THE NEW NASA ORBITAL DEBRIS ENGINEERING MODEL ORDEM2000

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ABSTRACT

A new orbital debris engineering model, ORDEM2000, has been developed by the Orbital Debris Program Office at NASA Johnson Space Center. The new model uses a more rigorous mathematical method to derive debris populations from observation and measurement data. It also uses a direct approach to build the debris environment. This new approach eliminates several limitations and assumptions utilized in the previous model (ORDEM96). The new model provides a better description of the current debris environment than ORDEM96 does. It is expected that ORDEM2000 will soon replace ORDEM96 as the standard model to evaluate the debris risk for the International Space Station (ISS) and for future Shuttle missions.

1. INTRODUCTION

In 1996, the NASA Orbital Debris Program Office released the first computer-based orbital debris engineering model, ORDEM96 [1]. Since its release the model has been widely used by the international space community to evaluate the debris risk for spacecraft in the Low Earth Orbit (LEO) region between 200 and 2,000 km altitude. Over the years, it has been shown to be an important and adequate debris risk assessment tool for LEO spacecraft operations as well as for debris measurements and observations.

Since the LEO debris environment is an evolving environment, it is necessary to update and upgrade the model on a regular and timely basis. With the aid of more recent debris observations and measurements and more powerful computers, a new model, ORDEM2000, has been recently developed and completed. This paper gives an overview of the new model. We outline the method adopted to derive debris populations from existing data in Section 2.1. The finite element model used to build the debris environment is described in Section 2.2. The verification and validation of the model is given in Section 3.

2. MODEL DESCRIPTION

ORDEM2000 is an engineering model that describes the orbital debris environment, in terms of object spatial density, flux, velocity, and inclination distributions in the LEO region. The model covers objects between 10 μm and 10 m in size and is valid between 1991 and 2030.

Fig. 1 outlines the approaches of ORDEM96 and ORDEM2000. Both models derive debris populations from available observational and measurement data, although ORDEM2000 uses a more rigorous mathematical method to accomplish the task (see Section 2.1). Once debris populations become available, ORDEM96 simplifies the populations into 6 inclination bands and 2 eccentricity families. It also assumes that the longitudes of the ascending node (Ω) and arguments of perigee (ω) of objects are randomly distributed between 0° and 360°. With additional assumptions regarding the debris size distribution and their altitude dependence, one can derive a set of equations to represent the LEO debris environment [1,2]. One can then take the equations and calculate the impact flux on an orbiting spacecraft or the debris flux expected to be observed by a ground-based telescope or radar.

ORDEM2000 takes a different approach to build the debris environment. A finite element model that divides the LEO region into numerous 3-dimensional cells is used to represent the environment (see Section 2.2). The contribution to each cell from each debris object is calculated directly. The orbital elements of each object, as derived from the observation/measurement data, are used in the calculation without any simplifications or assumptions. The LEO debris environment is represented by the "template" data files that store the spatial density, velocity distribution, and inclination distribution of particles of different sizes within each cell. Once the orbit of a spacecraft is specified, the model simply flies the spacecraft through the environment and calculates the impact flux directly.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

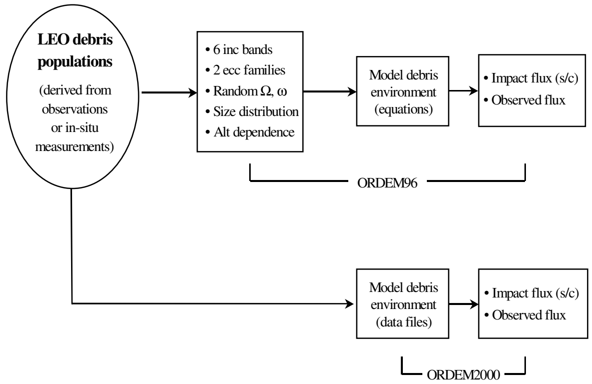


Fig. 1. Logical approaches of the two ORDEM models.

An additional new feature implemented in ORDEM2000 is a user-friendly Graphical User Interface. It is a convenient tool allowing the user to select and modify input parameters easily and, when the computation is completed, to access the output data or to export the results for additional analysis.

