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Computational Comparison of Debris Cloud Models

S. P. Barrows*
Smith System Engineering, Ltd., Surrey Research Park, Guildford, Surrey GU2 5YP, England, United Kingdom
G. G. Swinerd†
University of Southampton, Southampton, Hampshire SO17 1BJ, England, United Kingdom
and
R. Crowther‡
Defence Evaluation and Research Agency, Farnborough, Hampshire GU14 0LX, England, United Kingdom

On-orbit breakup events give rise to concentrations of debris that, for some time after the event, have spatial densities considerably higher than the background flux. Thus, a detailed knowledge of the extent to which the cloud will grow over a given time period and an accurate assessment of the risk of collision for a spacecraft passing through it are important considerations when determining the debris collision risk to orbiting spacecraft. This study examines and compares two sets of software models developed to address this problem and shows how such models can find use in real-life operational situations. Debris cloud modeling software developed at the University of Southampton is compared with The Aerospace Corporation's models on a case study of the Clementine/Titan II second-stage fragmentation. The comparison shows that although good overall agreement between the modeling software is observed, significant discrepancies still exist in the modeling of fragmentation events, and true validation of the models with real data is still to be achieved.

Introduction

FOR some time after a breakup event, the fragmentation debris produced may pose a significant threat of collision to orbiting spacecraft that encounter the cloud. The collision hazard due to the debris cloud acts in addition to that routinely experienced from the background debris environment and the natural particulate population. In the early stages of its evolution, the density of debris in the cloud may be several orders of magnitude higher than the background level. Interaction with the debris cloud produced by the fragmentation event may result in considerable spikes in a target satellite's overall, i.e., background plus cloud, collision probability vs time curve. If such order of magnitude increases above the background level were predicted to occur often enough and to be of sufficient severity, they could influence mission planning and the shielding strategies employed in the design of a future satellite.

Such short-term analyses, which consider a specific debris cloud and are concerned with time spans of hours to days, can be regarded as being complementary to longer-term investigations, which strive to model the debris environment as a whole and the subsequent danger that the background population poses to orbiting spacecraft. Cloud- and target-specific debris models can also find important use in real operational situations, as is shown by the analysis of the Clementine/Titan II breakup described later in this paper.

The estimation of collision probabilities for an object passing through a debris cloud is a problem for which comparison with real data is virtually impossible. Hence the comparison of results between different but similar models provides the only real opportunity to verify the predictions of collision hazard analyses. Two comparison studies are discussed here in which the University of Southampton's models are used to mimic case studies carried out using The Aerospace Corporation's software. The first comparison[1] is only summarized here and considers two simple cloud–target scenarios deliberately engineered to test and to illustrate the operational capabilities of The Aerospace Corporation's codes. The second study examines the fragmentation of the Clementine/Titan II second stage and is far more interesting because it considers an actual fragmentation event and the ensuing collision risk to manned spacecraft on orbit at the time of the event.

Software Overview

Space Debris Simulation Software Suite

The space debris simulation (SDS) software suite[2] consists of four main programs, a shared library of calculation modules, and a graphical user interface with numerous customized data-processing and plotting routines. The integrated structure of the software developed enables a wide variety of analyses to be conducted and simulations of both historic and potential future orbital fragmentation events to be performed.

Program BREAKUP uses a combination of empirical and analytical models to simulate catastrophic and noncatastrophic collisions and also variable intensity explosive fragmentations. Both isotropic and nonisotropic cloud models can be used. The former produces a spherical debris continuum in spread velocity space about the breakup position. The nonisotropic cloud representation is a novel parametric model for producing and controlling nonisotropic fragment spreads and generating discrete fragment orbital parameters.

TRAJECTORY acts as a testbed for the orbit propagation techniques employed in EVOLUTION and TARGET and also provides the facility for convenient and direct method comparison. Eight orbit propagation methods are available, including relative motion state transition matrix techniques, analytic orbit propagation methods, e.g., Ref. 3, and a simple numerical integrator.

