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Micrometeoroid and Orbital Debris Environments for the International Space Station

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14. ABSTRACT

Baseline micrometeoroid and orbital debris fluence estimates for spacecraft in low Earth orbit (LEO) are provided. For these calculations, an orbit similar to that of the International Space Station (ISS) is used.

15. SUBJECT TERMS
Micrometeoroid, Orbital debris, International Space Station, Low Earth orbit

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1. Introduction

Micrometeoroids and orbital debris (MMOD) are known threats to spacecraft. Impacts can result in plasma discharges, penetration of the spacecraft, sudden electrical disturbances (SEDs), RF transients, gyro-destabilizations, pointing anomalies, and other effects. Modern spacecraft are relatively well shielded from small particles (<1 μm in diameter), but the much less common larger particles are still a concern.

Any surface exposed in space is subject to impact from the background particles that are passing through the near-Earth environment. For large objects, anything that hits the primary satellite is probably going to be catastrophic, and even if the primary is not destroyed, it's going to suffer serious damage. Risk assessment in this case is concerned with computing and possibly reducing the probability of collision, P_C. For small particles, however, the issue is not whether the primary satellite is going to be hit or not. That is inevitable. The question for small particles is whether they penetrate the surface of the satellite and cause damage. Risk assessment for small particles then involves computing the probability of penetration, P_P. (Equivalently, the probability of no penetration, PNP, is often used in the literature.) Therefore, for small particles (micrometeoroids and orbital debris, or MMOD), the relevant parameter describing the MMOD environment is not simply the number of particles (i.e., flux), but also the velocity (magnitude and direction) and density (or mass).

Micrometeoroids are small particles produced by comets and asteroids that are composed of small micron-sized grains containing a core of denser silicate material surrounded by ice attached together through additional icy material. Micrometeoroids have been a threat to spacecraft in the past; in 1991, the Solar A spacecraft lost its optical telescope due to a particle puncturing the sun shade, and in 1993, control of Olympus I was lost when a Perseid meteoroid caused an electromagnetic pulse that convinced the satellite it had lost its lock on the Sun. Olympus I was then commanded into an automatic search for the Sun, and by the time operators realized this was unnecessary, almost all of the fuel had been exhausted, and the satellite had to be disposed. This is an important lesson for all operators and analysts: an unwarranted over-reaction can pose as great a risk to the mission as an actual impact.

The man-made orbital debris (OD) environment, like micrometeoroids, is also characterized by the flux, velocity, and density of the particles. In some respects, the OD modeling is more accurate than MM simply due to the fact that the space community is very aware of what is being put into orbit. In other respects, the modeling is more difficult since more (and more highly variable) sources go into the environment modeling than simple icy or silicate particles.

The fluxes for the micrometeoroid (MM) and orbital debris (OD) environments are similar for particles smaller than about 1 cm in diameter; for particles larger than this, the orbital debris flux becomes dominant over the micrometeoroids. However, the density and velocity distribution of the two environments can differ considerably, and this impacts just how dangerous the two populations are. The OD threat is assumed to primarily consist of metallic objects with a mean density close to aluminum

(2.8 g/cm^3) while the MM particles are composed mostly of ice with density ranging from 0.5 to 2 g/cm^3. These densities may be adequate to describe the bulk of OD and MM particles, but it is known that not all OD is composed of aluminum (and the shape of the particles can substantially deviate from spherical), and some meteoroid particles can be composed mostly of iron with densities approaching 8 g/cm^3. Similarly, the velocity for debris ranges from 6 to 16 km/s while meteoroids can have velocities in excess of 70 km/s. As a consequence of the greater kinetic energy of impact, smaller micrometeoroids can have as big a negative influence on ISS and STS as larger orbital debris particles.

In Figures 1 through 3, the fluence (flux) is shown as number of particles that impact a surface in space per square meter of that surface per year as a function of particle diameter in cm. These numbers refer to all particles whose diameters are equal to or greater than the indicated diameter. This includes those that approach obliquely, i.e., not perpendicular to the surface.

