IMPACT GENERATED SMALL DEBRIS AND ORBITAL EVOLUTION

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ABSTRACT

We study the production and evolution of secondary debris generated by a satellite submitted to the primary solid particles flux. A complete ejecta model is proposed and coupled to an orbital extrapolation routine in order to quantify the secondary flux at altitudes equal to and below those of the parent satellite. Spall fragments ejected at low velocities by solar arrays are the most polluting. Calculations for Spot and Globalstar constellation are presented. Evolution of the cumulated ejecta flux depends on the antagonist action of debris production and orbital decay. Smallest (1µm) and largest (1cm) ejecta tend to accumulate. The secondary flux generated by the Globalstar constellation on its own orbit after 20 years increases by 20% the flux of 1cm particles.

1. INTRODUCTION

Every time a debris or a meteoroid hits a satellite in orbit, a great amount of secondary particles, is ejected in the neighborhood of the parent body. This phenomenon is in peculiar important for brittle materials, such as used for solar generators. The secondary particles that do not impact other parts of the structure are added to the primary debris flux and increase the collision risks. A satellite is therefore naturally polluting its own orbit and all orbits below. The purpose of this paper is to evaluate the secondary impact risk for a given satellite, with peculiar application to Spot and to the constellation Globalstar. First, we present an ejecta model based upon in situ observations and laboratory simulations, that gives the size and the velocity distribution of ejected particles, as a function of primary impact parameters. Then, we describe the simulation method for ejecta production by a satellite, orbital evolution at later times, and associated secondary flux calculations. Paragraphs 4 and 5 are dedicated to application results.

2. THE EJECTA MODEL

An extensive bibliographic review has been performed (Ref.1). Most of published works deal with ground tests results or ejecta evidences on space retrieved materials. Other articles consider the ejecta phenomenon as an erosion/accretion process. A few theoretical works deal with thermodynamical and fragmentation models. The synthesis of bibliographic data allowed us to identify the main processes involved in ejecta phenomenon and to propose an analytical model.

2.1 Synthesis on ejecta phenomenon

When a projectile impacts normally a thick homogeneous target, three main phenomena have been identified.

- the jetting : it occurs at the very beginning of impact, when the projectile is consumed inside the target. A liquid jet is ejected in all direction at grazing angles (10° from the target surface) from the projectile/target interface, at velocities that can reach 3 times the impact velocity. Less than 1% of the total ejected mass is involved in this process.

- the debris cone : a few µs after impact, a great amount of small solid particles is ejected at elevation near to 60°, forming a revolution cone around an axis normal to the target. Their size varies between a 0.1µm cut-off value and a maximum size close to those of the impactor (most of them are µm-sized). Ejection velocity is inversely related to the size and is comprised between a few m/s and a maximum velocity close to the impact velocity.

- spallation : this phenomenon is due to the brittle fracture of material near free surfaces, therefore it is not usually observed on ductile targets. About ten spall fragments, of size similar or larger than the projectile size, are ejected at a few m/s, in a direction perpendicular to the target surface.

The total ejected mass scales with impact kinetic enegy $Ec^{1.133}$ (Ref.2). Distribution of mass between

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spallation and debris cone fragments depends on crater size : fraction of spall increases with crater size and reaches 40% for craters larger than 100μm.

Reasonably oblique impacts (less than 60° from the normal of the target) are similar : the total ejected mass is slightly decreased and the azimutal direction of impact is enhanced (more fragments ejected at higher velocities in this direction). For grazing incidences, the revolution cone evolves in a beam of fragments ejected at higher velocities and grazing angles, in the impact azimuthal direction (ricochet phenomenon).

