A MODELLING OF EJECTA AS A SPACE DEBRIS SOURCE

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ABSTRACT

When a micro-debris or a micrometeoroid impacts a spacecraft surface, secondary particles, called ejecta, are produced. These ejecta can contributes to a modification of the debris environment : either locally by the occurrence of secondary impacts on the components of complex and large space structures, or at great distances by the formation of a population of small orbital debris.

This paper describes, firstly, the ejecta production, and secondly, their lifetime and orbit propagation. Then, the repartition of ejecta in LEO is given. Results describing the ejecta number as a function of size and altitude are presented.

1. INTRODUCTION

Most current orbital debris models (with the exception of MASTER 99) do not take into account secondary fragments produced upon impact of high velocity particles on spacecrafts. The purpose of this paper is to present the mechanism of production and some results concerning the distribution of the ejecta in orbit.

Main sources of micro-debris identified until now are :

- small fragments of spacecraft break-up (with a size from 200 µm to 1 cm)
- Na/K droplets (leaks of Russian satellites Rorsat, 200 µm to 1 cm)
- paint fragments and degradation products of spacecraft (from 5 to 200 µm)
- propulsion residues (Al_2O_3 particles, size < 20 µm and from 5 mm to 3 cm)
- secondary particles called ejecta (from 1 µm to 5 mm)

These last particles are produced when a micro-debris or a micrometeorite impacts a spacecraft surface. Then, ejecta become an integral part of the space environment.

To compute the action of ejecta as a space debris source, the method described in the Fig. 1 is used.

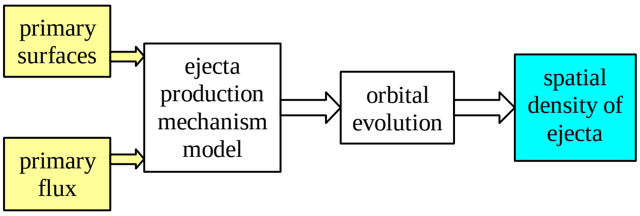

Fig. 1 : Computation of the contribution of ejecta at the space debris environment

For each orbit, the surface of solar arrays and painted surfaces is estimated, and the primary flux received by these surfaces is computed.

It is assumed that the meteorites impact these surfaces with a velocity of 15 km/s and the debris (that are taken into account only for low earth orbits) hit the target with a speed of 10 km/s. As it is considered that the direction of impact and the orientation of primary surface is random, it is supposed that the particles are ejected with a random angle. The argument of perigee (except for the orbit of the Molniya satellites), the right ascension of ascending node and the mean anomaly are assumed to be random. For each orbit, 400 representatives particles are considered.

Then, for each representative particle, its orbital evolution is computed. It is assumed that the number of the primary surfaces increases at a rate of 2% a year.

2. SURFACE DEGRADATION

When a micrometeoroid or a micro-debris impacts the surface of a spacecraft, secondary particles, called ejecta, are usually produced. The ejected mass is about 100 times higher on brittle target because there is no plastic deformation and fracture energy is lower.

Three ejection processes can be identified :

- jetting : small and fast liquid particles ejected at grazing angles, representing less than 1 % of the total ejected mass.
- cone : small and fast particles ejected at constant elevation angle and with a revolution symmetry for

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a normal impact. The elevation angle is about 60° for a normal impact and is scattered on a few degrees.

- spall fragments : large fragments ejected at low velocity in a direction perpendicular to the target. The mass ejected through this process increases with projectile size and can reach 90 % for mm-sized impacts on solar cells. For a ductile target, there is no spall fragments.

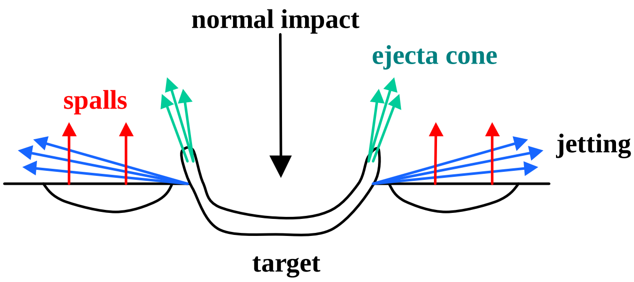

Fig. 2 : Ejecta production mechanism on a brittle target

The materials that produce the greatest amount of ejecta upon an hypervelocity impact, are brittle surfaces and especially multilayer targets. The brittle materials currently in orbit are mainly solar arrays and painted surfaces (thermal control coating of satellites, antistatic paint used on rocket bodies). The ejecta model previously developed at ONERA/DESP [1] has been improved and extended to the case of painted surfaces [2].