From a damage standpoint, the most important property of the particle is not its diameter, D, but rather its kinetic energy, E_K.

$$E_K = \frac{1}{2} mV^2,$$

where V is speed, and mass m is

$$m = \rho * \text{volume} = \rho\, 4/3\pi(D/2)^3 \text{ for a spherical particle.}$$

MMOD particles can have densities that range from less than unity (cometary particles) to greater than 7–8 g/cm^3 (iron-nickel micrometeoroids). The most common particles have densities in the neighborhood of 2–3 g/cm^3.

2. MMOD Model Predictions

Figure 1 shows the average man-made orbital debris particle flux for the year 2007 for the International Space Station (ISS), assuming an average altitude of 350 km and inclination of 51.6°. There are four models shown: ORDEM96 and ORDEM2000 (both produced by NASA's Johnson Space Center, respectively, in the years 1996 and 2000), and Master01 and Master05 (both produced by the European Space Agency in the years 2001 and 2005). Note that Master01 and ORDEM96 have been replaced by the newer models and are no longer supported by their organizations. However, Master01 and ORDEM96 agree much better with each other than any other pair of models, and a comparison between the newer ORDEM2000 and Master05 shows the widest discrepancy. In general, ORDEM2000 produces the largest fluxes for particles smaller than about 3–4 mm, and the smallest fluxes for particles larger than ~5 mm. Master05, on the other hand, produces the smallest fluxes for particles smaller than 5 mm while being comparable to Master01 and ORDEM96 for the larger particles. Some of these differences have to do with how ORDEM2000 and Master05 are generated. ORDEM2000 is a largely empirical model constructed from data retrieved from STS, HST, LDEF, and ISS data, and was specifically created to conduct risk assessment for those altitude regions; to get fluxes for altitudes and inclinations beyond the ISS/STS regime, theoretical extrapolations are used. Conversely, Master05 is a theoretical model based upon frequency and expected composition of breakup and debris-shedding events and covers the entire near-Earth altitude regime; Master05 is then adjusted based upon empirical data. A new ORDEM model is expected shortly and will be evaluated when it becomes available.

