The New NASA Orbital Debris Engineering Model ORDEM 3.0

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The NASA Orbital Debris Program Office (ODPO) has released its latest Orbital Debris Engineering Model, ORDEM 3.0. It supersedes ORDEM 2.0. This newer model encompasses the Earth satellite and debris flux environment from altitudes of low Earth orbit (LEO) through geosynchronous orbit (GEO). Debris sizes of 10 μm through 1 m in non-GEO and 10 cm through 1 m in GEO are modeled. The inclusive years are 2010 through 2035.

The ORDEM model series has always been data driven. ORDEM 3.0 has the benefit of many more hours from existing data sources and from new sources that weren't available to past versions. Returned surfaces, ground tests, and remote sensors all contribute data. The returned surface and ground test data reveal material characteristics of small particles. Densities of fragmentation debris particles smaller than 10 cm are grouped in ORDEM 3.0 in terms of high-, medium-, and low-densities, along with RORSAT sodium-potassium droplets.

Supporting models have advanced significantly. The LEO-to-GEO ENvironment Debris model (LEGEND) includes an historical and a future projection component with yearly populations that include launched and maneuvered intacts, mission related debris (MRD), and explosion and collision fragments. LEGEND propagates objects with ephemerides and physical characteristics down to 1 mm in size. The full LEGEND yearly population acts as an a priori condition for a Bayesian statistical model. Specific, well defined populations are added like the Radar Ocean Reconnaissance Satellite (RORSAT) sodium-potassium (NaK) droplets, recent major accidental and deliberate collision fragments, and known anomalous debris event fragments. For microdebris of sizes 10 μm to1 mm the ODPO uses an in-house Degradation/Ejecta model in which a MLE technique is used with returned surface data to estimate populations.

This paper elaborates on the upgrades of this model over previous versions highlighting the material density splits and consequences of that to the penetration risk to spacecraft.

INTRODUCTION

The ORDEM program was initiated in the mid-1980s in support of the Space Station Program Office.(1) It grew over the decades to serve as an aid to spacecraft planners of both crewed and robotic vehicles and environmental researchers in understanding the dangers of the growing orbital debris population. The current model, ORDEM 3.0, and its documentation are available electronically, from the NASA ODPO website (**http://orbitaldebris.jsc.nasa.gov/model/engrmodel.html**). The site provides directions on how to request it. The ORDEM 3.0 package includes the program graphical user interface (GUI), executable, data files and the ORDEM 3.0 User's Guide.

The debris flux encompassing a spacecraft, or through a ground sensor beam is the direct output of an ORDEM 3.0 calculation. Fluxes are tabulated by direction, debris size, velocity, and material density. The two analysis modes are termed the Spacecraft Mode and the Telescope/Radar Mode, respectively. Spacecraft designers would ideally verify candidate orbits and vehicle design by running ORDEM 3.0 to determine the directional debris flux on their spacecraft. They would then use a separate penetration risk calculation to gauge the debris risk to their critical systems and overall missions. Debris researchers, planning observation campaigns or sensor programs, would use

ORDEM 3.0 to estimate the requirements of their programs. In the recent past mission parameters have been redesigned to account for the ORDEM debris environment. For Example, the ORDEM 2.0 (formerly ORDEM2000) environment identified critical sub-system placement and shielding requirements on various robotic spacecraft and on crewed vehicles.(2,3) The new ORDEM 3.0 is currently in use for such studies.

ORDEM 3.0 FEATURES

The debris environment included in the ORDEM 3.0 package is represented by populations in multidimensional orbital element bins (see Tables 1 and 2). Each environment is a yearly snapshot and also includes information on size, material density, and population number uncertainties. In any given year there are many empty bins.

Table 1: Input File Population Bins for LEO to GTO*

Parameter	Binning Intervals	Total No. of Bins
Perigee altitude, h_p	$100 \le h_p < 2000$ km → 33.33 km bins $2000 \le h_p < 10{,}000$ km → 100 km bins $10{,}000 \le h_p < 40{,}000$ km → 200 km bins	287
Eccentricity, e	$0 \le \sqrt{e} < 0.02666 \rightarrow 0.02666$ bin $0.02666 \le \sqrt{e} < 1 \rightarrow 0.01333$ bins	74
Inclination, i	$0° \le i < 180° \rightarrow 0.75°$ bins	240

* From the "ORDEM 3.0 – User's Guide"

