A Proposal for Standardized MMOD Shielding for Robotic Spacecraft

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ABSTRACT

NASA robotic spacecraft are required to assess the potential for small debris induced failure for all disposal-critical components. Additional shielding might then be necessary in order to meet the acceptable risk requirement for the overall mission. Traditionally this requirement had been met with little or no additional shielding. Since the introduction of a high density debris population in Orbital Debris Engineering Model version 3.0 (ORDEM 3.0), some missions, especially those in higher portions of Low Earth Orbit, have needed additional Micrometeoroid and Orbital Debris (MMOD)-specific shielding in order for the mission to meet the requirement. This is a costly design effort when performed late in the project life cycle, which adds unexpected mass to the spacecraft components during the integration phase, and could disrupt thermal management.

A proposal is discussed to develop a more cost-effective approach to MMOD-shielding, which can be employed earlier in the hardware design phase. The development and adoption of standardized shielding assemblies allows early tailoring of the shielding around a component, so that the mass is accounted for, as well as the small particle penetration risk, at a point in the design phase when the cost and schedule impact are more manageable. A set of several assemblies can be developed with a range of protection thresholds, in order to control mass where less shielding is needed. Such shielding assemblies would be developed in collaboration with blanket assembly specialists and thermal control engineers to ensure manufacturability and thermal performance challenges are known and acceptable. One clear benefit of such an approach is that hypervelocity testing can be performed on each of the standard shield assemblies to refine and confirm their performance prior to use.

The challenges inherent in designing supplemental MMOD shielding will be discussed, including variations in the orbital debris environment and performance prediction. The benefits of a standardized shielding approach and example applications will also be presented.

1 INTRODUCTION

In addition to radiation and other threats inherent to the space environment, spacecraft hardware can be susceptible to penetration damage by micrometeoroids and orbital debris (MMOD). Meteoroids tend to be smaller, but have higher velocity than orbital debris particles. Orbital debris particle usually dominate the threat to spacecraft in the upper portions (~ 500 km to 1000 km altitude) of Low Earth Orbit (LEO), though both are considered when estimating the penetration risk. Fortunately, the flux of meteoroids and orbital debris decreases dramatically with increasing particle size, and shielding prevents the smallest particles from penetrating a component, so that the range of particles that represent a threat to the component is relatively narrow. Damage to critical equipment, generally in the form of penetration, could prematurely end a mission or prevent the planned disposal of the spacecraft.

Guidelines and standard practices at the international and US Government level address this concern, encouraging that “Spacecraft design should limit the probability of collision with small debris which could cause a loss of control, thus preventing post-mission disposal” from the IADC Guidelines [1]. This guideline is reflected at NASA in a quantitative requirement (NASA-STD 8719.14B, Requirement 4.5-2) based on detailed assessment: “For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal maneuver requirements does not exceed 0.01.” [2]. Note that the NASA requirement considers only hardware components that are required for active disposal (maneuvers), and not mission success. While science instrument payloads are not included, active disposal maneuvers generally require practically all of the spacecraft bus subsystems (power, communications, commanding, attitude control, and of course propulsion) to be available and functional.

The traditional approach has been to assess the risk to hardware after the design has been refined, usually around the time of the Mission Critical Design Review. One advantage of this approach is that the component selection, location, and orientation are relatively mature, minimizing repetition of effort due to design changes. Assessing the refined hardware design was relatively effective for many years, until the Orbital Debris Engineering Model version 3.0 (ORDEM 3.0) environment model was introduced in 2014 [3]. A few aspects of the new environment model led to generally higher assessed penetration risk, and a need for expensive supplemental shielding for some components, particularly for spacecraft with altitudes above 700 km.

The type of shields discussed here are usually referred to as bumper shields, used on spacecraft components that are exposed to space on at least one side. They consist of primarily two layers: a breakup layer and a stopping layer. In order to be effective, these layers need to be separated by some distance, allowing the secondary debris from the breakup to spread the impact energy over a wider area before striking the stopping layer. The two layers are typically defined using areal density (bulk density multiplied by thickness), expressed in grams per square centimeter. The breakup layer uses ceramic fabrics or other materials intended to inflict maximum damage to an incoming projectile. Stopper layers are selected for energy absorption, using tough, ductile metals in the chassis wall, sometimes supplemented with Kevlar fabric. One of the greatest challenges in manufacturing such a shield is devising a method to maintain the necessary spacing between relatively flexible layers.

