DEBRIS EVOLUTION IN THE EVOLVE MODEL: APPLICATION TO DSMC MODELLING

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ABSRACT

Investigation is presented of the evolution of debris clouds generated by the EVOLVE model which has been recently updated. Simulation of debris clouds assumes perturbations due to the Earth's gravitational potential to degree 4, and aerodynamic drag. It is found that above an altitude of 700 km, a debris cloud has sufficient time to become fully developed, and that the orbital elements of Right Ascension of the Ascending Node and the Argument of Perifocus at epoch are lost. These conditions are those necessary for the Direct Simulation Monte Carlo method used to model debris risk. Below 700 km the methodology is still found to be justified when there has not been a recent injection of a substantial volume of debris below 700 km.

1. Introduction

The Direct Simulation Monte Carlo (DSMC) method has been used extensively to evaluate the risk to satellites, and has generally shown good agreement with returned surfaces [1, 2, 3]. In a recent paper the model has also been extended to include the flux of naturally occurring micro-meteorites [4]. Again good consistency with surfaces from HST, Eureca, and LDEF has been obtained. The approach used for micro-meteorite modeling is somewhat different from that used to model the man-made space debris, in that due to the short period of time a micro-meteorite spends in the low earth orbit environment, there is no opportunity for the orbital elements to evolve with time. However, the model used for micro-meteorites assumes that within the narrow range of altitudes considered, relative to say the distance between the sun and the earth, it is appropriate to model the meteorite environment as homogeneous, albeit corrected for the apex motion of the earth about the sun, and the screening effects of the earth [4] relative to an orbiting body.

A key assumption in the DSMC model is that the man made debris may be considered to be fully evolved. Thus any cloud of debris particles which is created, has sufficient time that the evolution for particles in terms of the orbital elements of the Right Ascension of the Ascending Node and the Argument of Perifocus, have become uniformly distributed. Previous papers investigating this assumption have been published [5,6] but concern the overall evolutionary trends with evolution from the generalized deterministic models of McKnight [7] for collision fragmentation and explosion. In this paper the evolution of a cloud is more specifically considered in terms of the recently updated EVOLVE model [8] which uses a statistical description for developing the initial state vector of the cloud.

2. MODELLING APPROACH

2.1 <u>The DSMC Model</u>

A full description of the underlying methodology of Direct Simulation Monte Carlo, applied to rarefied gas dynamics, can be found in Bird [9]. The method solves the Boltzmann equation, which underlies Kinetic Theory using a computational approach.

The methodology separates out the effects of convective transfers in phase space from those arising from scattering. The process is dependent however on the specific assumptions that: a) it is possible to take a statistical sample of the population of particles which are to be modelled (i.e. a Monte Carlo Method); b) it is possible to separate out convective motion from the collision process if an appropriate collision time is defined which accurately represents the statistical nature of collisions within the system of particles and c) the individual particles within the system of particles have microscopically chaotic speeds which may be defined by some overall characteristic velocity distribution, as is fundamental to Kinetic Theory . The debris model developed at Queen Mary College[1] extends this methodology to the case were the external force field is that representative of the orbital environment.

2.2 <u>Evolutionary Model</u>

As noted in [5] it is important, in a differentially evolving debris cloud, to evaluate the influence of zonal harmonic gravitational terms to degree 4. It has

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also been found[5] that it is not necessary to include the effects of solar radiation pressure. In the analysis presented here the effects of these perturbations have been included in order to identify the time taken by a particle for its evolution in Right Ascension of the Ascending Node Ω, termed τ_{Ω} , and the Argument of Perifocus ω, termed τ_{ω}, to have progressed through $2*\pi$. These requirements have then been taken as the definition for the time taken for the cloud to randomize the values of Ω and ω, and thus randomize the speed distribution function. The longer of these two times is defined to be the time required to achieve the necessary chaotic motion.

The time taken for the debris cloud to re-enter the earth's atmosphere τ_L should then be compared with the values for τ_{Ω} and τ_{ω}. The dimensionless ratios τ_{char} defined to be τ_L/τ_{Ω} and τ_L/τ_{ω} are then used to evaluate whether or not a particular particle has time to evolve. In order to evaluate the time τ_L the model of King-Hele [10] has been adopted with the assumption of a static atmosphere. The simpler model for a static atmosphere has been adopted since the effect of atmospheric oblateness, has significantly less influence relative to the variation that arises during a solar cycle. Since in some evolutionary scenarios the lifetime is either greater than, or a significant fraction of the solar cycle [5], it is appropriate to use the static model. It is further shown below that for the EVOLVE size distribution of particles, for altitudes above 700km, it is appropriate to take average solar cycle conditions to define the atmospheric structure.

