Assessing the effectiveness of resonant corridors in passive debris disposal

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ABSTRACT
The ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies) project was concluded on March 31, 2019. The 3-year project involved 13 European partners and was aimed at studying, implementing and testing novel solutions for space debris mitigation. The focus was on passive means to reduce the impact of Space Debris by prevention, mitigation and protection. One key aspect of the project was a study on the dynamical disposal of spacecraft at the end-of-life by exploiting natural perturbations and identifying stable and unstable regions in the phase space, where the objects could be moved to exploit either long term “graveyards” or, possibly and preferentially, faster escape routes (the so called “de-orbiting highways”). In this work the efficiency of the “de-orbiting highways” is tested and validated with a “thought experiment” by means of long term propagation of a population of objects stemming from a specific traffic launch. It is shown how the de-orbiting corridors could be very effective in removing the majority of objects from the high LEO region at the end-of-life, thus contributing to the stabilization of the space debris environment.

1. INTRODUCTION
The impact of debris on the space activities has to be reduced by adopting a global strategy able to address the problem from different points of view, from the very beginning of the planning of a space mission. The choice of the orbit, of the spacecraft bus, of the spacecraft power system and propulsion, are all aspects that influence, and have to be optimized, having in mind not only the goal of the mission but also the minimization of the “environmental” impact of the spacecraft, in particular at its end-of-life. These aspects were considered within the Horizon 2020 project ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies). ReDSHIFT has been funded by the European Union in the framework of the PROTEC Call of Horizon 2020 (see http://redshift-h2020.eu/) [9][10]. The ReDSHIFT project was concluded on March 31, 2019. The 3-year project involved 13 European partners and was aimed at studying, implementing and testing novel solutions for space debris mitigation. The focus was on passive means to reduce the impact of Space Debris by prevention, mitigation and protection. The project was based on a synergy between theoretical and experimental aspects, such as: long-term simulations, astrodynamics, passive de-orbiting devices, 3D printing, design for demise, hypervelocity impact testing, legal and normative issues.

One of the main results of ReDSHIFT was the dynamical characterization of the circumterrestrial region, which had the purpose to identify the natural orbital mechanisms that can be exploited to improve the current end-of-life measures. In other words, the goal was to identify stable and unstable regions in the phase space where the objects could be moved to exploit either long term “graveyards” or, possibly and preferentially, faster escape routes. To this purpose, the most accurate dynamical mapping of the circumterrestrial space, from LEO to GEO, ever performed at this date was realized within ReDSHIFT. An electronic atlas with the maps was assembled and is now freely available from the project website. The analysis performed on the LEO [2], MEO [13] and GEO regions [6] showed the specific type and the effectiveness of the perturbations that can support a sustainable displacement at the end-of-life, according to the orbit.

In this work, we will focus on the effects on the orbiting population of the so-called “de-orbiting corridors” (see Sec. 2.), detected by the work carried out on the LEO region. The advantages brought by exploiting the de-orbiting corridors at the end-of-life will be shown with a comparative evaluation based on the number of objects at the end of a long-term evolution and also on the $\Delta V$-budget required to dispose the spacecraft.
2. DE-ORBITING CORRIDORS

In LEO, apart from the atmospheric drag, the natural orbital perturbation that can be exploited for an improved compliance with the current mitigation guidelines is the solar radiation pressure (SRP). The associated long-term effect that can be used to de-orbiting is a variation in eccentricity, that can become quasi-secular when coupled with the planetary oblateness. In previous works [1][12][2], we have shown how it is possible to model resonant conditions that can provide an eccentricity growth high enough to lower the pericenter altitude towards the drag domain.

From the theoretical point of view, the effect was explained by computing the equilibrium points and the corresponding stability of the dynamical system associated with solar radiation pressure and Earth’s oblateness [3]. In particular, it turns out that the natural de-orbiting can occur in two situations, either by following the hyperbolic invariant curves stemming from a saddle equilibrium point or by following a wide enough libration curve in the neighborhood of an elliptic equilibrium point. In the following, both behaviors will be referred also as “resonant corridors”. Indeed, the initial condition for the de-orbiting corridors can be computed as a resonant condition involving the rate of precession of $\Omega$, $\omega$ and the apparent mean motion of the Sun with respect to the ecliptic plane [1].

Figure 1 shows the location of the main resonances in LEO (assuming $e = 10^{-3}$). These resonances can sometimes be exploited as natural reentry corridors (the so-called “de-orbiting highways”) to improve the disposal of the spacecraft at the end-of-life.