The approach proposed in this paper is to proactively assess the threat posed by the environment, and plan to add standardized shielding blankets earlier in the design process, perhaps at the Preliminary Design Review. Benefits of this proactive approach include early knowledge of the thermal performance, mass, and installation costs earlier in the design cycle, as well as more reliably defined MMOD penetration risk. One potential liability is that it is not likely to provide optimized shielding (may impose higher mass than necessary). Standardized shielding may not apply to all components, but it is believed to be adequate for the vast majority of components. Other methods of mitigating the risk include locating components inside the spacecraft structure, so that the spacecraft structure panels provide additional shielding protection.

2 MMOD PENETRATION RISK ASSESSMENT PROCESS

For a typical MMOD penetration risk assessment, information is collected about the spacecraft including the orbit, mission lifetime, orientation with respect to the velocity, and the components critical to performing the planned disposal maneuvers. For each component it is necessary to identify the dimensions, chassis wall thickness and material, the location and orientation relative to the velocity direction, any redundancy in the design for that component, and any inherent shielding materials between the inside of the component and space. A simplified computer model is constructed representing the spacecraft construction with the critical component details. A software tool (Bumper in this case) is then used to calculate the exposure of the component surfaces to projectiles from all directions using Bumper's Geometry module [4]. The Response module then generates a table of penetrating MMOD diameters, velocities, and impact angles using user-defined ballistic limit equations (BLEs). Finally, Bumper's Shield module combines the previous module data with the orbital debris and meteoroid environment models to estimate the number of penetrations expected for each defined component surface, which in turn gives the probability of penetration for that surface. Any redundancy is then considered before the cumulative probability of penetration is calculated for a penetration of any critical component surface. Penetration of a component is assumed, perhaps conservatively, to constitute a component failure, which in turn prevents the planned disposal maneuvers from being performed.

A full assessment of penetration risk includes many factors: projectile velocity, impact angle, projectile density, shield design, component wall design and area, environment model version, assessment procedure, and more. Some of these are dictated by orbital mechanics and environment makeup. For example, the impact velocity for a given direction is tied to the orbital mechanics of a particle with the potential to strike a given surface. Typically the highest impact velocity, and therefore the worst case penetration potential for a given particle size, is directly into the velocity direction. Some other factors can be fixed by the user with a few simplifying (and perhaps conservative) assumptions, reducing the number of variables in the problem. Clearly this is most applicable to spacecraft with circular orbits, where simplifying assumptions can more easily be applied.

3 ORBITAL DEBRIS ENVIRONMENT CHARACTERIZATION

The ORDEM 3.0 environment model will be described here. Other orbital debris models as well as meteoroid models may use different approaches to approximate the environment, but generate similar data sets.

ORDEM 3.0 is the current version of the official NASA orbital debris environment model, to be used in all penetration risk assessments for NASA missions. It uses a catalog of tracked objects as the baseline for objects larger than 10 cm, along with several special populations (for example, debris from the FY-1C and Iridium-Cosmos events), propagated forward to the year of the assessment. The population is further adjusted to simulate potential breakups and degradation, which generate smaller particles. The primary output file is a six-dimensional matrix giving the flux of particles (in #/m^2-yr) for each combination of azimuth (10° bins), elevation, velocity (10° bins), population/ particle density (5 bins), and particle size (11 specific fiducial point sizes) for a specific orbit and year. Particle flux matrices for multiple years are combined into a single file, which is provided to Bumper as an input to the Shield module. The introduction of population bins into ORDEM 3.0, specifically the High Density bin, contributed to a dramatic increase in the assessed penetration risk and the need for supplemental shielding.

4 ORBITAL DEBRIS FLUX TRENDS

In order to establish a standardized shielding scenario, it is useful to understand how the debris flux varies with particle size, orbit, and time. Figure 1 shows a typical log-log plot of cumulative flux versus particle size generated using the ORDEM 3.0 model. Notice that the steepest part of the curve occurs over the 1 to 3 mm range. This region is also of great interest with regards to the penetration risk for robotic spacecraft. Particles smaller than about 1 mm have very high flux, but are generally prevented from penetration by even modest shielding over most component chassis walls. Particles larger than 3 mm will penetrate most shielding designs that are practical for robotic spacecraft, but the flux of such particles is so small that the likelihood of penetration is generally an acceptable risk.