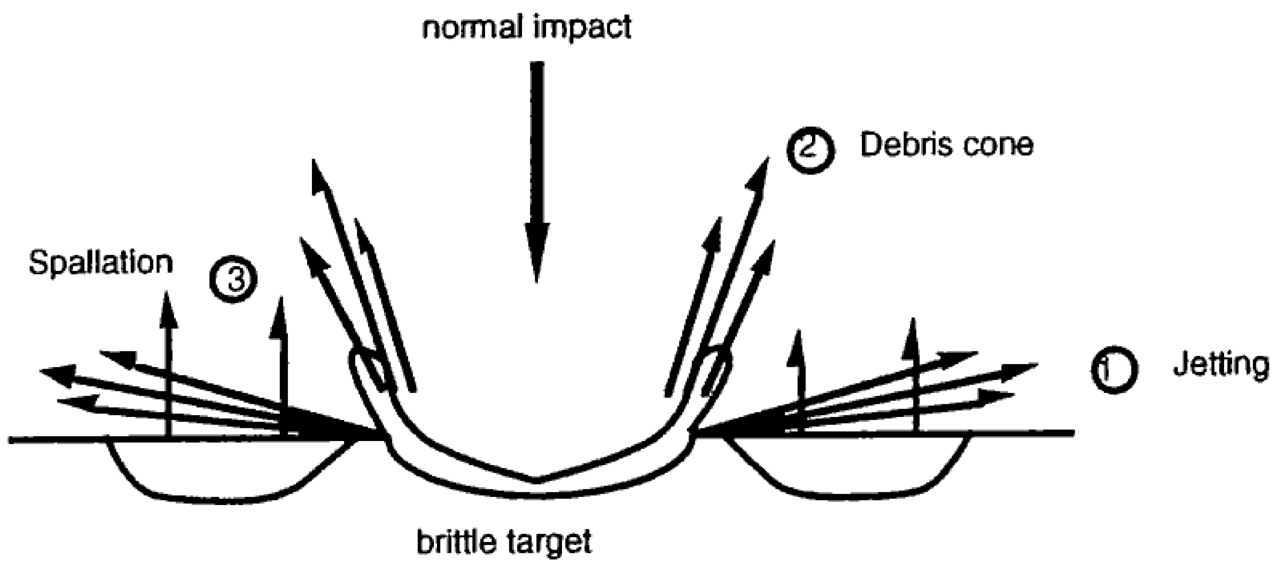

Fig.1: Schematic representation of ejecta phenomenon.

2.2 Mathematical model

To describe the ejection phenomenon, we propose an analytical model based on fragments size and velocity distributions (Ref.1). Inputs are : projectile size and density, target density and ductile/brittle nature, impact velocity and incidence. Model output is the number of particles of size δ between δ and $\delta+d\delta$ ejected in the solid angle $\sin\theta \, d\theta \, d\varphi$, where θ and φ are the zenith and azimuth angle measured in the local frame centered at impact point, with the z-axis normal to the target surface.

For debris cone ejecta, the size (δ) distribution is an inverse power law with a -3.5 coefficient, the θ distribution is a Gaussian centered on the maximum ejection angle (60° from the target surface for a normal impact), and the φ distribution is a sinusoidal function that accounts for the increase of number of fragments ejected in the impact azimuthal direction. For spall fragments, we consider 10 fragments of equal size uniformely ejected at zenith angles less than 5° (normal ejection). Mass ejected through jetting process is neglected. The normalisation constant depends on the total ejected mass, computed with Gault's experimental formula (Ref.2). Ejection velocity of fragments is inversely proportional to fragment size, with corrective coefficients accounting for azimuthal variations and impact parameters.

This model is valid for 1μm to 1cm projectiles impacting a thick homogeneous target at velocities between 1 and 20 km/s.

2.3 Case of solar arrays targets

Impacts features on solar cells are very peculiar, due to their highly heterogeneous multilayer structure. Investigation of craters on retrieved from space EuReCa and Hubble Space Telescope pannels has provided us with many informations on the behaviour of such target under hypervelocity impacts. For smallest projectiles (<20μm), the cover-glass of the cell (≈150 μm) can be considered as a thick homogeneous brittle target. For larger projectiles the underlayers are involved, delamination occurs at interfaces and large parts of cover-glass or solar cell Silicium are ejected. Jetting and debris cone formation are still present, but the number and size of spall is increased, involving more than 60% of the total ejected mass. The model described in §2.2 is used for solar cell targets, just adjusting the ratio of ejected mass in debris cone and spallation process.

Fig.2 : SEM cross section view of an impact on HST panel. The ratio between ejected mass and projectile mass is estimated to 2000 times (Ref.3).

3. ORBITAL EVOLUTION

3.1 General method

The aim is to simulate the production of ejecta by a parent satellite submitted to the primary flux between two dates T0 and T1 (operation time), and to characterize, at the date T1, the total secondary flux generated during the whole period.

The motion of the parent body is simulated by dividing the orbital trajectory in 20 segments. For each orbital revolution between T0 and T1, and for each orbital segment, a set of primary particles, representative of mass, velocity and direction of the primary micrometeoroids and debris flux, is selected to impact the parent satellite. For each impact, the ejecta model of Part 1 is applied, and a Monte-Carlo method is used to define a set of representative secondary particles generated by the primary impact. Each ejecta is characterized by its ejection date between T0 and T1, its size, and its Keplerian orbital elements, calculated from the position of the parent satellite at ejection date and the relative ejection velocity given by the ejecta model. Simulation of the orbital evolution of ejecta between its ejection date and the date T1 is achieved by a routine accounting for atmospheric drag effects. At the end of the simulation, we obtain the Keplerian parameters at T1 of all representative ejecta generated during the operation time.