Program EVOLUTION enables the complex dynamics of debris growth to be visualized and in particular the effects of propagation method to be examined. EVOLUTION uses the output from BREAKUP directly as initial conditions for the cloud.

TARGET employs a novel implementation of the method of probabilistic continuum dynamics to perform a collision hazard assessment for a spacecraft that encounters a debris cloud. TARGET also uses BREAKUP output directly to describe the fragmentation. Among the additional new developments available for use in TARGET are the consideration of atmospheric drag, a direct interface with a nonisotropic cloud model, the use of a cellular target spacecraft representation with an impact energy-related damage assessment algorithm, and a built-in satellite constellation analysis facility.

The modeling capabilities of the SDS software suite have been illustrated and tested through the use of several case studies, including the simulation of several historic fragmentation events and the

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*Senior System Engineer. Member AIAA.
†Senior Lecturer in Astronautics, Department of Aeronautics and Astronautics.
‡Principal Scientific Officer, Space Department.

debris cloud collision risks to ENVISAT-1 (Ref. 4) and the Iridium® satellite constellation.[5] The results produced by the software have also been verified by comparisons with other simulation software and, wherever possible, with actual breakup events, debris impact data, and trackable fragment orbits.[2]

The Aerospace Corporation Software

The Aerospace Corporation's programs IMPACT and DEBRIS are in essence equivalent software models to BREAKUP and TARGET, developed completely independently and using different but similar approaches but ultimately addressing the same problems. Programs IMPACT and DEBRIS are discussed in more detail in Refs. 6 and 7.

Previous Comparison Study

Reference 6 contains two numerical examples to illustrate the performance of DEBRIS3.1. These examples were used to compare the output from DEBRIS3.1 and TARGET3.1 (Ref. 1). Two runs of TARGET3.1 were made for each case, one using BREAKUP3.0 to simulate the fragmentation event described and the other using pseudo-IMPACT3.0 input. BREAKUP3.0 and IMPACT3.0 were the fragmentation model versions for TARGET3.1 and DEBRIS3.1, respectively. Note that the equal program version numbers was purely a coincidence. The pseudo-IMPACT3.0 input was obtained by sampling the two IMPACT3.0 fragment distribution curves that are included in Ref. 6 and converting the data obtained into the correct format for input to TARGET3.1. The use of what was effectively a common breakup model enabled the results produced by DEBRIS3.1 and TARGET3.1 to be compared directly. The runs that used a different fragmentation model allowed the effects of the fragmentation model to be observed.

The two examples showed that, although DEBRIS3.1 and TARGET3.1 appeared to be in good general agreement when used with a common fragmentation model, when IMPACT3.0 and BREAKUP3.0 were used to provide input to their respective partners, noticeable differences were observed in the results produced due to the different breakup models employed by the two codes. For the collision-induced fragmentations examined, the larger and denser BREAKUP3.0 debris cloud led to TARGET3.1 predicting higher risks of collision than DEBRIS3.1.