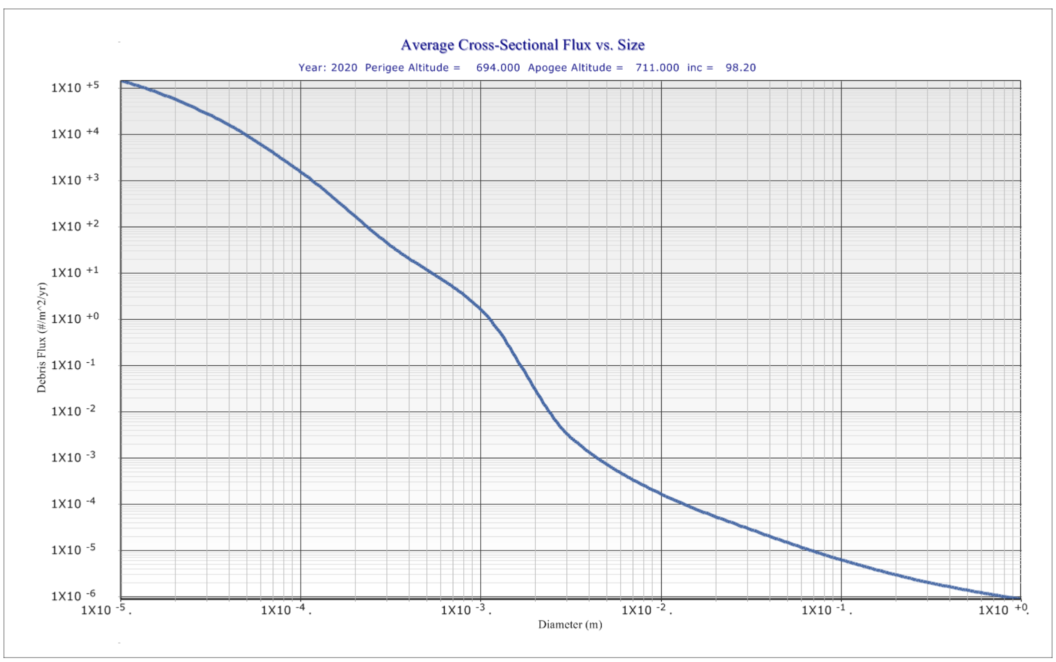

Figure 1. Flux vs. size curve for the Terra mission (EOS Constellation) in 2020.

Figure 2 shows the variation in flux over altitude, with the orbit inclination and year fixed as 28.5 degrees and 2020 respectively. The intermediate fiducial point curves (at logarithmic midpoints, multiples of 3.16) are omitted to simplify the plot. While there are several orders of magnitude differences in flux from one particle size to another, differences in flux across altitudes varies by approximately two orders of magnitude. Figure 3 shows a linear scale plot of the same flux, focusing only on the 1 mm fiducial point size. This plot shows that over the altitude range from 700 km to 1000 km the difference in particle flux is a more modest difference of only a factor of 3.3. The flux for 1 mm particles differs by only about a factor of 2 between 700 km and 800 km altitudes, where most of NASA's high-LEO missions operate (Landsat and JPSS, for example).