Table 2: Input File Population Bins for GEO*

Parameter	Binning Intervals	Total No. of Bins
Mean Motion, n	$0.5 \le n < 0.95 \rightarrow 0.01$ rev/day bins $0.95 \le n < 1.05 \rightarrow 0.001$ rev/day bins $1.05 \le n < 1.80 \rightarrow 0.01$ rev/day bins	220
Eccentricity, e	$0 \le \sqrt{e} < 0.5 \rightarrow 0.02$ bins	25
Inclination, i	$0° \le i < 0.2° \rightarrow 0.2°$ bins $0.2° \le i < 1.0° \rightarrow 0.8°$ bins $1° \le i < 25° \rightarrow 1°$ bins	26
Right ascension of ascending node, Ω	$0° \le \Omega < 360° \rightarrow 5°$ bins	72

ORDEM 3.0 top-level output features are compared to those of the retired ORDEM 2.0 in Table 3. The new model includes significant advances derived by the ODPO over the intervening years. The ORDEM altitude range has been extended to include 100 km through 40,000 km. This allows for the inclusion of debris in highly elliptical as well as geosynchronous orbits. Cataloged objects that are recognized as launched or released into orbit are defined as "Intacts". This category generally encompasses spacecraft and rocket bodies. Debris smaller than 10 cm are labeled by material density as displayed in the table. This feature is a significant upgrade that will be discussed in a later section. The total flux uncertainties are calculated for each ORDEM 3.0 run. Finally, the populations include fiducial points at half-decade cumulative debris size markers. These populations are derived from the statistical observational data.

These added features require much more free disk space and a longer runtime in general. For example, with the recommended igloo 10^ox10^ox1km/s a flux calculation in the spacecraft mode for the ISS orbit expands from seconds with ORDEM 2.0 to tens of minutes with ORDEM 3.0. Highly elliptical orbits will require several hours to complete. Telescope/radar mode recommendation of 50 km altitude bins from LEO to GEO also ranges from minutes to a few hours, depending on the telescope/radar pointing direction.

Table 3: Feature Comparison of ORDEM 2.0 and ORDEM 3.0*

Parameter	**ORDEM 2.0**	**ORDEM 3.0**
Spacecraft & Telescope/Radar analysis modes	Yes	Yes
Time range	1991 to 2030	2010 to 2035
Altitude range with minimum debris size	200 to 2000 km (>10 μm) (LEO)	100 to 40,000 km (>10 μm)** (LEO to GTO) 34,000 to 40,000 km (>10 cm) (GEO)
Orbit types	Circular (radial velocity ignored)	Circular to highly elliptical
Model population breakdown by type & material density	No	Intacts Low-density (1.4 g/cc) fragments Medium-density (2.8 g/cc) fragments & microdebris High-density (7.9 g/cc) fragments & microdebris RORSAT NaK coolant droplets (0.9 g/cc)
Model cumulative size thresholds (*fiducial points*)	10 μm, 100 μm, 1 mm, 1 cm , 10 cm, 1 m	10 μm, 31.6 μm, 100 μm, 316 μm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m
Flux uncertainties	No	Yes
Total input file size	13.5 MB	1.25 GB
Meteoroids	No	No

**While the geosynchronous transfer orbit (GTO) is not as well observed as LEO, the orbital dynamic forces and mechanisms for fragmentation are considered to be similar. The ODPO therefore allows for > 10 μm fluxes through GTO. For GEO the dynamics (including perturbation forces and impact velocities) as well as the size and structure of satellites are unique, though GTO and GEO physically overlap. The ODPO provides GEO debris fluxes for 10 cm and larger only. This is based on the SSN (1 m and larger), the MODEST uncorrelated target data (30 cm – 1 m) and the MODEST uncorrelated targets extended to 10 cm. Any fluxes below that 10 cm threshold at altitudes above LEO altitudes are solely due to GTO objects.

