SPACEFLIGHT HAZARDS OF ESCAPE-VELOCITY-DOMAIN IMPACT EJECTA IN THE CR3BP

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As a consequence of planned/proposed human lunar activity, the long-term effects of lunar debris and ejecta resulting from large-body (> 1000 kg) impacts on the lunar surface is investigated. The Escape-Velocity-Domain (EVD) ejecta behavior is characterized in terms of destination, duration in lunar orbit, and total displaced mass. Likewise, the amount of mass sent into geocentric orbit is also characterized and assessed as a function of impact location in terms of time, lunar latitude & longitude, and impact angle. Finally, a threat analysis is performed on critical assets in Earth and Lunar orbit such as the ISS, artificial satellite infrastructure, prospective lunar surface structures & equipment, and the Deep Space Gateway now under construction.

INTRODUCTION

The ongoing development of the Gateway and Artemis programs again bring Earth's moon into the spotlight and with it comes concerns over the repercussions of that increased activity. Some of these concerns include the generation of debris and pollution in the lunar environment. Previous efforts to document lunar operations were undertaken by Johnson [6] in the late 90's and estimated that the Low Lunar Orbit (LLO) orbital debris risk is expected to be very low with spacecraft or spacecraft parts numbering well under 100. However, efforts must be taken going forward to maintain this relatively pristine environment

More recent exploration of the moon in the form of the LRO/LCROSS missions showed that the range of debris generated from an impact by a spacecraft with a mass of 2 mT a velocity of 9 km/s generate ejected debris at speeds at and possibly exceeding 5 km/s [1]. Such ejecta velocities raised concerns that this debris could pose a risk to Lunar infrastructure both in space and on the surface. This is of special concern to the Deep Space Gateway, a spacecraft now under construction and which has it's first component expected to be in orbit as soon as 2022. Should lunar impact be the selected disposal option for the Logistics Module, the resupply portion of the Gateway, or any other spacecraft, it may generate debris at a similar range of velocities and pose a hazard to the Gateway from which it departed.

Yet the impact of lunar ejecta as space debris has not yet been fully assessed. While characterization of craters [2] is well understood and a range of velocities has been established [1], the displaced mass at high velocity is subject to some dispute [2,4]. Furthermore, although the lunar orbital environment is very unstable for many types of orbits, there exist a plethora of frozen orbits

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in which debris may remain for some time given the opportunity [5]. The collision of relatively large spacecraft ($>$1000kg) with the lunar surface may also result in debris being introduced into geocentric orbit that could exacerbate existing concerns in Space Situational Awareness (SSA). This work seeks to investigate and quantify the debris generated by such collisions, and characterize their behavior after achieving Escape-Velocity-Domain (EVD) speeds.

GATEWAY AND LOGISTICS MODULE BACKGROUND

NASA's Gateway [11] will serve as a staging -ground in lunar orbit as crewed and uncrewed missions use it as an outpost to fly to the lunar surface, low lunar orbit, and beyond cislunar space. Additionally, Gateway will serve as a proving ground for technologies needed to further NASA's goal of putting humans on Mars. The Gateway will be constructed modularly as additional components are attached to the spacecraft over time [12]. The Gateway will fly in an L2 Near Rectilinear Halo Orbit (NRHO) around the Moon [13]. This orbit presents multiple vital advantages to the Gateway architecture, but the proximity to the Moon places the Gateway in a highly dynamic environment.

The Circular Restricted Three Body Problem

The Circular Restricted Three-Body Problem (CR3BP) models the motion of three gravitationally interacting centrobaric bodies – the Earth, the Moon, and a spacecraft in the current analysis – under a set simplifying assumptions. The model assumes that the mass of the spacecraft is negligible in comparison with the masses of the two larger bodies, called primaries. Consequently, the two primaries form an isolated two-body system. The model further assumes that this two-body system possesses zero eccentricity, i.e. the two primary bodies move in circular orbits around their mutual barycenter. The spacecraft then moves freely under the influence of the two circling primary bodies. The assumptions made in the CR3BP produce five equilibrium points – called libration points – L1, L2, L3, L4, and L5. While no closed form analytic solution exists for the CR3BP, a single first order integral of the motion is found and called the Jacobi Constant. The CR3BP model is autonomous and allows for periodic motion; both stable and unstable periodic orbits exist in families. Among these families is the L2 Halo Family.

Gateway's Reference Orbit

The L2 NRHOs are defined as the members of the L2 Halo family with bounded stability indices [14]. The current baseline orbit for Gateway is the NRHO in this family that possesses a period such that it is in a 9:2 synodic resonance with the Sun-Earth-Moon system [13]. An orbit with this resonance characteristic is called a Lunar Synodic Resonant (LSR) orbit. A p:q LSR orbit completes p orbits in q repetitions of the Sun-Earth-Moon geometry (around 29.5 days). Therefore, the period of the 9:2 LSR NRHO is around 6.5 days. The resonance of the 9:2 LSR NRHO is leveraged to nearly eliminate eclipses on the Gateway from the Earth's shadow, satisfying mission requirements on the duration of eclipses due to power and thermal constraints [13]. Therefore, while many lunar orbits, including Low Lunar Orbits (LLOs), experience consistent and long duration eclipses, the 9:2 LSR NRHO allows for consistent line of sight to Earth as well as ensuring the Gateway and Orion spacecraft are not shadowed longer than permissible. Beyond the eclipse characteristics, the baseline NRHO also yields relatively low transfer costs from Earth and low station keeping costs, as well as many opportunities to transfer to nearby orbits and the lunar surface [15].