Software Comparison: Simulation of Clementine/Titan II Fragmentation

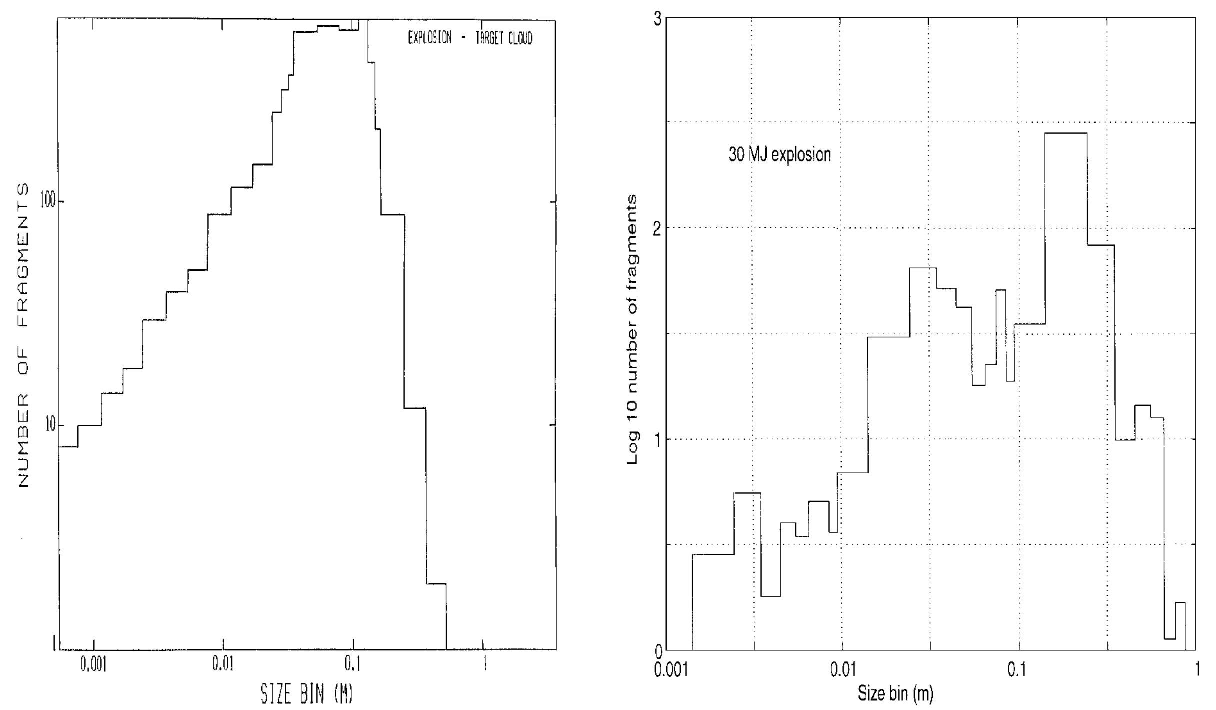
Background

On Feb. 7, 1994, the Clementine/Titan II second stage (G-11) unexpectedly fragmented, spreading debris throughout the low-Earth-orbit environment. The debris cloud produced by the breakup was potentially hazardous to two manned orbiting vehicles, the U.S. Space Shuttle Discovery and the Russian space station Mir. A hazard analysis was performed by The Aerospace Corporation while the Shuttle was still in orbit in an attempt to quantify the collision risks to the two manned vehicles. The results of the initial analysis and a follow-up study are presented in Ref. 7. This provides an excellent opportunity for results verification on a real-life example. Such a real-life analysis, carried out in real time, also illustrates the importance of being able to accurately model fragmentation events and the short-term risk they pose to orbiting spacecraft. Had a high-risk encounter been predicted for the Shuttle, for example, evasive maneuvers could have been taken to minimize the collision risk, provided that the risk exceeded acceptable levels and that the objectives of the mission were not severely impaired.

Breakup Simulation

The U.S. Space Surveillance Network detected over 700 fragments from the Clementine/Titan II second-stage breakup. The low altitude of the rocket orbit prebreakup (240 km, near circular, 67-deg inclination) meant, however, that a significant proportion of the debris produced is likely to have re-entered the Earth's atmosphere before it could be detected. The maximum apogee altitude of a tracked fragment was approximately 1700 km, indicating that a considerable amount of energy was associated with the fragmentation.

The fragmentation is modeled by IMPACT[7] as an explosion with breakup energy of 30 MJ. An explosion was considered to be the most likely cause of the fragmentation due to the stage's inability to vent or deplete residual fuel or oxidizer. An estimate for the energy associated with the event was determined from the spread velocities of the trackable fragments. Figure 1a shows the fragment number distribution for the event generated by IMPACT; 1940 fragments are produced by the simulation, with debris of around 10 cm in size being the most populous. The fragment size distribution produced by BREAKUP4.0 is shown in Fig. 1b. The fragmentation was also



a) IMPACT simulation: version 3.0

b) BREAKUP simulation: BREAKUP4.0 fragment size distribution

Fig. 1 Fragment size distributions of Clementine/Titan II fragmentation.