SUPPORTING DATA, MODELING, AND RESULTING ENVIRONMENT

The debris environment is highly dynamic and as it changes over time, so does the utility of available datasets. The ODPO faces the continuing challenge of supporting tried data systems while shepherding new ones. The mainstay dataset for all ODPO activities over the years has been the Space Surveillance Network (SSN) nearly complete to 10 cm in LEO and 1 m in GEO. As the orbital debris populations have evolved several other data sources that were central to ORDEM 2.0 development have been retired and replaced by others that have matured. The radar systems Haystack and Haystack AuXiliary (HAX) continue to contribute heavily, with Haystack and HAX routinely providing as many as 1250 hours/year of statistical data (> 5.5 mm and > 3 cm, respectively). The Goldstone radar is currently a minor contributor with tens of hours/year, but within the critical under-sampled size region of 3 mm to 8 mm. The Michigan Orbital Debris Survey Telescope (MODEST), along with the SSN, provides the ODPO with its only available data for the GEO region (> 30 cm). Finally, the Space Transportation System (STS) impact database, generated at JSC by the Hypervelocity Impact Technology group (HVIT), and the Scanning Electron Microscope (SEM) Laboratory tabulates over 600 microdebris impactors.

These data contributed to the development of a Bayesian statistical approach to population derivations with NASA's debris evolutionary model, LEGEND, as the a priori condition for debris down to 1 mm. A maximum likelihood estimation technique was applied to a Degradation/Ejecta model as the a priori condition below 1 mm.

ORDEM 3.0 population files also include sets of "special populations" that have been identified independently of the debris background (See Table 4). These are notable by their release mechanism, detrimental effect on the environment, or lack of obvious source. They include the aforementioned sodium-potassium NaK droplets which were released passively in each of 16 RORSAT nuclear core ejection events, fragments from the Iridium 33 /Cosmos 2251 accidental collision, the FY-1C antisatellite test, and shedded pieces from the Snapshot vehicle, the Transit series of vehicles and some unidentified parent at 56 °. The NaK droplets are the only special population that is identifiable to the ORDEM 3.0 user. All others were added to the debris background.

Table 4: Special Populations

Source	Objects/mechanism	Estimated parent orbit at event date	Debris event date
RORSAT satellites	NaK droplets Low-energy release (leakage)	~900km (one at 700km), ~65 °	16 events, 1979-1988
Iridium 33	Fragments High- energy collision	~790 km, 86.4 °	10 Feb 2009
Cosmos 2251	Fragments High- energy collision	~790 km,74.0 °	10 Feb 2009
FY-1C	Fragments High- energy collision	~850 km, 98.8 °	11 Jan 2007
Snapshot	Fragments Low- energy release (shedding)	~1300 km, 90.3 °	Single large event in 1984
Transit satellites	Fragments Low- energy release (shedding)	~1100km, 90 °	End of mission 1960s
56°	Fragments Low- energy release (shedding)	~1300 km, 56°	Unknown

The ORDEM 3.0 output flux for the International Space Station (ISS) is presented in Figure 1. Contributing sensors and their dominant regions of influence are highlighted. The region from 1 mm to 3.16 mm is currently very sparsely populated with data. The flux through that region is an interpolation.

