THE SHORT-TERM AND LONG-TERM COLLISION RISK CAUSED BY FRAGMENTATION CLOUDS

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ABSTRACT

The collision probability shortly after a breakup event is assessed with a new semi-deterministic tool - DETACT. The paper describes its theoretical background. Uncertainties in the fragmentation models are accounted for by describing each fragment's location within an ever increasing volume. The collision risk or flux vs. time is derived via the intersection of two volumes, representing projectile and target. The program can be used to calculate the collision flux caused by a given population of projectiles, for example a fragmentation cloud, on a number of targets. Comparison of test cases with established models such as MASTER result in coherent data. As an example, DETACT is applied to the IRIDIUM constellation, assuming a breakup of one of its members.

1. INTRODUCTION

The collision risk with orbital debris has become an important design issue for space missions. The potential danger is highest in regions where a high spatial density of debris objects coincides with a large number of potential targets, i.e. satellites or upper stages. A distinction has to be made between the collision probability caused by the existing background population (assessed by programs such as MASTER or NASA96) and the risk induced by the fragmentation of a larger object in this particular region.

The latter case could become even more crucial for satellite constellations which are being planned for the near future, some of them in altitudes of high spatial densities. Fig. 1 shows how the fragments of a satellite in LEO are spread along its initial orbit after only one revolution. With DETACT, a tool has been developed which renders the collision probability from shortly after the breakup up to a long-term assessment.