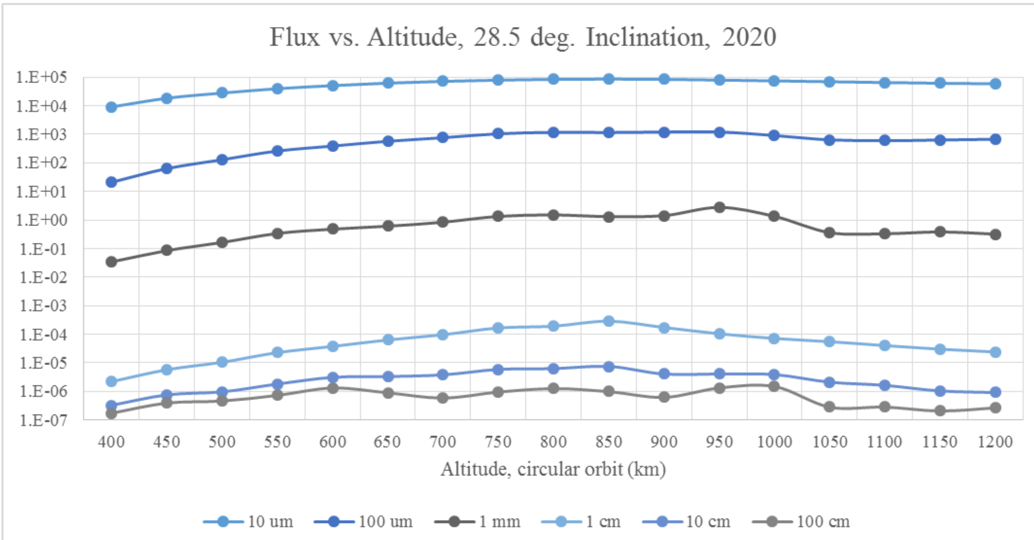

Figure 2. ORDEM 3.0 particle flux variations with altitude for a fixed inclination and year, using a logarithmic flux axis.

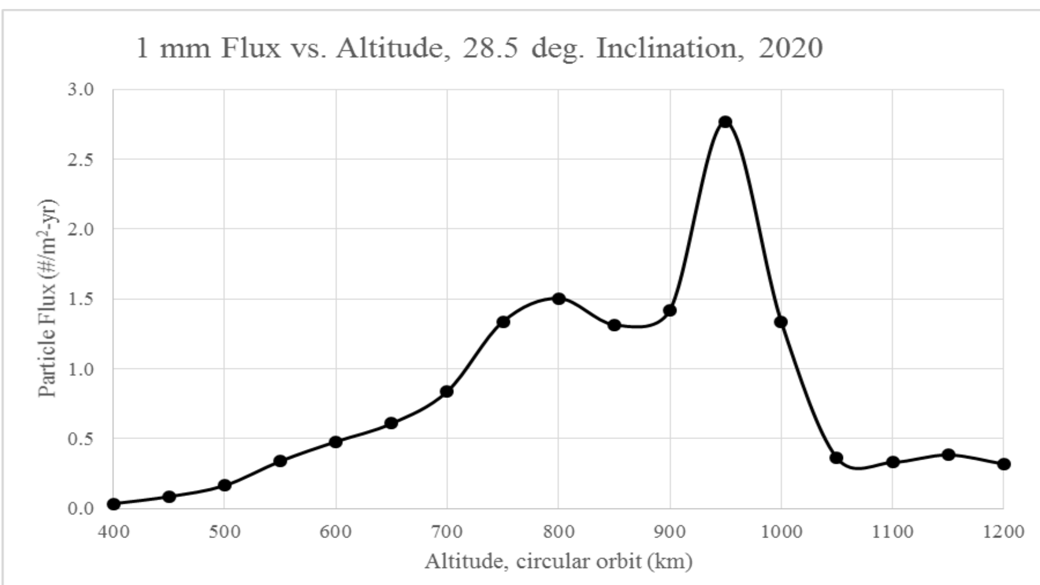

Figure 3. ORDEM 3.0 particle flux variations for 1 mm particles with altitude for a fixed inclination and year, using a linear flux axis.

Figure 4 shows the slight variations in particle flux over orbit inclination, using a fixed 750 km circular orbit altitude for the year 2020. Variations are within about a factor of 2, indicating that orbit inclination is not a strong driver for the overall orbital debris threat. Inclination is very important, though, in terms of determining the directionality of the threat. Figure 5 shows polar plots of flux for orbits with relatively low inclination and Sun-synchronous nearly polar inclination, demonstrating the effect on directionality. The low inclination orbit causes higher particle flux on the port and starboard sides of the spacecraft relative to the higher inclination orbit case.

