SPACE JUNK: THE RISK OF SPACE MISSIONS AND THE PROPOSAL OF SOLAR SAIL TECHNOLOGY TO MITIGATE THE PROBLEM

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Abstract: Space debris are all objects created by man that are in Earth orbit but that do not perform any function, being a problem for polluting the extraterrestrial environment, bringing risks to satellites and operational ships. Solar sail technology, which uses the Sun as a sustainable energy source, is a strong tool for removing objects from space located in low Earth orbit (LEO), which is currently the most congested. To validate the use of the solar sail as a space debris mitigation method, we performed numerical simulations of the orbital motion to prove the decay of the perigee radius (r_p) over the years. Based on current technological parameters, we note, therefore, that the solar sail is efficient in this function.

Keywords: Solar sail; Space debris; Sustainability; Low earth orbit

LIXO ESPACIAL: O RISCO AS MISSÕES ESPACIAIS E A PROPOSTA DA TECNOLOGIA DE VELA SOLAR PARA MITIGAR O PROBLEMA

Resumo: Detritos espaciais são todos os objetos criados pelo homem e que estão em órbita da Terra mas que não desempenham função alguma, sendo um problema por poluir o meio ambiente extraterrestre trazendo riscos a satélites e naves operacionais. A tecnologia de vela solar, que usa o Sol como fonte energética sustentável, é uma forte ferramenta para remover objetos do espaço situados em órbita baixa terrestre (LEO), que atualmente é a região mais congestionada. Para validar o uso da vela solar como método mitigatório do lixo espacial, apresentamos as simulações numéricas do movimento orbital para comprovar o decaimento do raio do perigeu (r_p) ao longo dos anos. Com base nos parâmetros tecnológicos atuais, constatamos, portanto, que a vela solar é eficiente nessa função.

Palavras-chave: Vela solar; Detrito espacial; Sustentabilidade; Órbita baixa terrestre

1. INTRODUCTION

Space exploration began with Sputnik 1, in 1957, launched by the former USSR, then Explorer 1 sent into space by the USA (then creating NASA), the Ranger program and among many others. These missions at first sight were concerned with new explorations of unknown places, but they did not pay attention to what their consequences would cause to the space environment, leaving several objects in space. Space debris (space junk) are all objects created by man and that are in Earth orbit but that do not perform any function, being a problem for polluting the extraterrestrial environment, bringing risks to satellites and operational ships.

1.1 Space junk in LEO

According to [1], there is a serious problem in the space environment due to the accumulation of space debris that has been proliferating as more objects are discarded in space missions, and by the fragmentation events in orbit caused by collisions and explosions in space. In [1] it is also reported that in the year 2021, more than 30,000 objects larger than 10 cm in Earth orbit were cataloged, in which it is estimated a population of millions of objects with smaller size in space.

The big factor that characterizes space junk as problematic, in addition to the amount of expression, are the peculiarities if compared to the other types of objects also characterized as garbage. The space junk in low earth orbit (LEO), for example, tend to have a greater speed of translation and shorter periods than in other orbits, due to being closer to Earth suffering greater influence of the gravitational field and therefore requiring a larger tangential velocity of revolution corresponding to the centripetal acceleration. Consequently, according to [2], it is recorded that debris in this type of orbit can reach a speed 7 times greater than of a projectile of pistol, reaching up to 27,000 km/h. In future missions, space conditions, accidental and catastrophic problems may arise if objects of these speed orders collide with ships, satellites or stations. Because of this, an exacerbated congestion of future space debris in LEO would be worrying, as it would make new safe launches difficult and the likely impracticability of using the space environment.

According to [2-5], another alarming problem with space debris is related to the duration of "life" in Earth orbit. In GEO (geostationary orbit), which is of utmost importance due to the amount of existing active satellites located in its surroundings, the altitude favorable and synchronization with Earth's rotation, space debris can remain in orbit for hundreds of years at risk of collision and overfilling of the orbit due to the almost non-existent evasion of this debris. The same goes for debris in LEO for perigee altitudes above 500 km where there is no effect of atmospheric drag, as [2-4], which in turn are also more susceptible to the unpredictability of the trajectory, causing more collision risks, due to the greater range of geopotential effects (EGT) due to the low altitudes.