From these results, orbit-averaged secondary fluxes (/m2/year) are calculated for a towards velocity oriented plate flying on a circular orbit at a given altitude.

3.2 Preliminary results and simplifying hypothesis

Preliminary simulations have shown that most of the small particles from the debris cone, ejected at high velocities (>1km/s), have hyperbolic trajectories and immediately escape the Low Earth Orbit environment. A few of them have highly elliptic trajectories with eccentricities >0.1 and remain in the vicinity of Earth. As our orbital evolution routine was not accurate enough for such orbits, it was decided not to trace them.

Spall fragments ejected at low velocities (≈10m/s) have initial trajectories very close to the parent body. Under atmospheric drag action, their altitude decreases with time, but they remain in nearly circular orbits and their inclination is stable. The right ascencion of the ascending node is naturally modified by solar perturbations and tends to be distributed uniformely with time on the whole 360° spectrum. Therefore, ejecta density can be considered as uniform in the toric volume delimited by parent satellite's inclination.

In summary, spall fragments generated on brittle materials are identified as the main contributors to secondary fluxes in LEO. As solar arrays are both the largest and the most efficient spall producing surface on a satellite, it was decided to study the secondary flux generated by the solar panels only. Preliminary tests have shown no directionnal effects due to the panels orientation towards Sun, so they are assimilated to a randomly tumbling plate.

3.3 Program tool description

Based under previously described models and assumptions, a program has been developped to quantify the secondary flux generated by any satellite. Inputs are : T0 and T1 dates, parent satellite orbit parameters at T0, size of solar panels, primary flux data at parent satellite altitude. Outputs are : fluxes of secondary particles of size larger than 1μm, 10μm, 100μm, 1mm and 1cm at parent satellite altitude, and at each 100 km bin altitude between 100 and 2000 km.

4. APPLICATION 1 : SPOT

Spot satellites are heliosynchronous satellites at 800km altitude and 98° inclination. Four satellites are foreseen (three activated yet) on the same orbit. Such polar orbits are already very busy and the risk of self-pollution by ejecta should not be neglected.

4.1 Pollution of parent body orbit

The program has been run for one Spot satellite. Secondary fluxes generated by the parent satellite on its own orbit after increasing time in orbit, have been computed. Fig. 3 shows the evolution with time (0 to 20 years) of the secondary to primary flux ratio for different particles sizes. The primary flux is considered constant in time.

Evolution with time of the secondary flux depends primarily on the size of ejecta considered : smallest ejecta are produced in great amount but are very sensitive to atmospheric drag, while largest fragments are scarcer but have very long lifetimes in orbit. Therefore, the value of secondary flux is determined by the antagonist action of a source term (production under primary flux) and a sink term (decay by atmospheric drag).

For 1μm ejecta, the production process overcomes the decay process, and we note an increase of the secondary to primary flux ratio, corresponding to an accumulation of micrometric particles at Spot's altitude. Flux values increase regularly but reach only 3.10^{-6} times the primary flux after a 10 years operation time. For 10μm to 1mm ejecta, the ratio increases during the first year of activity and remains stationary for longer operation times, showing the predominancy of the decay process. Flux values are stabilized at less than 10^{-5} times the primary flux. For 1cm and larger ejecta, the source term is weak but is nevertheless greater than the atmopheric drag sink term, and the associated secondary flux increases with operation time, up to 10^{-3} times the primary flux after 10 years.

4.2 Pollution of lower altitudes

Spot's generated particles naturally decay and pollute lower altitudes. Fig.4 shows the secondary flux of ejecta larger than 1μm as a function of altitude, calculated for different time in orbit of Spot. After 10 days, first ejecta have decayed down to 600km. After a few months, all altitudes between 100 and 800km have been populated, and secondary fluxes increase with time. Finally, after 2 years a time-stabilized constant secondary flux is established below parent body's orbit, resulting from balance between arrival of particles from upper altitudes and decaying of particles to lower ones. Accumulation of 1μm particles at Spot's altitude, described in §4.1, is clearly visible. The stabilized secondary flux is at least four orders of magnitude inferior to the primary debris and meteoroids flux.

Fig.5 represents the same results for the 10μm ejecta. Pollution of lower orbits is slower, as these particles are less sensitive to atmospheric drag. First ejecta reach 300km after 3 months, and a few years are needed to stabilize the secondary flux. As observed in §4.1, there is no long term accumulation of 10μm ejecta at Spot's altitude. Results for 100μm particles are similar, with longer time scale.

For 1mm particles, atmospheric drag effects are much less efficient and all ejecta are still concentrated at 800km after 1 year. After 20 years, first ejecta have decayed down to 400km only, and the stabilized flux observed for smaller particles had not enough time to be established .

The results for 1cm particles outline their very slow decay : after 20 years they remain in the 800km altitude bin, accumulating and increasing the secondary flux at Spot's altitude.