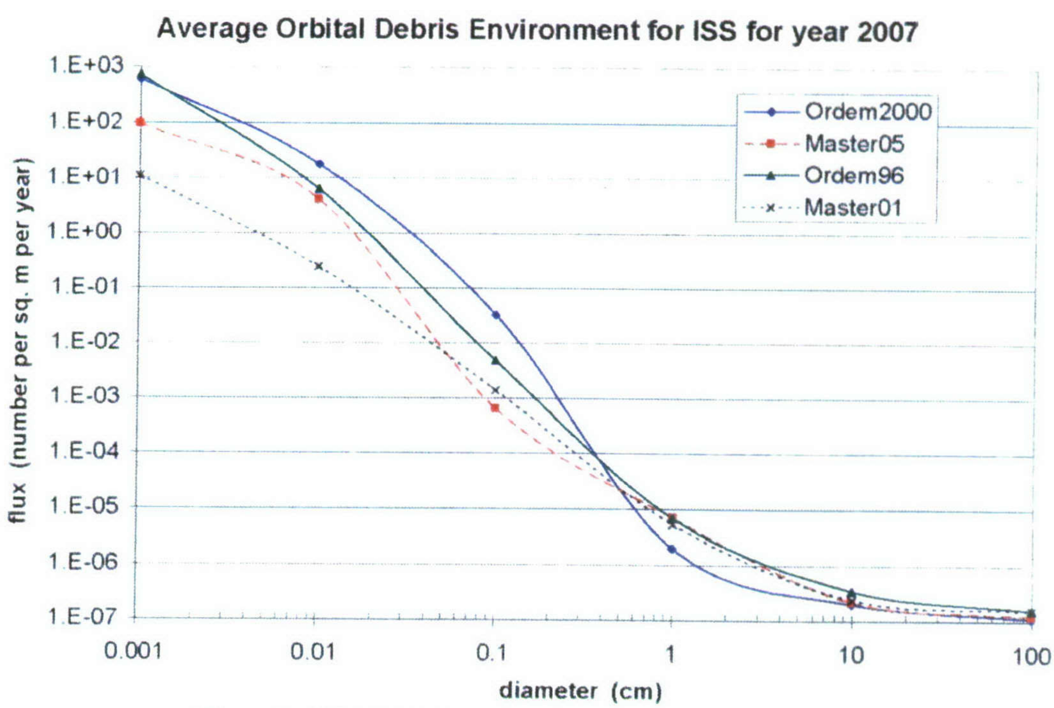

Figure 1. Orbital debris particle fluxes from various models.

Figure 2 shows the average micrometeoroid particle flux for several different models. "D/S" stands for the Divine/Staubach model that is implemented in either the Master01 or Master05 models. Neither ORDEM model contains a micrometeoroid component; to perform micrometeoroid threat assessment, NASA currently utilizes a model presented in document SSP 30425 (Boeder 1994), although it is planned that SSP will be superceded by Marshall Space Flight Center's Micrometeoroid Engineering Model (MEM) once work is completed on that project. For the particle flux, the SSP is essentially equivalent to the widely referenced Grün meteoroid model modified for the gravitational attraction of the Earth. The difference between micrometeoroid models is not as pronounced as the difference between the orbital debris models.

The above calculations do not include the as yet unknown change in OD particle number and distribution due to the recent Chinese ASAT experiment. Such events are certain to increase the number of orbiting particles. Some people have suggested that a relative small number of explosions in LEO can eventually render LEO space uninhabitable for satellites because one large particle can cause an explosion that leads to further particles that hit more spacecraft until a runaway situation is reached.

There is an additional factor involved when choosing a meteoroid model to use that one should be aware of. In the Divine/Staubach models as implemented in Master, slight discontinuities appear at certain altitude boundaries. The reason for this is unknown, but both Master01 and Master05 show this behavior. It is not known whether there is an issue with the Divine/Staubach model itself, the implementation in Master, or user error. Figure 3 shows the Divine/Staubach flux for 1 mm and 1 cm particles as compared to the Grün model adjusted for Earth's gravity; the discontinuities are consistently present regardless of particle size. They are not large in magnitude, but users should be aware they exist.