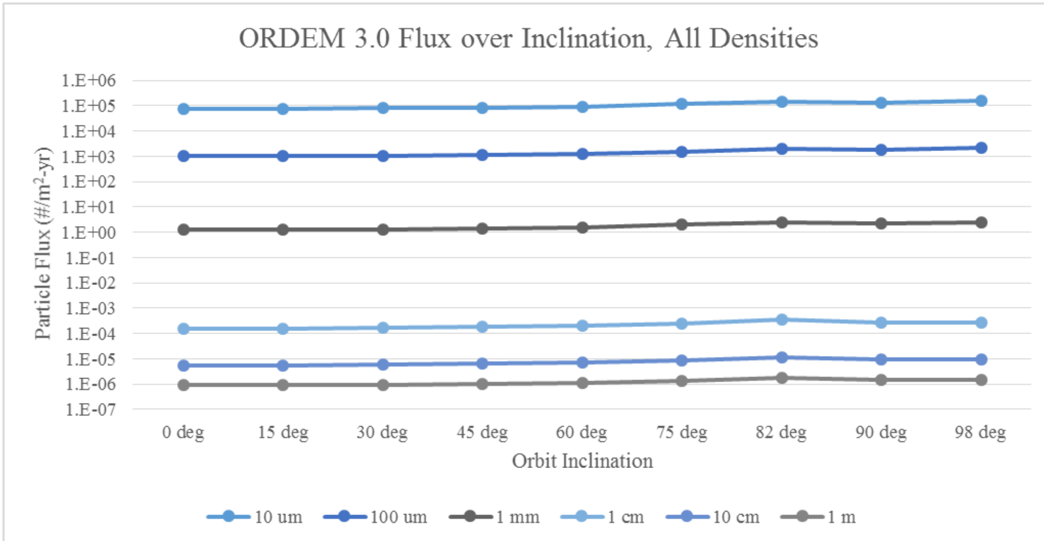

Figure 4. ORDEM 3.0 particle flux variations with orbit inclination for a fixed 750 km altitude in 2020.

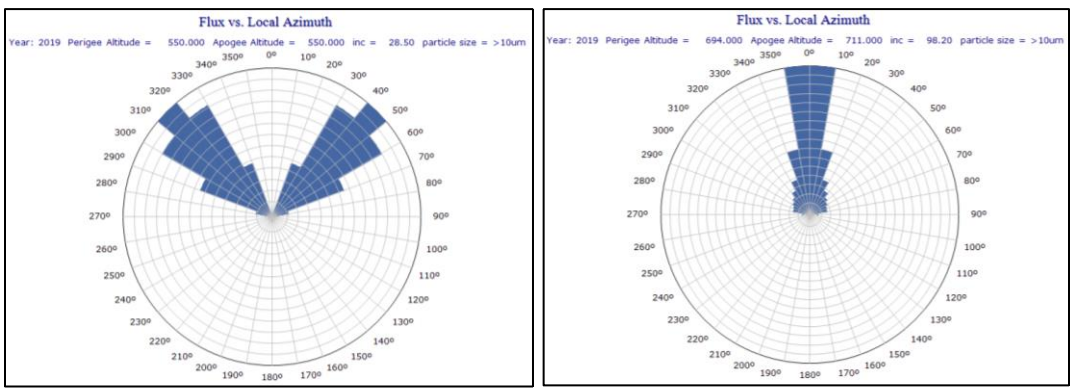

Figure 5. Polar plots of particle flux variations with local azimuth for relatively low inclination (left) and nearly polar inclination (right) orbits. Note that flux is negligible in the wake, or anti-ram, direction.

The combination of altitude and orbit inclination lead to sometimes strong differences in the orbital debris flux from mission to mission. Table 1 shows the orbits used for ORDEM simulations of six typical NASA missions, and Figure 6 shows the resulting ORDEM flux curves for each of these mission orbits in 2019. The JPSS family of spacecraft occupies one of the most aggressive orbital debris environments that NASA uses, followed by Terra, Landsat, and other missions in the orbit occupied by the EOS Constellation. Not surprisingly, HST and Fermi missions have nearly identical debris flux curves, though an important difference between them is illustrated later. The International Space Station is in a relatively benign flux environment compared to most other missions, but the consequences of a penetration are extremely serious so the shielding is generously more robust than for robotic missions. Finally, the TDRS satellites, in geosynchronous orbit, are believed to experience a relatively benign small particle environment. The consequences of a penetration in GEO, however, might leave a large spacecraft in a crowded region long-term, where a collision could have very serious implications for other spacecraft for a very long time.

Table 1. Orbit inputs used to evaluate six different typical NASA missions.