5. APPLICATION 2 : GLOBALSTAR

The Globalstar constellation contains 48 satellites distributed on 6 orbital planes at 52° inclinaison and 1400km altitude. Secondary fluxes generated by one of these satellites have been calculated and compared to Spot simulation results.

Fig.6 shows the secondary to primary flux ratio at parent satellite altitude. Accumulation of smallest and largest ejecta is very clear, while secondary flux of intermediary size particles reach a stationary state. The main difference with Spot occurs for the 1mm particles, for which the production slightly overcomes the decay process, due to the lower atmospheric density at 1400km. Because the ejecta should remain longer times in the vicinity of parent satellite, increased secondary to primary flux ratio were expected, but this effect is counter-balanced by the larger dispersion volume at higher altitudes (that scales with the cubic power of orbital radius). Calculated secondary to primary flux ratio for the different size ranges are similar or slightly higher than those obtained in the Spot case. For 1 cm particles, the secondary flux reach 0.5% of the primary flux after 20 years.

Pollution of lower orbits is clearly slower than for Spot's ejecta, because of the combined action of higher initial altitude and lower atmospheric density. For 1μm ejecta, more than 10 years are needed to reach the steady-state secondary flux between 100 and 1400km. This flux is about twice the Spot's generated secondary flux.

Fig.7 shows that the first 10μm ejecta need more than 10 years to decay down to the lowest altitudes. The secondary flux stabilization is not achieved yet after 20 years. The 100μm-sized particles are still limited at altitudes higher than 900km after 20 years. No dispersion is observed for largest ejecta (larger than 1mm) that remain in the 1400 altitude bin.

6.CONCLUSIONS

Simulations show that the secondary flux generated by one satellite, on its own orbit and at lower altitudes, remains well below the primary flux values for particles smaller than 1mm, even after 20 years in orbit. Largest ejecta (1mm and 1cm) can accumulate at the parent body altitude, creating an increasing hazard. In the case of Globalstar constellation, the secondary fluxes should be multiplied by the total number of satellites (48), that gives a 20% increase of 1cm particle flux due to secondaries after 20 years of activity. Polar orbits like Spot's are also very busy and the long term pollution by secondaries should be assessed.

In this simulation, we consider only low velocity spalls ejected by solar arrays. Other sources of ejecta, like paint flakes or erosion products, have similar characteristics and should be added to the secondary flux. Use of thin flexible solar pannels would generate at least twice more large spalls, that are the most hazardous. High velocity ejecta from the debris cone with elliptic orbits also increase the risk.

Extrapolation of secondary flux results to the total ejecta flux produced by the whole LEO satellites population is difficult, but it is clear that the ejecta phenomenon will be an important component of the debris environment evolution, specially in the hazardous 1mm-1cm range. The recent development of satellites constellation programs, that will be responsible for the lauching of more than 500 satellites until year 2000, is likely to constitute a major increase in the secondary flux. This study gives preliminary clues for including secondaries in debris models.