LEO's congestion makes it stand out against a worrying scenario, given that it is located right after the planet leaves for space and gives access to the other orbits. However, it is stated in [6] that it is currently characterized as the Earth's orbit more congested in that among all the space objects cataloged up to the 40 thousand km of altitude, 75% are in LEO. Not only is the huge growth in the amount of space junk, the number of launches each year and the ability of rockets to carry more and more satellites as well makes orbits more congested, in terms of satellite and spacecraft traffic. As reported [1], since 2015 space traffic has intensified in LEO, which is being constantly fueled by the miniaturization of space systems and the deployment of large constellations, as in the case of the constellations of the Starlink project.

There is space debris whose trajectory is eccentric, which has irregular displacement, being able to move between the other orbits causing greater probabilities of collisions. This behavior in LEO is a major risk to the space environment, as it is an already congested region and collisions can significantly increase the debris population, as already occurred in 2009 when the Russian satellite Cosmos-2251, launched in 1993 and at the time deactivated, collided with the American communications satellite Iridium 33. As comment in [2], the accident occurred at an altitude of 790 km, over northeast Siberia, creating a gigantic cloud of debris, estimated after impact to be a cloud of more than 1600 new debris, bringing dangers to satellites in LEO and disabling the coordinates of the orbit where the accident occurred, where few have an estimate of re-entry into the atmosphere in the next 30 years after the collision.

According to [1], since 1957 more than 560 events have been confirmed of in-orbit fragmentation, with an average of 2.6 non-deliberate fragmentations occurring per year over the past two decades. This returns to the undesired scenario of the possibility of the beginning of the emergence of Kessler syndrome, in which chain collisions can nullify any space mission project and make the space calamity almost irreversible. So, in an extrapolation of the cumulative amount of catastrophic collisions in space (collisions with great capacity to generate fragments) following the current behavior for the future prediction, made by [1], it is indicated that by the year 2100 it may already have occurred a total of more than 200 collisions of this type.

1.3 Solar sail technology

Taking into account the importance of space exploration, the perpetuation of the practice needs to be thought of in the long term, taking sustainable parameters that guarantee the future of space missions. An effective method to enable the sustainability of future missions spacecraft is the use of solar sail technology, attached to a device to each object that has potential to be dropped into space. Beyond In addition, the technology can also be used for the removal of debris that is already in space with coupling by sailing devices such as CubeSats, by means of mechanical arms or harpoons, as shown in [7] in the 2017 RemoveDebris mission, in which after the opening of the candle in LEO, the CusbeSat back to Earth in a few weeks. On re-entry, most of the debris spacecraft burn in high-velocity friction with the atmospheric fluids, showing the use of this effective concept for space junk disposal from complete form.

The use of solar sails in space is similar to the use of sails on terrestrial sailing vessels, however their motion is related to the increased effect of solar radiation pressure (SRP). According to [5,7,8], for the solar sail to maximize its functionality, it is taken into account that the reflectance will cause the SRP effect to be maximum on the surface of the sail and, therefore, the greater the area/mass coefficient in the system of the body attached to the sail, the greater the effectiveness of the acceleration that this system can provide, cleaning space debris in shorter measures of time. The solar sail, in addition to enhancing the ability of the SRP to increase the eccentricity of the orbit, as predicted [5], is also capable of acting as a drag sail by increasing the frictional contact with the atmosphere at lower altitudes, losing tangential velocity of rotation and re-entering more quickly.With the advancement of technology today, it is very common to send small satellites in low Earth orbit, the Cubesats. Like the constellation of satellites from the company SpaceX. In this case, these small satellites can be sent into space with a built-in drag sail so that at the end of its useful life it is opened to increase friction with the Earth's atmosphere to be incinerated.

Since the accumulation of space debris endangers the future of space exploration, the main objective of this work is to investigate the effectiveness of using solar sails, a technology which has as an abundant and sustainable energy matrix the Sun itself. Numerical simulations are the main tools to predict the behavior of the sail-debris system, as it is essential to observe the effects that this system can have on orbital evolution. The adopted parameter in the A/m coefficients, it takes into account what current technology can provide as the main example of LightSail 2, which according to [7] had a coefficient of almost 7 m^2/kg.

2. METHODOLOGY

The data collected on the orbital parameters of the debris such as eccentricity (e), inclination (i), semimajor axis (a), longitude of the ascending node (Ω) and perigee argument (ω), as well as orbital velocities and periods, were extracted from the online website https://www.privateer.com/. The site simulates real-time projection and scans most of the bodies in orbit, classifying and subdividing them into active satellites, satellites inactive, rocket bodies, debris and uncategorized.