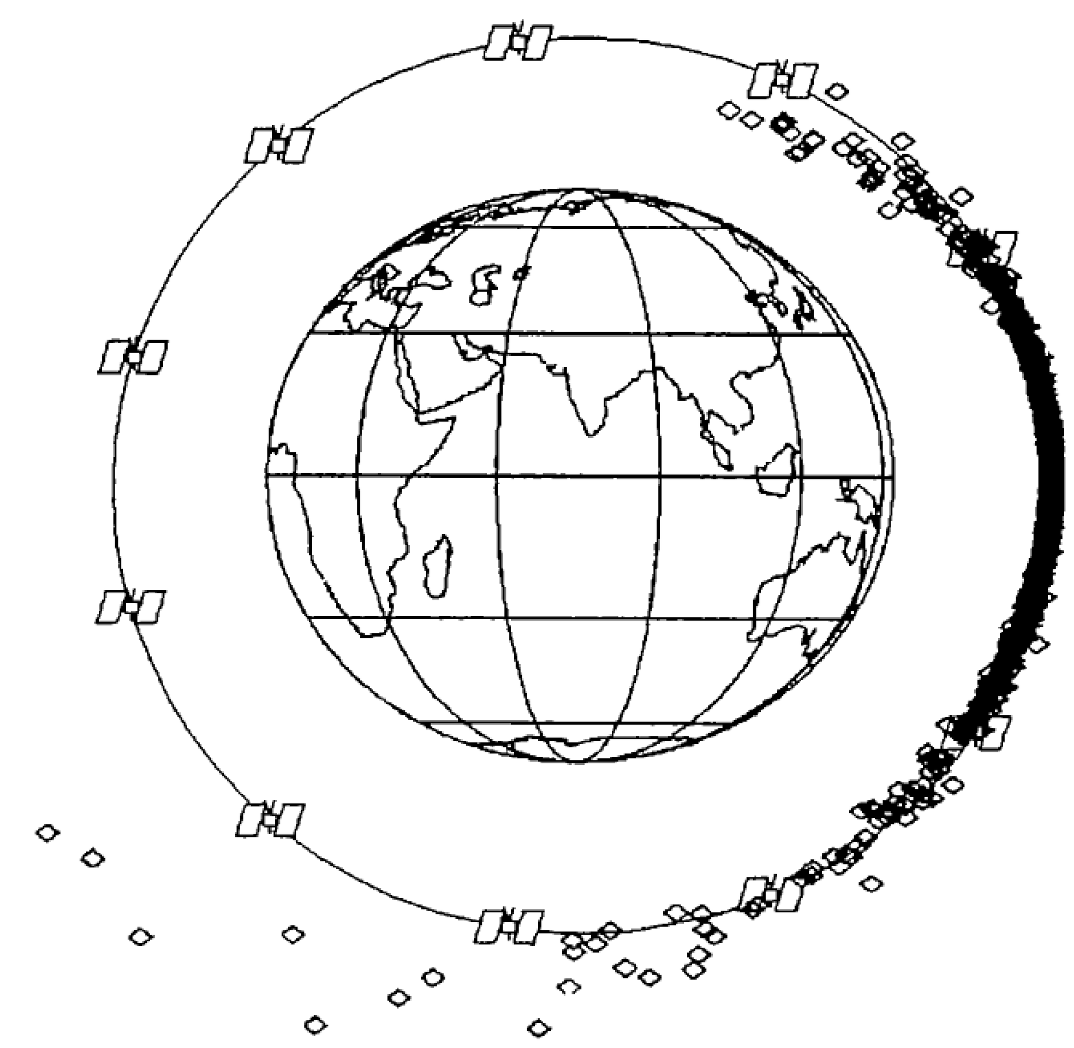

Figure 1. Fragment distribution in LEO after one revolution.

2. DETACT - THE SEMI-DETERMINISTIC TOOL

Both, targets (usually payloads or larger objects) and projectiles (fragments) are described by their respective residence volumes. For the target, a constant volume represents the uncertainty of its position. The uncertainty of the actual projectile position is introduced as an additional velocity dv, added to the (explosion induced) breakup velocity Δv (see Fig. 2).

