Apollo 12 landing site from LRO NAC [5]. We estimate the particle size distribution from [3] & [4] and the initial particle velocity from [2] & [4]. We assume an isotropic distribution of particles radially from the landing site and a velocity distribution as a function of particle size estimated from [2]. We used a simplified ballistic trajectory model, treating the regolith as a collection of individual spherical particles that follow ballistic trajectories without complex interactions such as collision with other particles or plume entrainment. After constructing an array of the DTM (Figure 3), we determine whether the trajectories of particles, by size, are impeded by existing terrain. Figure 4a shows a cross-section of particles ranging from 0.6μm to over 1cm launched at an angle of 3˚ at a 315˚ azimuth, replicating the estimated trajectory angle and direction of ejecta toward Surveyor III. Figure 4b, shows the potential ground surface damage of particles binned between 2.5 – 4.3mm.

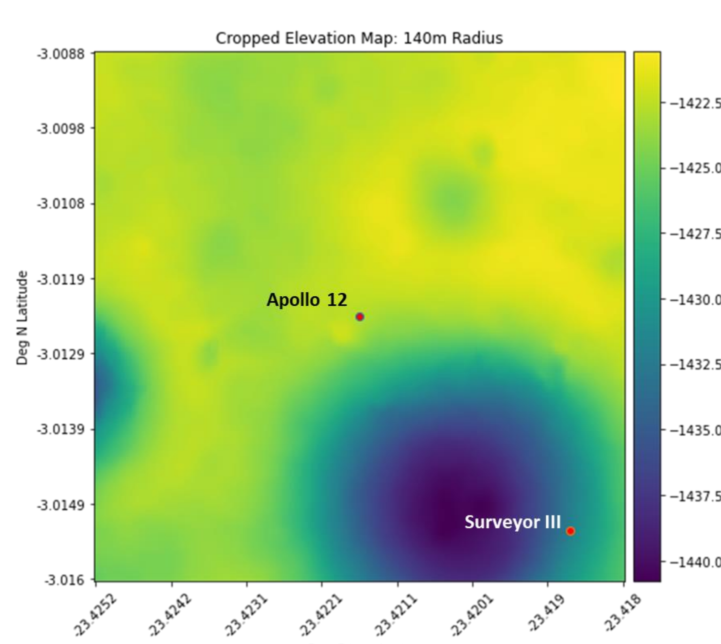

Figure 3. LRO NAC DTM cropped as a 2D array of elevation values. LRO NAC spatial resolution is 2 meters per pixel (mpp).