Lunar Module Disposal Risks

As the Orion spacecraft brings crew to the Gateway for missions to the lunar surface and else-where, uncrewed Logistic Modules (LMs) will arrive to resupply the Gateway [16]. Following the rendezvous of an LM with Gateway and transference of supplies, the LM will be jettisoned to a safe destination. Boudad et. al explored the disposal of LMs into heliocentric space in [16] and Davis et. al expanded on this analysis in [12]. Alternatively, impacting the LM into the lunar surface provides an alternative to delivering the LM to heliocentric space. Lunar impact provides shorter, more predictable disposable trajectories and removes the concern regarding long-term uncertainty in trajectory behavior present in the heliocentric disposal case. However, lunar impact presents new issues. Ejecta produced by lunar impact must not present danger to the Gateway or any ground operations. Additionally, impacting spacecraft must avoid historical heritage sites on the Moon. This requires accurate and reliable prediction of the exact location of impact. Understanding of this risk provides a body of knowledge for comparison of disposal techniques.

Scope

This work encompasses small-to-moderately sized impacts anywhere on the lunar surface and focuses exclusively on the EVD debris. It is estimated that the moon is regularly pelted with small, marble-to-golf-ball-sized impacts throughout the year, the sum total of which is on the order of the thousands of kilograms [10]. However, these impacts themselves generate very little ejecta at or exceeding EVD speeds. That being said, the generation of dust at these speeds may itself be a concern. It was observed that during the Apollo landings the dust ejected from the lunar lander plumes exceeded escape velocity. Such particulates, however, lie outside the scope of this work.

As explained below, there is a large amount of debris generated below EVD speeds that is characterized by an extensive lunar footprint, and a modest portion of debris that exceeds EVD speeds that also end up in geocentric orbits that further pollute the Terran space environment. Although the focus of this work is to explore the ejecta specifically in the EVD range (2.33~2.37 km/s), the reader is encouraged to keep in mind that there is a up to 16 Mt of displaced mass faster than 2.37 km/s and 90 mT slower than 2.33 km/s and faster than 2.37 km/s that may also pose similar hazards given the opportunity, given the parameters below and assuming a 45° impact angle.

Assumptions

To understand where EVD ejecta goes, one must generate expectancy values for a given set of impact parameters. These values are achieved by performing bulk simulations that examine groups of ejecta across a range of departure vectors and how they perform relative to one another and under a range of conditions. Due to the vast parameter space of this problem (impact location, angle, ejecta angle and speed, impactor mass, Sun-Earth-Moon angle, among others not parameterized), it is self-evident that many assumptions must be made. Some assumptions are situation-specific, such as impactor properties detailed below. These assumptions are based primarily off of a combination of the work of Holsapple [2] and Artemieva [4], and are explained in Figure 2. Other assumptions are globally applicable, such as lunar surface properties. For example, it is assumed that the moon has a flat, uniform surface with uniform composition. Naturally, this is not the case but given a specific input point or mission-specific situation, these estimates can be refined.

Simulations are performed with the FreeFlyer software. The bodies considered in the simulation are the Moon, calculated with an eighth order zonal and tesseral gravitational effects, the Earth, a
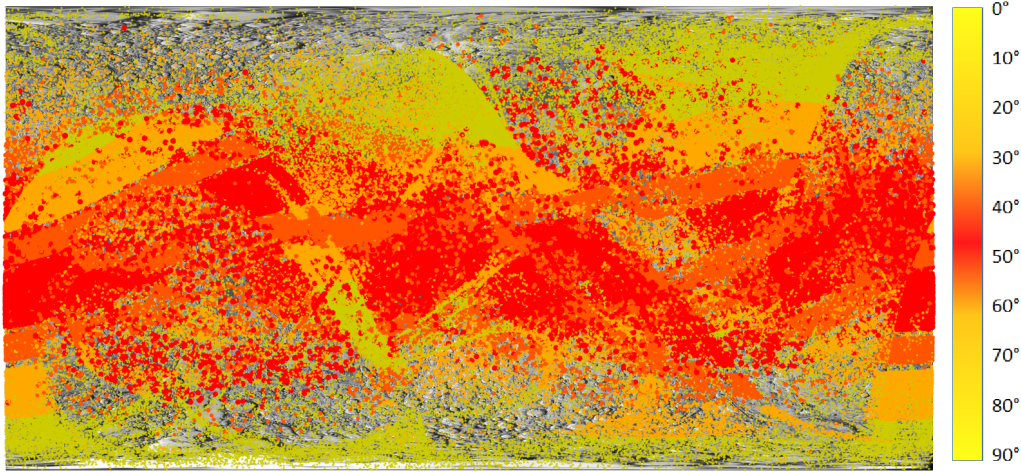
Figure 1. A high-fidelity plot of impact locations based on a departure velocity from NRHO of 1 m/s. Large, red impacts have a near-45° impact angle, while the small, yellow impacts are near-perpendicular or near-vertical

point mass, and the Sun, also a point mass but with solar radiation pressure considered.