3. CLOUD EVOLUTION SIMULATION

A variety of scenarios have been investigated to establish the degree of evolution expected in a debris cloud, prior to re-entry. To gain an impression of the influence of specific parameters concerning the initial state vector of the pre-fragmentation orbit, and the breakup velocity and area to mass ratio, deterministic calculations were performed. Using the model developed by McKnight [7] relating velocity to area to mass ratio, figures 1 and 2 show the value of τ_{char} for an explosive event with the velocity vector at breakup directed forward, along the instantaneous velocity vector at fragmentation, or directly opposed to this velocity, at varying orbit altitudes.

Figure 3 shows similar data for a collision event at a single altitude of 400km.In each of the cases plotted the initial orbit is assumed to be near circular, with an eccentricity of 0.001.

The general trends identifiable from these graphs are unsurprising, in that as altitude increases the value of τ_{char} increases. Further as a result of the velocity being imparted to a large mass is less than that to a small mass, then the value of τ_{char} will decrease with mass for a forward directed velocity, but this trend is reversed for rearward directed velocities.

In any given breakup event, either collision induced or an explosive event, fragments will be created having a randomly oriented velocity vector. Thus to model such an event a statistical sample of events must be simulated in order that the properties of the evolving cloud can be evaluated. Currently the EVOLVE model is being reevaluated, and at present the generation for particles greater than 1cm only, is available [8], with work on the particles in the 1mm to 1cm range becoming available later this year.

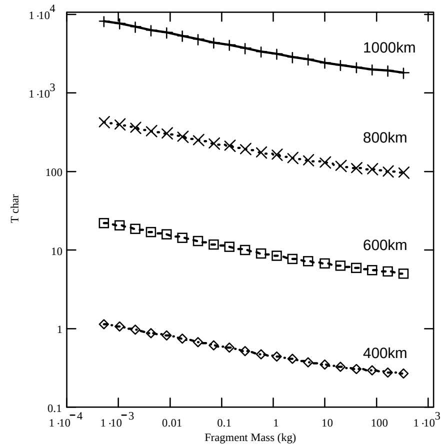

Fig. 1. τ_{char} vs mass for forward directed velocity after explosion

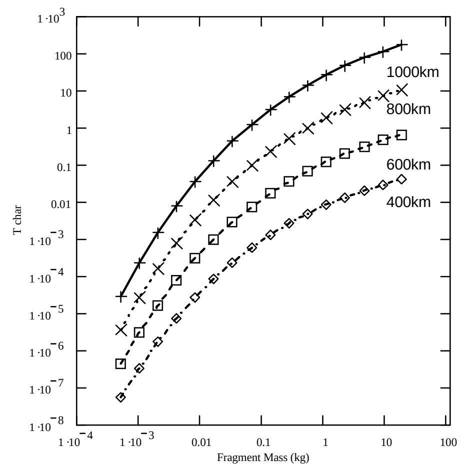

Fig. 2 τ_{char} vs mass for rearward directed velocity after explosion

A variety of simulations was therefore undertaken to ascertain the value of τ_{char} for each of the 9324 particles generated in the EVOLVE model.

For each individual break-up event it is possible to calculate the τ_{char} probability distribution for the ensemble of particles modeled by EVOLVE. In fig. 4 this distribution is shown for an initial orbit at an altitude of 800 km, with an inclination to the equator of 30˚. Both the evolution due to τ_Ω and τ_ω are shown. In this case the determining evolution rate is that due to the Right Ascension of the ascending node; whilst this is most generally the case, this is not always so.

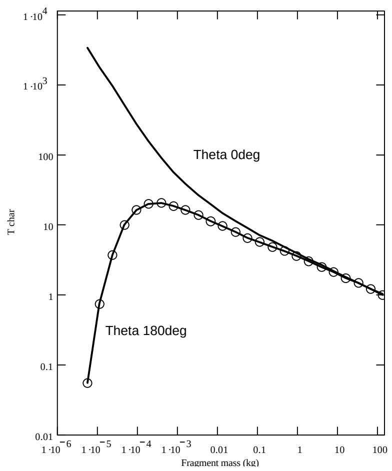

Fig. 3 τ_{char} vs mass for collision induced breakup at 400km altitude.