Mission	Perigee (km)	Apogee (km)	Inclination (degrees)	Design Mission Lifetime (years)
ISS	400	400	51.6	15
HST	550	550	28.5	15
Fermi	524	541	25.6	5
Terra	694	711	98.2	5
JPSS-1	825	825	98.8	7
TDRS	35786	35786	15	15

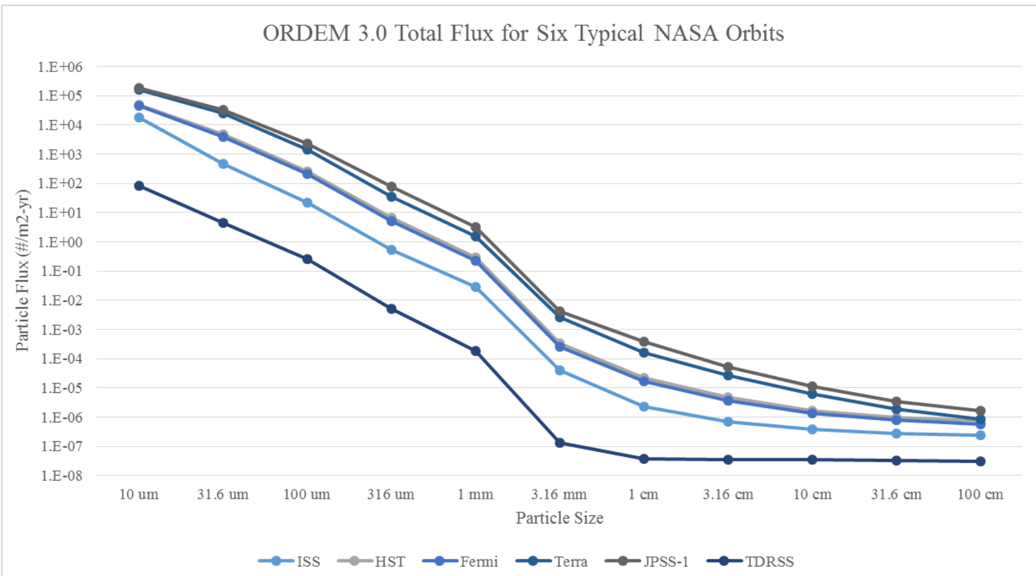

Figure 6. ORDEM 3.0 particle flux variations over particle size for a sample of typical NASA missions.

Another driver in the small particle penetration risk is time. While the mission duration is a major driver in estimating the threat, the time period over which the spacecraft is operating also has some effect. Variations in solar flux cause both large and small objects orbits to decay, removing them from the catalog population in a cyclic fashion. Meanwhile, ORDEM estimates a launch cadence that introduces new large intact objects, and breakup and degradation (erosion) mechanisms that generate more small particles. Figure 7 shows the variations in total debris flux predicted by ORDEM 3.0 for a fixed orbit from 2015 through 2027. For most particle sizes there is little perceptible change on this logarithmic scale, but the difference between the highest and lowest flux over this twelve year period is a factor of 1.75 for 1 mm particles, so the start date for the assessment is important to consider.

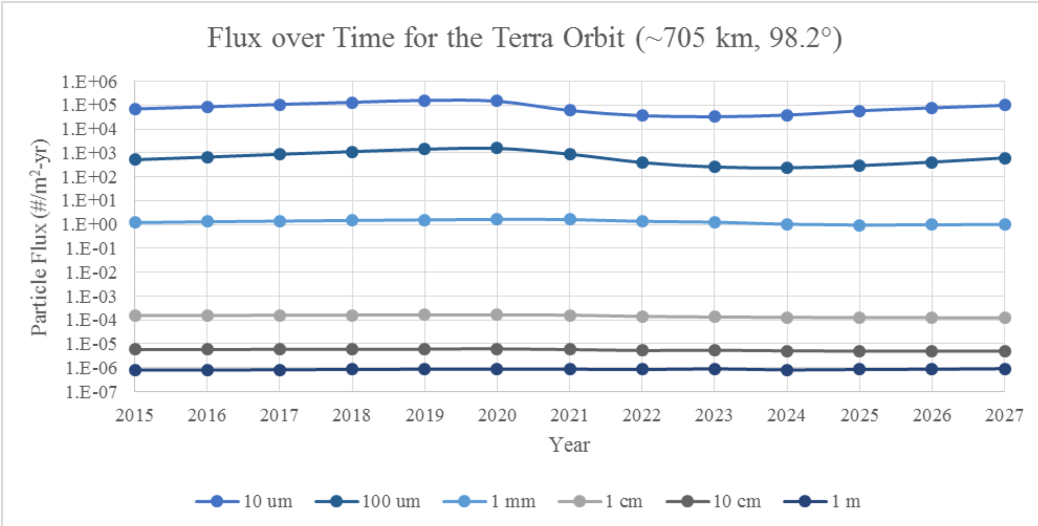

Figure 7. ORDEM 3.0 particle flux variations over time for a fixed altitude and inclination.