Specifically, it is assumed that the impactor is a spacecraft with an 8000 kg mass impacting at roughly 2.5 km/s. Varying this mass and/or velocity within one order of magnitude does not significantly effect the estimated ejecta mass (it likewise remains within an order of magnitude, and could be refined on a mission-by-mission basis if needed), so these results are presumed to be applicable to most spacecraft impacting with the moon. For the mass estimates, it is also assumed that the spacecraft are impacting at or near a 45-degree angle. This stipulation arises due to a discrepancy between the presumed ejecta mass of Holsapple [2], which assumes a vertical impact, and Artemieva [4], which assumes a worst-case scenario, 45-degree impact. By simulating the impact location and angle of spacecraft with low-separation delta-V (1, 5, and 15 m/s) from the NRHO, one can gather an understanding of where and how it will reimpact the surface [9], as illustrated in Figure 1.
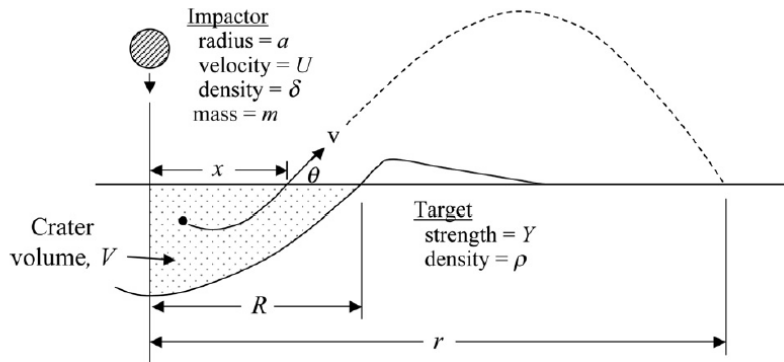
Figure 2. The first figure from [1] that defines the variables used in the method for calculating crater, ejecta, and impactor properties. In this paper, the properties of the impactor and target are known and described below.

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IMPACTOR

As stated above, the assumptions about the Logistics Module (LM) forms the basis for the impactor model. The LM is estimated to be 8000 kg in mass, have a radius of 2 m, and an impact velocity of 2.575 km/s as predicted from a scenario involving a ˜15 m/s burn at the apoapsis of the NRHO in the velocity direction. Characterization of the LM's porosity takes several assumptions into account. First, it is assumed that the "crumple zone" is created by the pressurized section is negligible at speeds on the order of kilometers per second. Second, it is assumed that the contents and structure of the LM are by-and-large incompressible, therein leading to the approximate material-dependent exponent of 0.55.

These assumptions are applied to all spacecraft/impactors in this study. However, if one observes alternative impact parameters such as meteoroids the mass of marbles (0.04 kg) traveling at 20 km/s as one might expect from the average lunar debris impact, predictably, the ejecta mass changes significantly. For example, assuming a 45-degree impact angle and a LM-like impactor, the displaced mass within the EVD is on the order of 40-60 kg. By comparison, the aforementioned marble at the same angle and assuming incompressibility generates only 2 milligrams at EVD speeds using this model. This fact is highlighed because of the aforementioned difference between regular, small, high-speed impacts with the sum total mass on the order of thousands of kg would generate about 10 kg of mass at EVD speeds over the course of a year, while a single impact of something like the LM at much slower speeds generates over four times as much debris within the EVD.
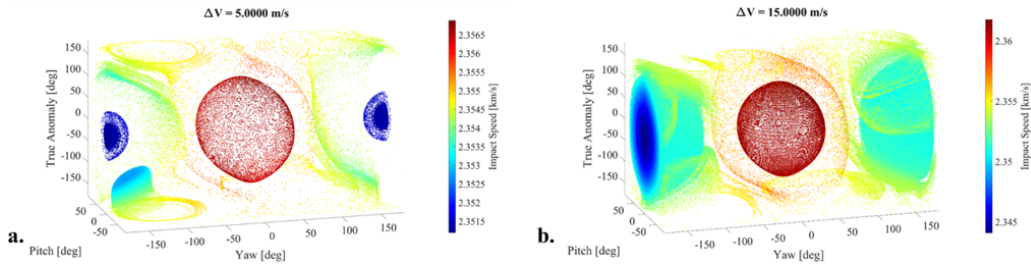
Impact Locations

As the Orion spacecraft brings crew to the Gateway for missions to the lunar surface and elsewhere, uncrewed Logistic Modules (LMs) will arrive to resupply the Gateway [16]. Following the rendezvous of an LM with Gateway and transference of supplies, the LM will be jettisoned to a safe destination. Boudad et. al explored the disposal of LMs into heliocentric space in [16] and Davis et. al expanded on this analysis in [12]. Alternatively, impacting the LM into the lunar surface provides an alternative to delivering the LM to heliocentric space. Lunar impact provides shorter, more predictable disposable trajectories and removes the concern regarding long-term uncertainty in trajectory behavior present in the heliocentric disposal case. However, lunar impact presents new issues. Ejecta produced by lunar impact must not present danger to the Gateway or any ground operations. Additionally, impacting spacecraft must avoid historical heritage sites on the Moon. This requires accurate and reliable prediction of the exact location of impact. Understanding of this risk provides a body of knowledge for comparison of disposal techniques.

