DSMC SPACE DEBRIS SIMULATION AND COMPARISON WITH LDEF IMPACT EXPERIMENTS

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ABSTRACT

The DSMC (Direct Simulation Monte-Carlo) debris model (Refs.1,2,3) developed at QMW provides a statistical analysis in order to predict orbital man-made space debris environment with the aim to improve space vehicle risk assessment. This objective is achieved by assuming that debris can be modelled through employing a large sample of representative particles to simulate the real debris population. The DSMC determines the debris collision probability and statistical behaviour of the debris environment. This model has been used to predict debris population growth. In this paper, the validation of the model is demonstrated by means of comparison between LDEF (Long Duration Exposure Facility) impact experiments with the predicted collision and flux results.

1. INTRODUCTION

The Direct Simulation Monte-Carlo (DSMC) model established and developed at Queen Mary and Westfield College assumes a statistical approach for better understanding of the orbital space debris. Thousands of sample particles are employed to represent the real space debris environment. The mathematical formulation of the DSMC method for multi-variable analysis enables the debris DSMC model to be almost unrestricted in the complexity of the debris environment evolution that can be analysed given sufficient computing power. Debris evolution with fragmentation, followed by subsequent cascading can be predicted if suitable corresponding models for these events can be provided. Since the routines for handling the representative collisions will be called repeatedly in a typical scenario and both time and ensemble averages can be performed, the statistical uncertainties can be kept minimal.

LDEF was designed to provide long-term data on the space environment and its effects on space systems and operations. It successfully carried scientific and technology experiments that have revealed a broad and detailed collection of space environmental data. Considerable analysis of experimental data has been presented in the literature, especially in 1st, 2nd and 3rd LDEF retrieval symposia.

In this paper, the DSMC model at QMW is verified by comparing results with the LDEF impact experimental data. The debris collision probability and debris spatial flux are selected for this analysis. The evidence from the comparisons presented in this paper adds further credence to the validity of the DSMC model.

2. THE DSMC MODEL

In the DSMC debris model, it is assumed that a large sample of simulated particles can adequately represent, in a statistical way, the behaviour of the far larger number of space debris particles within the earth environment. The simulations are performed within a framework of cells in physical space and the sample representative particles carry with them the phase-space-time information of position and velocity that are necessary for the true evolution of the real debris environment. The DSMC model produces solutions analogous to those of the Boltzmann equation (Ref.1) (if the debris chaotic environment is assumed) by decoupling the collision and convection terms in the equation by means of a suitable time-interval discretisation. This time step interval must be chosen in a way that both the convective and collision terms can be approximated with expected accuracy. Each term is calculated alternately and independent of the other in successive time intervals. The two independent steps are repeated until convergence is approached. The particle convection with respect to time is performed by using the so-called debris orbit propagator. The particle collision is based on a debris break-up model. The representative particles are assigned to a series of real debris distribution functions.

2.1 Debris particle convection routine

The debris convection in phase-space-time is based on a debris orbital propagator[3]. Each sample debris particle in this space is expressed by use of the six

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orbital elements (semi major axis a, eccentricity e, true anomaly θ, inclination i, right ascension of ascending nodes Ω and argument of perigee ω) evolved with time. These can then be used to identify the location of each particle at each time step[7]. The orbital elements change due to perturbations such as aerodynamic drag, distorted earth gravitational field and luni-solar perturbations. King-Hele's atmosphere/satellite interaction model[8] is employed and predicts changes in the semi major axis a and eccentricity e. The effect of the earth oblateness introducing a distorted gravitational field and migrating the right ascension of ascending nodes Ω and the argument of perigee ω with time is also predicted and is also based on the King-Hele model.

As mentioned above, a suitable time interval must be selected to achieve the consistency of the debris collision and the debris convection. Although a small time interval is suitable for accurate debris tracking, a large time interval value is chosen to achieve a consistent computation of the collision term due to the relatively low collision rate. The representative debris particles are ascribed to their most probable location, based on a time-weighted residence.

Numerically, for a particle with altitude r and eccentricity e, the time spent in the altitude range Δr is calculated by

$$\Delta t = \sqrt{\frac{p}{\mu u}}\Delta r$$

where

$$u = e^2 - \left(\frac{p}{r}\right)^2 + \frac{2p}{r} - 1 \quad \text{and} \quad p = a\,(1-e^2).$$

The probability is calculated as: $P(r,e) = \Delta t/T$, where T is period.