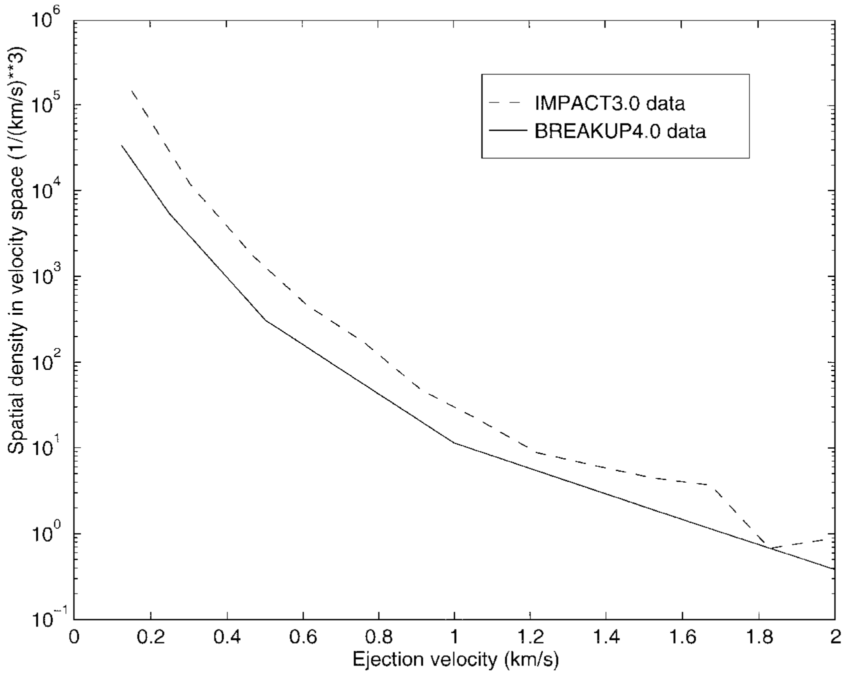
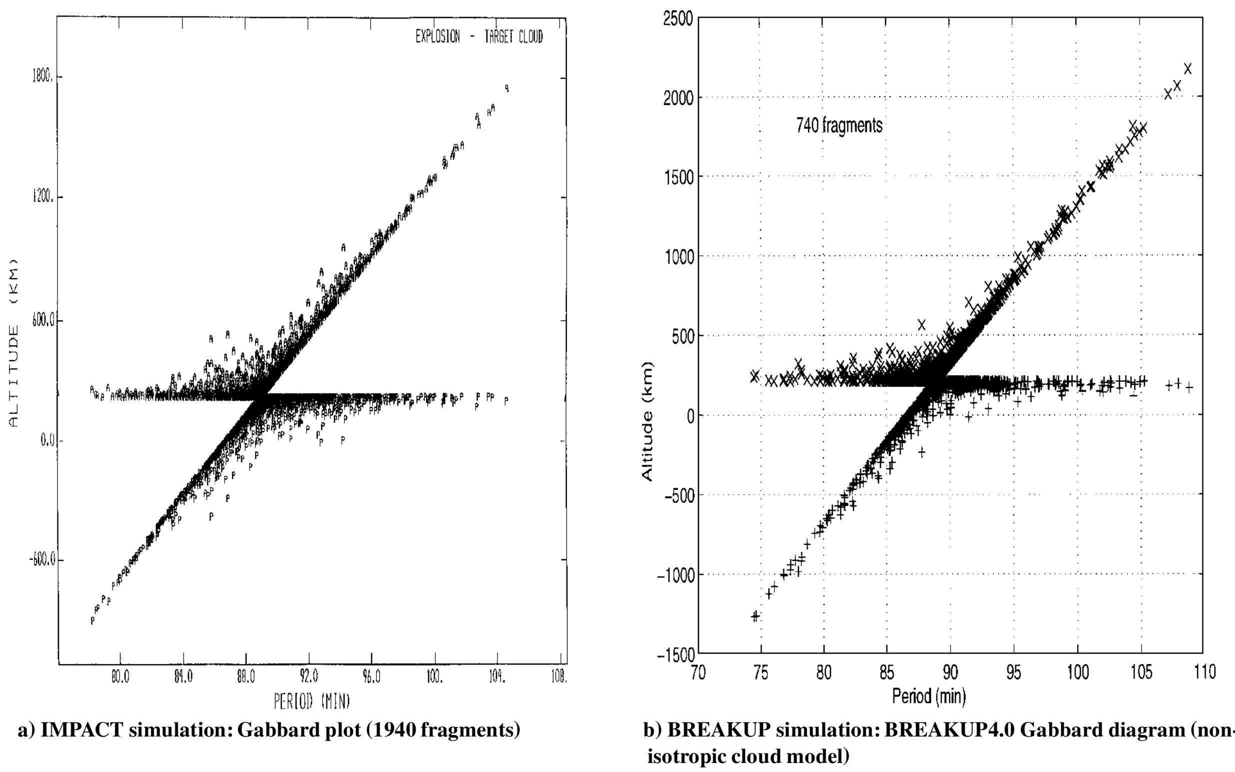