The initial maneuver directions are decomposed into yaw and pitch using the Velocity-Normal-Binormal (VNB) frame at the departure location, and the impacting directions are colored corresponding to their impact characteristics. The impacting points at several departure locations colored corresponding to the impact angle are appear in Figure 3. Clearly, impact angle is highly sensitive to initial condition with nearby maneuver directions presenting unpredictable impact angles. Furthermore, all impact angles are represented. Structure is observed at higher departure maneuvers near periapse (TA = 0°). These structures correspond to burns in the anti-velocity direction yielding multi-revolution impact trajectories. While these structures do present ordered motion in the anti-velocity direction at low true anomalies and high maneuver magnitudes, prediction of the impact angle in the general case is impossible without explicit propagation. Therefore, ejecta study should incorporate the worst-case scenario for a given impact.
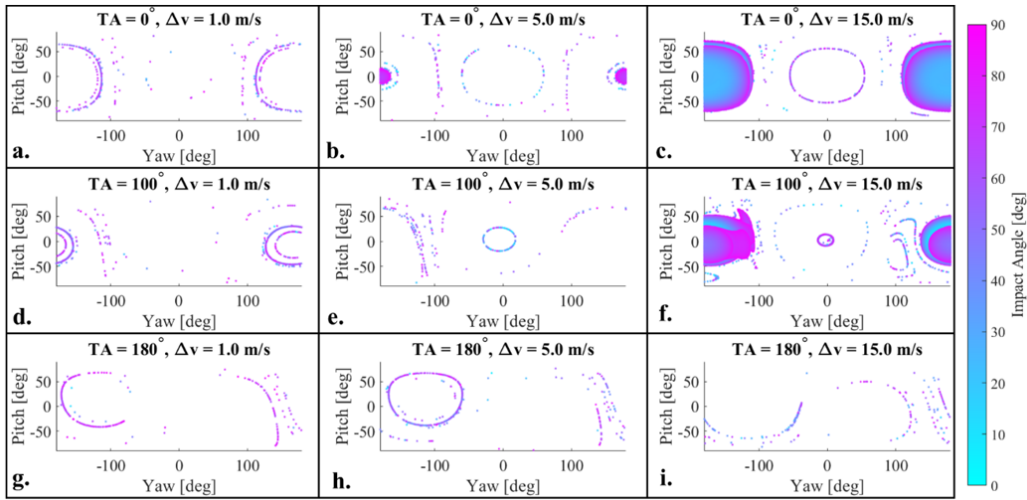
Figure 3. Impact angle maps for various departure locations and magnitudes around the NRHO.

In addition to impact angle, impact speed is of great importance for analysis of ejecta. Figure 2 displays the impact speed as a function of the departure pitch, yaw, and true anomaly in three-dimensional space for the 5 m/s and 15 m/s cases. Davis et al. present a method of bounding the impact speed resulting from departures of the NRHO in [7]. Impact speeds remain relatively constant between 2.34 km/s and 2.36 km/s for the analyzed departure maneuver magnitudes granting a higher level of predictability in the impact speed compared to the impact angle. Additionally, the regions of similar impact speed appear to be generally well defined in Figure 4, in contrast with the highly varying color observed in Figure 3

Figure 4. Impact speed for a) 5 m/s and b) 15 m/s burns off of the NRHO.

Along with impact angle and velocity, the location of impact plays a large role in the study of the ejecta. Figure 5 depicts the location of impact on the lunar surface colored by the impact angle. The latitude and longitude are defined with respect to the Earth-Moon rotating frame. It is observed that impact velocity around 2.355 km/s exist across the entire lunar surface for the analyzed maneuvers. Furthermore, at low maneuver magnitudes and near apoapsis, the impact location becomes highly chaotic and difficult to predict. For a true anomaly of 180° and a maneuver magnitude of 15 m/s, Figure 1i shows relatively few impacting trajectories, however, it is apparent in Figure 3 that these points cover nearly the entire lunar surface. This chaotic nature of impacting trajectories is typical of the multibody regime. However, at higher departure maneuver magnitudes, there exists two types of structures in Figure 5. The first structure is a high velocity impact group forming a horseshoe

