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A systematic study of laser ablation for space debris mitigation

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ABSTRACT

The increase in the number of artificial objects in orbit around the Earth represents a serious threat to the future utilization of space. The scope and nature of the problem require an international effort. The Trento Institute of Fundamental Physics and Applications (TIFPA) participates in a study of laser ablation for space applications, propulsion and space debris mitigation, in the context of the New Reflections program initiated by the Italian Institute of Nuclear Physics (INFN). An evaluation of the performance of laser ablation for debris removal in Low Earth Orbit (LEO), for different scenarios of ground and space-based lasers is presented. The ultimate aim is to provide a performance evaluation of the technology over the wide range of debris parameters, for both space-based and ground systems.

Introduction

The likelihood that the increase of the number of objects launched in space results in an artificial debris belt around the Earth was pointed out by D.J. Kessler and B.G. Cour- Palais in 1978 [1]. The authors developed a model to predict the evolution of the debris population created by satellite collisions based on the available inventory of artificial objects in orbit around the Earth (size, speed, orbit). The process of mutual collisions is similar to the mechanism responsible for the creation of asteroids from larger planet-like bodies. While the time scale of the latter is of the order of billions of years, the much smaller volume occupied by the satellites results in a significantly shorter time scale.

The *Kessler Syndrome*, the cascade in the number of collisions rendering the exploitation of space unfeasible for future generations, has led to a large consensus among national space agencies on the importance of the problem [2].

The number of tracked objects, which exceeds 19,000, form two distinct populations: a ring in geostationary orbit (GEO) and a cloud in LEO (Fig. 1). The information is used by NASA to defined collision avoidance processes for all human space flight missions and for maneuverable robotic satellites in LEO, and within 200 km of GEO [4].

The satellites and debris in orbit around the Earth are subject to the frictional force of the atmosphere and the pressure due to solar activity. *A priori* the objects in LEO will eventually deorbit due to these natural effects. One of approaches in active debris removal is to search for technological solutions which would shorten significantly the orbital lifetime of the debris.

Orbital mechanics

The impulse, applied in the direction opposite (parallel) to the orbital velocity, required to lower (raise) a object in a circular orbit is given by the Hohmann transfer. The momentum change is defined by the difference between the original orbital velocity, and the velocity at the perigee (apogee) of the elliptical transfer orbit tangent to the circle of the lower (higher) altitude orbit (Appendix, Fig. 23). The expression for the momentum change required to displace a mass m in an circular orbit of radius R_1 to an orbit radius $R_2 < R_1$ is

$$m\Delta\upsilon = MG\cdot\left(\sqrt{\frac{1}{R_1}} - \sqrt{2\frac{R_2/R_1}{R_1+R_2}}\right) \quad (1)$$

where M is the mass of the Earth and G is the gravitational constant.

The impulse required to lower the altitude of the satellite R_1 to R_2 equal to the Earth's radius[1] $R_{E,}$ and $R_E + 150$ km are shown

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[1] Mean equatorial radius 6378 km.

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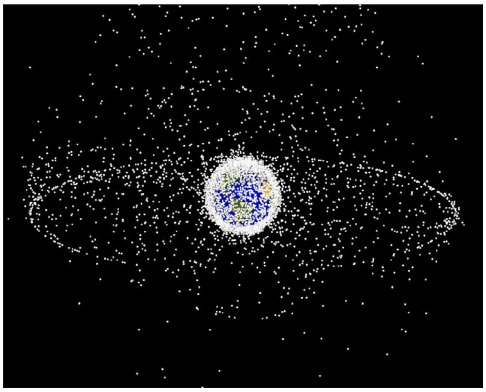

Fig. 1. The principal space debris populations include a ring of objects in GEO and a cloud of objects in LEO [3].

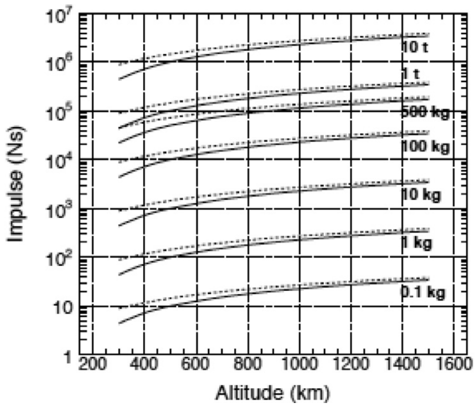

Fig. 2. The impulse required to lower a given mass to a final orbital altitude of 150 km (solid lines) and to the Earth's surface (dashed lines).