Fig. 2 Fragment density distributions of Clementine/Titan II fragmentation: comparison of BREAKUP4.0 and IMPACT3.0 debris density profiles.



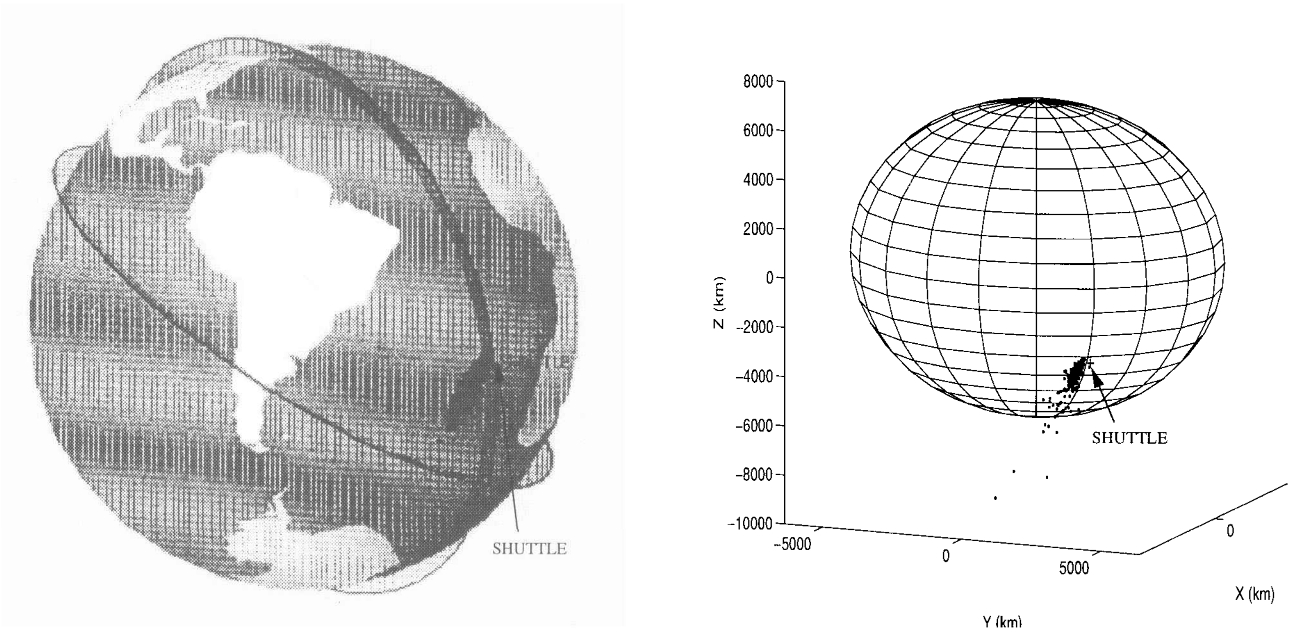
a) IMPACT simulation: Gabbard plot (1940 fragments)

b) BREAKUP simulation: BREAKUP4.0 Gabbard diagram (non-isotropic cloud model)

Fig. 3 Gabbard diagrams of Clementine/Titan II fragmentation.

