A COMPARISON OF DAMAGING METEOROID AND ORBITAL DEBRIS FLUXES IN EARTH ORBIT

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ABSTRACT

Low Earth orbit is populated with a substantial amount of orbital debris, and it is usually assumed that the flux from these objects contributes to most of the hypervelocity particle risk to spacecraft in this region. The meteoroid flux is known to be dominant at very low altitudes (<300 km), where atmospheric drag rapidly removes debris, and at very high altitudes beyond GEO (geostationary), where debris is practically non-existent. The vagueness of these boundaries has prompted this work, in which we compare the fluxes of meteoroids and orbital debris capable of penetrating a millimeter thick aluminum plate for circular orbits with altitudes ranging from the top of the atmosphere to 100,000 km. The outputs from the latest NASA debris and meteoroid models, ORDEM 3.0 and MEMR2, are combined with the modified Cour-Palais ballistic limit equation to make a realistic evaluation of the damage-capable particle fluxes, thereby establishing the relative contributions of hazardous debris and meteoroids in near Earth space.

1 ENVIRONMENT MODELS

MEMR2 – The meteoroid environment used in this work was produced by NASA's Meteoroid Engineering Model, Release 2.05 (MEMR2) [1]. It is NASA's most current and accurate description of the meteoroid environment, superseding older models such as that in NASA TM-4527 [2], which was used in the design of the International Space Station. Unlike past NASA models, MEMR2 incorporates dynamically evolved distributions of virtual meteoroids ejected from comets and asteroids. These distributions are scaled such that the model environment for Earth matches ground-based radar observations and the *in situ* measurements comprising the basis of the 1985 Grün model [3]. This produces a reasonably accurate representation of the sporadic meteoroid environment from 0.2 to 2 au; outside of this range, object types not included in the model sources (e.g. Kuiper Belt Objects) may become significant producers of meteoroids. MEMR2 does not generate fluxes for particles with masses less than 10^{-6} grams (124 μm for MEM's assumed density of 1 g cm^{-3}), as particles smaller than 100 μm begin to be significantly affected by non-gravitational forces such as Poynting-Robertson drag. Also, particles with sizes below this limit are generally not capable of inflicting significant damage in a single impact (though they may erode optical or sensitive surfaces over time).

Risk assessment codes such as NASA's BUMPER [4] and ESA's ESABASE [5] require that the meteoroid/ orbital debris models produce fluxes as a function of direction and speed, and the outputs of MEMR2 have been tailored to interface smoothly with these programs. However, impactor bulk density is also a required input of the damage equations used by BUMPER and ESABASE to assess penetration/damage probabilities. Unfortunately, meteoroid densities have been, and still are, notoriously difficult to measure. Meteorites, which originate from the most robust subset of meteoroids, have had their volatiles depleted by hypersonic travel through the atmosphere, biasing densities to higher values. The same applies to *in situ* capture of small particles in aerogel, though to a lesser extent. Ground-based attempts to measure meteor densities through deceleration have been foiled by the fact that the vast majority of meteoroids (>90%) fragment soon after contact with the upper atmosphere, eliminating the use of physics applicable to monolithic bodies. One of the most extensive studies of meteoroid densities was that performed by Drew et al. [6], which indicated that the mean density of meteoroids was around 1 g cm^{-3}; this value has been adopted for use with MEMR2, as it yields cratering rates in reasonable agreement with measurements when combined with the model directionality and speed distribution.

ORDEM 3.0 – The latest NASA orbital debris environment model, ORDEM 3.0, incorporates significant improvements over its predecessor, ORDEM 2.0 (previously known as ORDEM 2000), which was released in 2001. ORDEM 3.0 includes the first-ever uncertainties in the flux estimates and segregates the debris population into material density classes. It has also been extended to characterize the orbital debris environment from low Earth orbit to just beyond geosynchronous orbit (100 to 40,000 km altitude). ORDEM 3.0 can also compute debris fluxes on spacecraft with highly elliptical orbits (ORDEM 2000 could do so only for vehicles in circular orbits) [7].