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pattern in the northern hemisphere labeled with the green arrow. The other structures are the low-velocity impact streaks down the center of the maps labeled with the red arrows. The horseshoe and streak structures correspond to the ring centered around the velocity direction and the lobes in the anti-velocity direction in Figure 1, respectively. These two structures demonstrate relative predictability in impact angle, velocity, and location. Therefore, these structures may be of interest in the design of future impacting trajectories.
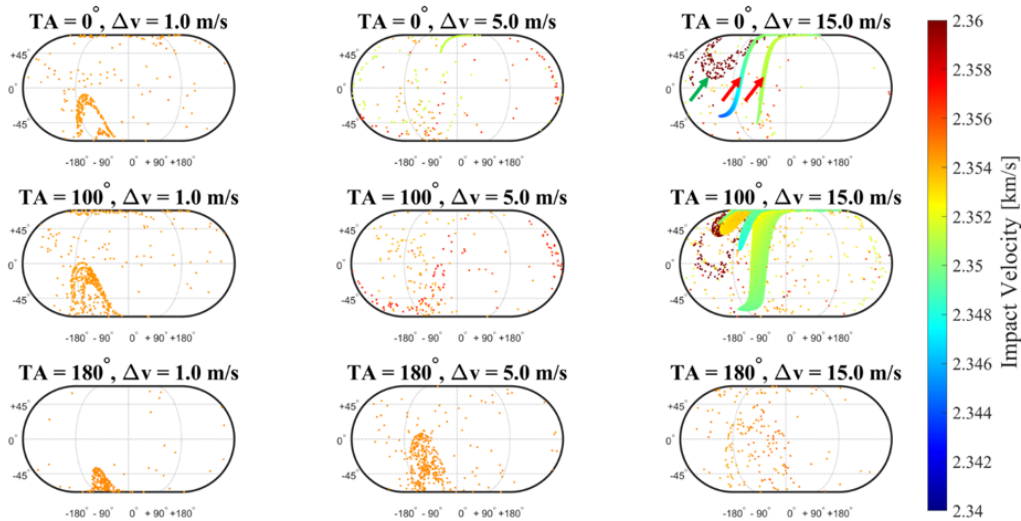
Figure 5. Impact locations on moon colored by impact speed.

While some structure exists, a large percentage of the impacting trajectory behavior is dominated by chaos. Impact velocity may be bounded as shown by Davis et al. [17], but angle and location present great challenges to the prediction of complete impact characteristics. Regions of structure exist and may be leveraged but without explicit control, consistency in behavior is not likely. Ultimately, the ejecta study should look at the worse-case scenario within the observed numerical results.

Impact locations are taken a six locations on the Moon at latitude and longitudes listed in the first two columns of Table 1. These locations were chosen to encompass a wide a range of impact locations around the moon.

Impact Analysis

The LM is assumed to impact the moon at a velocity of at least 2.4 km/s, which represents lunar escape velocity and the velocity with which LCROSS and GRAIL both impacted the surface. The Logistics Module would similarly have an estimated impact velocity of 2.475 km/s.

The methods outlined by Housen & Holsapple [2] are used to calculate the volume of ejecta. Figure 1 illustrates the definition of variables. The formula used to compute the volume determines the mass ejected faster than velocity threshold v in terms of the impactor (LM) properties. Those properties can be defined by a single constant:

$$C = aU^{\mu}\delta^{\nu} \tag{1}$$
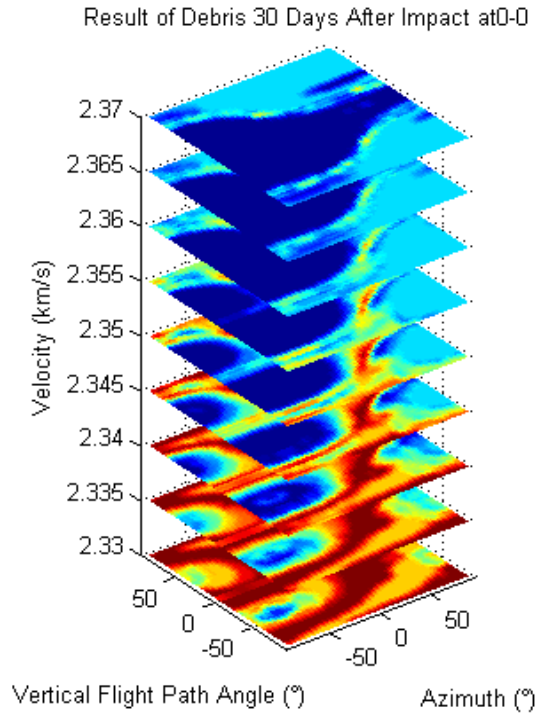
Figure 6. The resulting slice plot of determining the destination of debris at all azimuth and elevation angles and within the velocity regime that has the possibility of resulting in lunar orbit. This plot as taken at an RA/Dec of (0,0).

Where ν is a material-independent exponent valued at 0.4 regardless of material type [3], U is impactor velocity, δ is density, and μ is the material-dependent exponent and is a volatile variable. Considering the LM is not a porous object, but rather an amalgamation of mostly incompressible objects and fluids, the material-dependent exponent μ is left as 0.55 - the same as that of water or metal. The crater material constant of k, seen in equation 2 below, is taken to be 0.3, the average between the presumed extremes of 0.2-0.4, and what is given at the closest approximation of Weakly Cemented Basalt (WCB), the material of which the maria region (dark areas) of the lunar surface is composed.

$$M(v) = m \frac{3k}{4\pi} C_1^{3\mu} [\frac{v}{U} (\frac{\rho}{\delta})^{\frac{3\nu-1}{3\mu}}]^{-3\mu} \tag{2}$$

An examination of ejecta trajectories at near-escape velocities reveals a region of the parameter space of azimuth, elevation, and velocity in which ejecta remain in orbit for more than 30 days. This region appears at varying azimuth and elevation, but always at a velocity between 3.335 and 3.365 km/s.