In practice, a table is made given time as a function of e and r and a bilinear interpolation is conducted for each particle in the simulation to find its most probable location to enhance the computational efficiency.

2.2 Debris collision probability routine

The collision term is simulated by employing proper collision probability and collision dynamics schemes. The collision probability routine has been improved since that outlined in our earlier paper(Ref.2). A major modification has been to introduce variable weighting factors (a weighting factor F_N is defined as the number of real particles that a simulated particle represents) for particles of different sizes. This improves efficiency by recognising that the number of debris particles of different sizes are quite different. In reality, whilst there are only a few thousand large debris particles, there are millions of small particles. Simulation error can be large if a single value of weighting factor was applied to these different size particles. Therefore, we use small value of F_N for large particles and large value of F_N for small particles. The detailed collision probability calculation is the following.

Consider, a simulation domain divided into cells, with cell volume ΔV_c in which each simulated particle represents F_N real particles. The number of collisions selected in this cell in time interval ΔT is

$$N_c = 1/2\, N_m N_n F_{Nm} F_{Nn} [(\sigma_{Tmn}\, c_{r,mn})_{max}]\, \Delta T/\Delta V_c$$

where N_m is the instantaneous number of particles of component m, N_n is the time averaged number of particles of component n, σ_{Tmn} is the collision cross-section $c_{r,mn}$ is the relative velocity of the two simulated particles, $(\sigma_{Tmn} c_{r,mn})_{max}$ is the maximum value of $(\sigma_{Tmn} c_{r,mn})$ of component m, n.

A collision is depicted based on the following probability formula:

$$P = (\sigma_{Tm\,n}\, c_{r,\,mn}) / (\sigma_{Tm\,n}\, c_{r,mn})_{max}$$

Riemann rejection scheme [2] is used to determine if the selected collision pair is accepted or rejected. This enables the detailed collision process to be depicted.

In DSMC model, the fragmentation of each collision follows a scheme which combines both the power law and the exponential law. The power law of Bess model (Refs.4,5) is employed to determine the post-collision number and size of fragments. The cumulative number of fragments N_{cum} can be expressed as:

$$N_{cum} = k\,(M_f/M_e)^{-b}$$

where M_f is the fragment mass; M_e is the ejecta mass; b lies in the range 0.4 to 0.7 (nominal 0.65) and k is determined by the mass conservation. The post-collision velocity v_f is determined by

$$\log(v_f/v_r) = 0.225 - 0.1022\,[\log(d_f/d_{min})]^2$$

where v_r is relative velocity, d_f is fragment size and $d_{min} = E_p^{1/3}/6.194\times10^7$, where E_p is projectile energy. The cumulative number of fragments N_{cum} following the exponential law is given by:

$$N_{cum} = TM_b \exp(-UM_f^{1/2})$$

The mass available for break-up M_b is the mass of the target minus the ejecta mass; T=0.0005; U is determined by mass conservation. The post-collision velocity v_f is obtained using a baseline model (Ref.7):

$$\log v_f = -0.0676 (\log d_f)^2 - 0.804 \log d_f - 1.514$$

Finally, given the velocity and position vectors of each new fragment, the six orbital elements can be then determined.

3. LDEF EXPERIMENTS

3.1 LDEF structure

LDEF had a nearly cylindrical structure, and its 57 experiments were mounted in 86 trays about its periphery and at its two ends. It measured 30 feet (9.15 meters long) by 14 feet (4.27 meters in diameter) (~ cross-section 39m^2). The total exposed surface area was 130m^2 with 14 facing surfaces. The launch weight was 21,500 pounds (9724 kg) with experiments.

3.2 LDEF mission

LDEF was deployed in orbit on 7 April, 1984 by the space shuttle Challenger. The nearly circular orbit was at an altitude of 257 nautical miles (476km) and an inclination of 28.4 degrees. LDEF remained in space for 5.78 years and completed 32,422 Earth orbits. It experienced one-half of a solar cycle, as it was deployed during a solar minimum and retrieved at a solar-maximum. Its orbit had decayed to 179 nautical miles (331km) when it was retrieved on 11 January, 1990 by space shuttle Columbia.