5 DIRECTIONALITY

Figure 5 above illustrates how the direction from which particles might strike a component varies based on the orbit inclination. ORDEM 3.0 provides the data to examine the flux from different directions for specific orbits, through manipulation in a spreadsheet or similar tool. Past experience has shown that only in the cases of very high eccentricity orbits or components that are inclined with respect to velocity is there a significant risk contribution from particles in the nadir or zenith direction. Therefore, these directions were omitted from this study. If either of those cases were present, flux data can be considered for those directions using the same methods.

The ORDEM 3.0 flux data matrix for the JPSS-1 orbit was imported into an Excel spreadsheet, and filtered to isolate the flux for just the ram (aka velocity), wake (aka following or anti-ram), port, and starboard directions. Initially the directions were defined as being +/- 30 degrees from the principal direction, with elevation of +/- 5 degrees from local horizontal. It was found that by increasing the direction spread to +/- 40 degrees, consideration of the entire flux environment increased from 82% to 94%, so the direction spread was redefined to the wider arc for remaining missions. Increasing azimuth spread to +/- 15 degrees made practically no difference in the portion of the flux included (but tripled the amount of data to handle), so +/- 5 degrees was retained as the azimuth definition. Figure 8 shows the directionality used for this part of the assessment.

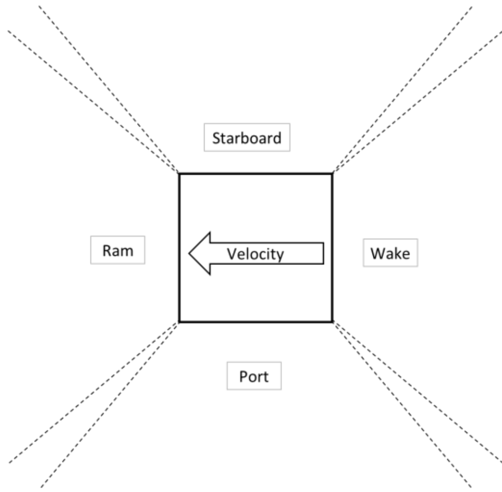

Figure 8. Illustration of the directionality used in the proposed standardized shielding approach.

The directional flux was determined for all four directions for the Fermi, Terra, and JPSS-1 missions for both the 1 mm and 3.16 mm fiducial points. In all three cases the threat from the OD environment is primarily in the velocity (ram) direction. Impact velocity in that direction averages approximately 15 km/s. There is practically no particle flux in the nadir and zenith direction for these basically circular orbits, so considering four directions is sufficient.

Most Earth science missions operate in one or more orientations that have a constant velocity direction. Each of these orientations needs to be considered in order to determine the comprehensive directional threat. Space science missions, on the other hand, often slew from target to target, dwelling on a target while the velocity direction constantly changes. This is the case for the Hubble Space Telescope (HST), and will be termed 'omnidirectional pointing' for the purposes of this paper. Rather than using directional flux, then, a constant flux will be applied to all directions. The total particle flux for all directions was divided by five, because the telescope must never point in the nadir direction, but may point in other directions including zenith. Five-directional average fluxes were calculated for both the 1 mm and 3.16 mm fiducial points.

6 STANDARDIZED BLANKET SELECTION CONCEPT

What follows is a notional concept for a method of proactive shielding design, and not a fully developed and tested approach ready for implementation. The shield selection thresholds, as well as the concept itself, will likely need to be adjusted and developed further before it could be used for an actual spacecraft design.

By combining some variables and making a few simplifying assumptions, directional threat to a spacecraft component can be reduced to only two variables: the total environment flux in the direction of the critical surface and mission duration. Impact velocity, impact angle, and projectile density contributions are all factored into the design of the shield, so need not be considered when selecting from among the standardized blankets. The critical surface area is nullified by the blanket area, so it can be excluded from the basic selection approach. If a specific spacecraft has an unusually high exposed area of critical components, that may be grounds for shifting to a higher level of shield for one or more surfaces. Some judgement will always need to be to be employed in the blanket selection process.