2.1 Debris populations

The ORDEM2000 template files cover objects from five different size thresholds: 10 µm and greater, 100 µm and greater, 1 cm and greater, 10 cm and greater, and 1 m and greater. In the following sections, they will be described simply as 10 µm, 100µm, 1 cm, 10 cm, and 1 m populations. The Space Surveillance Network (SSN) catalog is used to build the 10 cm and 1 m populations. The Haystack radar data [3] is used to build the 1 cm population while the Long Duration Exposure Facility (LDEF) measurements [4] are used to build the 10 µm and 100 µm populations. The 1 mm debris information in the model is based on an interpolation between the 100 µm and 1 cm populations. Goldstone radar data for 2 mm objects are used to justify the interpolation. The standard output from the model includes information on particles of the above-mentioned six different sizes. In addition, a cubic spline interpolation [5] is used in the model to allow the user to obtain information for objects with any arbitrary size between 10 µm and 1 m.

It is generally believed that the SSN catalog does not provide a complete coverage of objects 10 cm and greater in the LEO region. This can be seen from Fig. 2. The cumulative size distribution (N_{cum}) of all objects, from the SSN catalog at the beginning of 1999, as a function of diameter is shown as the top curve. When it is separated into two components (non-breakup and breakup), the level-off of the breakup fragment component just above 10 cm is a clear indication that the coverage is incomplete at 10 cm (due to the sensitivity limit of the radar). The characteristic of the level-off appears to be the same even when the breakup fragment component is further divided into components with different altitude, eccentricity, and inclination (triangles and circles in Fig. 2).

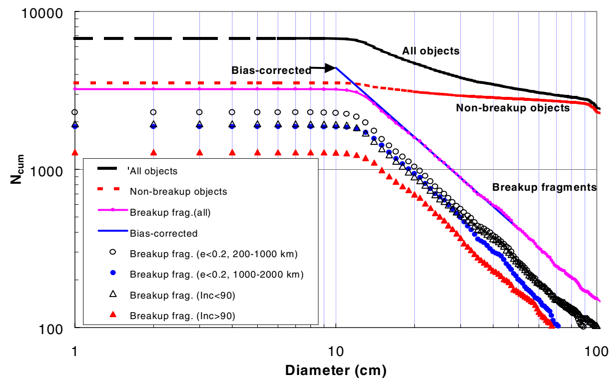


Fig. 2. Cumulative size distribution from SSN catalog on the first day of 1999.

To account for the incompleteness problem, a simple bias correction is applied to the SSN catalog objects to form the ORDEM2000 10 cm population. It is based on the following two arguments: (1) the current breakup fragments are dominated by explosion fragments, and (2) the size distribution of explosion fragments follows a simple power law that, when plotted on a logarithmic (N_{cum} vs. size) chart, mimics a straight line [6]. The ORDEM2000 10 cm population is obtained by increasing the contribution of catalog breakup fragment and real 8x,xxx objects by 13 % to where the bias-corrected straight line intersects the 10 cm line (see Fig. 2) plus all known non-breakup objects.

The ORDEM2000 1 m population is taken directly from the SSN catalog without any modification.

One of the difficulties in dealing with radar or *in situ* impact measurements of the orbital debris environment is that the desired information is often incomplete. Data from the Haystack radar, for instance, give good flux information at a particular altitude, but in general do not give good orbit eccentricities. Returned surfaces give information on cratering fluxes, but do not indicate whether the particle was a small object traveling quickly or a larger object traveling more slowly.

The actual number of craters on a given oriented surface or in a radar range/range-rate bin due to a particular orbit is determined by the unknown number of objects in that particular orbit. However, the ratio of detected objects in one measurement bin to another measurement bin is a function of the geometry of the orbit and the physics of the detection process (e.g., cratering). The expected ratios among the various measurement bins can be computed for all allowed types of debris populations. If the populations are chosen carefully, then the "fingerprints" for each orbit population are linearly independent. In other words, the measured data represent a convolution of these data "fingerprints" for the actual debris populations in orbit. If the distribution in the measured parameters z (e.g. range/range-rate pairs) is given by m(z) dz and the distribution in the actual population parameters x (e.g. orbit inclination and eccentricity) is given by n(x) dx, then these two are related by the instrument response function f(z|x) dz that determines the detection rate of a given population x with measurement parameters z. The instrument response function can be computed based on the characteristics of the measuring instrument and the orbital behavior of the populations. These distributions are related by:

$$m(z) = \int dx\; n(x)\, f(z \mid x)\,. \qquad (1)$$

If these parameters are binned, the integral can be cast as a summation

$$m_j = \sum_i f_{ij}\, n_i\,. \qquad (2)$$

The values in each bin m_j are measured, and the values in each bin of f_{ij} can be computed. All that remains is to solve for the values of n_i under the assumption that the $n_i \geq 0$. In general, this equation cannot usually be solved directly. However, a best-fit solution can be arrived at using a Maximum Likelihood Estimator (MLE). For our purposes, this is achieved by using the Expectation Maximization (EM) algorithm [7]. This algorithm finds a solution for n_i that maximizes the Kullback-Leibler information divergence:

$$\sum_j \left\{ m_j \ln\left(\sum_i f_{ij}\, n_i \right) - \sum_i f_{ij}\, n_i \right\}. \qquad (3)$$

This particular method works well when the data values m_j represent statistical sampling of the data space. This method is used to derive the ORDEM2000 1 cm population from the Haystack radar measurements and the 10 µm and 100 µm populations from the LDEF surface impact data sets. Once debris populations are derived from a set of data, they are projected to the year 1999 based on a dynamical model that includes the historical launch traffic and the effect due to solar activity.

2.2 Debris environment model

ORDEM2000 adopts a finite element model to represent the LEO space. The region between 200 and 2000 km altitude is divided into (5° x 5° x 50 km) cells in longitude (θ), latitude (90°-φ), and altitude (r), respectively (Fig. 3). When a debris population is derived from observations, the resident time of each debris particle within each cell is calculated using the fractional time it spends in that cell. For example, if a debris particle spends 3% of its orbital period within a given cell, 0.03 "objects" is assigned to that cell. Once the same procedure is completed for every debris particle in the population, the spatial density of this debris population within each cell is simply the sum of objects within that cell divided by its volume.

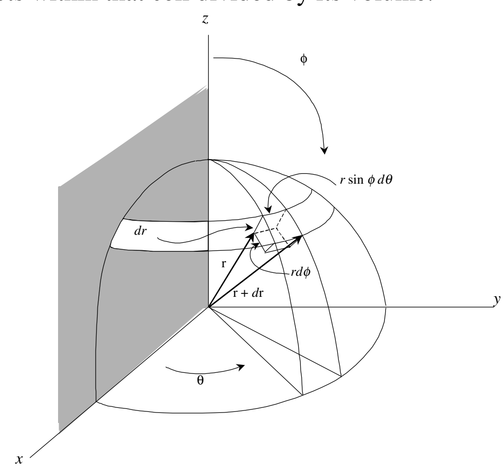
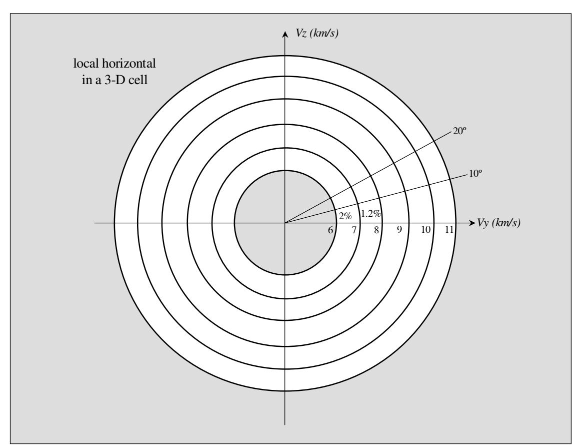


Fig. 3. ORDEM2000 finite element model.

No assumptions regarding debris particles' orbital inclinations, eccentricities, or orientations in space (longitudes of the ascending node and arguments of perigee) are required in this approach. Nor are their altitude dependence and size distribution. However, a decision is made to randomize the longitudes of the ascending node of objects. This is justified since the orbital planes of LEO debris particles have fast precession rates, except for Sun-synchronous orbits. However, only a small fraction of objects in retrograde orbits are in Sun-synchronous orbits and their distribution in longitude is nearly random, so that this approach is justified for these orbits as well.



A velocity distribution is calculated within each cell by evaluating the orbital velocity vector of each population member in the cell. Only the local horizontal velocity component is stored in the templates. This is justified since the radial velocity component is generally less than 0.1 km/s while the horizontal velocity component is about 6-11 km/s. The velocity distribution is stored in both magnitude (between 6 and 11 km/s with an increment of 1 km/s) and direction (10° resolution) as shown in Fig. 4. The inclination distribution of debris particles of a given size and greater is also calculated for each cell and is saved as part of the templates. This distribution covers inclinations between 0° and 180° with an increment of 2°.