3.3 LDEF impact data

The LDEF impact data from the Interplanetary Dust experiment (IDE) was investigated by the Meteoroid and Debris Special Investigation group.

The Interplanetary Dust Experiment (IDE) provided high time resolution detection of micro-particle impacts on the LDEF satellite. Particles, in the diameter range from 0.2 microns to several hundred microns, were detected impacting on six-orthogonal surfaces. As LDEF was gravity-gradient stabilised and magnetically damped, the direction of the normal to each detector panel is known for each impact. The results from nearly 12 months' tape-recorded data set, represents the most extensive record gathered of the number, orbital location and incidence direction for micro-particle impacts in low earth. Due to high resolution monitoring on board, the collision rate between LDEF and micro-debris is quite high. A total of 15,000 impacts were recorded on 459 detectors during the active phase of the mission (348 days).

A centi-metre size debris particle impact was recorded as the only one large impact of the mission. This impact was spotted at the space end of LDEF at low impact velocity. There were also a number of relatively large particles (cm size) flying by LDEF.

The Meteoroid and Debris Special Investigation group (MDSI) documented and photographed more than 5000 visible impacts including craters (>500μm) and penetrations (>300μm) on LDEF surfaces during their inspection at KSC. These documented craters ranged in size from approximately 0.5mm to 5mm.

The experiments demonstrated the difficulties of distinguishing debris sources. Further investigations (Ref.11) suggested that about 80 to 85 percent of the craters were caused by meteoroids, leaving 15 to 20 percent to be caused by the man made space debris. These percentage figures vary for different directions of the impact particles with 25 to 30 percent on the leading edge and 10 percent on the trailing edge of the craters to be caused by man made space debris, as estimated by Zhang and Kessler (Ref.10).

4. DSMC VS. LDEF

4.1 Simulation conditions

It is assumed for the simulation that LDEF was kept at a mean altitude of 458 km. Debris collision frequency, flux and impact velocity were evaluated and the simulated results compared with some corresponding LDEF experimental results.

The simulation is repeated 100 times by setting different groups of random numbers so that ensemble averages are achieved for statistical analysis using DSMC prediction. Each run lasts about 2 hours. The simulation enables identification of the debris flux and impact velocity.

4.1.1 Simulation domain

The simulation domain includes the low earth orbit (LEO) region up to altitude of 2000 km. This then allows the debris particles from high orbit, above LDEF, to decay due to aerodynamic drag into lower regions. To reflect a highly evolved debris environment, the simulation domain is divided into 40 sub-domains, each representing a spherical 50km shell, centred on the earth. The analysis performed suggests that such an evolved structure will happen on a time scale short compared to the orbit decay time scale, and thus this assumption is valid for the type of study being undertaken. As the average mean collision time is approximately several days, the time step in the simulation is one day.

4.1.2. Debris mixtures

Debris of various sizes is modelled as *'a debris mixture'* in DSMC model (typical simulation is from sub-millimetre micro-particles to full-scale spacecraft, several meters in extent) as the collisions among the debris mixtures can be easily handled by the DSMC formulation. Practically for the simulations, debris particles are grouped together depending upon their size and mass. As the LDEF experiment has shown that most of the collisions are between LDEF and micro-debris, the simulations concentrates on the interactions between LDEF and micro debris. Consequently, the simulated debris particles are binned into 10 groups based on their sizes: 20μm, 40μm, 65μm, 0.1mm, 0.24mm, 1mm, 1cm, 10cm, 3m and LDEF. Group 10 is specially for LDEF which is assumed to have an averaged effective diameter size of 7.0 meters, with a collision cross-section $39m^2$ and exposure area of $133m^2$.

4.1.3 Debris distribution functions

The debris size population distribution versus altitude is critical to obtain the correct collision rate and spatial flux. Parameters included in our model are those of semi major axis, eccentricity, inclination and size distribution of particles. Statistical sampling techniques are used so that the modelled parameters represent the environment.

The debris population in this study is shown in Figure 1 as the cumulative number density as functions of debris size and altitude up to 2000km. Obviously the large objects and small fragments do not follow the same distributions. Large spacecraft are generally launched to lower altitude under 1100km, while the region for altitude 1100-2000km contains mostly break-up fragments and few large satellites.