ORDEM 3.0 incorporates a large set of observational data (both *in situ* and ground-based) that reflect the current debris environment, covering debris sizes from 10 µm (*in situ* measurements) to 1 m (radar and optical observations). Unique to these data is the cratering information obtained from inspection of Space Shuttle windows and radiators after the orbiters' returns from space. These data, spanning 81 Shuttle missions from the mid-1990's to the last one in 2011, consists of over 600 impactor features, most of which have been chemically identified through the use of scanning electron microscope (SEM) equipment. Maximum likelihood estimation and Bayesian statistics are employed to determine the orbit populations used to calculate population fluxes and their uncertainties. The model outputs fluxes of debris in several density classes (Table 1) by direction and velocity for use in spacecraft risk assessments or by range bins for sensors (predominately radars) on Earth's surface.

Class	Density (g cm^{-3})
NaK droplets	0.9
Low density	1.4
Medium density/Intact objects	2.8
High density	7.9

Table 1. ORDEM 3.0 density classes.

2 DAMAGE EQUATION

A few past studies [2] have compared the mass or size limited meteoroid and debris fluxes at a specific altitude. These comparisons can be misleading as to the importance of the debris environment versus that of meteoroids in terms of spacecraft risk, as mass limited fluxes ignore the significant difference in the speeds (11-72 km s^{-1} for meteoroids as opposed to 1-16 km s^{-1} for debris). Some of these studies compare meteoroids and debris within a narrow range of altitudes that favor debris impacts; these comparisons cannot be extrapolated to any arbitrary altitude. In this work, we have chosen to mitigate the deficiencies of previous comparisons by calculating the number of penetrations of a 1 millimeter thick aluminum plate facing in the six 'standard directions' – ram, wake, port, starboard, and orbital zenith ('space') and nadir ('Earth'). The depth of penetration is computed using the modified Cour-Palais equation [8]:

$$d = 5.24\, s^{19/18} B^{-1/4} \left(\rho/\rho_t\right)^{1/2} \left(v/c\right)^{2/3} \qquad (1)$$

where d is the crater depth, s, ρ, v are the diameter, density, and speed of the impactor, and ρ_t, B, c are the density, Brinnell hardness, and speed of sound for the target. In the case of aluminum, ρ_t, B, and c have values of 2.7 g cm^{-3}, 90, and 6.1 km s^{-1}, respectively.

3 CALCULATION OVERVIEW

Runs of MEMR2 and ORDEM 3.0 were made for circular orbits with altitudes in logarithmic steps from 100 to 100,000 km (16 instances) and inclinations of 0°, 45°, and 90°. The model outputs were then used in conjunction with Equation 1 to compute the number of penetrations for each of the six directions. Manual checks were performed to ensure the reasonableness of the results, which consisted of 16x6 arrays for each orbital inclination and model.

4 RESULTS

4.1 Meteoroid (MEMR2) environment

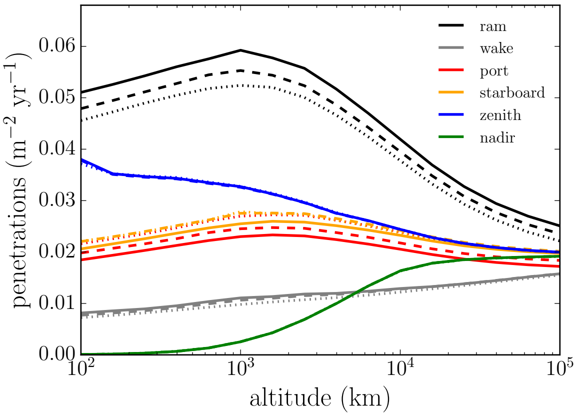

Figure 1. Number of meteoroid penetrations by surface and altitude for circular orbits at the three study inclinations (solid – 0°, dashed – 45°, and dotted - 90°).