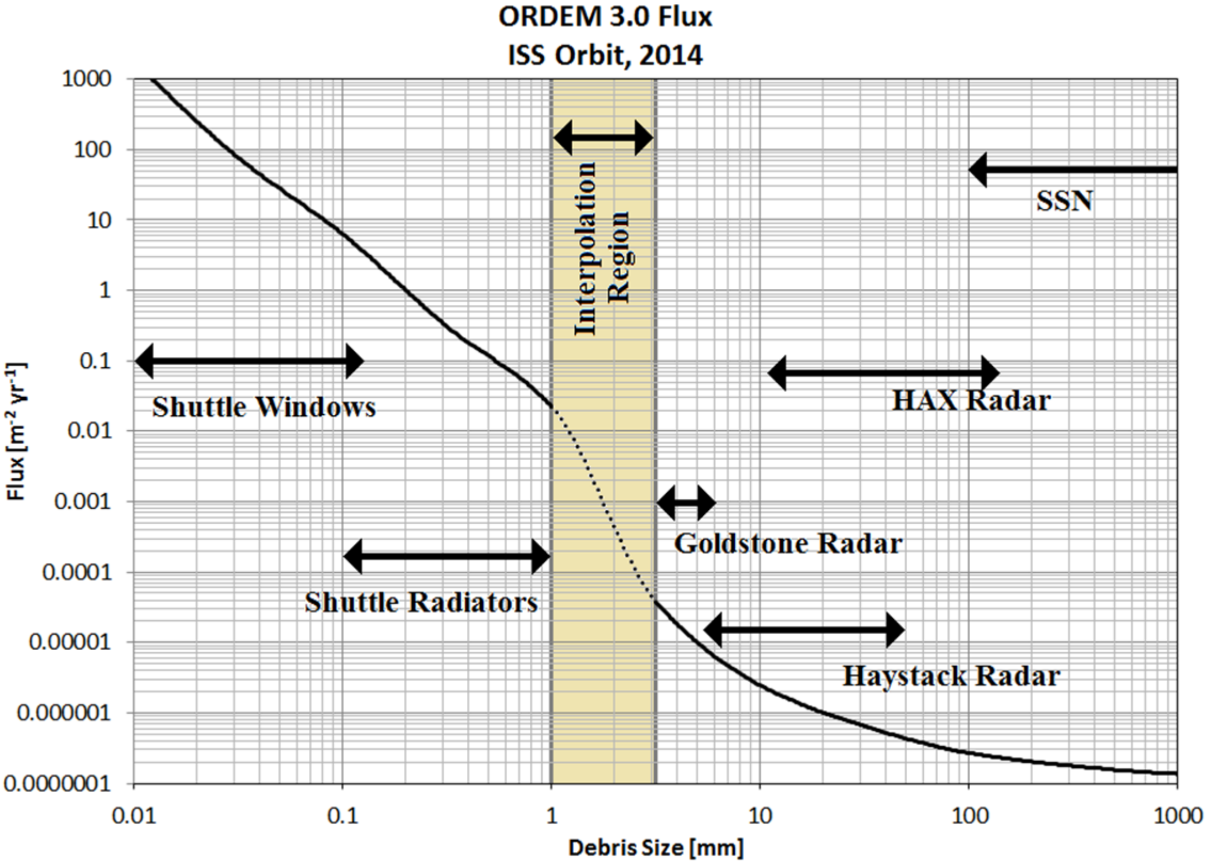

Fig.1. ORDEM 3.0 total flux at the typical ISS orbit (400 km x 400 km, 51.6° in 2014.

MATERIAL DENSITY

Before ORDEM 3.0 was released the ODPO surmised that its small debris (1 mm to 10 cm) and microdebris (10 μm to 1 mm) populations that were tagged with material density would lead to changes in the modeled environment. Earlier versions of ORDEM modeled debris smaller than 10 cm as aluminum spheres. Investigations over the years since ORDEM 2.0 release led to the ODPO separating materials into three categories; low-density representing plastics and phenolic, medium-density representing aluminum and paint, and high-density representing steel and copper. These categories were shown to be general in spacecraft and rocket body designs though percentages within these vehicles vary.(4) Spacecraft appear to contain a higher percentage of low-density material. Rocket bodies are heavier on medium- and high-density materials. The ratio of rocket body to spacecraft breakups is 3 to 1.

The HVIT group maintains the aforementioned STS database. It covers STS missions from STS 71, in the mid 1990's, to STS-135, the last STS mission. At the time of ORDEM 3.0 development the database included over 600 impactor events on STS radiator and window surfaces, a majority of which had also been chemically identified along with observations of crater dimension. Each of the returned STS vehicles was subjected to a visual inspection of those surfaces. Craters were identified and in many cases measured. Where impactor remnants were present, they were extracted, and attempts were made to identify chemical properties with the SEM Laboratory equipment. In all about 2/3 of the impactors were successfully identified chemically. Chemical identifications of radiator impactors are shown in Figure 2. A majority (59%) of the impactors are identified as paint, aluminum, and titanium (medium-density material) with high-density steel following closely at 35%.

Debris Sources	
D: Paint	38
D: Steel	27
D: Al	7
D: Na/K	2
D: binders	1
D: Ti	1
D: waste	1
D: Ag	1
D: Al2O3	0
D: Cu	0
D: NiCd	0
D: PCboard	2
D: Plastic	0
Total	**80**