7. REFERENCES

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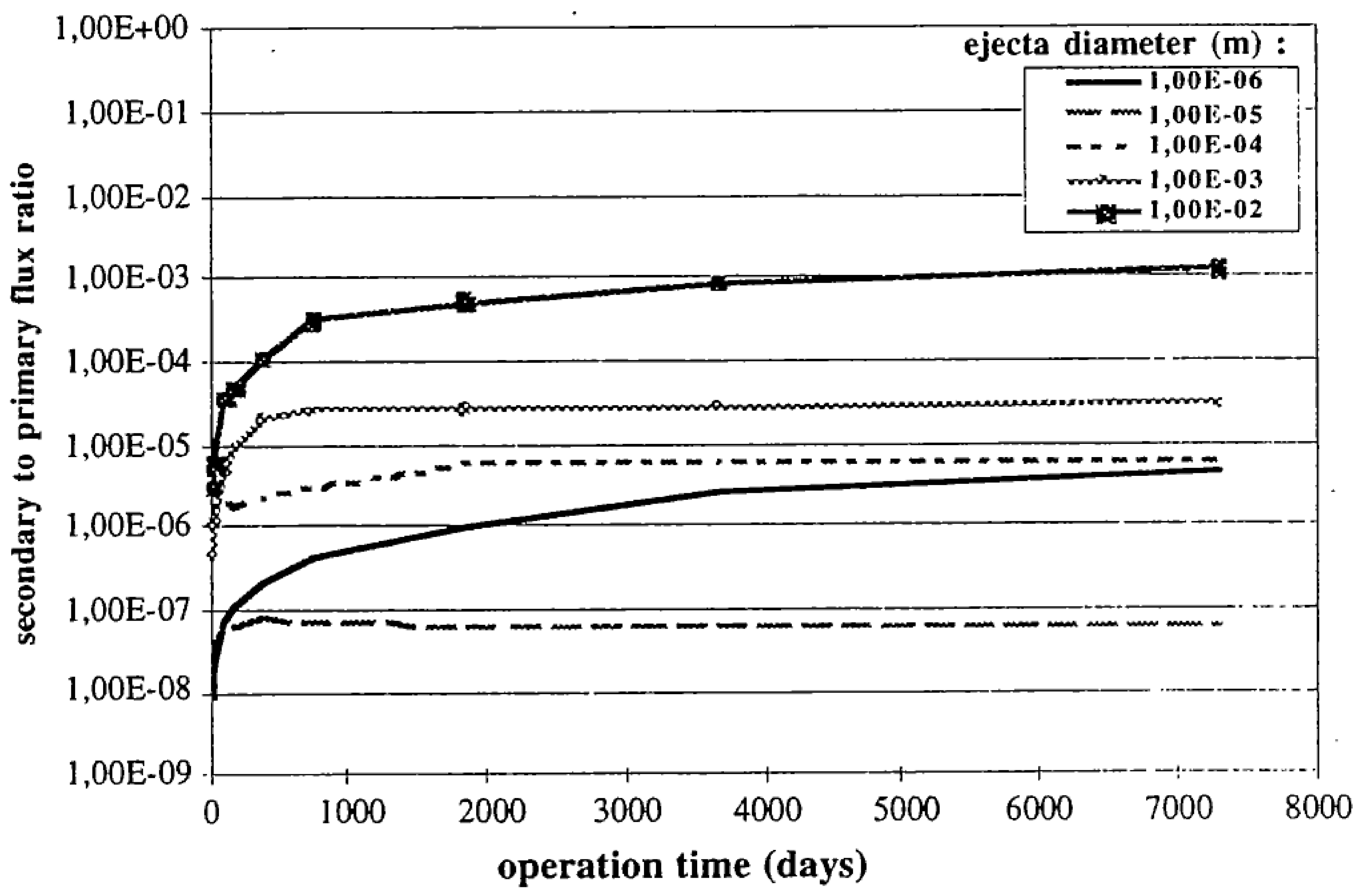

Fig. 3 : Evolution with time of the secondary to primary flux ratio at Spot's altitude (800km), for 1μm, 10μm, 100μm, 1mm and 1cm particle size range.