However, it is apparent from LCROSS [1] that ejecta from the impact tend to have a maximum velocity of 5 km/s. Reasonably, ejecta velocities aren't asymptotic relative to mass, but rather have a finite maximum velocity based on impact conditions. The more kinetic energy, the higher the maximum speed. For the purposes of the current study, the velocity ceiling for modern-day spacecraft is assumed to be the same as LCROSS, since the range of possible masses may range from
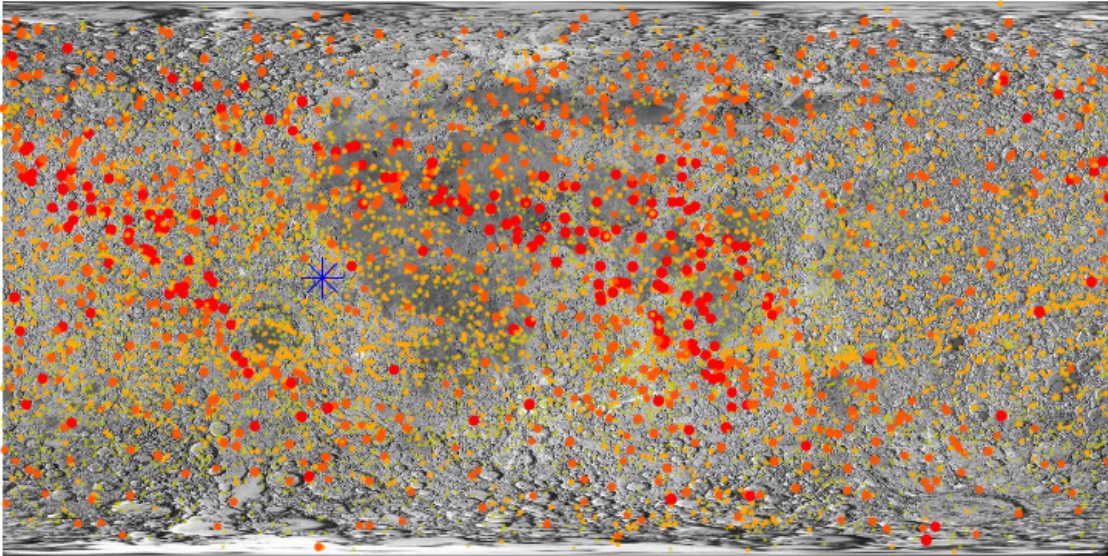
Figure 7. Reimpact locations of EVD ejecta impacting at a latitude and longitude of 0°N and 76°E (indicated by the blue star). The larger, red spots are higher likelihood if impact given an impactor angle of (45,0) for its azimuth and elevation.

hundres of kilograms to tens of thousands of kilograms, but will not reach hundreds of thousands of kilograms. The LM itself is estimated to be 8000 kg.

The formula given above predicts an end behavior that asymptotically approaches zero. However, as stated above the maximum speed of eject is capped at 5 km/s. To adjust this function while not neglecting the mass that is predicted to exceed this speed, a cumulative distribution function (CDF) is applied to adjust the end behavior and redistribute the mass that exceeds 5 km/s about a 4 km/s center point with a σ^2 of 200 as follows:

$$M_{adj}(v) = M(v) + M(5000)\frac{1}{2}[1 + erf[\frac{v - 4500}{\sigma^2\sqrt{2}}] \tag{3}$$

Although this CDF allows for the redistribution of mass to suit observation, there exists no known simulation that can accurately describe how this end behavior may realistically be produced and exactly how accurate this distribution is. This CDF only fits the observation that the maximum velocity observed following the impact of LCROSS was 5.0 km/s. This observation leaves room for the possibility that faster debris existed but was not observed, or the likely opportunity that larger impacts result in a higher velocity. Furthermore, there is some function that may describe end behavior as a function of the kinetic energy of an impact. Further work in to this dynamic would yield a more accurate mass estimate. As it stands, there is enough information to determine how much mass may be placed into lunacentric and geocentric orbit at EVD speeds to perform a risk analysis.

Assuming a uniform ejecta distribution at the impact site and adjusting for interpolation and double-counting at the poles, the percentage of debris destined for reimpact, lunacentric, geocentric, and heliocentric orbit at different impact locations are indicated in Table 1 below. The position

of (-90,-30) is Earth-facing, and notably generates the lowest lunacentric ejecta and lowest likelihood of reimpact, but at the cost of generating the most debris in geocentric orbit, the hazards of which are covered in section 5. The maximum amount of debris that remains in orbit from any of the trials examined is 20 percent, with a mass of just under 80 kg for a 45° impact angle.

Table 1 shows the destination of EVD ejecta after 20 days. Impact, Luna, Helio, and Geo refer to reimpacting the lunar surface, luna-, helio-, and geocentric orbits respectively. In all cases, the mass is 401.5 kg and is the total displaced mass at EVD assuming a 45° impact angle.