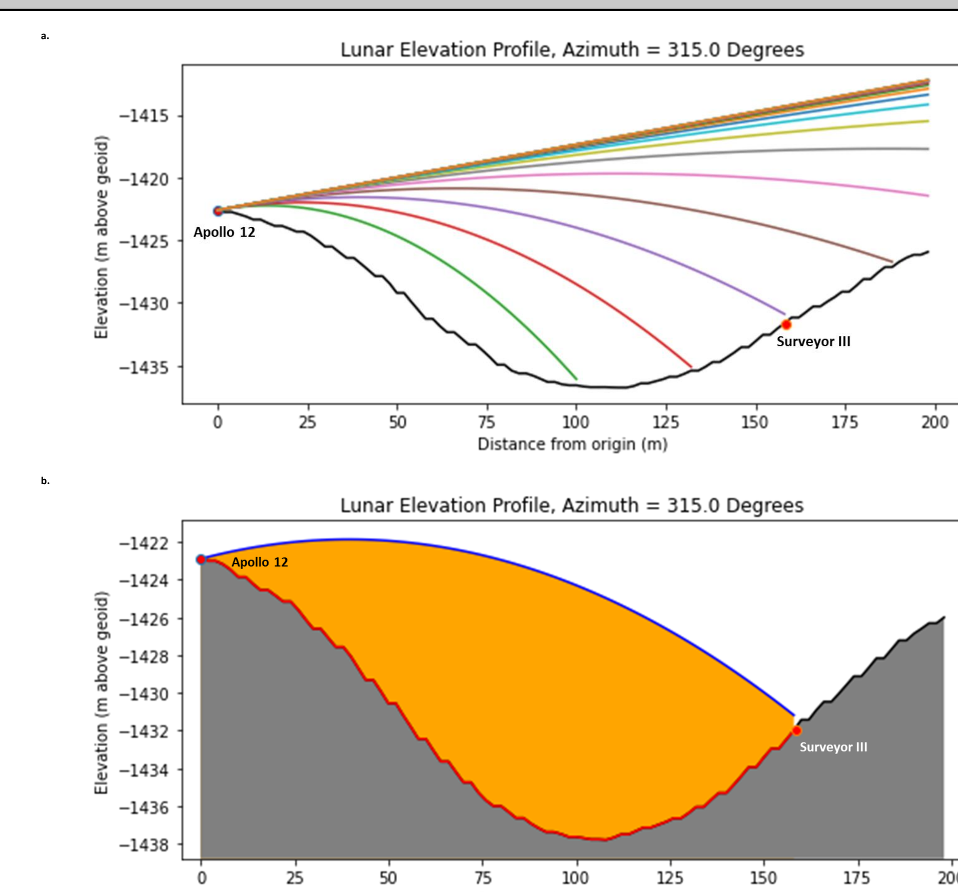

Figure 4. (left)

(a) Trajectories of 20 different particle sizes between 0.6μm and 1.2cm launched at a directional azimuth of 315˚ at a launch trajectory angle of 3˚.

(b) Trajectory of particles binned between 2.5 – 4.3mm. Red outline shows the ground surface susceptible to impact damage from particles of these sizes launched at 3˚.

Results

Our index model aims to take the 2-dimensional cross-section seen in Figure 4 and apply it 360˚ around the landing location and radially outward to a specified radius of analysis. We restrict the DTM array to only the points (pixels) within the radius (Figure 5a). Using a particle distribution with a set number of bins, we look at the size and corresponding velocity of the smallest particle in each bin. We use a set trajectory angle of 3˚ to determine the trajectory model of each sized particle. Comparing this trajectory model to the elevation at every point within the radius allows us to determine if a particle of a certain size will travel to or beyond that point. If it does not, we further restrict the array to include only the points where a particle of that size could land (Figure 5b).

For our index model, we have chosen to assess the index as a function of impact momentum. Impact momentum is defined as the product of a particle's mass and velocity. Assuming a spherical particle and a grain density of 3100 kg/m³, we associate each particle size with a momentum value. The total momentum at a given pixel would be the sum of the product of the number of particles landing in that pixel and their momentum value. We could estimate the total number of particles blasted by Apollo 12 using [4], but to decrease the computational complexity, we assume a total of 1e6 particles.

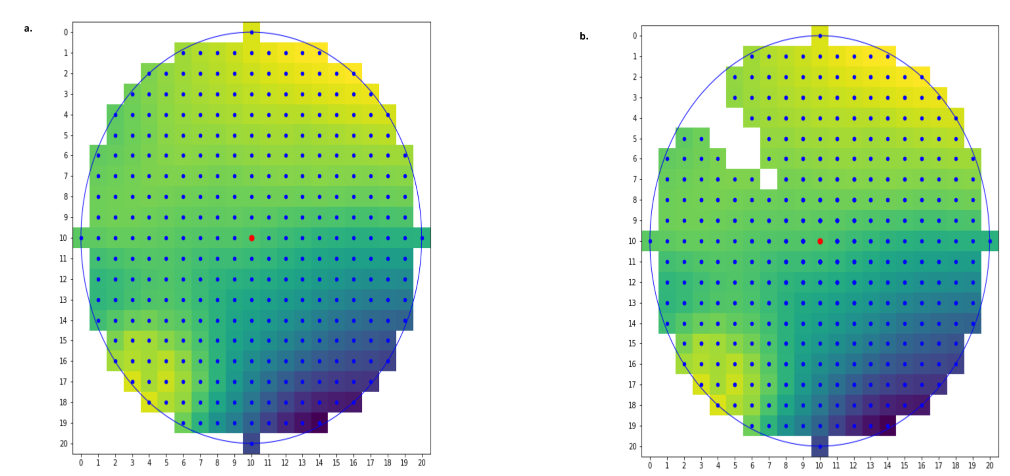

Figure 5. (a) DTM is restricted to points within 20m of A12. (b) DTM restricted to points accessible to 320μm particle at 3˚ launch angle.

The updated index product is an overlay of the ejecta assessment within the specified radius (Figure 6). The index values are the log of the summed momentum values at each pixel. A higher index value represents higher damage potential from ejecta.