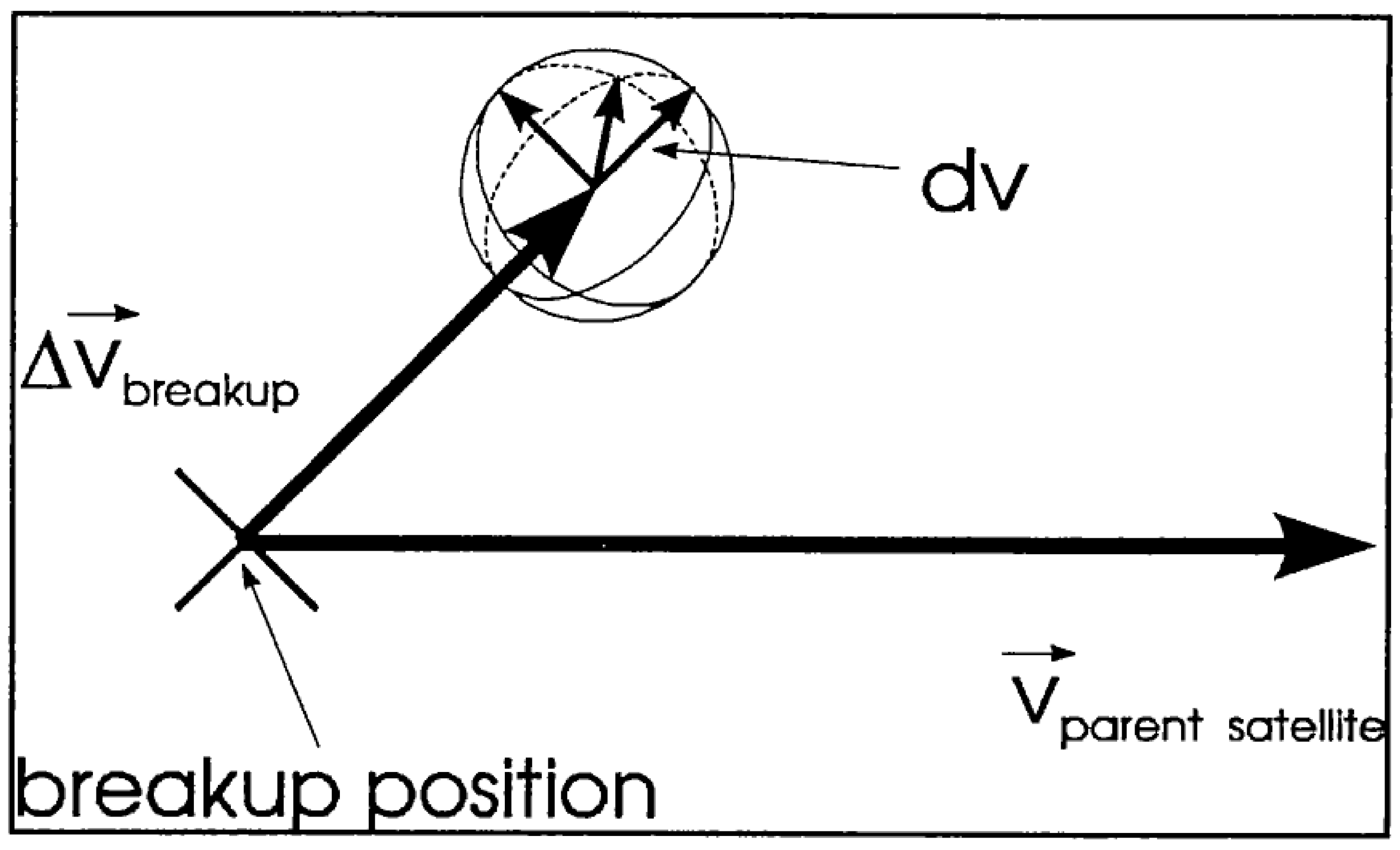

Figure 2. Origin of the projectile residence volume.

Characteristic points of this envelope are propagated. The resulting residence volume inflates with time. Following the laws of orbital mechanics, its shape changes from the initial ellipsoid to an 'open torus' (see Fig. 3) and eventually to a torus. The pinch point

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(breakup location, common point of all fragments' orbits) and the pinch line (opposite the pinch point) can be identified until they are 'dissolved' by orbit perturbations.