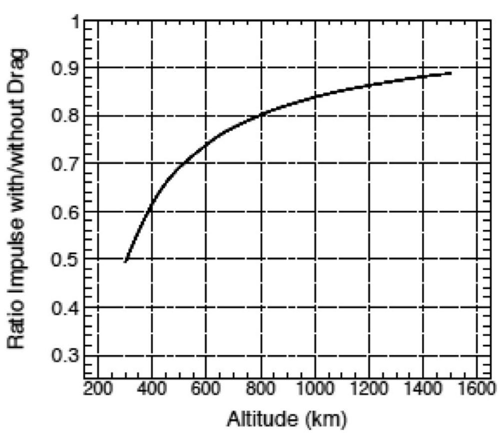

Fig 3. The ratio of the impulse required to deorbit the debris mass with and without the presence of the atmosphere.

in Fig. 2. The latter represents an altitude where the effect of atmospheric drag will deorbit the mass. The ratio of the impulse with and without atmospheric drag, i.e. the ratio of the impulses required to lower the mass to an altitude of 150 km and to the Earth's surface, are shown in Fig. 3.

Effect of the impulse direction

The Geant4 [5] application PLANETOCOSMICS was used to quantify the effect of the direction of the applied impulse. PLANETOCOSMICS performs a detailed simulation of the propagation and interaction of elementary particles in the Earth's magnetic field and atmosphere. The Earth's gravitational field was added to the program. Figs. 4 and 5 show the orbits of a 500 kg point mass which is placed at an altitude of 600 km, with the velocities of 10.0 and 7.6 km/s.

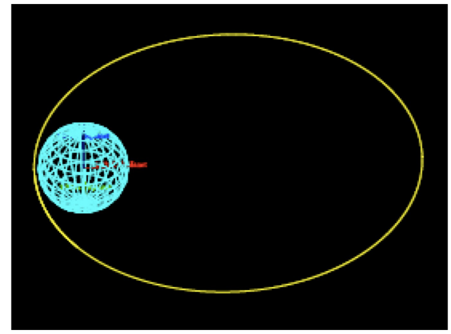

Fig. 4. The elliptical orbit in the Geant4 simulation of the 500 kg mass with a velocity of 10.0 km/s. The trajectory corresponds to 13 h, the period of an elliptical orbit with a semi-major axis equal to ~4 Earth radi.

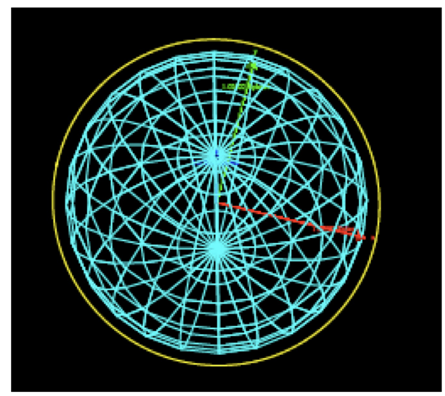

Fig. 5. The circular orbit at an altitude of 600 km of a 500 kg mass with a velocity of 7.6 km/s. The trajectory corresponds 97 min, the period of the circular orbit.

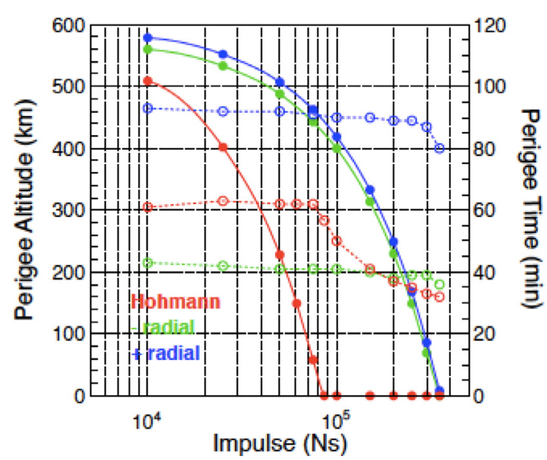

Fig. 6. The change in the perigee altitude (•) for three different impulse directions, opposite to the orbital velocity of the 500 kg mass (Hohmann), towards the center of the Earth (negative radial) and the local zenith (positive radial), are indicated on the vertical axis on the left, the time required to attain the perigee (◦) on the vertical axis on the right.

The change of the perigee altitude produced by an impulse applied in the direction opposite to the orbital velocity, and in the directions along and opposite to the vector drawn from the Earth's center to the debris position at the 600 km altitude in Fig. 5, are shown in Fig. 6. The simulated time is 97 min, corresponding to the period of the initial circular orbit of the 500 kg mass. The impulse is applied 16.7 min after the start of the simulation. The effect of atmospheric drag is absent.