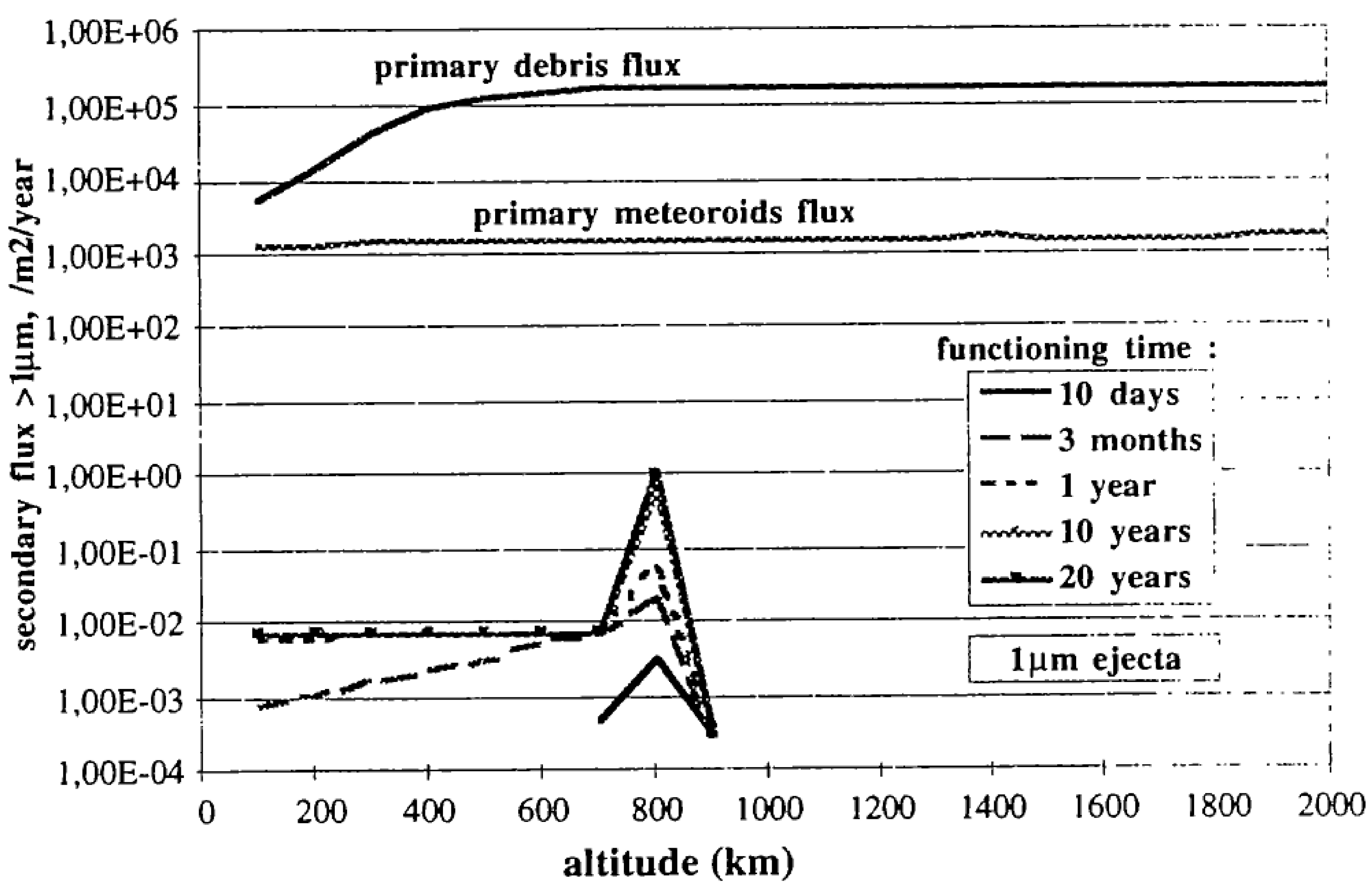

Fig. 4 : Secondary flux of particles larger than 1μm produced by Spot's solar arrays at lower altitudes, after mission duration from 10 days to 20 years.