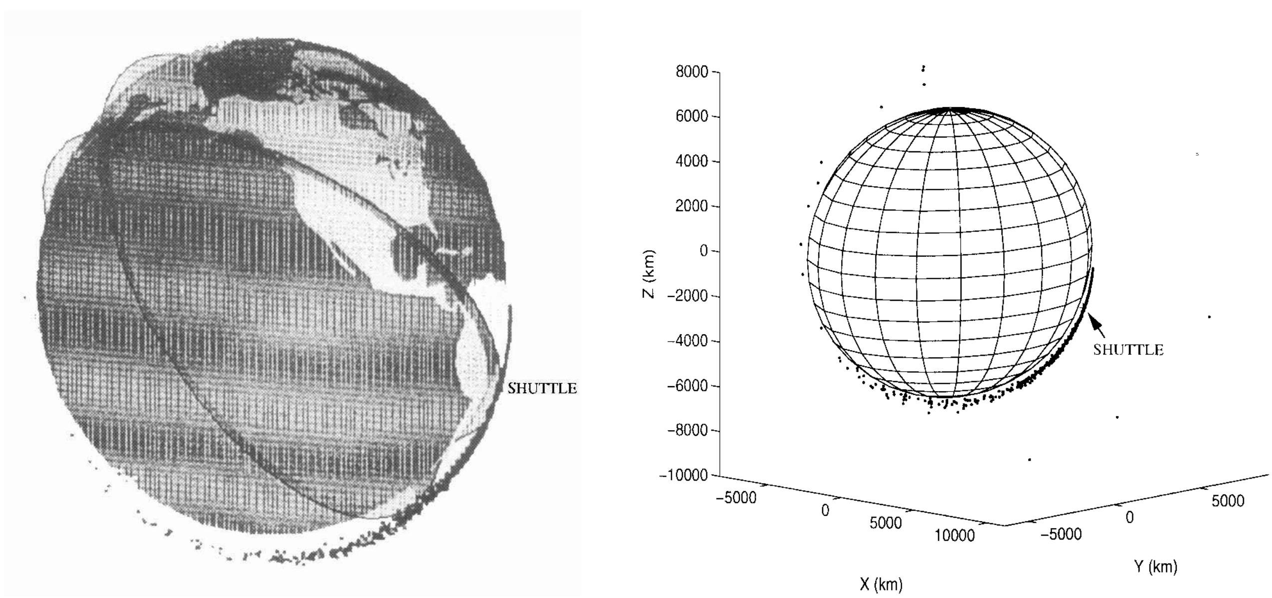
modeled as an explosion with breakup energy of 30 MJ; 740 fragments of 1 cm in size and larger were generated. The two curves in Fig. 1 are similar in shape, with peaks at approximately the same debris sizes, but the BREAKUP4.0 curve is more uneven due to the randomized spread made about the nominal distribution. The factor of 2.6 difference between the number of fragments produced by the two simulations is certainly well within the bounds of uncertainty associated with the different, predominantly empirical, fragmentation models employed by the two codes, coupled with the effect of the BREAKUP4.0 number randomization. Running BREAKUP4.0 again with a different random seed would produce a slightly different number distribution, and the average of many runs would be closer in shape to Fig. 1a.

Figure 2 compares the debris density vs spread velocity distributions produced by the two models. The IMPACT distribution is replotted on the same axes as the BREAKUP4.0 curve for ease of comparison. The BREAKUP4.0 distribution is generated using its isotropic cloud model. The two curves show an almost identical tailoff of debris density with ejection velocity. The densities on the IMPACT curve are factors higher than on the BREAKUP4.0 curve, as one would expect given the difference in the numbers of fragments produced. The simulated event Gabbard diagrams (plots of debris apogees and perigees vs orbit period) are shown side by side in Fig. 3. Here, the BREAKUP4.0 nonisotropic cloud model is employed to generate a set of discrete fragments and orbits. The matching of the two diagrams is excellent, with BREAKUP4.0 predicting



a) DCSIM simulation b) EVOLUTION simulation

Fig. 4 Orbital geometry of cloud and Shuttle at time of first encounter, 34 min after breakup.



a) DCSIM simulation b) EVOLUTION simulation

Fig. 5 Orbital geometry of Shuttle and cloud at time of maximum encountered debris flux, 215 min after breakup.

just slightly higher maximum ejection velocities, which correspond to higher apogees and lower perigees.