The spatial density, velocity distribution, and inclination distribution templates form the debris environment in ORDEM2000. Once the user specifies the orbit of a spacecraft, the model simply "flies" the spacecraft through the environment and calculates the impact flux from debris particles of six different sizes and greater. The shape of the spacecraft is assumed to be spherical. A cubic spline interpolation is applied to the output to obtain the flux from any arbitrary size debris between 10 μm and 1 m. A similar function to predict the flux observed by a ground-based sensor is also included in the model.

A potential problem with this finite element model is in the grid-size of the cells. One can certainly make the cells smaller to increase the resolution. However, the physical size of the resultant template files may not be manageable by a regular computer. In addition, the statistical noise will increase with decreasing grid-size in a finite element model. It may produce unrealistic transitions between cells. On the other hand, one needs to make sure the grid-size of the cells is sufficiently small enough to preserve important fine features in the environment. The template files with the standard resolution in ORDEM2000 have a total physical size of about 14 MB. A special sensitivity study has been performed to determine if the resolution is good enough. New templates with (1° x 1° x 10 km) cell dimension and (0.1 km/s x 1°) velocity distribution were created and implemented into the model. Average impact fluxes on a spacecraft with a Shuttle-like orbit were calculated using both the standard templates and the special ones. The comparison shows that there is no significant difference between the two. Another study with a spacecraft of ISS-type orbit also shows similar results. These comparisons indicate that the grid-size used in ORDEM2000 is a reasonable one.

Because a spacecraft program can span several decades from planning to end-of-life, it is beneficial to have a time-projection function implemented in ORDEM2000. For 1 mm, 1 cm, 10 cm, and 1 m populations, the functions are based on the spatial density variations at each altitude bin between 1991 and 2030 from the NASA orbital debris evolutional model EVOLVE 4.0 [15]. A business-as-usual future launch traffic that repeats the 1992 through 1999 traffic and the NOAA solar activity projection are used in the future projection mode in EVOLVE. Since EVOLVE does not include objects smaller than 1 mm, the projection factors for objects smaller than 1 mm are based on a simple model that includes the effects of atmospheric drag and solar radiation pressure. Their future production rate is assumed to be proportional to the total area of intact objects from EVOLVE's future projection.

3. MODEL VALIDATION

In addition to the major sources used to build the ORDEM2000 templates, the following data are used to validate the model: HAX radar [3], Goldstone radar [8], impact measurements from Hubble Space Telescope Solar Array (HST-SA) [9], European Retrievable Carrier (EuReCa) [10], Shuttle [11, 12], MIR [13], and Space Flyer Unit (SFU) [14].

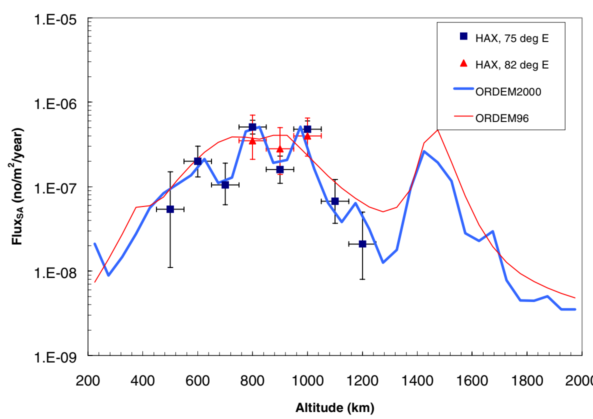


Fig. 5. The 1 m population comparison with the HAX data (1999).

Figs. 5-7 compare the predictions from the two ORDEM models with the Haystack and HAX radar observations for 1 cm, 10 cm and 1 m populations in 1999. Overall, ORDEM2000 provides a very good description of the recent debris environment.