Inversely, the index tool also provides the ability to protect locations. Figure 7 is centered on Surveyor III. Each pixel's index value now represents the ejecta damage potential to Surveyor III from landing at that point.

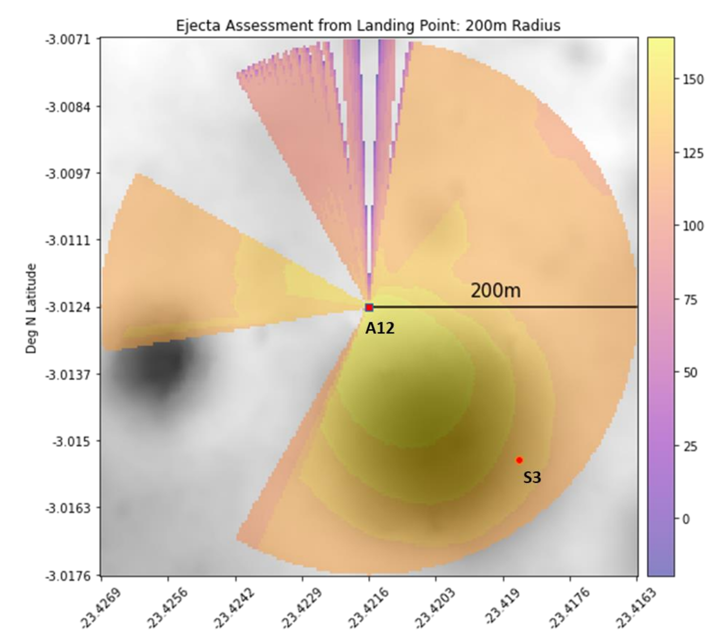

Figure 6. (left) Centered on the Apollo 12 landing site, the index overlay shows the potential damage done by regolith ejecta within 200m of the landing site.

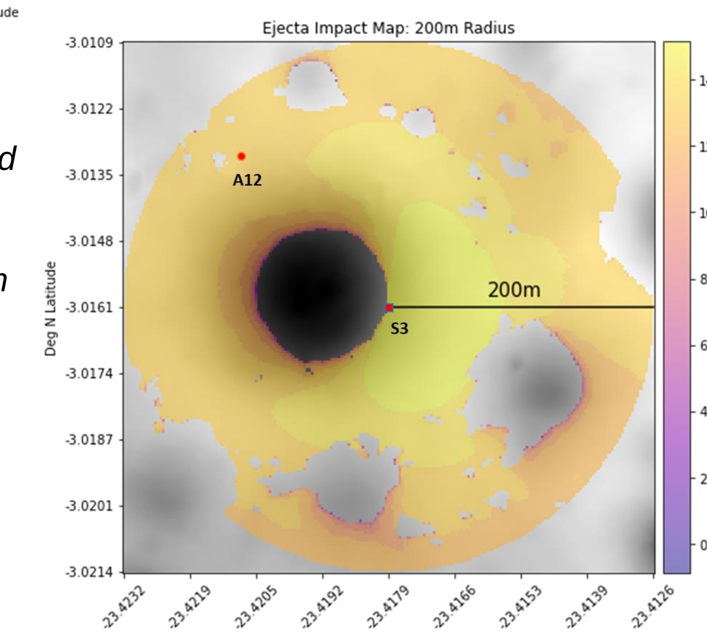

Figure 7. (right) Centered on Surveyor III, the inverse index shows the damage done to S3 from landers landing at any point within 200m of S3. The optimal landing locations are those with no index value presented.

Discussion

Current trajectory models, even simplified ballistic models, are computationally intensive and therefore time consuming. The creation of an index tool that can efficiently map the comparative safety and hazards presented by PSI ejecta will visually assist planners in the downselection of landing sites within a desired distance from resource-rich ROIs and eventually extraction and processing infrastructure.

Inputting a particle size distribution currently poses a challenge, as such distributions can only be accurately estimated from returned lunar samples. [7] is currently working on a thermophysical model that would derive a global lunar map of regolith properties, including grain radius.

This tool also provides the capability of visually showing the benefits or drawbacks of infrastructure placement. Since the DTM is a simple 2D array of elevation values, we can simulate infrastructure by manipulating the elevation values in the array. For example, building a 10m long by 2.5m tall berm directly southeast of the Apollo 12 landing site would result in the overlay shown in Figure 8 with no apparent damage to Surveyor III. This could be optimized to show the minimum height of berms required to protect infrastructure or the maximum height of buildings allowed that would minimize their exposure to ejecta.