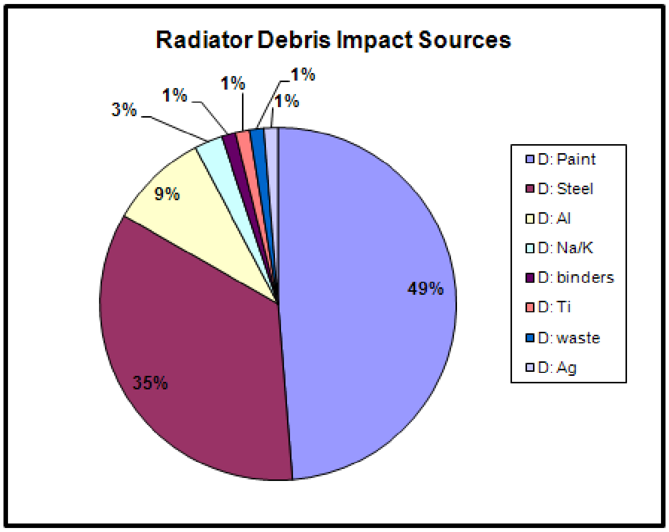

Fig.2. Radiator data from 81 distinct STS missions, with impactors identified as orbital debris by the HVIT and the SEM Laboratory. (Figures courtesy Mr. J. Hyde)

Debris Sources	
D: Al	123
D: Paint	116
D: Steel	33
D: Al2O3	7
D: Cu	2
D: Plastic	2
D: Ag	1
D: Na/K	0
D: binders	0
D: Ti	1
D: waste	0
D: NiCd	0
D: PCboard	0
Total	**285**

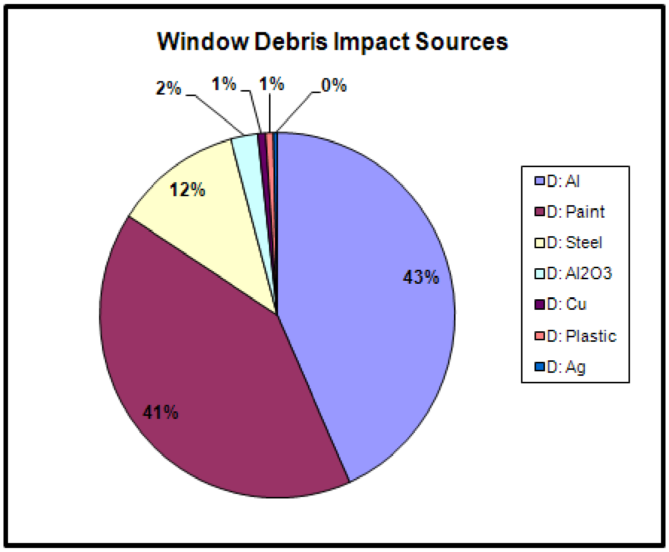

Fig.3. Window data from 81 distinct STS missions, with impactors identified as orbital debris by the HVIT and the SEM Laboratory. (Figures courtesy Mr. J. Hyde)

Chemical identifications of window impactors (Figure 3) show a much larger majority (85%) of impactors identified as paint, aluminum, and titanium (medium-density material). High-density steel and copper follow far behind at 13%.

The radiator panels, which are aluminum, make it very difficult to identify aluminum impactors. Many of the craters are considered by HVIT as being of unknown material, as is shown by the very low number of chemical identifications (80) compared to the window number of 285. This is even more striking when the surface area of all windows is compared to that of the radiator panels (1:15). The conclusions drawn from the HVIT database are that microdebris aluminum and paint particles are very similar in population at STS altitudes and they out number high-density steel by about 9 to 1. Plastics (low-density materials) are very sparse in the database, which could indicate a dearth of the material on-orbit, possibly related to the lower breakup rate of spacecraft, a very fast orbital decay rate due to high area-to-mass, or both.

An independent study of small debris reached a similar conclusion in the ratio of medium-density to high-density materials. The Satellite Orbital Debris Characterization Impact Test (SOCIT) in 1991 was a set of hypervelocity impact tests at Arnold Engineering Development Center.(5) The fourth and final test targeted a flight-ready, U.S. Transit navigation satellite, yielding collision fragments in the size regime of sub-millimeter through tens of centimeters. The spacecraft materials offered a view of a typical mid-20th century satellite structure. All three of the material density categories were represented in that test. The collection and measurement of the fragments was performed by Kaman Corp. The resulting database in the 1mm to 10 cm is used for Figure 4, a display of material density relative percentages by size.(6)

The SOCIT4 ratio of medium-density vs. high-density materials only (see Figure 5) however shows a value very close to the HVIT database result (9 to 1) over the entire size range of 1mm to 10 cm.