In Fig. 2, we show again the resonant corridors of Fig. 1, assuming $e = 10^{-3}$ and $A/m = 1 \text{ m}^2/\text{kg}$. In this picture the corridors are highlighted in black, while the colored points denote the initial conditions of the orbits that can reach the de-orbiting highways by using at most 200 m/s. The required maneuver is indicated by the colorbar in m/s and it has been computed by means of the ReDSHIFT software [7][5], assuming to target the optimal $(a,i)$ pair by means of the Gauss equations [11]. The maneuver can change both the inclination and the semi-major axis of the orbit.

It should be noticed that in the neighborhood of two corridors (#5 and #6 such that the inclination ranges from about 50 and 60 degrees and from about 70 to 65 degrees, respectively), we do not find exploitable initial conditions at values of
semi-major axis higher than 8000 km and 8500 km, respectively. This is due to the fact that these two highways are less effective in terms of de-orbiting time for the natural increase in eccentricity. In other words, we can target the resonant condition with the available ∆V, but once there, the spacecraft, equipped with a sail such that $A/m = 1$ m$^2$/kg, will not reenter to the Earth in less than 25 years. On the other hand, below 7500 km in semi-major axis the figure shows a relatively wider region in the neighborhood of all 6 resonances, that is associated with a low ∆V-budget (blue area). This is due to the fact that the sail can act also as a drag sail. In particular, it was shown in [2] that, assuming $A/m = 1$ m$^2$/kg, the compliance with the 25-year rule can be achieved by means only of the atmospheric drag from an altitude of about 1000 km. The initial conditions depicted in Fig. 2 below $a = 7500$ km and associated with $\Delta V < 20$ m/s can reenter in less than 25 years thanks to the combined effect of solar radiation pressure and atmospheric drag. Actually, by considering the same maximum allowed $\Delta V = 200$ m/s and the possibility of exploiting only the drag, it is possible to comply with the 25-year rule from quasi-circular orbits, at any inclination, with a semi-major axis at most equal to 7400 km. Note that the advantage of a pure drag de-orbiting with respect to the SRP+drag effect is certainly the fact that the drag is effective at any values of inclination, but the benefit in terms of reentry time in the two cases should be analyzed in detail in the future.

It is worth noting here that the upper LEO regions, above 1000 km of altitude, might become more popular in the coming years (e.g., with the forthcoming large constellations) in view of the relatively low spatial density of objects in those orbits. For these upper LEO satellites the possibility to exploit the “de-orbiting highways”, represented by the corridors, offers a mean to significantly decrease the required $\Delta V$, thus saving propellant and pushing towards a better compliance to the 25-year rule.

3. LONG-TERM SIMULATIONS

Here we briefly summarize the results of a set of long-term evolution simulations aimed at testing the effectiveness of the proposed dynamical disposal in limiting the accumulation of large objects in LEO after the end of the operational life. A branch of the SDM model [8] is used for this purpose.

The main idea underlying the new set of simulations is to consider a standard 8-year repeating launch traffic scenario.
which is cycled all along the simulation time span. All the intact objects (including satellites, upper stages and MROs) are propagated for 200 years, disregarding in-orbit fragmentations. An operational lifetime of 8 years is assigned to every satellite. Different post-mission disposal strategies are simulated considering the exploitation either of impulsive maneuvers, with different levels of applied $\Delta V$, or the use of much smaller (in terms of $\Delta V$) maneuvers coupled with the use of resonant corridors and area augmentation devices:

1. an impulsive maneuver is performed at the apogee to lower the perigee, thus sending the spacecraft into an elliptic orbit aimed at reentry;
2. an impulsive maneuver is performed to move the object towards the closest resonant corridor;
3. an impulsive maneuver is performed to move the object towards the closest resonant corridor and then a sail is opened changing the area-to-mass ratio $A/m$ of the spacecraft. For sake of simplicity, it is assumed that all the sails are such that the new $A/m$ equals $1 \text{ m}^2/\text{kg}$.

The maneuvers are applied only up to the maximum $\Delta V$ chosen for any particular simulation, irrespective of the residual lifetime achieved. The maneuvers performed in the strategies 2) and 3) usually imply a significant change in inclination, thus requiring a large $\Delta V$, possibly exceeding the one available on board. For this reason, a series of simulations are performed assuming a new launch traffic where the satellites are moved in inclination closer to the resonant corridors with a variable level of $\Delta i$ in the different simulated scenarios. Thanks to this “artificial” displacement more satellites can actually enter the resonant corridors by means of the end-of-life maneuver, thus allowing to show the benefits associated with the exploitation of the corridors. The left panel of Fig. 3 shows the original launch traffic (red circles) and the displaced launch traffic (yellow circles) in terms of inclination (3 degrees as a maximum), superimposed on a map showing the location of the resonant corridors. It can be noticed how the most “powerful” resonances lie at high values of semi-major axis and how most of the launches are actually towards lower LEO, where drag alone is usually capable of de-orbiting a spacecraft equipped with a sail.