The total ejected mass (in SI units) is given by [3] :

$$M_e = K\,7.41 \cdot 10^{-6} \sqrt{\frac{\rho_p}{\rho_t}}\, E_i^{1.133} \left(\cos\theta_i\right)^2 \qquad (1)$$

with : E_i : impact kinetic energy

r_p : projectile density

r_t : target density

q_i : impact incidence angle (from normal direction). $q_i < 60°$

K : depends on the target material and on the incident particle size. It is equal to 1 for a projectile with a diameter larger than 10 µm impacting a brittle target.

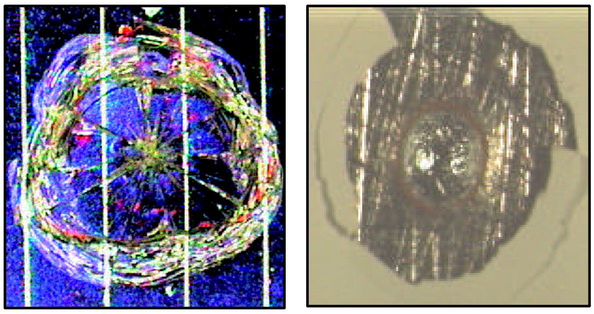

Fig. 3 : Impact on a solar cell and on a painted surface

The size of cone fragments ejected from brittle surfaces varies between 0.1 µm and about the projectile size. The smallest particles are ejected with a velocity close to the impact velocity, and the largest particles are ejected with a velocity comprised between 10 and 100 m/s. Spall fragments which are about 20 for each impact, are also ejected with a velocity between 10 and 100 m/s.

For an impact on a painted surface, the model assumes that the incident kinetic energy is split in two parts. One produces the crater into the paint layer, and the other part creates the crater in the substrate. The paint fragments are quite large and ejected with a low velocity [2].

3. EXPOSED SURFACES EVALUATION

By an extensive use of the database DISCOS, satellites and rocket bodies currently in orbit have been identified, as well as their orbital parameters, their shape and size, whenever information was available. Determination of solar array and painted surfaces area has been additionally performed with a search of current printed sources [4, 5, 6].

The area of solar arrays is computed taking into account both sides of the panels. The entire surface of rocket bodies and 10 % of the area of the satellites are assumed to be painted.

The solar arrays surfaces in orbit is estimated at about 43 000 m² and the painted surfaces at about 63 000 m². 95 % of these painted surfaces are situated on the rocket bodies.

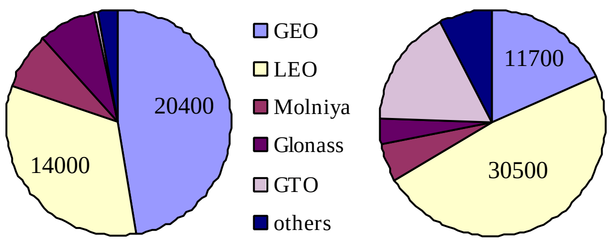

Fig. 4 : Solar arrays and painted surfaces repartition

In LEO, there are about 14 000 m² of solar arrays and 30 500 m² of painted surfaces. 65% of these surfaces have their inclination comprised between 73° and 91°.