Figure 1 shows the number of meteoroid penetrations of the aluminum plate per square meter per year by altitude for each of the six directions and each orbital inclination. Surfaces facing ram experience the greatest penetrating flux, due to the motion of the vehicle. The altitude dependence of the meteoroid flux arises from the combination of the Earth's gravitational focussing and the obscuration of part of the sky by the Earth. Focussing tends to increase the flux at the lower altitudes, but the Earth also subtends a larger solid angle for these smaller orbits. This results in a peak flux at around 1000 km altitude, below which Earth shielding begins to have the greater influence. Port and starboard show a similar trend as ram, but the flux is lower due to the loss of the additional speed from the spacecraft motion. Ram's counterpart, wake, is relatively unaffected by these competing factors, showing a modest uptick in penetrations with increasing altitude. The zenith (‘space’) and nadir (‘Earth’) facing surfaces also conform to expectation, with the zenith showing a decreasing flux with altitude (due to being solely affected by gravitational focussing) and the nadir an increasing flux with altitude (being governed by Earth shielding). Above 20,000 km, the number of penetrations on the nadir-facing surface is relatively independent of altitude. At such large geocentric distances, the Earth no longer shields the spacecraft from a significant portion of the meteoroid environment.

Figure 1 also shows that ram exhibits the greatest variability due to the inclination of the orbit with the ecliptic plane. The nadir, zenith, starboard, and wake surfaces show practically no dependence on orbital inclination, with the curves lying on top of one another. Notice that impacts on the nadir surface begin to exceed those on wake starting around 5,000 km altitude.

4.2 Orbital debris (ORDEM 3.0) environment

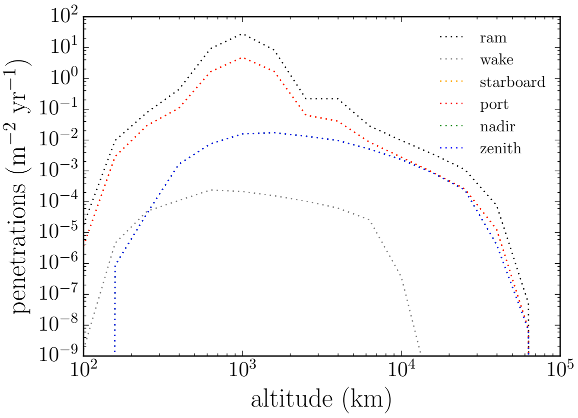

Figure 2. Orbital debris penetrations on the surfaces for 90° orbital inclination.

Figure 2 highlights the major difference between the meteoroid and orbital debris environments. Whereas the number of meteoroid penetrations varied by a factor of a few across orbital altitude and the various surfaces, penetrations due to orbital debris vary by six orders of magnitude. The penetrating flux is a strong function of the vehicle speed, evidenced by the hundred-fold difference in the number of penetrations between the ram and wake surfaces. The concentration of debris in low Earth orbit (LEO) is also obvious; ram, port, and starboard surfaces show a rise in the penetrating flux starting around 400 km (the altitude of the International Space Station), peaking around 1000 km. The concentration of debris ends at 2500 km altitude, after which there is a decline in the debris penetrations on all surfaces, trailing off to zero beyond geostationary altitudes (GEO). The flux values around GEO should be viewed with caution; even though ORDEM 3.0 incorporates the very best data and model results, there are practically no data for millimeter and sub-millimeter particles at that altitude. Ground-based radar and optical sensors do not have the sensitivity to detect small particles at these distances, and no recent impact detectors have been placed in geotransfer or geostationary orbits.