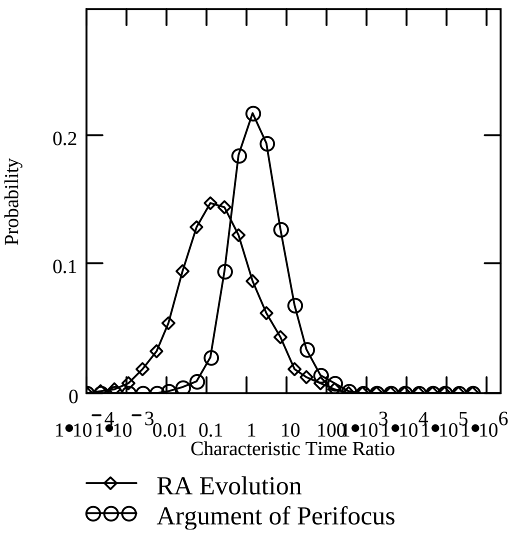

Fig. 4 Probability distribution for fragmentation particles generated by EVOLVE at an altitude of 800km.

Fig.5 shows the cumulative probability distribution for the same event shown in fig. 4. Following 20 simulations of the event, it was found that 85+/-1% of the particles have sufficient time for evolution in τ_Ω whereas nearly 98% of particles evolve in Argument of Perifocus. For each of these simulations average solar activity was assumed.

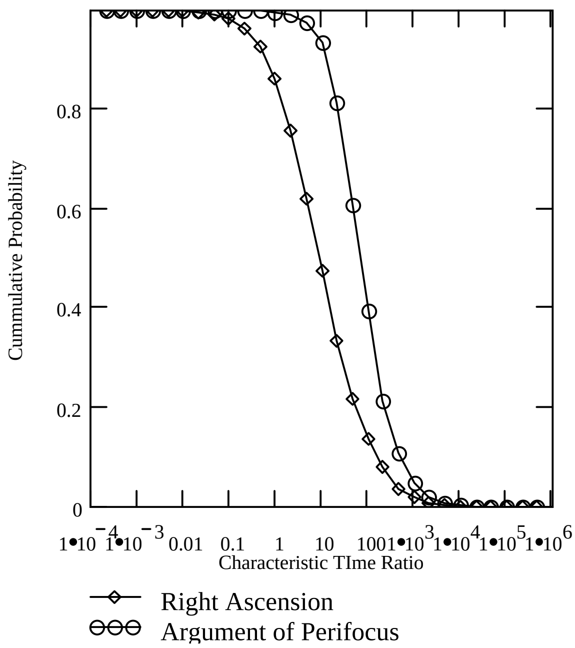

Fig. 5 Cumulative Probability Distribution for 800km altitude break-up.

Simulations were performed at various altitudes and for various inclination angles, in each case with the initial orbit eccentricity of 0.001. In table 1 the cumulative probability data, showing the proportion of debris particles exceeding the value of τ_{char} = 1, is given. At 1000km more than 95% of all particles evolve, independently of inclination. Non circular initial orbits show an increase in the percentage of particles evolving, and hence the near circular orbit at epoch provides the more demanding requirement for DSMC methodology evaluation..

The trends shown in the tabulated data confirm how the fraction of particles evolving increases with altitude. Further the data shows that as the inclination angle increases there is a reduction in the fraction of particles which evolve.

It is interesting to note which of the particles in the model is able to evolve, and which do not. Fig. 6 presents data showing the ratio of the area to mass ratio for those particles having τ_{char} which are greater than 1 for evolution due to Regression of the Line of Nodes, and for the Precession of the Argument of Perifocus, for an initial orbit at an altitude of 600 km and inclination 30°.

Table 1 Proportion of debris particles having $\tau_{char} > 1.0$ for an initial orbit eccentricity of 0.001

Altitude km	800	700	600	400
Inclination				
10°	84 %	66%	37%	5%
30°	83%	63%	36%	4%
60°	76%	53%	26%	3%
80°	59%	33%	13%	2%

These data clearly show the influence of area to mass ratio. However neither plots of size nor mass for those particles which do evolve, show the same distinctive trends. This is confirmed from fig. 7. This is as a result of the approach used in the EVOLVE model, wherein there is not the same deterministic relationship between area to mass ratio and size, rather a statistical relationship is assumed. This may be seen clearly from fig. 8 which displays for part of the EVOLVE distribution a scatter plot for area to mass vs. the length scale of the fragment generated.