The numerical simulations for plotting graphs that take time (t) as an independent variable via integration numeric (Runge Kutta 4), were made in the software Maple. The motion equations were integrated via Lagrange planetary equations, Equation 1, 2, 3 and 4, which are a system of nonlinear differential equations in Keplerian terms (orbital elements) that describe the motion of bodies orbiting a central body (in this case Earth). In [8], the Lagrange planetary equations restricted to the models are

$$\frac{de}{dt} = \frac{-\sqrt{1-e^2}}{n\,a^2 e}\,\frac{\partial R}{\partial \omega} + \frac{1-e^2}{n\,a^2 e}\,\frac{\partial R}{\partial M}, \quad (1)$$

$$\frac{di}{dt} = \frac{-1}{n\,a^2\sqrt{1-e^2}\,sen(i)}\,\frac{\partial R}{\partial \Omega} + \frac{cos(i)}{n\,a^2\sqrt{1-e^2}\,sen(i)}\,\frac{\partial R}{\partial \omega}, \quad (2)$$

$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{n\,a^2 e}\,\frac{\partial R}{\partial e} - \frac{cos(i)}{n\,a^2\sqrt{1-e^2}\,sen(i)}\,\frac{\partial R}{\partial i}, \quad (3)$$

$$\frac{de}{dt} = \frac{-\sqrt{1-e^2}}{n\,a^2 e}\,\frac{\partial R}{\partial \omega} + \frac{1-e^2}{n\,a^2 e}\,\frac{\partial R}{\partial M}. \quad (4)$$

Where M is the average anomaly and R is the perturbing function given in [5], modeled to orbital parameters considering elliptical and inclined orbits, and with reduced degree of freedom, where is the sum of the main forces that perturb the orbital motion of the debris-sail system, represented as

$$R = R_{EGT} + R_{SRP} + R_{PTC}. \tag{5}$$

Where R_{EGT} is the effect due to deformation and mass non-uniformity of the Earth, R_{PTC} is the effect of the gravitational interaction of the Moon and the Sun, and R_{SRP} is the solar radiation pressure caused by the transfer of momentum of light falling on a surface.

In Maple, line graph simulations lasted around 5 hours for plotting individually, using a single GPU capable of 2.3 GHz average processing time over four independent cores (AMD Ryzen 7 3700U). For numerical simulations, values such as mass, equatorial radius, zonal coefficients and mean radius of the Earth, made available by the online platform of NASA "Jet Propulsion Laboratory".

3. RESULTS AND DISCUSSION

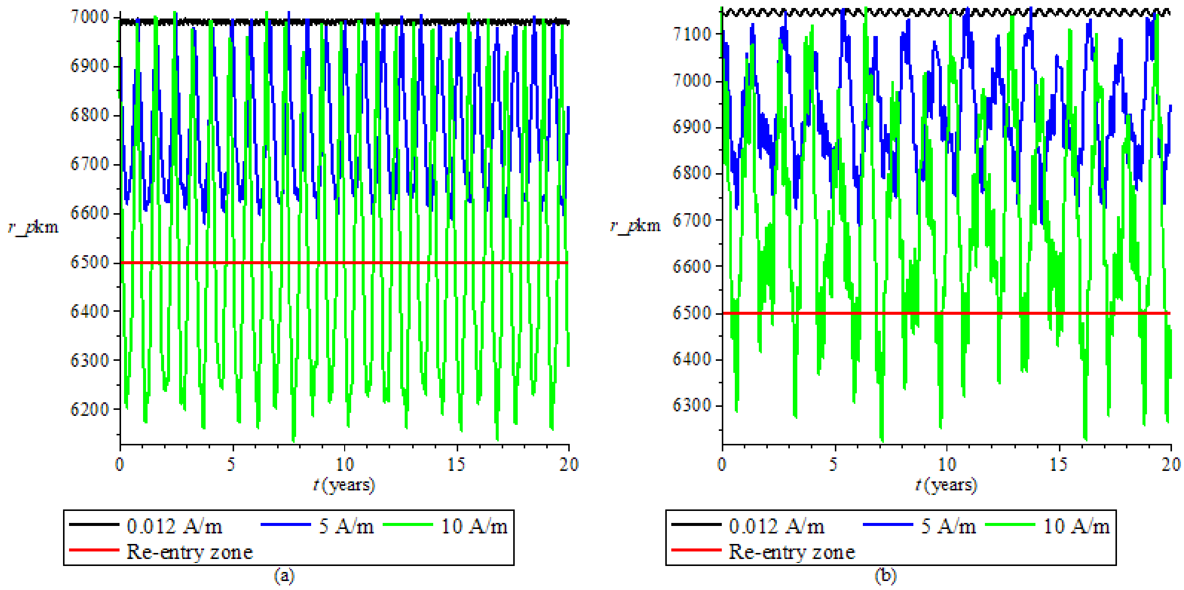
To perform numerical simulations, debris located in LEO with initial conditions and identification were used checked in Table 1