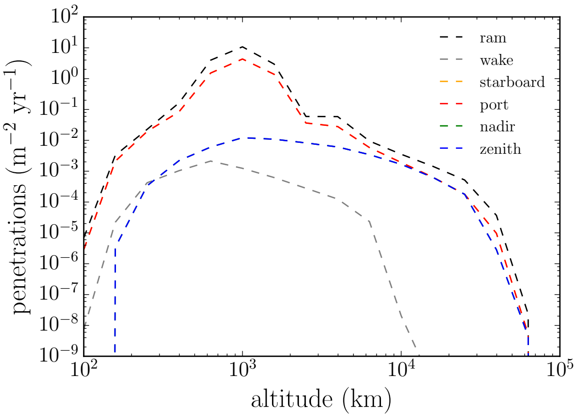

Figure 3. Orbital debris penetrations on the surfaces for 45° orbital inclination.

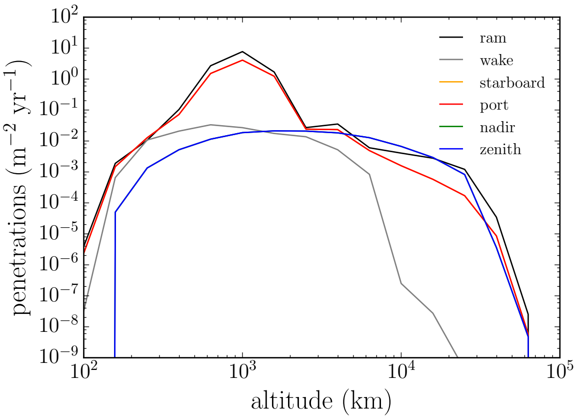

Figure 4. Orbital debris penetrations on the surfaces for 0° orbital inclination.

Figures 3 and 4 show the number of penetrations on the surfaces for the 0° and 45° orbits. Note that the number of impacts on ram, port, and starboard is highest for the 90° inclination case (Figure 2). This is not good news for satellites in sun-synchronous and other high inclination orbits, as the ORDEM 3.0 numbers indicate there could be over 20 one millimeter penetrations on a one square meter aluminum surface facing continuously into ram for a year. This is due in part to the presence of sub-millimeter steel particles in the LEO debris population, which are capable of producing more damage than other, less dense, debris types. In addition, there is a significant population of debris in high-inclination orbits. The geometry of orbit encounters causes satellites in high-inclination orbits to experience an enhanced flux of head-on (ram) collisions from these high-inclination debris. It