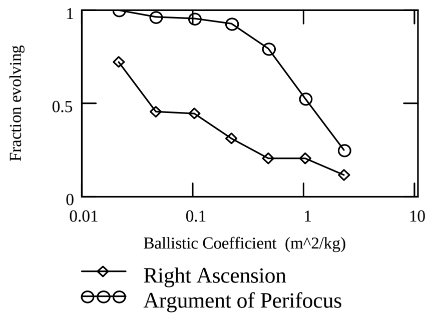

Figure 6 Fraction of particles with $\tau_{char}>1$ as a function of ballistic coefficient, for an orbit of 600km altitude.

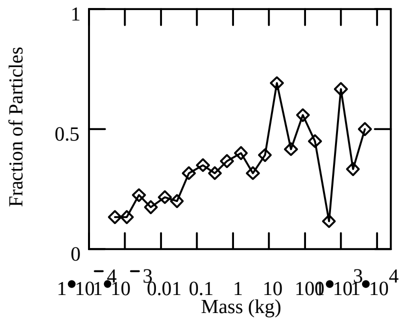

Figure 7. Fraction of particles with $\tau_{char}>1$ as a function of mass, for an orbit of 600 km altitude.

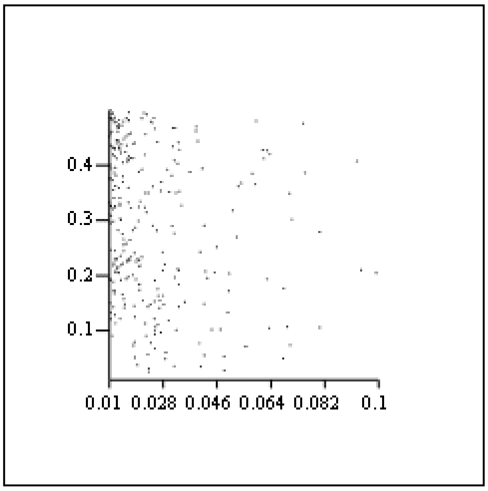

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Figure 8 Distribution of Ballistic coefficient (y-axis) to length (x-axis) for part of the EVOLVE model

4 DISCUSSION

At present the most recent version of the EVOLVE model only considers particles with sizes greater than 1 cm. The results presented here therefore need to be considered as preliminary. It is however apparent that if a fragmentation event takes place at one of the lower altitudes investigated here, considerable filtering of the debris particle distribution function will arise. The fundamental feature controlling debris evolution is the variation of ballistic coefficient for individual particles. In this paper conversion between ballistic coefficient and area to mass ratio is via an assumed value for the drag coefficient of 2.2 throughout the altitude range considered and the shape of individual particles The control exhibited by the ballistic coefficient is seen in fig. 6; those particles having a smaller value of ballistic coefficient are evidently retained in the environment for a longer period of time, as is expected.

At a given altitude, the debris environment will comprise of particles which have been generated from fragmentation events occurring both above and below the target orbit. In this paper we have considered principally events initiated from a near circular orbit. The debris which then arrives at a given altitude from events initiated below that altitude, are those particles whose eccentricity and semi-major axis have increased, relative to the parent object, as a result of the fragmentation event. These particles must be created with a positive component of velocity in the direction of the instantaneous tangent to the orbit at the time of fragmentation.

In the simulation adopted here *apriori* a uniform distribution of dispersion velocity direction has been assumed, and thus on average half of the generated particles may be anticipated to have increased the value of their semi-major axis, and eccentricity. However due to the nature of the assignment of velocity to a particle being a statistical process, it has been found that even if only positive ΔV dispersion velocities are considered, there is little change in the overall fraction of particles which evolve.

The appropriateness then of the DSMC model for simulating impacts is dependent upon the origin of the debris environment at a particular epoch. That is to say what proportion of events populating a particular height, may be assumed to have originated at that height, or from above that height. From Table 1 it is apparent that at an altitude of 600 km the majority of debris particles will have insufficient time to evolve to the chaotic state required for DSMC validity. However a breakup at approximately 700 km will, under conditions of average solar activity, have had sufficient time for evolution. Thus below an altitude of approximately 700 km, for the DSMC model to be valid, debris, if it has achieved a 'chaotic' state, must have been generated predominantly from above.