The eccentricity distribution also varies for debris of different sizes. Large debris particles follow circular or near circular orbits as observed. Small particles are mostly fragments caused by the collisions between orbital objects and may become highly eccentric. This feature is crucial in establishing DSMC model since it is from this distribution that the highest collision velocities are derived; this will have an influence on LDEF collision frequency. Debris will largely retain the inclination at which it was produced since it is only slightly changed due to the aerodynamic drag. The inclination values are mostly populated from 60° to 110°. We assume that this is the case for both large objects and small fragments. All other orbital elements are assumed to be uniformly distributed for all sizes.

4.2 Simulation results and comparison with LDEF

4.2.1 Debris flux

At the debris size lower limit of order of micrometers, the collision probability routine of the DSMC model is compared with the LDEF flux data. The 65μm is used as smallest particle size for producing crater size larger than 500μm. This particle size is about 2 to 8 times smaller than that of the crater, depending on the collision incidence and impact velocity. Particles smaller than this size are only used for testing the flux routine of the model.

The spatial flux predicted in the simulation is plotted in Figure 2 as a square symbols for debris particle sizes 240 μm, 100μm, 65μm, 40μm and 20μm. These flux data can be compared with the orbital debris flux data from the Interplanetary Dust Experiment (IDE) analysis given by Simon, *et al.* in Ref.12, plotted in a solid line. As the IDE data are given for debris size of up to 100μm, a dashed line is used here for the IDE data to be extended to 240μm in order to compare with the DSMC results. This comparison shows that for debris size larger than 40μm and 65μm, the DSMC prediction values are slightly higher than the IDE data. The predicted flux fit well for 20μm and 0.1mm debris with the IDE measurement. As a whole, the DSMC prediction agrees with the IDE measurement well.

4.2.2 Collision frequency

Tables 1 illustrates the simulated number of collisions between different debris groups based on ensemble averages. The data above the diagonal show that the averaged total collision rate between the particles of different sizes, while the data under the diagonal show the collision rate of an individual object colliding with another debris particle. It can be seen that the collisions between 0.1mm or smaller debris particles and LDEF dominate the total number of collisions. For example, 660 and 2295 impacts by 0.1mm and 65μm particles are predicted for the life of the LDEF mission. This leads to collision rates of ~113 (0.1mm) and ~396 (65μm) collisions per year for LDEF by these micro debris.

A more critical way to compare LDEF data with the DSMC model is to evaluate which of the simulated collisions would produce a crater size greater than 500μm, taking into account both the size and velocity of the impacting debris. The average value obtained over the 100 simulations was 783 impacts. As noted above, the analysis by MDSI documented 5000 craters of this size. The simulation results only calculate impacts due to man-made debris. Thus the ratio of our simulated impacts to observed impacts implies that 16% of the observed impacts should be due to debris, the remainder being due to natural environment effects. This percentage is in excellent agreement with the conclusions of Humes (Ref.11), indicating that the man-made debris accounted for between 15 and 20% of the impacts on LDEF.

The simulated collision rate between LDEF and larger debris particles is low and this agrees with the LDEF post-retrieval analysis that large craters are caused by natural debris. However, as the collision rate between LDEF and a 1mm-sized debris particle is close to 0.1 per year, the risk of an impact from a 1mm man-made debris is high. To quantify the probability of rare events like collisions, a Poisson model is used and is plotted in Figure 3. This simulated collision rate (0.1/yr) tells us from the solid curve in the figure that the simulated probability of no collision between LDEF and a 1mm particle within 5.7 years is 56%. In other words, the simulated probability of having at least one collision is 44% within 5.7 years. This probability value may explain why there was a mm-size debris particle creating a 5.2 mm crater, the largest crater on LDEF.

4.2.3 Impact velocity

From LDEF post-retrieval study, it was found that the large majority of the craters appeared to be the results of hypervelocity impact with a velocity around 10km/s. The DSMC model is able to sample the impact velocity distribution; this is plotted in Figure 4. From this figure, it is seen that the most probable impact velocity appears to be approximately 14km/s with the average impact velocity of 10.3km/s. The lower average impact velocity is a consequence of larger low speed population of the velocity distribution function.