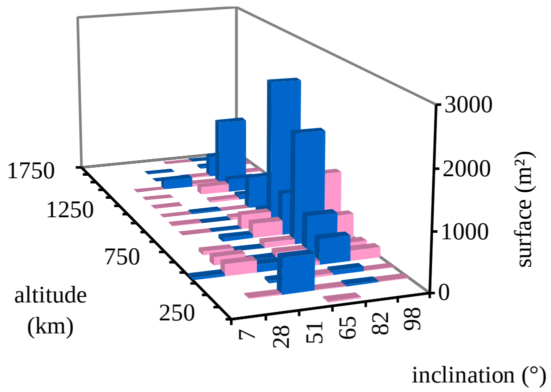

Fig. 5 : Solar arrays repartition in LEO

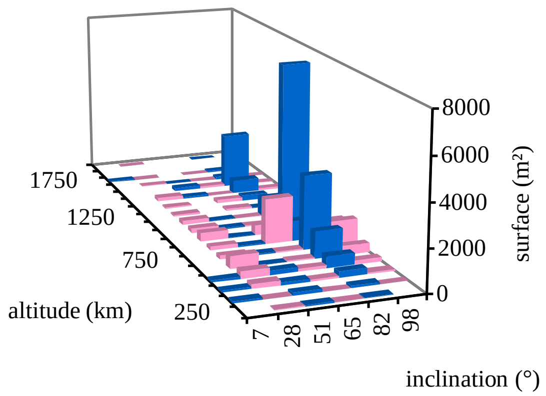

Fig. 6 : Paint surfaces repartition in LEO

4. ORBITAL EVOLUTION

Cone particles are ejected with a high velocity, so their initial orbit is very different from the one of the parent object and some particles (about 23%) are ejected on a re-entering or a hyperbolic trajectory. On the other hand, spall particles (and paint particles) are ejected with low velocity and their initial orbit is close to the parent body.

The perturbing forces applying on a particle in orbit, in addition of the central gravitation, are : moon gravity, solar gravity, atmospheric drag, solar radiation pressure, electromagnetic forces, the force exerted by the flattening of the Earth (J_2 term) and the non-spherical terms in the Earth's gravitational field.

In LEO, the dominant perturbing forces on a micro-particle are atmospheric drag, solar radiation pressure and the force exerted by the flattening of the Earth. In HEO, the main perturbing forces are the same minus the atmospheric drag [7].

Using a simplified, semi-analytic model of orbital evolution, the lifetime of micro-particle has been computed.

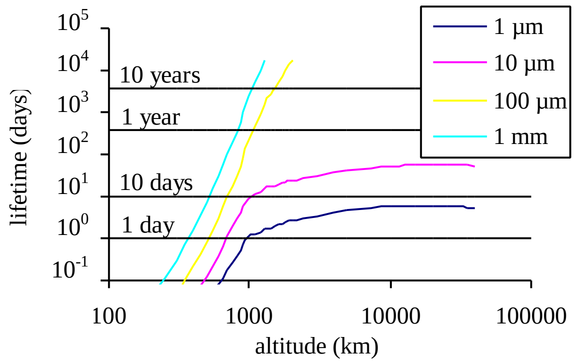

Fig. 7 : Lifetime of debris in orbit (in days) as a function of their size and their initial altitude

Fig. 7 represents the lifetime calculated for a particle initially in circular orbit with a low inclination. Debris with a size smaller than 10 µm re-enter into the atmosphere quickly (in less than a year) whatever the initial orbit because of the solar radiation pressure. Indeed, solar radiation pressure, which is proportional to the ratio surface to mass, induces an augmentation of the eccentricity, and the perigee decreases until the atmospheric re-entry. On the other hand, particles larger than 100 µm can stay in orbit for a long time. Therefore, there is an accumulation of large particles on their orbit of ejection.

5. SPATIAL DENSITY

Ejecta with a size smaller than 10 µm stay in orbit during a short time, but as they are produced in a large number and quasi continuously, they are the most numerous.

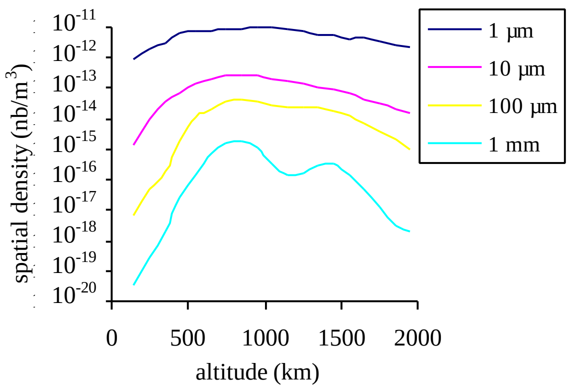

Fig. 8 : Spatial density of ejecta in LEO

The spatial density of ejecta is maximal between 800 km and 1400 km of altitude. Under these altitudes, the spatial density decreases because of the increase of the atmospheric drag. Above, the spatial density diminishes, because primary surfaces are less numerous. The decreasing of spatial density at high altitudes of small particles is less important, because the ejection velocity disperses the initial orbits. The number of ejecta, in the millimetre size range, reaches 5 % of the total debris density at 800 km of altitude.