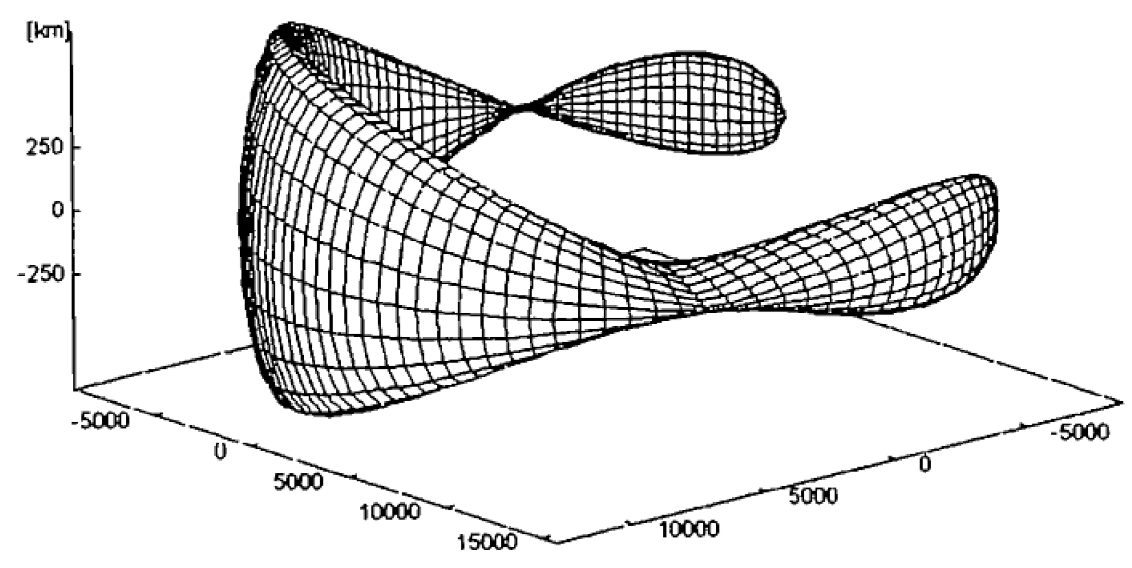

Figure 3. Residence volume of projectile *(open torus)*

The calculation of the intersection volume of the target and the projectile residence volume as well as of the collision velocity renders the flux on the target. The program DETACT allows to take into consideration up to 15,000 projectiles whose orbital parameters are generated by a state-of-the-art fragmentation model. The second input file comprises up to 3,000 targets identified by their orbital elements and the dimensions of their residence volumes.