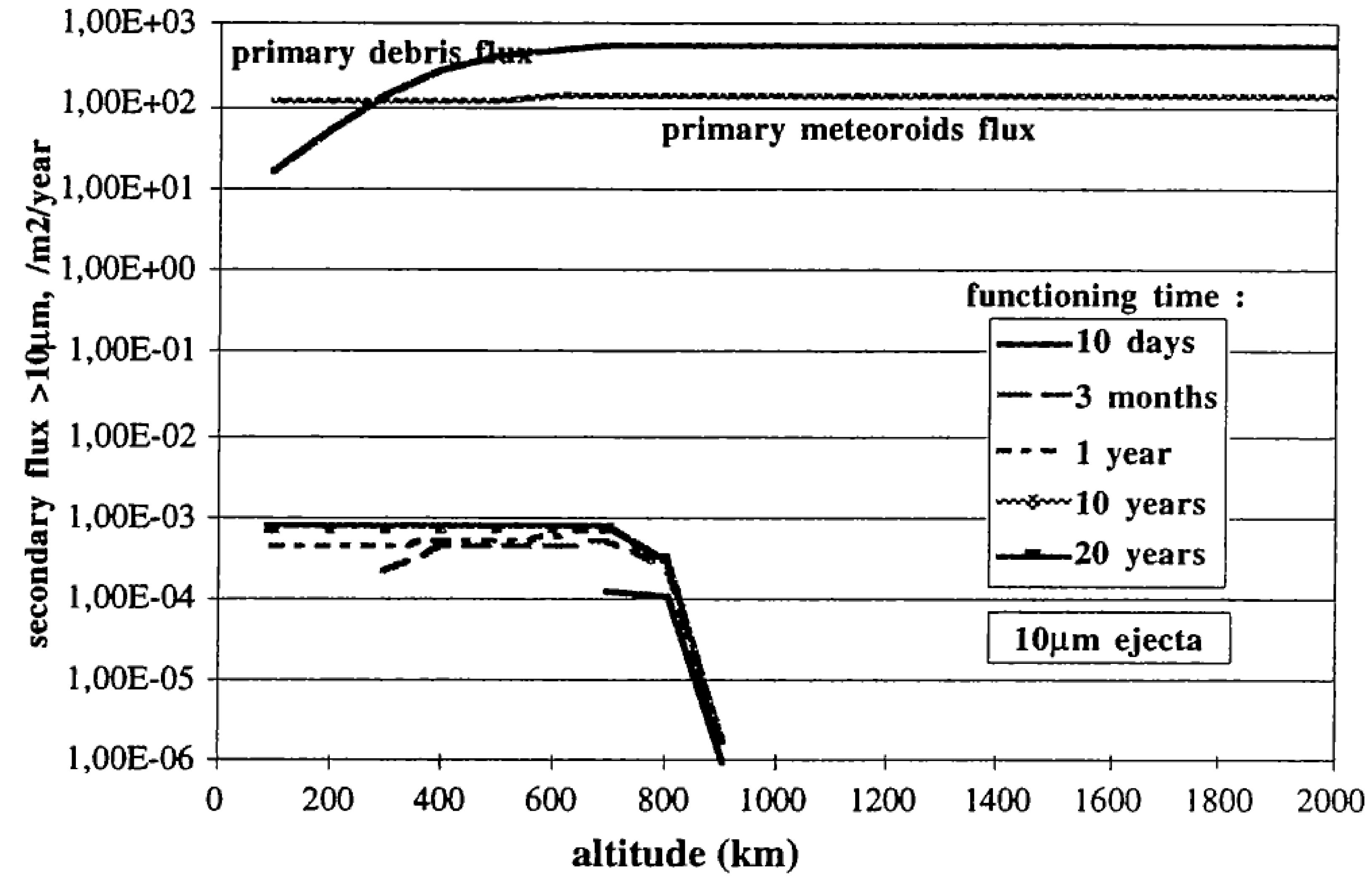

Fig. 5 : Secondary flux of particles larger than 10µm produced by Spot's solar arrays at lower altitudes, after mission duration from 10 days to 20 years.

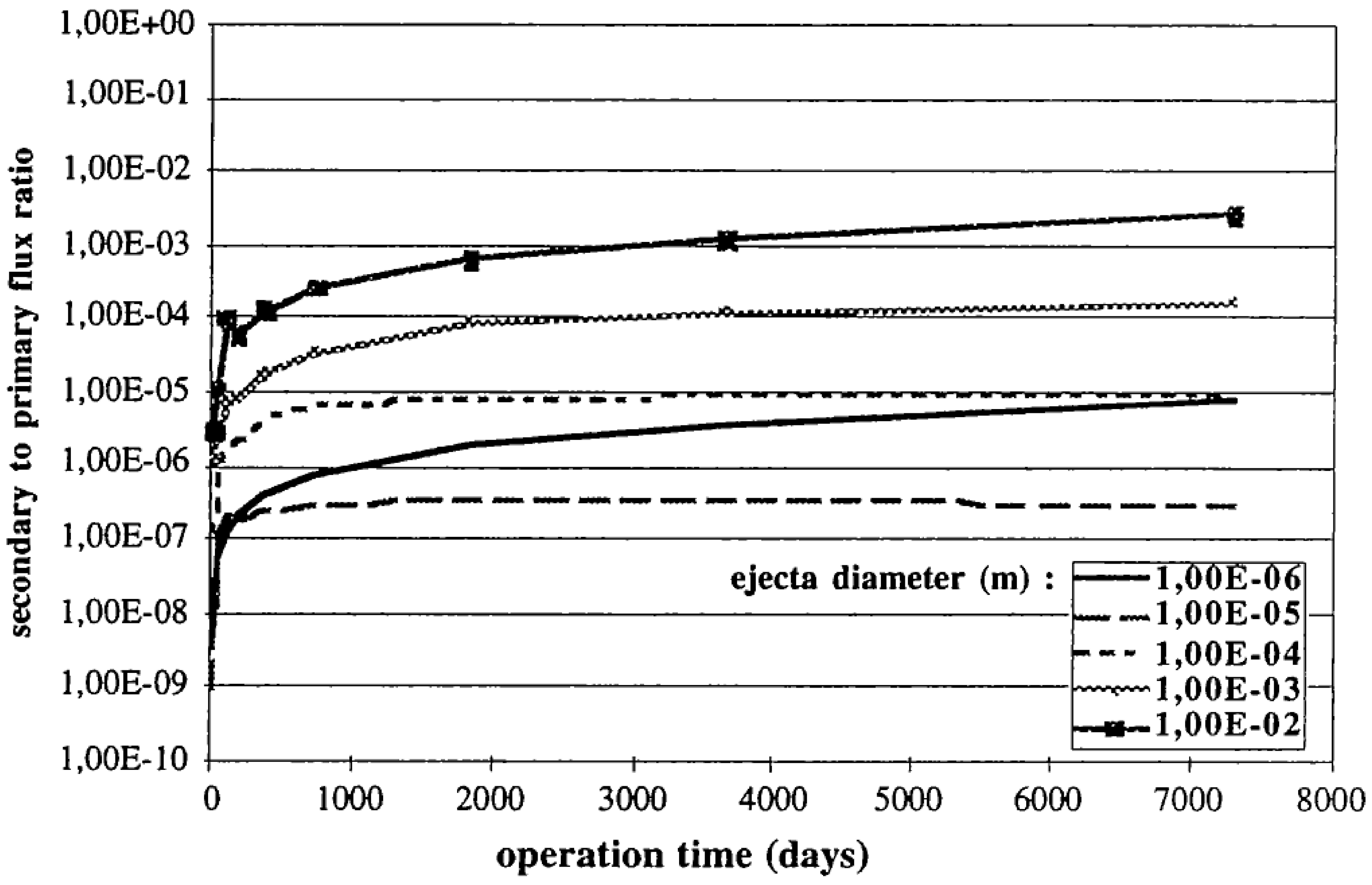

Fig. 6 : Evolution with time of the secondary to primary flux ratio at Globalstar's altitude (1400km), for 1µm, 10µm, 100µm, 1mm and 1cm particle size range.