In accordance with LDEF post-retrieval investigation, the findings of impacts on the trailing end led to a prediction of existence of elliptical man-made micro debris in orbit. As indicated above, the DSMC model employs a high eccentricity distribution function, the simulated impacts on the trailing edge can be deduced as a logical consequence.

5. CONCLUSIONS

It is clear from the above analysis that the DSMC model predicts collision frequency data which is consistent with the observed LDEF results, given the statistical uncertainty in both the DSMC and LDEF analysis. It is concluded that the DSMC model is a robust model which is consistent with observations and may be used to predict future space debris hazard.

The finding of a large number of craters on LDEF is a strong proof of the space debris hazard. Further experiments have quantitatively confirmed that a large fraction of craters were caused by man-made debris.

In this paper, the DSMC debris model has been verified by means of comparison of the predicted collision data with the LDEF impact data and a good agreement has been shown for the collision frequency. The success of the DSMC model has led us to predict long-term debris population growth and will be used for further debris study such as debris collision cascading and risk assessment.

6. ACKNOWLEDGEMENTS

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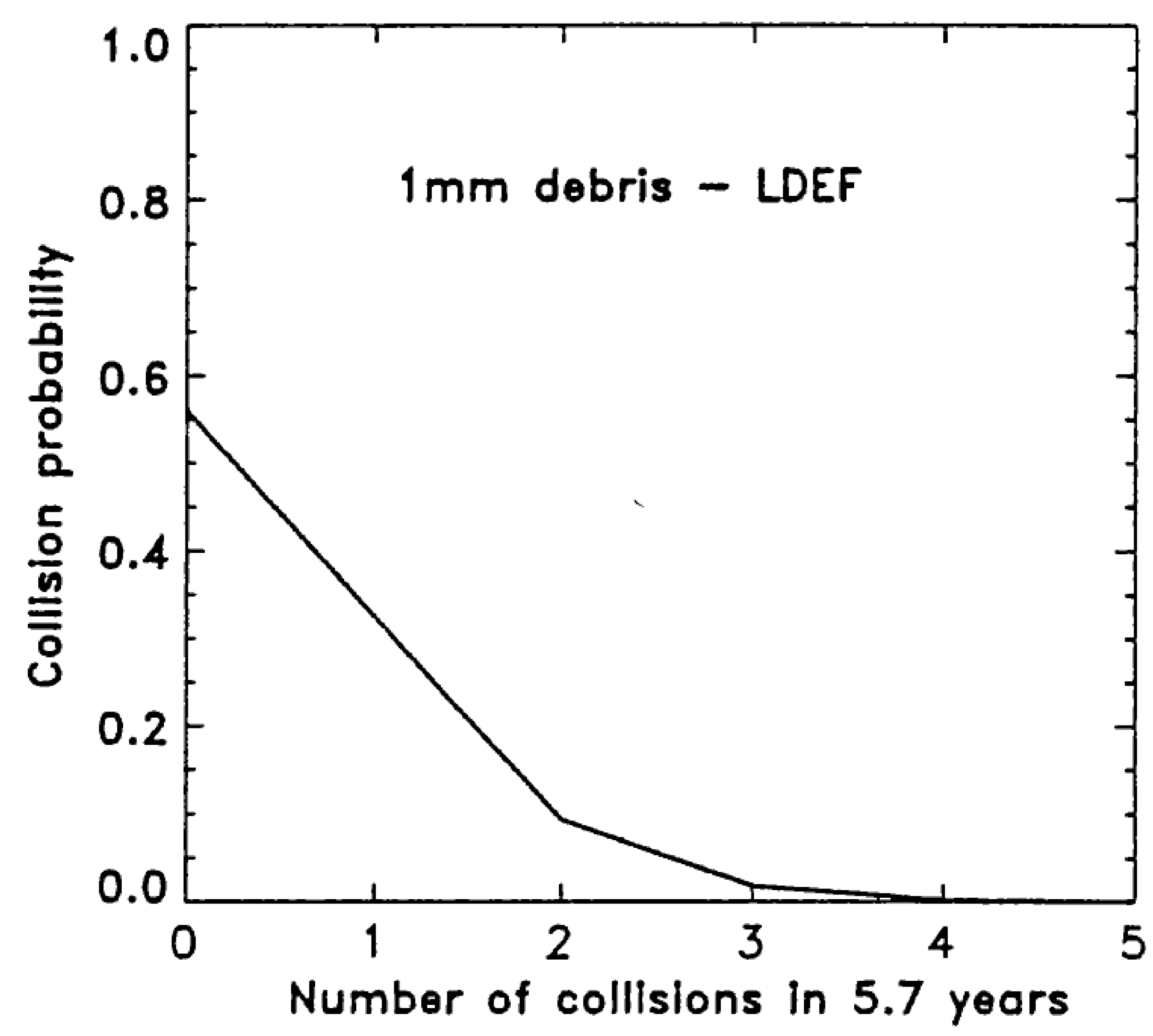