The semi-deterministic approach allows the resolution of the output flux values for single targets as well as for single time steps which are in the order of one to 10 seconds. The CPU time increases heavily with larger number of objects as with decreased time steps and requires parallel processing techniques.

3. VERIFICATION OF THE PROGRAM

For evaluation, DETACT has been compared with ESA-MASTER as a state-of-the-art model for the orbital debris environment. The short-term evolution, however, cannot be assessed with MASTER, which is based on a given background population. Therefore, a test case has been defined to allow adaptation of DETACT to a Kepler-Orbit-Scenario of MASTER's Analyst application.

Only in the third phase (torus), the residence volume in DETACT encloses the whole projectile orbit which is comparable to the MASTER assumption that a debris object can be located anywhere along its flight path. Thus, the simulation time has to be sufficiently long (>10^7 sec) to represent all projectiles by tori. Secondly, a subset of the MASTER background population, relevant to the altitude band of the considered target, has been defined as projectiles for DETACT.

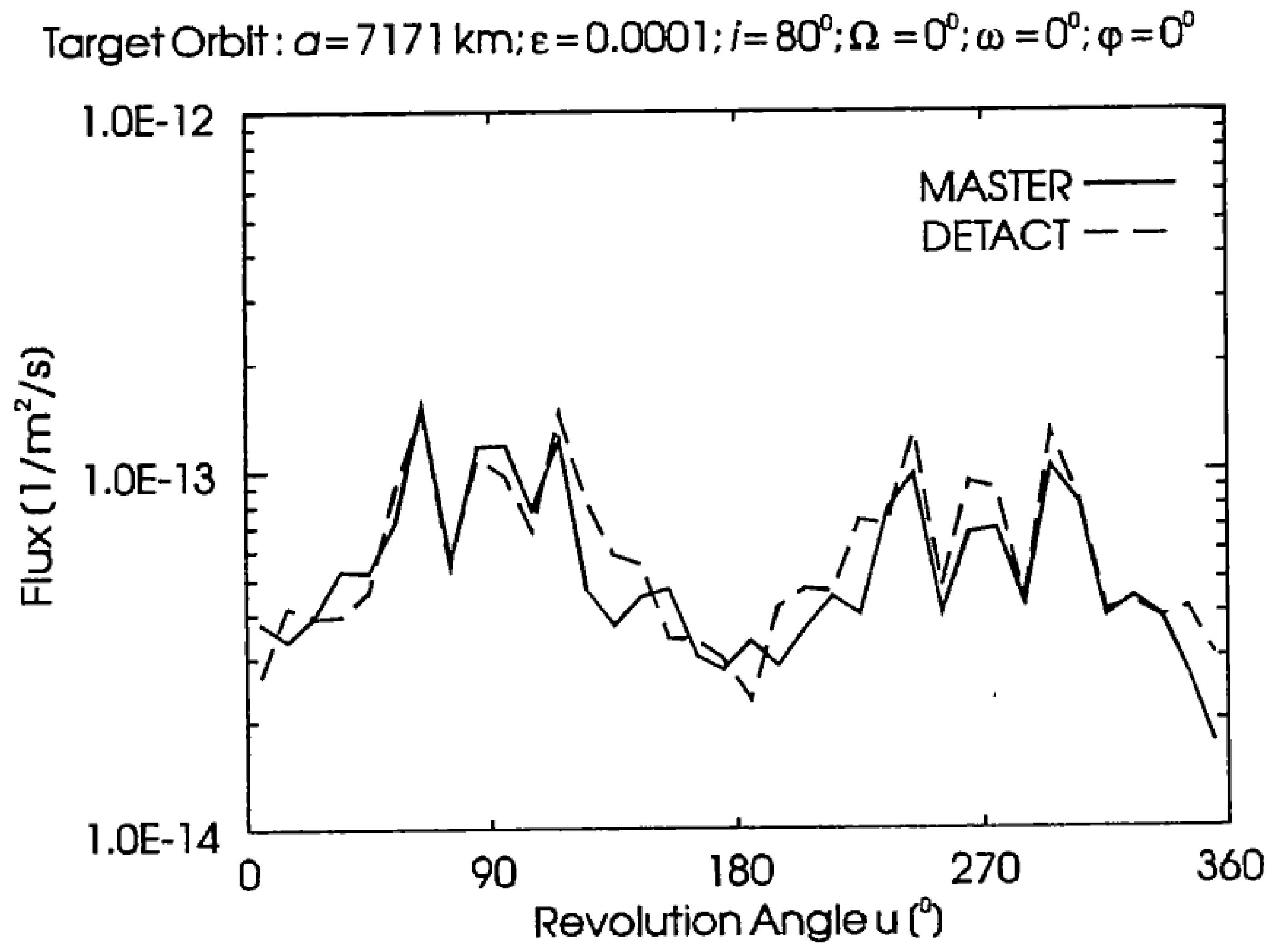

Figure 4. Flux on a target in 800 km altitude, comparison between MASTER and DETACT.

Targets in circular orbits of 400 km, 800 km and 2000 km, with various inclinations (0° to 90°) and a wide range of right ascensions of the ascending node (0° to 315°) have been selected for the comparison of both models. Figures 4 and 5 show the resulting flux vs. target revolution angle for two targets at 800 and 2000 km altitude.