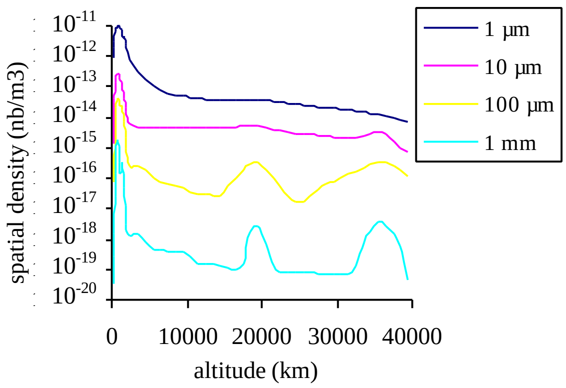

Fig. 9 : Spatial density of ejecta in all orbits

The spatial density of ejecta is maximal in LEO, at the altitude of navigation satellites (Glonass and GPS) and at geostationary altitude. The number of ejecta, in the millimetre size range, represents about 1% of the total number of debris in GEO.

6. FLUX OF EJECTA

The ejecta number as a function of size, altitude and inclination is computed and approximated by functional forms. As in the ORDEM 96 model [8], this model approximates the ejecta environment by a limited number of representative orbits : six inclination bands and two eccentricity families. It is assumed that the ejecta produced from LEO space vehicles have a circular orbit, and that the ejecta produced from HEO spacecraft, that have their perigee at low altitude, have an highly elliptical orbit with their apogee fixed at 20 000 km altitude.

The number of ejecta in circular orbit is maximum at 65°, 82° and 98° inclination bands (cf. Fig. 10 and Fig. 11) (almost 80 % of the ejecta in circular orbits have their inclination included between 73° and 91°). Concerning the ejecta in elliptical orbits, they are mainly located at 7°, 28° and 65° inclination bands.

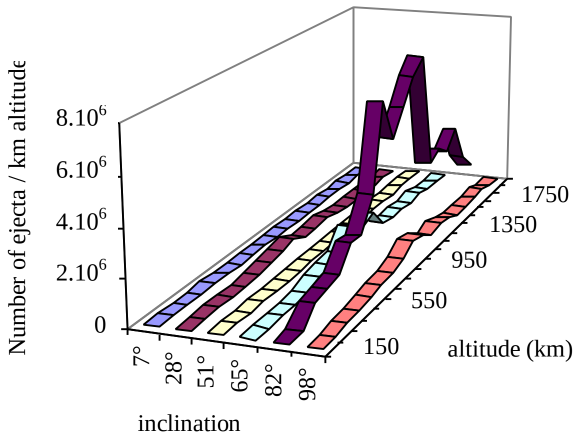

Fig. 10 : Number of ejecta in LEO with a size larger than 1 µm as a function of altitude and inclination

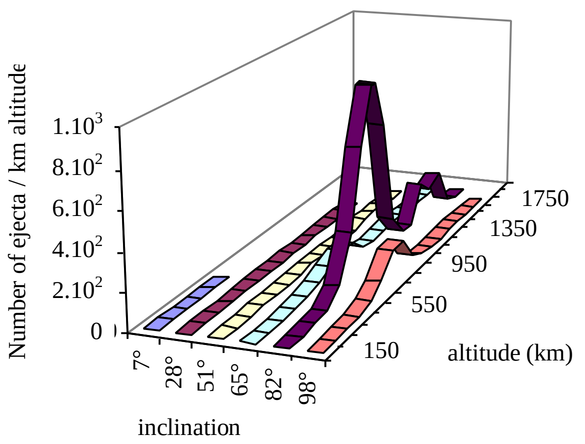

Fig. 11 : Number of ejecta in LEO with a size larger than 1 mm as a function of altitude and inclination

The functional forms used to represent the number of ejecta, as a function of size and altitude, result from fitting the results of computation. The altitude distributions of ejecta vary with the particle size and the two variables can not be separated. Therefore, the functional forms used in this model are more complicated than those used in the ORDEM 96 model. For circular orbit, functional forms use 26 parameters for each inclination band. For elliptical orbit, there are 18 parameters.