Figure 3. Simulated collision probability

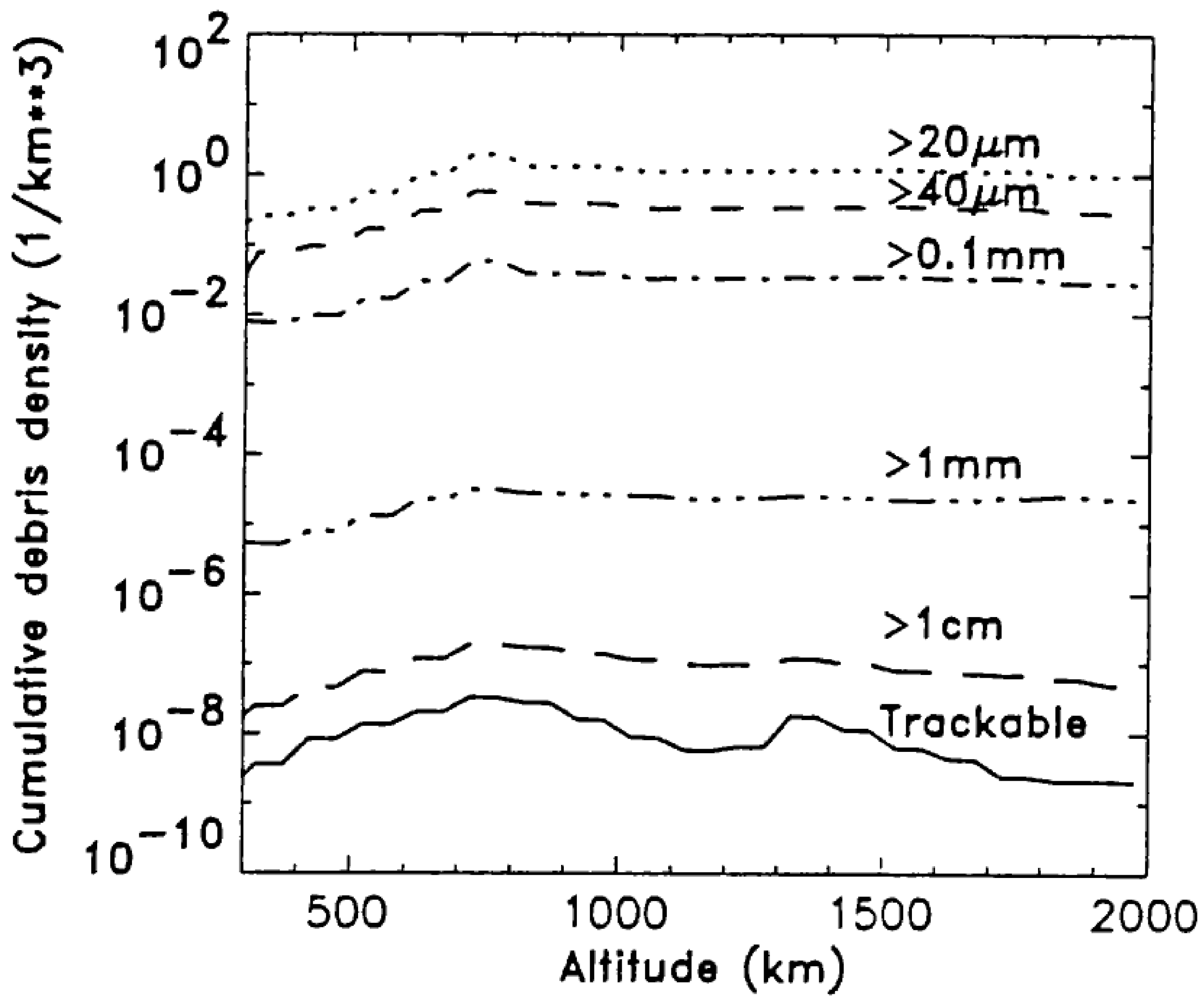

Figure 1. Debris density distribution for debris sizes: 20μm, 40μm, 0.1mm, 1mm, 1cm, trackable objects.