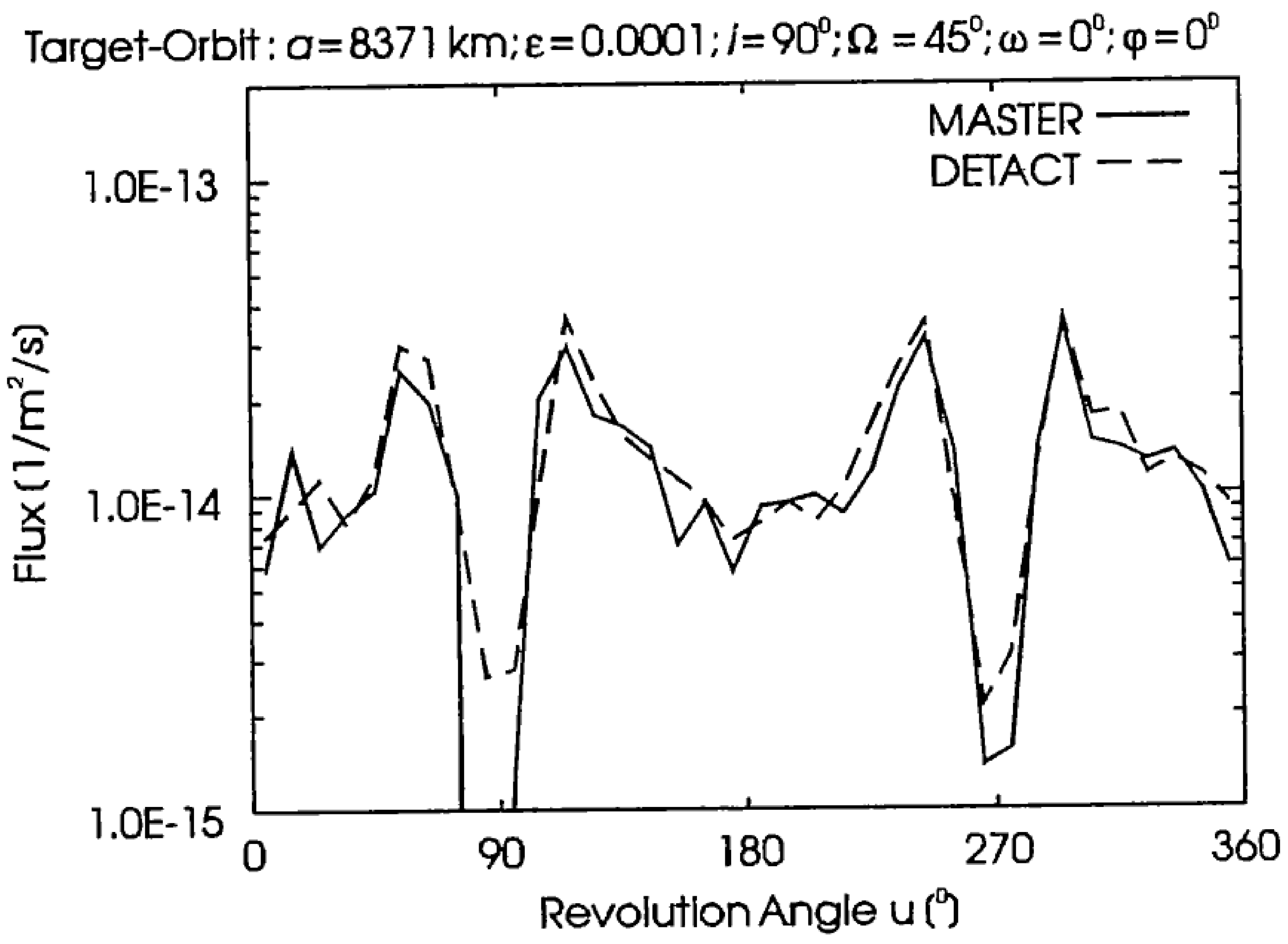

Figure 5. Flux on a target in 2000 km altitude, comparison between MASTER and DETACT.

The results are of the same order of magnitude. Also the flux distribution wrt. the target revolution angle verifies the modeling approach in DETACT. A similar conformity could be achieved with nearly all simulated target orbits. After this verification, DETACT can now be applied to investigate the influence of breakup clouds on the collision risk.

4. DETACT APPLIED TO SATELLITE CONSTELLATIONS

A number of satellite constellations are being planned for the near future. DETACT allows the the risk analysis for constellations in case of a breakup event within the same set of satellites. The program allows both the short-term and the long-term evaluation. This renders the temporal resolution of the flux contributions due to a debris cloud, for example as flux over time respectively vs. target revolution angle.

Here, DETACT has been applied to the current IRIDIUM constellation whose first satellites will be deployed soon. It will contain 66 satellites in 6 orbital planes. The following test case has been simulated: one of the 66 satellites fragments due to a low-intensity explosion near the intersection of the 6 orbital planes at a target revolution angle of 90°. The debris cloud resulting from the breakup was computed with a state-of-the-art fragmentation model, rendering about 880 debris objects, which define the projectiles in DETACT. The targets are the remaining 65 satellites of the constellation.

The resulting collision probabilities are plotted as flux on the IRIDIUM satellites vs. target revolution angle in Figure 6 (differential flux values) and Figure 7 (cumulated flux values). Due to the high temporal resolution, the differential flux plot allows the identification of single collision events (i.e. the intersection of at least one projectile volume with the target residence volume). As could be expected, the mere number of such events is highest for the remaining satellites in the orbital plane where the breakup occured (here plane 6).