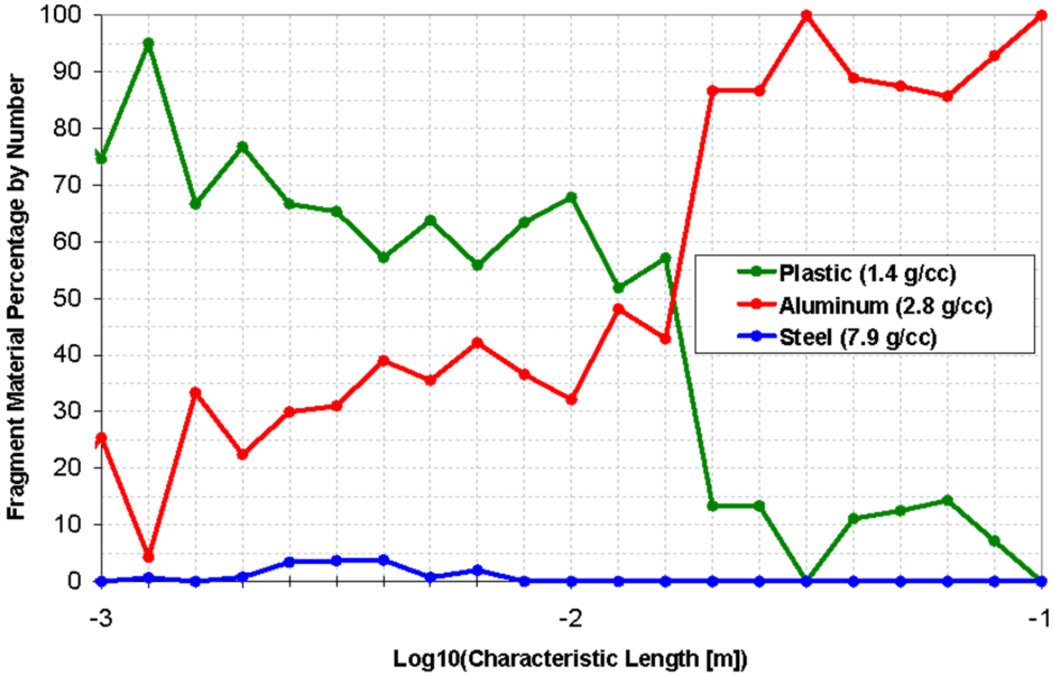

Fig.4. Relative density percentages for spacecraft fragments derived from the SOCIT4 data.(4,7)

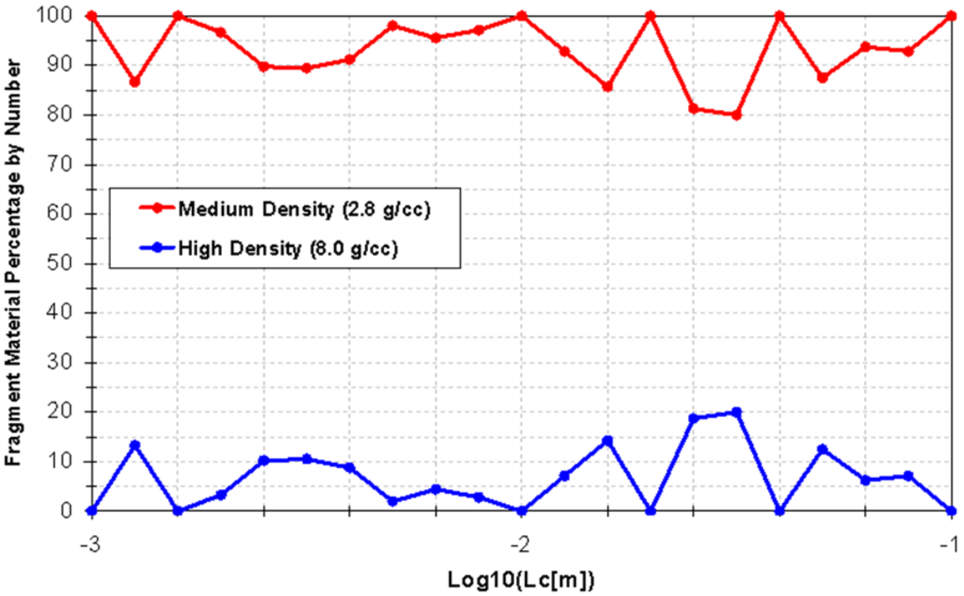

Fig.5. SOCIT4 material medium- and high-density relative number percentages vs. debris size. Medium-density material here is aluminum. High-density material includes steel and copper.(7)

Based on the information above the ODPO chose a percentage of material in rocket body microdebris and small debris fragments to be 90% medium-density and 10% high-density. For spacecraft the small debris fragmentations include the percentages in Figure 4. An example of the calculated ORDEM 3.0 outcome for the ISS flux in 2014 is shown in Figure 6. The total ORDEM 3.0 flux is compared to that of ORDEM 2.0. The total ORDEM 3.0 flux is also separated by material density.