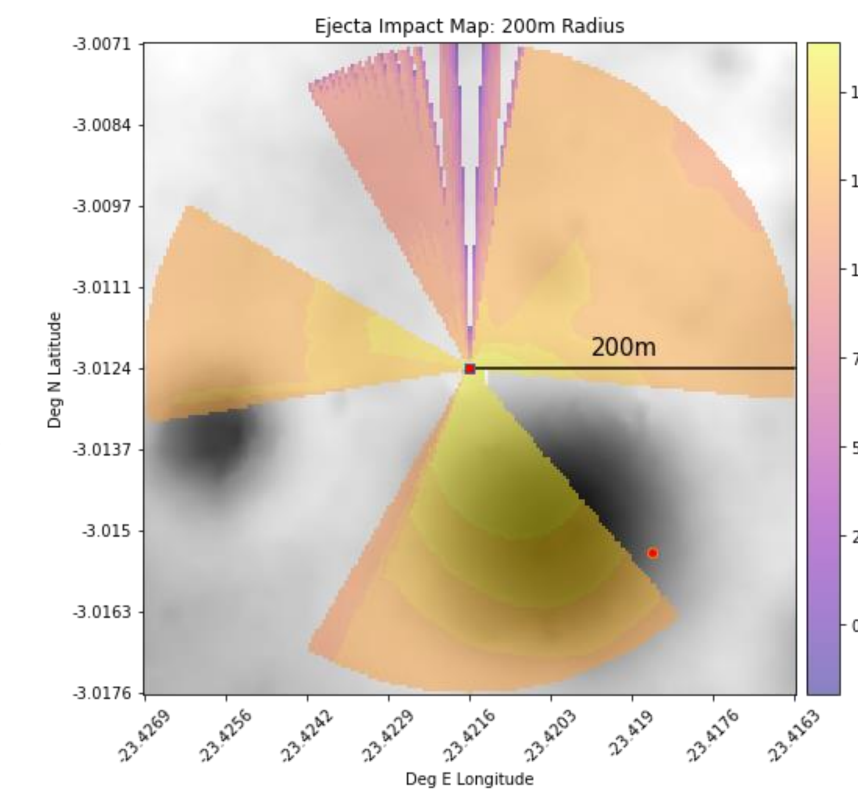

Figure 8. 10m x 2m x 2.5m berm, oriented N/S, constructed 10m SE of A12 landing site. A berm constructed at this location would have minimized damage to Surveyor III.

Conclusion

This index tool aims to provide mission planners with a simplified method of downselecting potential natural landing sites optimized toward minimizing localized erosion risks to terrain, infrastructure, and equipment. Ideally, a finalized version of this proposed tool would present a user interface that allows users to input the coordinates for the potential landing or protected site and the desired radius of analysis.

The tool would also allow for the construction of simulated infrastructure (e.g., berms or habitats) to analyze the benefits and drawbacks of protected and unprotected structures. If building material is known, the estimated penetration depth of pitting ejecta into infrastructure could also be estimated and used as an additional indicator of risk [6] (Figure 9). Another variable to consider as an input is lander type, which can influence the number of particles blasted from the landing site as a function of thrust [4].

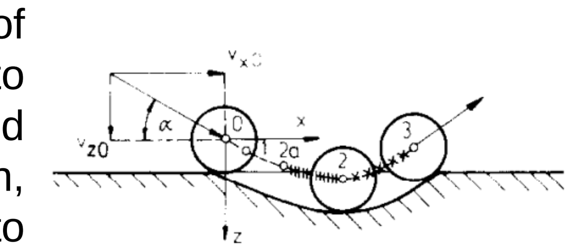

Figure 9. The path of a singular regolith grain penetrating infrastructure as modeled in [6].

References

[1] Immer et al. (2011), *Icarus, 211(2)*, 1089-1102. [2] Lane & Metzger (2015), *Acta Geophysica, 63(2)*, 568-599. [3] Graf (1993), *NASA Reference Publication 1265*. [4] Katzan & Edwards (1991), *NASA Contractor Report 4404*. [5] Henriksen et al. (2017), *Icarus, 283*, 122-137. [6] Beckmann & Gotzmann (1981), *Wear, 73(2)*, 325-353. [7] Bürger et al. (2023), *54th LPSC Abs. 1185*.