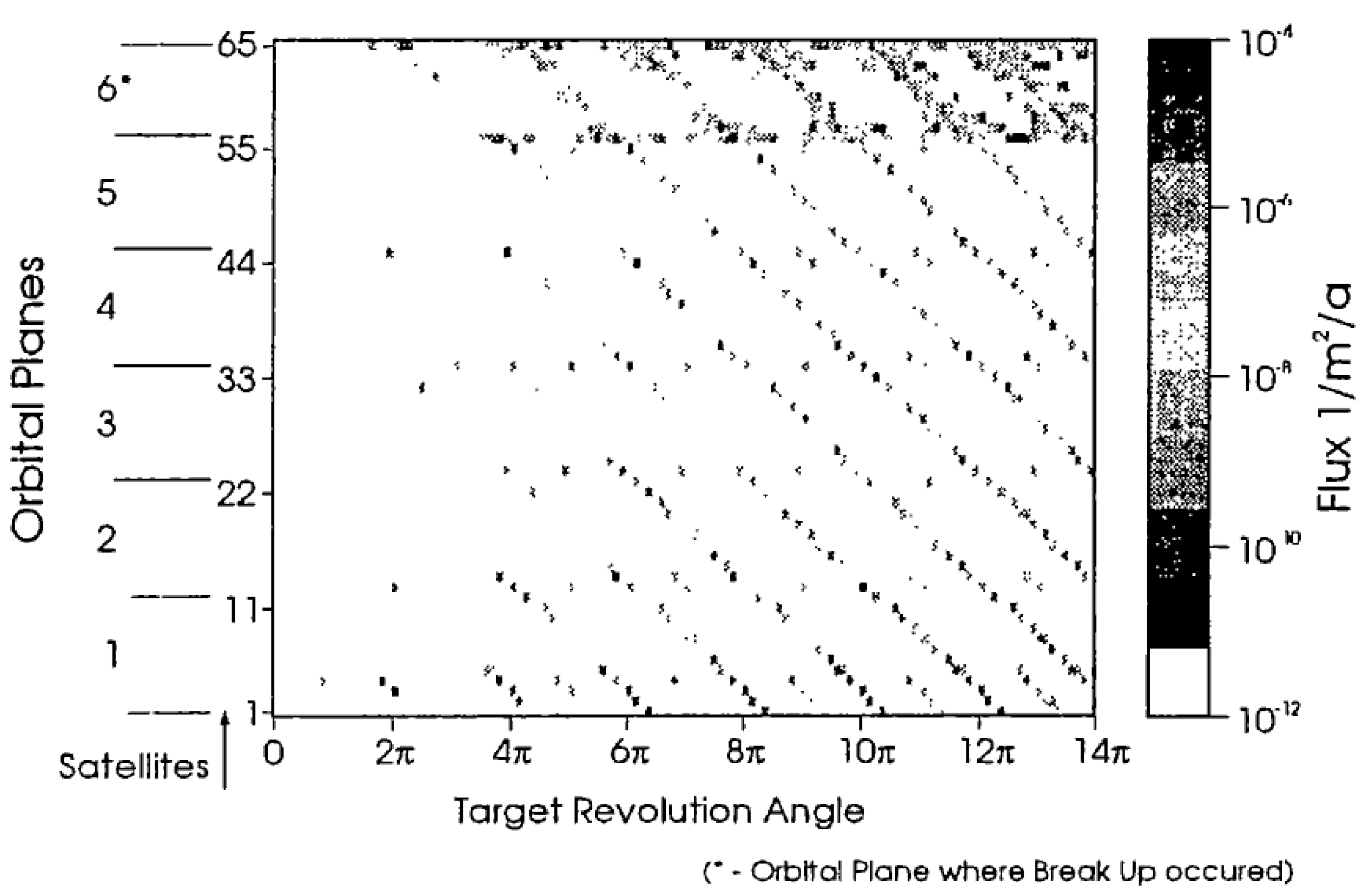

Figure 6. Flux to the remaining 65 satellites of the IRIDIUM constellation due to a break up.

Constellation members in the other planes are only threatened by the debris cloud when they are crossing the orbital plane of the breakup. Their flux exposure in a single event, however, can be considerably higher due to the larger relative velocity. Therefore, satellites outside the plane of the event can accumulate fluences in the same order of magnitude or even higher than spacecraft within. Generally, it can be observed that the cumulated flux ranges over some orders of magnitude. DETACT allows the identification of the individual members of the constellation which are exposed to the highest fluences. They are found in different orbital planes.