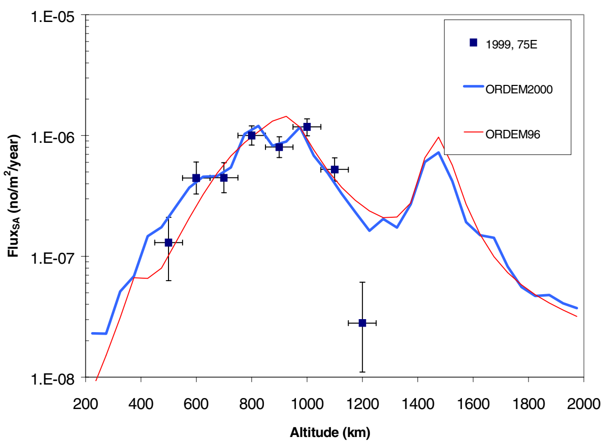


Fig.6. The 10 cm population comparison with the HAX data (1999).

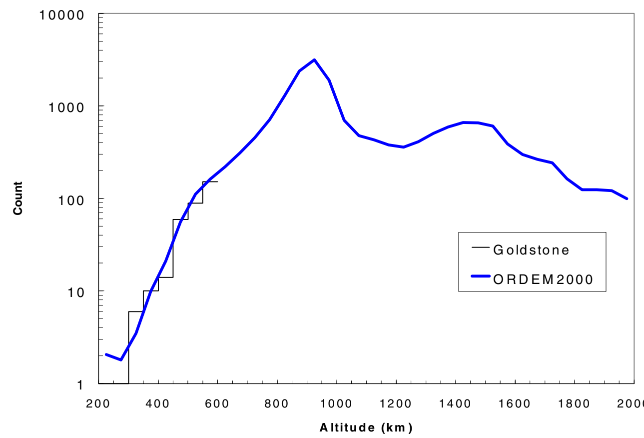


Fig. 8. The 2 mm population comparison with the Goldstone radar data.

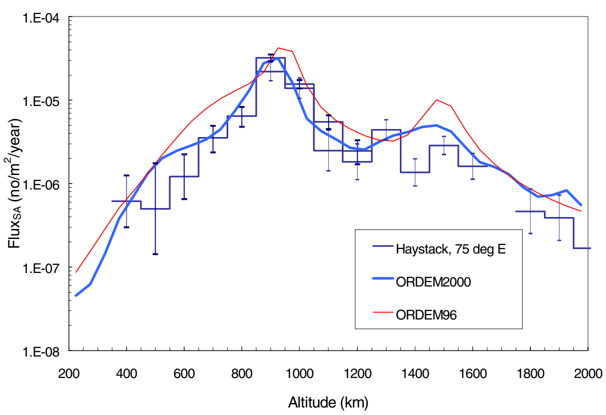


Fig. 7. The 1 cm population comparison with the Haystack data (1999).

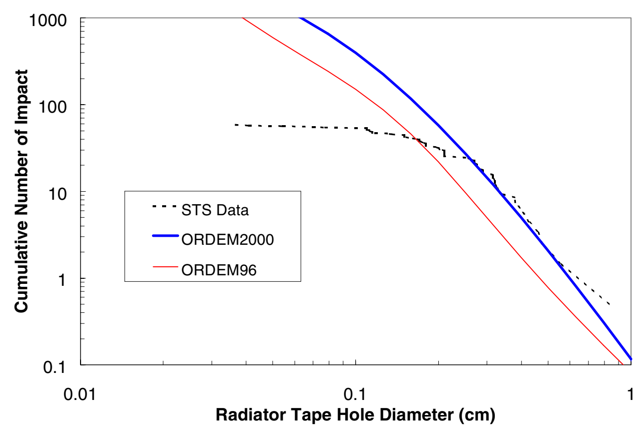


Fig.9. Shuttle radiator impact comparison.

The comparison with Goldstone radar data, in terms of total detection between 1994 and 1998, for objects 2 mm and greater is shown in Fig. 8. Again, there is an excellent agreement between the model prediction and the data.

The comparison with debris impacts on Shuttle radiators is shown in Fig. 9. A projectile material density of 2.7 g/cm^3 and the standard STS impact penetration equations [11, 12] are used in the conversion. There is a good agreement between ORDEM2000 predictions and the actual data.

4. CONCLUSION

The objective of ORDEM2000 is to provide spacecraft designers/operators and debris observers an updated state-of-the-art tool to evaluate the debris environment. The model uses the best available debris data with a more rigorous mathematical approach. The predictions appear to agree well with the data. The NASA Orbital Debris Program Office will release the final version of the model in 2001. ORDEM2000 will become the new official tool for evaluating the debris risk for ISS and for future Shuttle missions.

5. ACKNOWLEDGMENTS

We thank Sara Portman for preparing several figures for the manuscript.

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