Table 1. Initial conditions of space debris

Space debris	COSMOS 2112	ORBCOMM FM111	GLOBALSTAR M001	SL-8 R/B
ID	**21014**	**40089**	**25162**	**5730**
Altitude	**772,4514 km**	**614,6371 km**	**1.510,2859 km**	**386,0319 km**
a	**7.164,2 km**	**7.018,5 km**	**7.897,9 km**	**7.240,6 km**
e	**0,0019**	**0,0034**	**0,0012**	**0,0658**
i	**74,1803º**	**47,1477º**	**52,0679º**	**74,0272º**
ω	**201,9241º**	**313,6443º**	**129,8721º**	**318,4871º**
Ω	**76,6367º**	**75,4739º**	**24,1519º**	**117,8565º**

We take the re-entry of the debris at an altitude of perigee radius (*r_p)* less than the Earth radius altitude, approximately 6380 km from the center of the Earth to the surface, plus 120 km where the atmosphere is denser. So it is admitted that below 6500 km of altitude, where the friction with the atmosphere makes re-entry imminent, according to [3-5], taking this region as the re-entry zone, represented by the lines red in the *r_p* evolution graphs over 20 years, in the same way as it was admitted in [5]. All the initial conditions of the simulated debris, in Table 1, are substituted in the disturbing potential and in the equations of orbital motion. The lines in black, blue and green represent the evolutions for each sail size given by coefficients A/m, in units of m^2/kg.

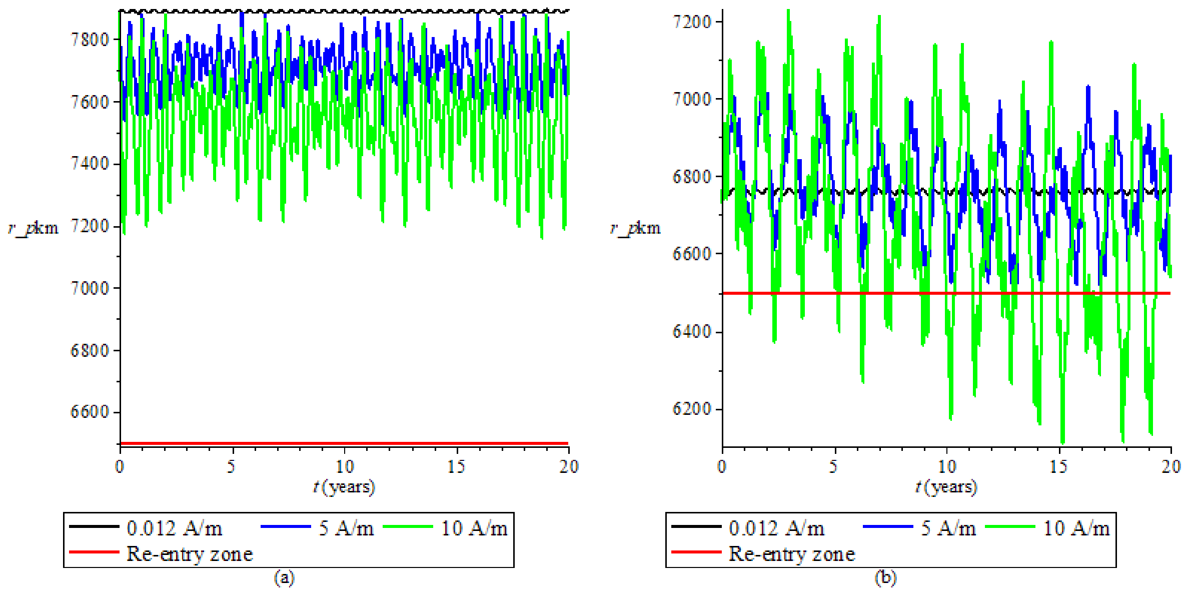
Figure 1. A/m in m^2/kg. $r\_p\ x\ t$ (20 years). (a) ORBCOMM FM111, (b) COSMOS 2112