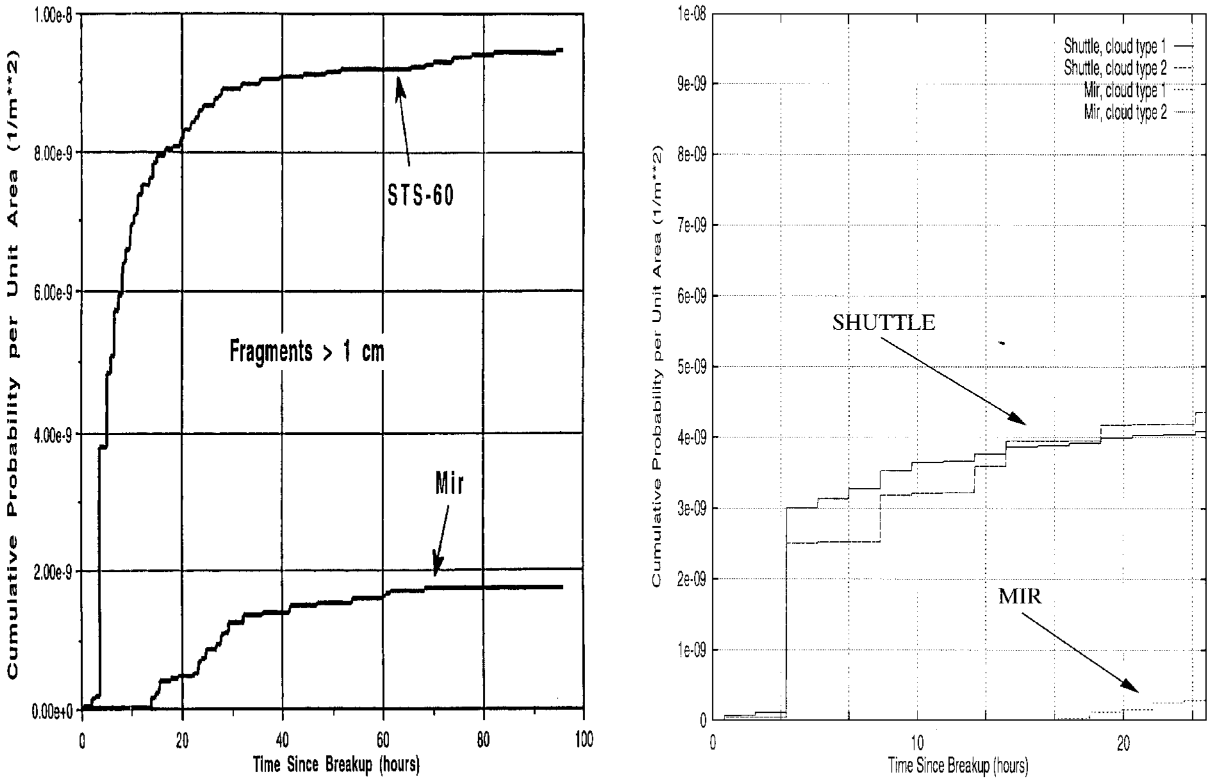
Cloud Evolution

To visualize the orbital geometry of the evolving debris cloud and the two manned vehicles, the graphical simulation program DCSIM is employed in Ref. 7. DCSIM evolves the cloud of fragments produced by the IMPACT simulation of the breakup and the orbits of the Shuttle and Mir using a Keplerian plus J_2 propagator. The orbits of both manned vehicles were over 100 km higher than that of the Titan II stage. Discovery was moving in a near-circular orbit with an altitude of 358 km and an inclination of 57 deg. Mir was in a near-circular orbit at an altitude of 384 km and an inclination of 51.6 deg. Figure 4a shows the relative geometry of the debris cloud and the Space Shuttle at the first debris cloud penetration by Discovery, approximately 34 min after breakup, as generated by DCSIM. The equivalent cloud–Shuttle geometry produced by applying EVOLUTION3.0 with Keplerian plus J_2 propagation to the nonisotropic BREAKUP4.0 cloud is shown in Fig. 4b.