Table 1 - Destinations of EVD Ejecta Within 20 Days

Latitude	Longitude	Impact(%)	Luna(%)	Helio(%)	Geo(%)
90° N	166° E	24	15	26	35
90° N	77° E	21	20	35	24
90° N	103° W	21	20	26	33
0° N	76° E	25	16	35	24
0° N	166° E	15	14	45	26
0° S	14° W	14	14	26	46
22° S	173° E	14	12	27	47

EJECTA ORBIT ANALYSIS

The next task was to characterize the debris that remains in orbit in terms of the repercussions of secondary and tertiary impacts on lunar surface activity, likelihood of ending up in a frozen orbit, and the chances that his debris would contact gateway or existing artificial satellite infrastructure.
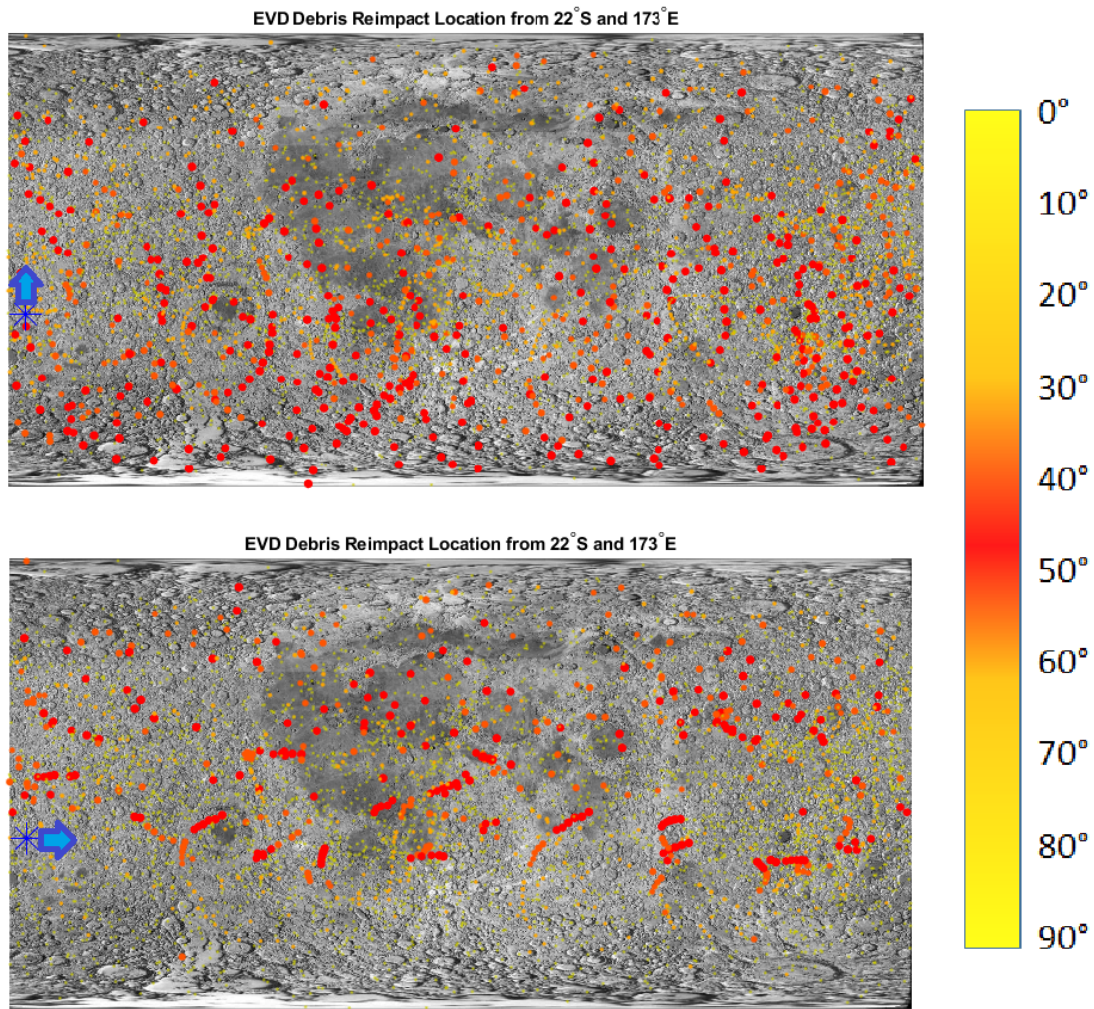
Reimpact

From Table 1, it is apparent that the chances of reimpact of EVD impact ejecta are high enough to warrant attention. These reimpacts only account for those which reimpact within the first 20 days, and not those that may yet impact much later. As with the debris orbit analysis, the mean duration of EVD orbital debris after the 20-day threshold is 50˜60 days. Of that debris, a significant portion (roughly half) of those also eventually reimpact.

Thus, looking only at the trajectories that reimpact within 20 days, there is still a global distribution for impacts. This distribution is not uniform and depends on the impact location and angle at time of impact. By varying the impact direction, we can determine the likelihood that a given reimpact location will be hit and with a larger particle size. This is illustrated in figure 8 below. Points corresponding to a higher likelihood of reimpact are marked with a larger spot shifted towards the red end of the color map.

Frozen Orbits

Concerns regarding a permanent presence of debris in orbit have proven to be unjustified, as none of the debris generated by the EVD simulations resulted in a insertion into a frozen orbit. Although some debris lingers in lunar orbit for years to even decades after impact, this is an extreme minority of debris and none of it seems to be permanent, let alone in a frozen orbit. Although this work has not entirely eliminated the possibility of lunar ejecta migrating to a frozen orbit, it has determined that it would take a vast number of large collisions to populate those orbits to the point of them being a hazard or pretent spacecraft from exploiting the advantages of this family of orbits.