It can be seen in Figure 1a and Figure 1b that the motion becomes more disturbed as the SRP effect increases with sail growth, with larger amplitudes for 10 m^2/kg (green line). According to [5], the average coefficient of A/m for a space debris without the expansion of its area by a sail, is 0.012 m^2/kg (black line). Therefore, it is observed that even considering all the perturbations, the debris analyzed naturally in 20 years does not tend to be removed from space, an observation that goes against the assertion that a debris can remain hundreds of years in orbit, characterizing this one of the problematic conditions of the theme, as expected [1]. When A/m = 5 m^2/kg , in both cases the debris already has a much more flagrant evolution, and when A/m = 10 m^2/kg, the debris in Figure 1b already undergoes re-entry very quickly in a period close to 6 months and the debris in Figure 1a, even faster. In this work, the proposal to use technology for mitigating debris in LEO is affirmative, since it is proven from simulations of orbital evolution in Figure 1, that a sail of 10 m^2/kg is already capable of achieving the sustainable objectives of mitigating space junk and promoting greater safety in the space environment.

According to [3,4], zones where the *r_p* of an orbit has an altitude lower than 500 km above the Earth's surface, the disturbing effect of atmospheric drag is highlighted and makes the object re-enter the atmosphere in an average period of 30 years. As in this work this disturbing effect was not considered in Equation 4, it can be assumed that with this effect, the debris in Figure 1 coupled to a solar sail with 5 m^2/kg would already be removed from space, even if in a long period of time. These results, therefore, demonstrate the effectiveness of the solar sail for the rapid and sustainable removal of space debris. The technology, therefore, can be adopted for use on objects that would otherwise be discarded in space, and as an adjunct to methods of removing objects that are already in space and are likely to remain in that state for hundreds of years.

Figure 2. A/m in m^2/kg. $r\_p \; x \; t$ (20 years). (a) GLOBALSTAR M001 , (b) SL-8 R/B



In [5] it is reported that at higher altitudes such as in the GEO region, it would be necessary to use solar sails with coefficients of A/m greater than 20 m^2/kg. As a counterpoint to the simulated debris in Figure 1, which are at an altitude of 600-800 km, the simulated debris in Figure 2a at an altitude higher than 1500 km does not lose sufficient *r_p* altitude to re-enter the atmosphere, even if over 20 years with a sail of 10 m^2/kg. This result demonstrates that for higher altitudes, even in LEO, better solar sail construction parameters are still needed to mitigate space debris. Its counterpart in Figure 2b, a 386.0319 km debris that re-enters naturally over time due to atmospheric drag, demonstrates a decaying behavior of *r_p* with a 10 m^2/kg sail, where it re-enters very quickly in 1 year. In this case, we noticed that a sail with 5 m^2/kg also caused the re-entry of the object in real circumstances, in a period of 10 years. The behavior of debris in the absence of a sail behaves, where the *r_p* remains stable.

4. CONCLUSION

For debris in LEO at an altitude greater than 500 km, where the effect of atmospheric drag is more rarefied, space debris tends to remain in the space environment for hundreds of years, which is one reason for the main problem of congestion. For that, a sail solar with 10 A/m m^2/kg, which has the role of amplifying the effect of solar radiation pressure (SRP), is already efficient enough to remove debris up to the 800 km of altitude from space, in a few months. The solar sail with the slightly lower area-to-mass ratio may also be effective, removing space junk more slowly, if the perturbation from atmospheric drag is considered.

Therefore, the proposal to use solar sail technology for the mitigation of space junk and as a tool to make space exploration more sustainable, if makes it valid with comparisons of current parameters of A/m of sails built. Satellites and ships in LEO can use this technology at the end of life, to be removed from space and not further pollute the space environment. Pieces of rockets that are most often discarded at LEO, can be solar sail trailers that will prevent the long-term perpetuation of debris from this source no space. The technology can still be used for other purposes, such as navigation, and further studies and building enhancements can make the future usable technology for waste removal space at higher altitudes. Finally, further studies are needed in the scope of disorders, with emphasis on the inclusion of atmospheric drag perturbation for simulations in LEO.

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