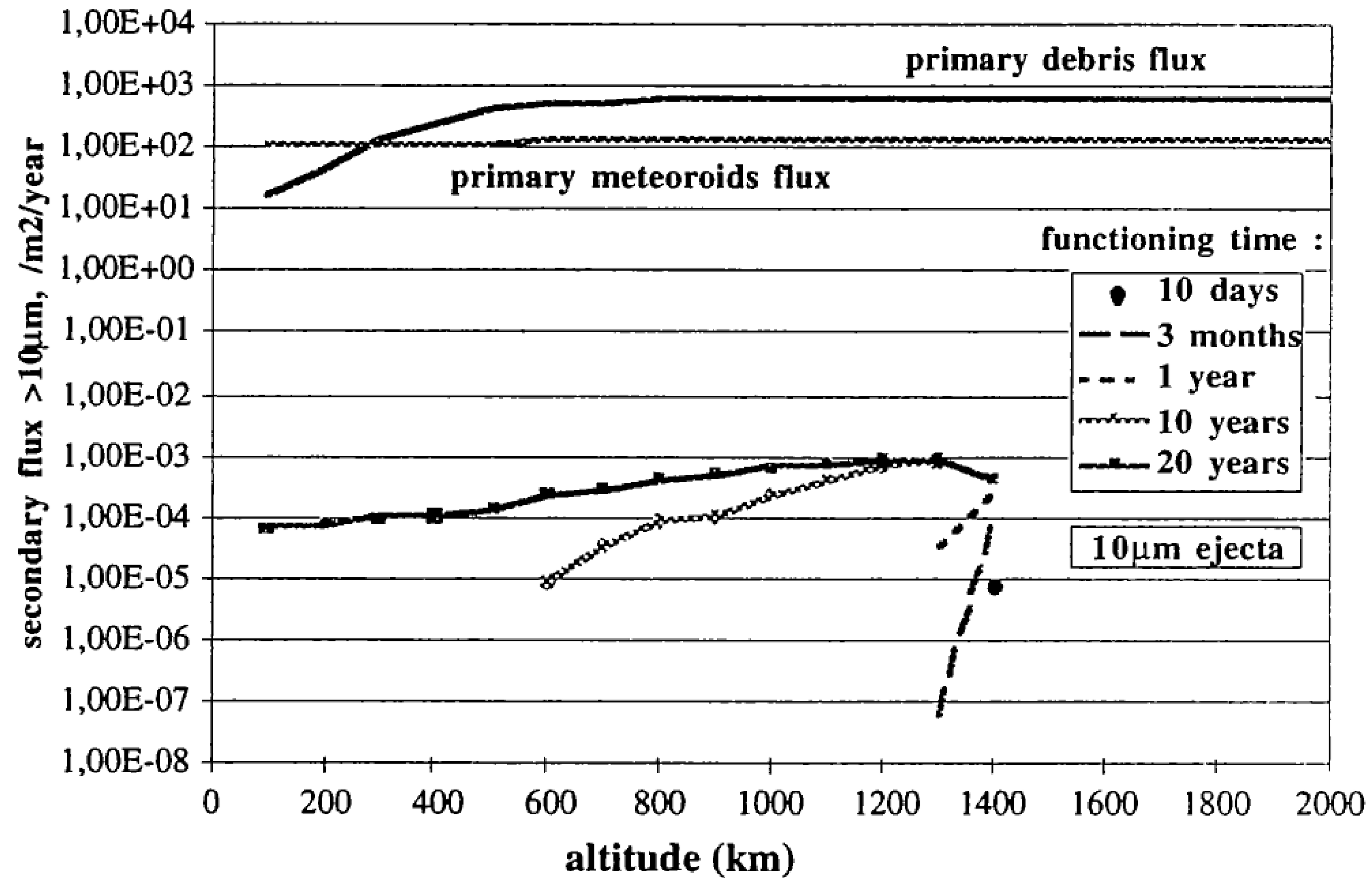

Fig. 7 : Secondary flux of particles larger than 10µm produced by the solar arrays of a satellite from Globalstar, at altitudes lower than 1400km, for mission duration from 10 days to 20 years.