The life time of debris generated in the EVOLVE model at an altitude of 400 km is shown in fig.9. From this data, showing a minimum life time of 2 days for particles having the largest ballistic parameter, it is evident that for a stable population of particles, the debris at low altitudes must indeed be principally as a result of higher altitude debris particles decaying. Fig. 10 shows the mean lifetime of particles as a function of the altitude of release. The mean lifetime for the EVOLVE distribution at 700km is nearly 16 years, significantly greater than the solar cycle. As such when considering particles which have been released above 700km it is justified to use the average solar activity conditions.

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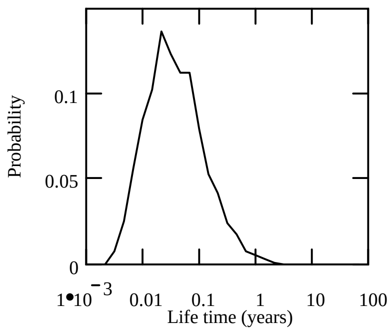

Fig. 9 Life time probability distribution for particles created by EVOLVE model at 400 km.

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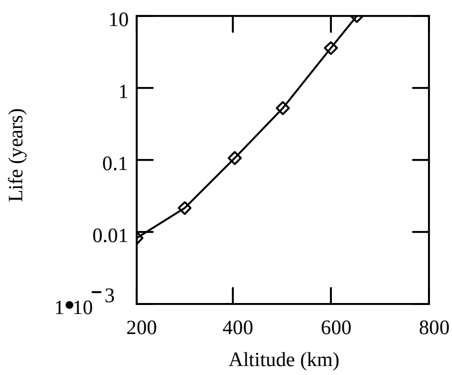

Fig.10 Mean life for debris in EVOLVE model as a function of altitude of release

The issue of the time taken for a debris cloud to decay from a given altitude now needs to be considered. The foregoing analysis has ascribed to a particular altitude the debris created at that altitude. This is clearly an over simplification since during evolution to the 'chaotic' state, the cloud is decaying in altitude. The analysis presented above indicates that before a debris cloud has decayed from an altitude of 700km, it will have had sufficient time to evolve. The height that the cloud will then have reached is however below the initial altitude. Again using the analysis presented by King-Hele [10], it is possible to identify the time taken for the cloud to decay. For the case of a cloud initiated at 800 km data is presented in fig. 11. Debris particles are taken in 50 km bands from 300km to 800km. Below 300km particles are assumed to have reentered. The probability distribution shown in fig. 11 has been evaluated at a time τ_Ω after the fragmentation, when it may be assumed that the cloud has evolved.

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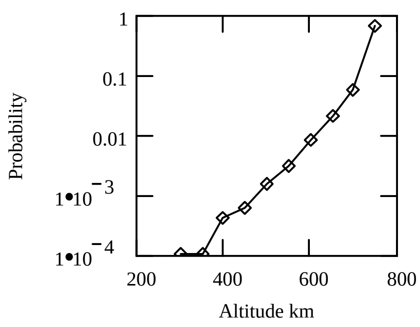

Fig. 11 Probability distribution for particles generated at 800km after a time τ_{Ω°

It is evident from this data that the majority of the debris particles have not decayed significantly in altitude during this time. Indeed 67.5% of debris particles are still above a height of 750km after a time τ_Ω. At this time a further 23% of particles have decayed below 300km and are considered to have reentered. These observations are significant since even for debris clouds which are generated just above the minimum height for the criterion for evolution to be satisfied, during the period τ_Ω those particles which remain in orbit are still at high altitude. Clearly these particles will then slowly lose altitude, populating lower orbits, however by this time they are in a chaotically evolved state.

In summary it appears for the range of particles generated with the EVOLVE model, having particles larger than 1cm, the DSMC methodology is appropriate in all cases above approximately 700km. Below that altitude since the debris is predominantly derived from higher orbits, the DSMC methodology is still valid due to the dominance of debris at these altitudes derived from higher altitude injection events, having had the time to evolve. However there is also the case where the methodology is inappropriate. If specific risk assessments for a vehicle are to be performed at low altitudes below 700km, and there has been a relatively recent fragmentation event which has also occurred below 700 km, the model is less well justified. It does appear however that the DSMC method is appropriate as a general risk evaluation tool for low earth orbit satellites.

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