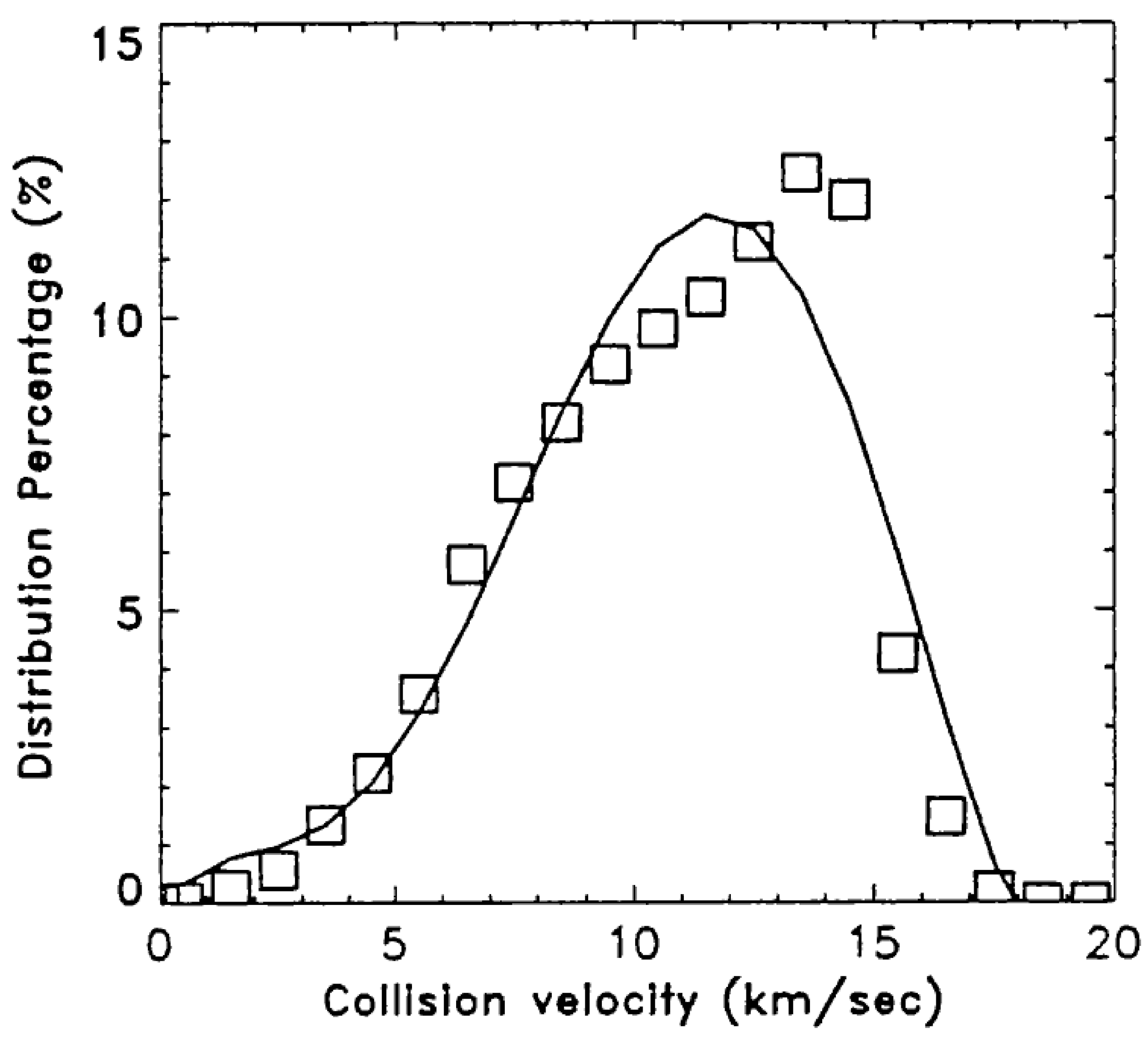

Figure 4. Simulated debris impact velocity distribution on LDEF

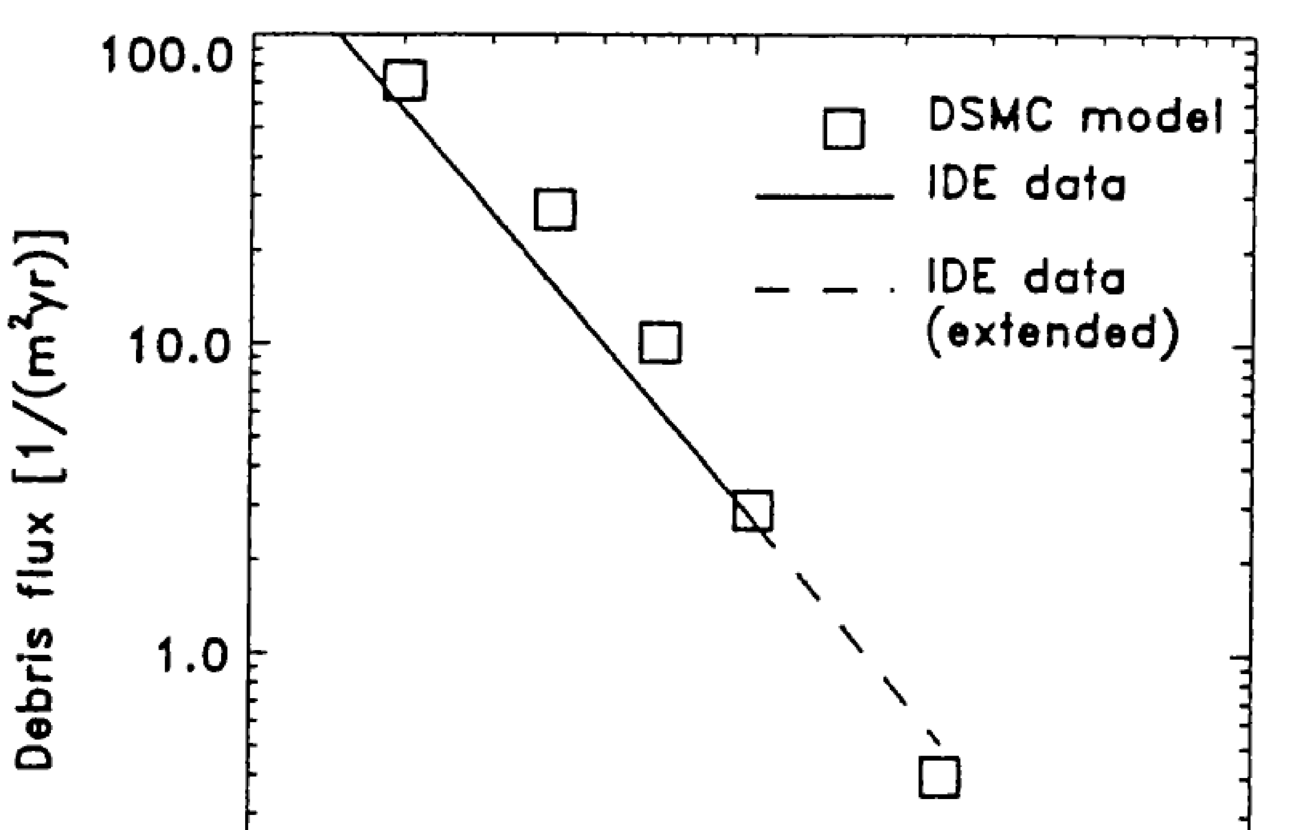

Figure 2. Simulated debris flux data.

Table 1. Simulated collision frequency (impacts/year)

Group	65μm	0.1mm	240μm	1mm	1cm	3m	LDEF
65μm	–	–	–	–	255	422543	396
0.1mm	–	–	–	–	–	120064	113
240μm	–	–	–	–	–	15206	16
1mm	–	–	–	–	–	629	0.1
1cm	255		–	–	–	0.3616	0.001
3m	285	81	10.3	0.42	0.002	–	–
LDEF	396	113	16	0.1	0.001	–	–