Figure 8. A comparison between a latitudinal impact and a longitudinal impact and the resulting debris distribution.

GATEWAY RECONTACT PROBABILITY

Recontact risk is characterized by debris passing within 100 km of Gateway, as defined by Davis et al. 2019 [8]. In order to obtain a high-fidelity model for the recontact assessment, a specific impact instance is analyzed - that of one on the Earth-facing side of the moon at which the minimum orbital debris is generated. In this minimal case, it was found that there is a minimum of 3.4e-4% chance of any given piece of ejecta posing a contact hazard to Gateway for an impact with a uniform, hemispherical debris distribution. This was determined by plotting debris each degree from -90 to 90 degrees in both right ascension and declination in increments of 1 degree, and a velocity range of 2.33-2.37 km/s in increments of 1 m/s. Since impacts do not generate a uniform hemisphere of debris, one may narrow down the debris field to a Gaussian distribution. By assuming a 45° impact angle with a one-sigma Gaussian cone of 30.69 degrees and assuming that all trajectories within that cone have some form of EVD ejecta of any particle size, the minimum impact chance of ejecta within at EVD speeds posing a hazard to Gateway is estimated at 4.4e-3%.

VULNERABILITY OF ARTIFICIAL SATELLITE INFRASTRUCTURE

To assess the threat EVD ejecta may have on existing satellite infrastructure, debris objects that reach heliocentric trajectories are simulated for one year. Geostationary infrastructure (GEO) is considered threatened if debris pass within 3500 km (1% of geostationary range relative to earth) of the geostationary belt around Earth. Low Earth Orbit (LEO) is considered threatened if any EVD ejecta pass within 2000 km of Earth's surface.

Table 2 shows the likelihood of ejecta generated at different impact locations posing a threat to Terran assets. N/A poses no hazards, GEO poses a threat to geosynchronous assets, and LEO poses a hazard to Low Earth Orbit assets.

Table 2 - Hazards Posed by Geocentric Debris

Lat	Long	N/A(%)	GEO(%)	LEO(%)	Reimpact(%)
90° N	77° E	82.2	2.6	0.5	14.7
0° N	166° E	76.1	3.0	0.7	20.1
0° S	14° W	77.9	2.9	0.7	18.5
22° S	173° E	74.3	2.7	0.5	22.5

Ejecta in Table 2 that are listed as (N/A) remain in geocentric orbit for longer than 1 year. From work done by Gladman [7], it was shown that although some impact the Earth within a few decades or escape to heliocentric orbit on the order of tens of thousands of years and thus this debris is not expected to pose a risk to geostationary infrastructure. The amount that passes within 3500 km remains in the high second percentile regardless of impact location, but even so this is a large bubble there is much room for misses within 1 percent of the orbit. Even so, the risk does exist and should be considered.

RISK ASSESSMENT FOR LUNAR SURFACE ASSETS

Natural impacts are estimated to result in the chance of an impact on Apollo-level infrastructure once every 1,380 years, making the chance of impact during 7 days of surface operations negligible [10]. One impact from a spacecraft produces an additional years worth of debris on the surface (including debris leaving at less than EVD). Thus, the general risk of lunar infrastructure being hit is likewise doubled presuming it has the same footprint as Apollo to about 0.0004 %. With the growth of lunar activity, the risk would likewise increase. For a lunar base including solar panels, robotic ice mining, and habitats, one may reasonably expect that the dimensions of such activity would be much greater than that of Apollo-era moon landings, increasing the risk by a factor of 4 for an area twice as large, and 16 for an area 4 times as large. Even so, the risk remains negligible for distant impacts.

CONCLUSION & FUTURE WORK

By applying the function derived by Housen & Holsapple for vertical impacts to match the simulated mass ejection results determined by Artemieva, an estimate for high-velocity ejecta on the lunar surface was found. Then, using numerical simulations provided by the Freeflyer software, the desination of debris in every direction was determined, generating a probability field. Applying a gaussian distribution in the desired direction, it is possible to generate a prediction of where ejecta will go and how much eject to expect given any impact location and angle on the lunar surface.

Results from these studies show that although the possibility of debris reaching a stable lunar orbit remains negligible, the overall generation of debris from lunar impact is not and results in a continually exacerbated SSA environment both around the moon and in Earth orbit. It is therefore not advised to allow uncontrolled lunar impacts to become standard operating procedure - especially so long as there is the presence of spacecraft in lunar orbit or operating lunar surface infrastructure. For each impact on the order of 1000kg, there exist secondary and tertiary impacts across the lunar surface, any one of which have the capability to puncture a habitat. While the risk of Apollo operations remained low with an estimated impact on surface assets once every 100 years, uncontrolled impact of hardware on the surface at least doubles this.

Future work seeks to use the knowledge gained to determine optimum surface departure vectors and to create a global estimation function for ejecta destination and quantity. It also seeks to take the Sun-Earth-Moon angle into account to determine the degree that this effects ejecta destinations.

ACKNOWLEDGMENTS

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