Table 2 shows the directional orbital debris fluence for four example missions. In this simple example, the flux for one year has simply been multiplied by the mission duration, but for actual cases ORDEM or a similar model should be used to generate actual fluence for each year of the mission duration. The entries in Table 2 have been grouped into five threat levels to show a notional way in which different standardized shields might be assigned to all critical component surfaces in each direction.

Table 2. Directional orbital debris fluence (particles/m^2) for four typical NASA missions, binned into A-D shielding levels based on fluence.

Mission	Port	Ram	Starboard	Wake	Zenith
HST	2E-04	2E-04	2E-04	2E-04	2E-04
Fermi	2E-04	5E-04	2E-04	1E-07	
Terra	1E-03	1E-02	1E-03	3E-07	
JPSS-1	3E-03	2E-02	3E-03	1E-06	

No concern	< 1E-05 particles/m^2
A	1E-03 to 1E-04 particles/m^2
B	5E-03 to 1E-03 particles/m^2
C	1E-02 to 5E-03 particles/m^2
D	> 2E-02 particles/m^2

The Landsat 9 mission is currently being integrated for launch in 2020 into an orbit very close to that of Terra. The project has recently developed and tested particle penetration shields for various surfaces that might represent potential B and C shield blanket candidates. Hypervelocity impact testing has allowed particle penetration experts to develop Ballistic Limit Equation (BLE) adjustment factors specific to these blanket designs, and spacecraft integration will resolve any manufacturing and thermal concerns. The Landsat 9 designs can then be modified to create candidates for standard A and D blankets, which would then be tested to confirm their effectiveness and develop custom BLEs for them.

When a full set of standardized blanket designs is developed and tested, it will only be necessary to determine the directional fluence over the course of a mission, then apply the blanket selection ranges in order to select protective shields for the exposed surfaces of each component. As previously stated, it will always be necessary to employ some degree of engineering judgement in the selection of shielding blankets, but the standardized blanket approach provides tested and confirmed starting points for early inclusion into the spacecraft design.

The component chassis wall is the main stopping layer for incoming projectiles, so it is critical that the wall design meet at least a minimum areal density. It is not uncommon for component chassis wall thickness to vary from component to component, which could present a challenge for the use of standardized shielding blankets. Testing by NASA's Hypervelocity Impact Technology team has examined the performance of Kevlar layers when supported by the chassis wall, and shown that sufficient Kevlar can be added to a chassis wall as needed to achieve stopping performance equivalent to at least the minimum areal density for the standardized shield blanket.

7 SUMMARY

A notional concept for a proactive MMOD shielding design is discussed. Variations in the orbital debris environment are a major driver in determining the debris penetration threat, and have been examined in terms of altitude, inclination, and time aspects. Orbit altitude was shown to have the greatest effect on the debris threat, though it is necessary to consider the entire mission profile, including mission duration, launch year, and the anticipated spacecraft behavior attitude in order to determine the threat level. A sample of typical NASA missions has been examined to illustrate the wide variety of threats imposed on different surfaces throughout the mission. These threats have been notionally categorized into five levels, and previously tested blanket designs are proposed as candidate shields for two of these levels. Identifying the shielding needs and including shielding blankets to prevent penetration early in the design process will minimize the cost and schedule impact, as well as preventing unexpected thermal and manufacturing difficulties during integration.

8 FUTURE WORK

In order to make this proposed approach practical, a full suite of blanket designs is needed. Blanket candidates for A and D shields will be proposed, and their effectiveness estimated using existing equations. Samples of these blankets will need to be constructed and tested to confirm their effectiveness and to generate blanket-specific BLEs to use in future assessments. In addition, penetration risk, shield mass, thermal performance, and manufacturability will be examined for a sample of historical and upcoming missions based on these candidate blankets, to confirm that they represent practical solutions.

9 REFERENCES

1. Inter-Agency Space Debris Coordination Committee. "IADC Space Debris Mitigation Guidelines", Revision 1, September 2007.
2. National Aeronautics and Space Administration. "Process for Limiting Orbital Debris," NASA-STD-8719.14B, approved 2019-04-25.
3. Stansbery, E. et al. *NASA Orbital Debris Engineering Model ORDEM 3.0 – User's Guide*, NASA/TP-2014-217370, Available at https://orbitaldebris.jsc.nasa.gov/modeling/ordem-3.0.html, April 2014.
4. Bjorkman, M. et al. *BUMPER 3 Micrometeoroid and Orbital Debris Risk Assessment Tool Software User Manual*, February 2014.