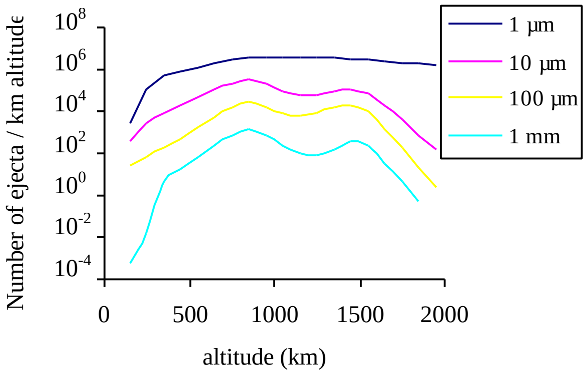

Fig. 12 : Number of ejecta (functional forms) in circular orbit in the 82° inclination band as a function of altitude and particle size

Using the collision probability equations given by Kessler [8], the flux of ejecta on a given orbit can be computed. As examples, the flux computed on ISS, Spot and Globalstar orbits are presented and compared with the total debris flux given by the model ORDEM 96.

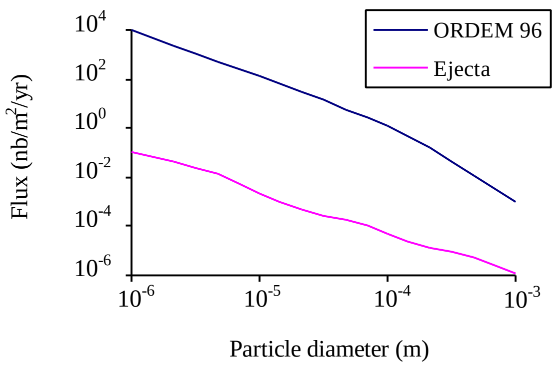

Fig. 13 : Comparison of the ejecta flux and the total debris flux (ORDEM 96) on ISS orbit on a non-oriented surface

On ISS orbit (altitude : 360 km, inclination : 51.6) (Fig. 13), the ratio of the ejecta flux by the total debris flux varies from 10^{-5} (for µm-sized particles) to 10^{-3} (for mm-sized debris).

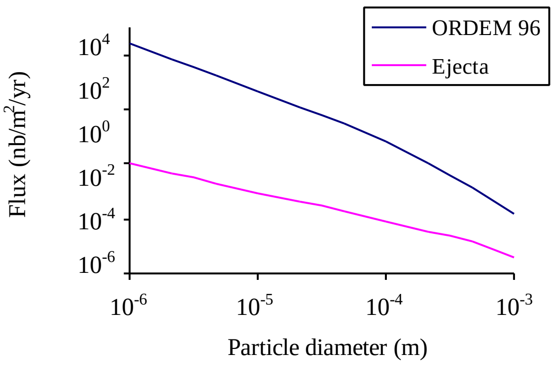

Fig. 14 : Comparison of the ejecta flux and the total debris flux (ORDEM 96) on Spot orbit on a non-oriented surface

On Spot orbit (altitude : 825 km, inclination : 98.7) (Fig. 14), the flux of ejecta, in the millimetre size range, reaches 2 % of the total debris flux given by the model ORDEM 96.

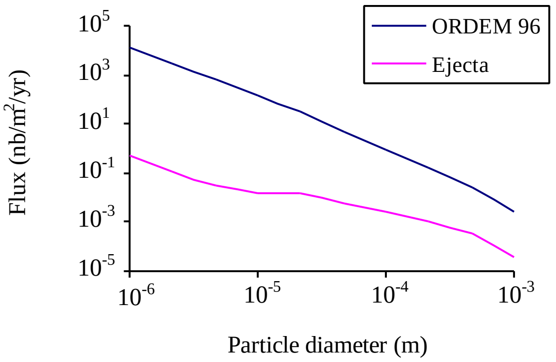

Fig. 15 : Comparison of the ejecta flux and the total debris flux (ORDEM 96) on Globalstar orbit on a non-oriented surface

On Globalstar orbit (altitude : 1414 km, inclination : 52°) (Fig. 15), the flux of ejecta represents about 1.5 % of the total debris flux for the debris with a size larger than 0.5 mm.

7. CONCLUSIONS

This study shows that the number of ejecta is indeed smaller than the total number of debris. In 2000, the ejecta flux reaches about 3 %, in the millimetre size range, of the total debris flux, at 800 km altitude, and 1 % at 1500 km altitude. For GEO, the spatial density of ejecta represents about 1 % of the spatial density of debris given by MASTER 99, in the millimetre size range. Now, the lifetime of a millimetre size object is longer than 100 years for altitudes higher than 1500 km. Therefore, the larger ejecta will continue to accumulate at high altitudes and this population is likely to increase in the long term.

8. REFERENCES

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