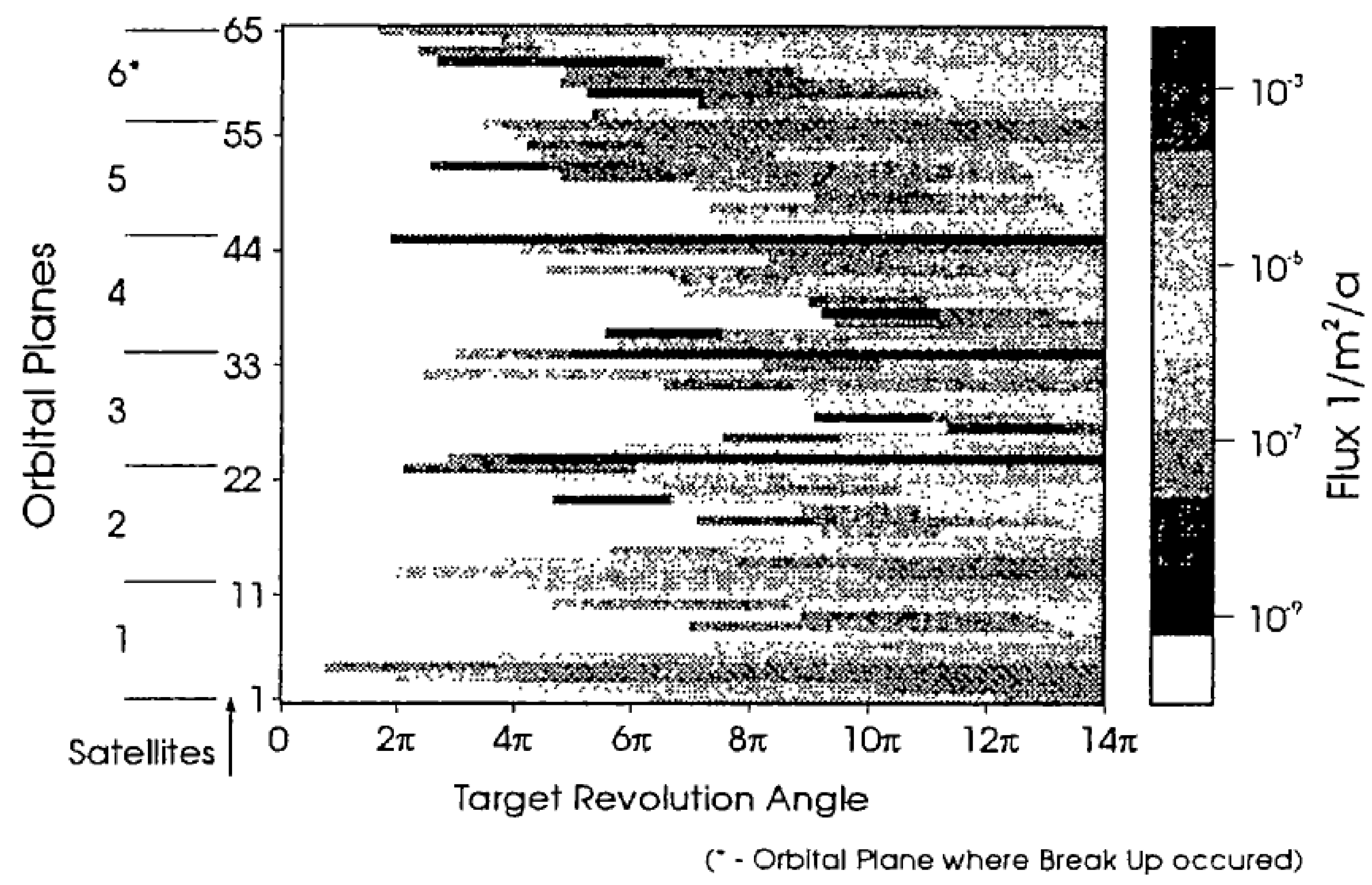

Figure 7. Cumulated flux to the remaining 65 IRIDIUM satellites due to a break up.

DETACT can be used also for parametrical studies to assess the influence of the location of the fragmentation. This allows the analysis and comparison of various concepts for satellite constellations. These methods can be applied as well to densly but randomly populated regions. Of particular interest, due to their economic importance and limited extensions, are the geosynchronous orbit and the altitude band between 800 and 1000 km for sun-synchronous orbits. Here, new or alternative mitigation procedures can be evaluated based on calculations with DETACT.

CONCLUSION

The method of describing each debris object in a fragmentation cloud by a residence volume whose envelope is inflated and shaped by the influence of orbital mechanics has been satisfactorily verified by comparison with the ESA MASTER Model. The semi-deterministic approach in DETACT allows a high-resolution risk analysis in the context of breakup events. The temporal resolution allows both short- and long-term assessments while the deterministic calculation renders flux values for each individual target satellite.