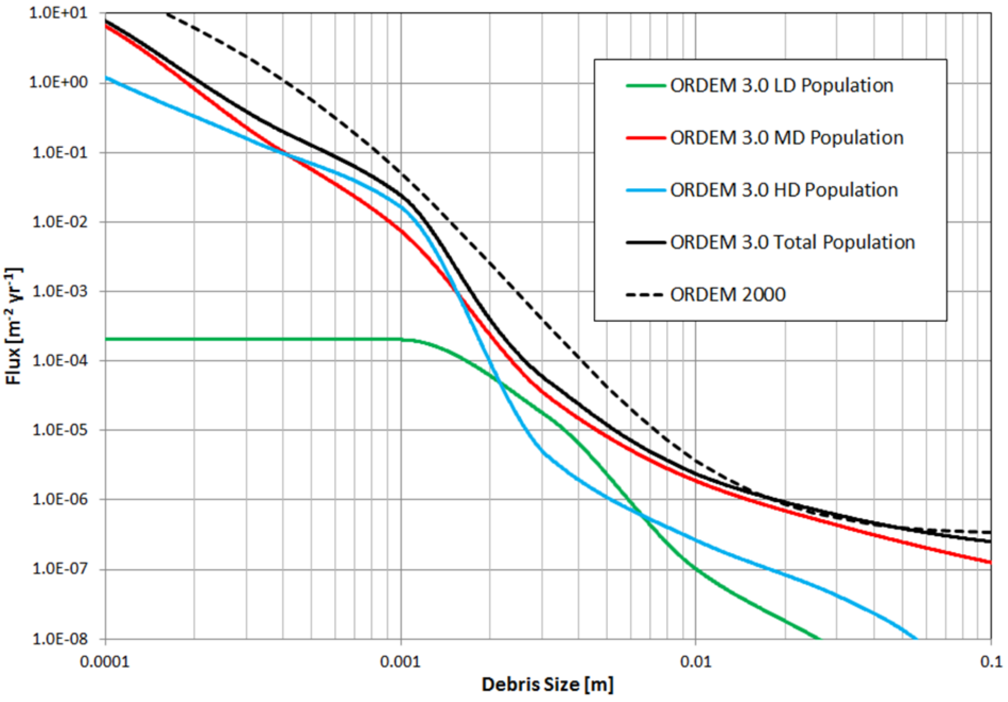

Fig.6. ORDEM 3.0 Populations for 2014 ISS flux as a function of debris size.

In response to the ODPO material distributions the HVIT group has begun a test program at White Sands Test Facility (WSTF) to impact spacecraft materials (aluminum plates, window material) with steel microdebris. This program is ongoing. But HVIT analysis of the penetration risk to ISS based on these material density categories indicates the following assessments.

- ORDEM 2.0 fluxes are somewhat higher than those of ORDEM 3.0 at ISS altitude
- The steel (high-density) component of orbital debris contributes majority of risks with the ORDEM 3.0 environment model
- 94% of the penetration risk is due to steel orbital debris
- The ISS MMOD penetration risk over next 10 years is 40% higher with ORDEM 3.0 compared to ORDEM 2.0
- ISS plans to add MMOD protection to ISS cargo vehicles (in late 2015)

SUMMARY

The NASA ODPO orbital debris engineering model, ORDEM 3.0, has been released and is in use by several spacecraft and sensor programs to assist in vehicle safety and environment studies. The new model encompasses a far larger region in space than did the previous version, and therefore allows more varied orbits and sensor orientations to be analyzed. Upgrades include the expansion of observational program datasets in underrepresented regions, the addition of orbital debris flux uncertainties to each set of outputs, and most critically the labeling of debris by material density. Impact data from HVIT's STS returned surface database and the ODPO analysis of the SOCIT4 fragment materials and sizes, agree on the percentages of medium-density material to high-density material, (90% to 10%, respectively), by size from microdebris to small debris (10 μm to 10 cm). The consequences of high-density material in Earth orbit are being studied. But preliminary tests show a less benign environment.

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