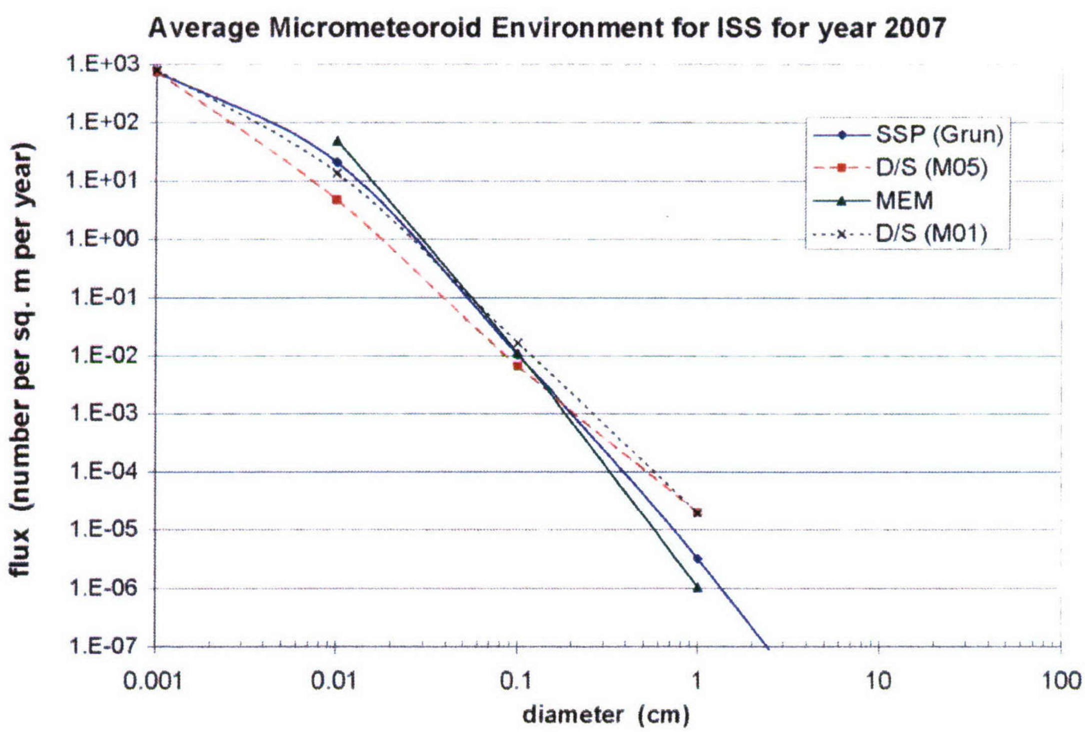

Figure 2. Micrometeoroid particle fluxes from various models.

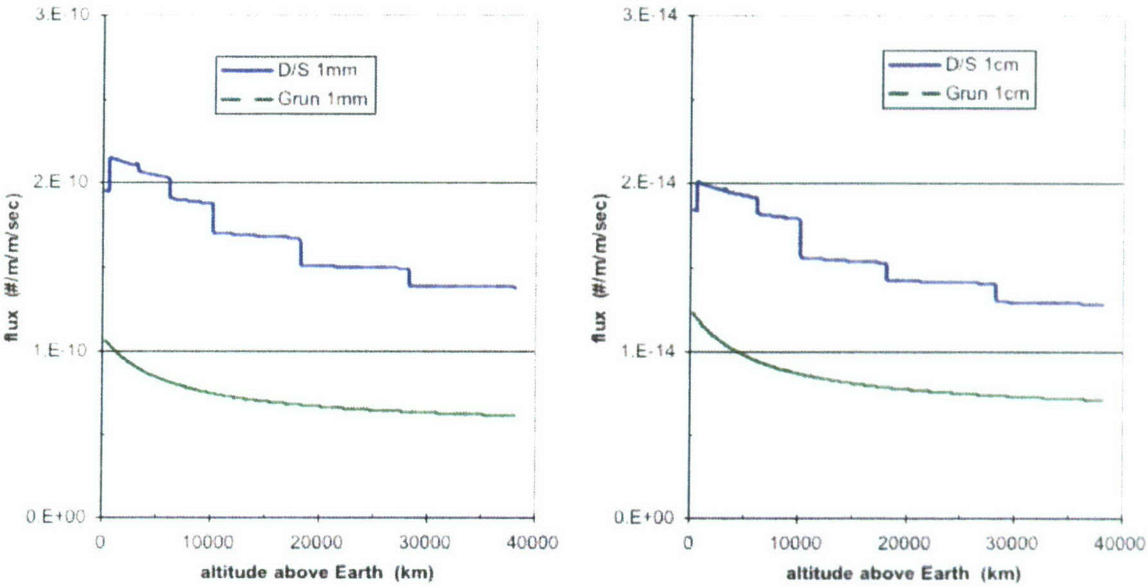

Figure 3. Comparison between Divine/Staubach and Grun micrometeoroid models.

3. Recommendations

For the MM, the recommendation is to utilize the Grün model (multiplied by 2 to be conservative and adjusted for Earth's gravity) since it gives smooth behavior, and, since Grün is analytic, it is very easy to implement.

For the OD, the best practice is to use both Master05 and Ordem2000 and present the results as a range of values. For particles larger than ~1 cm, the two models are in fairly good agreement, although ORDEM2000 produces lower fluxes by less than an order of magnitude; however, for sub-cm particles, they diverge substantially, and the range of produced values can be 2 orders of magnitude, with ORDEM2000 now producing higher values.

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