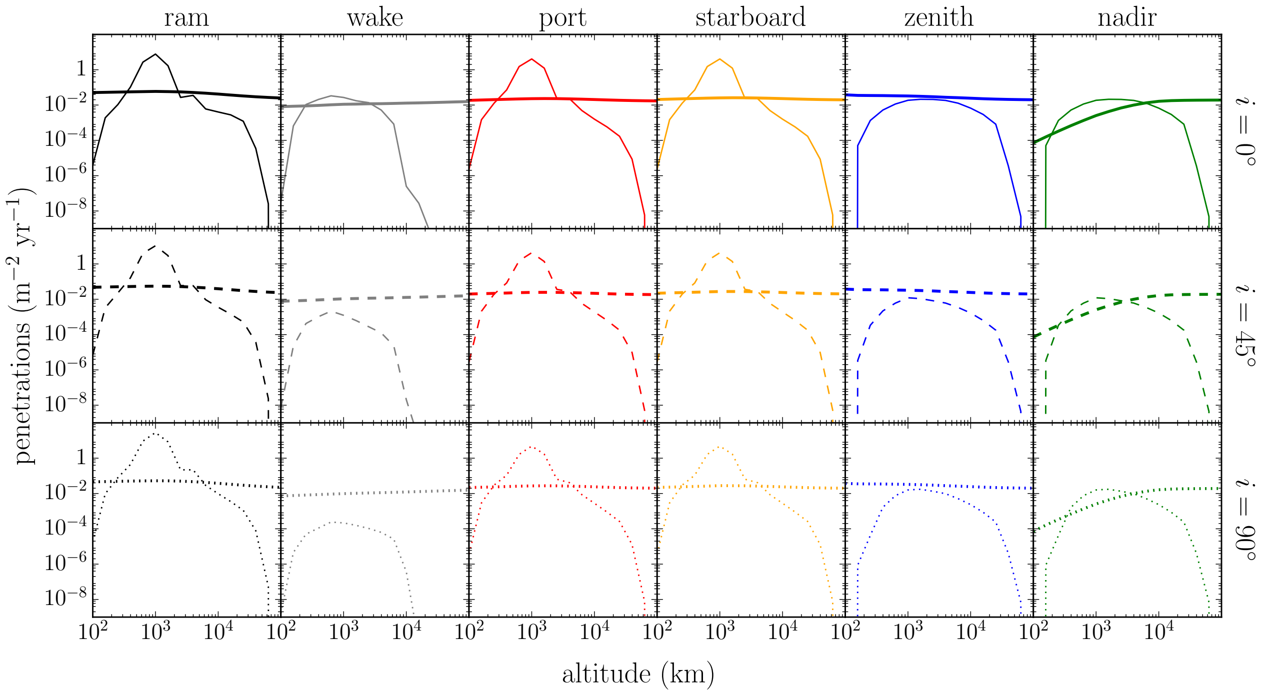

Figure 5. Comparison of meteoroid penetrations (bold) to those of orbital debris as a function of altitude for the six surfaces and three inclinations.

is seen that the flux on the wake-facing surface shows the strongest dependence on orbital inclination, with the penetrating flux of orbital debris particles decreasing as the inclination approaches 90 degrees.

4.3 Orbital debris/meteoroid environment comparison

Figure 5 compares the meteoroid/debris penetrations for all six surfaces at the three orbital inclinations. For ram, port, and starboard, the number of debris penetrations dwarf that of meteoroids for altitudes ranging from 250 km to about 4000 km. At its peak at 1000 km, the ram penetrating flux is almost 500 times that of meteoroids, pointedly driving home the importance of orbital debris at those altitudes. In contrast, the debris penetrations on the zenith and wake surfaces are factors of a few to tens below the meteoroid values, marking these locations as suitable for the placement of meteoroid-only shields (conventional Whipple shields - if shielding is deemed necessary). Meteoroids dominate the nadir surface up to 300 km altitude and above 2500 km; between these limits, the debris penetrating flux equals or exceeds that of meteoroids up to a factor of three. As the inclination of the orbit decreases, the number of debris penetrations on ram, port, and starboard decrease, reaching one half the 90 degree values at 0 degree inclination. Conversely, the impacts on nadir, zenith, and wake increase to the point where meteoroid induced penetrations exceed that of debris throughout Earth orbit only for zenith. The increase in the wake is particularly dramatic, being almost two orders of magnitude.

5 SUMMARY

In this study we have placed the ORDEM 3.0 debris and the MEMR2 meteoroid environments on equal footing by computing the number of penetrations of a one millimeter thick aluminum plate oriented in six directions as a function of orbital altitude and inclination. The comparison has illustrated the great dynamic range of the orbital debris environment (several orders of magnitude) compared to that of meteoroids (factors of a few), and has produced several noteworthy revelations:

- Meteoroids dominate the one millimeter penetrating flux at altitudes below 250 km and above 4000 km.
- Only surfaces facing orbital zenith ('space') are dominated by meteoroids for all considered altitudes and inclinations.
- The number of one millimeter aluminum plate penetrations caused by orbital debris greatly exceeds that of meteoroids for ram, port, and starboard facing surfaces in the 250 to 2500 km altitude regime, reaching peak values over two orders of magnitude above the corresponding meteor penetrations around 1000 km. The debris penetrating flux on these surfaces increases with orbital inclination, indicating increased risk for vehicles in sun synchronous and other high inclination orbits.
- Orbital debris penetrations on the wake side increase with decreasing orbital inclination. At 0 degrees, the debris penetrating flux on the

wake side equals or exceeds that of meteoroids from 250 to 2500 km altitude.

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