On their own, the DCSIM and EVOLUTION3.0 figures can only provide qualitative information, but they do enable the extent of the debris spread around the globe to be easily visualized and also the locations of cloud–target encounters to be visually determined. Figure 5 shows the debris cloud penetration by the Space Shuttle 215 min after breakup. Here the Shuttle appears to pass though the cloud in a region of particularly high debris density. This observation is substantiated by the collision hazard analysis discussed next. The general matching of debris cloud characteristics and relative target positions between the DCSIM and EVOLUTION3.0 simulations can be seen to be very good.

Collision Hazard Analysis

To determine the collision hazard to Discovery and Mir from the Titan II debris, program DEBRIS was employed,[7] the debris cloud being defined by the IMPACT spread velocity distribution shown in Fig. 6. The simulation was performed for four days from the breakup epoch to account for the remainder of the Shuttle mission. During this time, both the Shuttle and Mir passed through the cloud



a) DEBRIS simulation b) TARGET4.0 simulation

Fig. 6 Cumulative collision probability per unit area vs time for the Shuttle and Mir.

on numerous occasions. The collision probabilities calculated for the two vehicles by DEBRIS are shown in Fig. 6a. Only fragments of size 1 cm and larger are considered, and the collision probabilities quoted are per square meter of target. The collision probability curves for both spacecraft are seen to level after the first day as the cloud disperses, with the collision risk to the Shuttle being approximately five times greater than that experienced by Mir. The lower risk predicted for Mir is due to the extra time taken for it to first encounter the cloud. The risks to both vehicles are relatively low, with the encounter between Discovery and the cloud 215 min after breakup, shown earlier in Fig. 5 and evident again in Fig. 6, proving to be the most hazardous.

The collision hazards calculated using TARGET4.0 are shown in Fig. 6b. For each vehicle, simulations are performed using both BREAKUP4.0 cloud types. Once again only fragments of 1 cm in size and larger are considered, and the collision probabilities are for unit target area. The simulations are run for one day only to cover the highest risk portion of the cloud's lifetime. The same y axis scaling is used on Figs. 6a and 6b for ease of comparison. The lower initial cloud densities produced by BREAKUP4.0 compared with IMPACT are seen to result in the lower collision risks predicted by TARGET4.0 compared with DEBRIS. For the Shuttle, TARGET4.0 predicts cumulative collision probabilities at the end of the first day around 2.5 times lower than DEBRIS for both cloud types. This factor difference is directly in line with the breakup model fragment density difference. The risk to Mir estimated by TARGET4.0 is around an order of magnitude less than that for the Shuttle and around six times less than that predicted by DEBRIS. The lower collision risk to Mir is again due to the lower debris spatial densities and higher ejection velocities predicted by BREAKUP4.0 compared with IMPACT for particles of the same size. The different ejection velocities predicted by the two models result in different debris orbits and rates of cloud growth. Mir is thus encountering a different cloud region in each case.

Conclusions

The two software comparison studies described in this paper show that, although DEBRIS and TARGET appear to be in good general agreement when used with a common fragmentation model, when IMPACT and BREAKUP are used to provide input to their respective partners, noticeable differences are observed in the results produced. In the first comparison, which involved the simulation of a collision-induced fragmentation, the larger and denser BREAKUP debris cloud led to TARGET predicting higher risks of collision than DEBRIS. For the explosive Titan II breakup, the opposite was true. These discrepancies serve to illustrate the importance of the breakup model used when attempting to assess the collision risks associated with debris clouds.

The dearth of suitable flight data means that the comparison of collision hazard assessment models can only provide a mutual verification of simulation results. Different software models may be shown to be in good agreement, but how realistic the models actually are is far more difficult to ascertain.

Acknowledgments

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A. C. Tribble
Associate Editor