Therefore, to further highlight the effects and the benefits of the resonant corridors we devised two more classes of scenarios where the semi-major axis of all the launches are moved “up” by 300 or 500 km (in case they remain less than 2000 km in apogee). E.g., the right panel Fig. 3 shows the launch traffic with the semi-major axis increased by 500 km and a displacement in inclination, by a maximum of 5°, towards the closest resonant corridor.

4. RESULTS

In the following the results of the main simulations related to the cases with the launches shifted towards high semi-major axis will be shown, since these are the most relevant ones to highlight the peculiarities and the benefits of the resonant corridors.

The left panel of Fig. 4 shows the total number of objects as a function of time in 4 different scenarios:

1. the blue line (almost coincident with the orange one) shows the number of objects in the case where an impulsive maneuver with $\Delta V = 100 \text{ m/s}$ is performed in order to lower the perigee. Note that in the legend of the figure (and in all the following figures), this kind of maneuver is dubbed “Hohmann” since it actually corresponds to the first “half” of a classical Hohmann maneuver to move the satellite to a lower circular orbit;
2. the orange line refers to the case similar to the one of the blue line (impulsive maneuver with $\Delta V = 100 \text{ m/s}$), where the launches are also displaced in inclination towards the resonant corridors;
3. the yellow line (almost coincident with the purple one) refers to a case similar to the one described above in 1) with a $\Delta V = 200 \text{ m/s}$ maneuver;
4. the purple line refers to a case similar to the one described above in 2) with a $\Delta V = 200 \text{ m/s}$ maneuver.

Looking at the left panel of Fig. 4 a few comments are in order. No sails are used in these scenarios; hence the solar radiation pressure resonances are very faint. Therefore, it can be noticed that the cases where the corridors are targeted at launch (blue and yellow lines) almost coincide with the cases where no targeting is performed. The large difference in the number of objects left in orbit after 200 years between the two curves is due to the doubling of the $\Delta V = 100$
Figure 3: Left panel: original (red circles) and displaced (yellow circles) launch traffic, superimposed on the map showing the location of the resonances in LEO and the maximum change in eccentricity produced by a given resonance (on the colorbar), as a function of the initial inclination and semi-major axis. The launches shown by the yellow circles are displaced in inclination by a maximum of $3^\circ$ and the arrows indicate the direction of the displacement. Right panel: the same as in the left panel, but where the displacement in semi-major axis is 500 km and the launches are also displaced in inclination towards the resonant corridors by a maximum of $5^\circ$. The arrows show the direction of the displacement in inclination. In the end, the red dots represent the final upward, inclination optimized, traffic launch.

applied from 100 to 200 m/s. It is worth stressing that in this (and in all the subsequent figures) a large fraction of the objects remaining in orbit is represented by the MROs which of course do not undertake any disposal maneuver. In the right panel of Fig. 4, the scenarios 1 and 3 described above are compared with two cases where at the end of the operational life all the satellites are supposed to open a sail bringing the area-to-mass ratio to a fixed value of 1 m$^2$/kg and only a small maneuver of 10 m/s (yellow line) or 20 m/s (purple line) is performed aiming at the closest resonant corridor. It can be noticed how the exploitation of the area augmentation device gives a final result, in terms of number of objects left in space after 200 years, very close to the one obtained with the use of an impulsive maneuver that is about one order of magnitude more expensive in terms of $\Delta V$. Note also that, due to the very low $\Delta V$ applied in the sail cases, the two sail scenarios are very close. As a matter of fact, with only a few tens of meters per second only a tiny change of inclination can be reached.

In Fig. 5 the orange and blue line refers to the scenarios 2 and 4 described above and they are compared with two cases where the area augmentation devices are used at the end-of-life, along with a small maneuver of 10 m/s (yellow line) or 20 m/s (purple line). Contrary to the case of Fig. 4, now the launches are also pre-displaced towards the closest resonant corridors by, at most, $5^\circ$. The possibility to better exploit the solar radiation pressure resonances, thanks to the displacement of the launches already towards the corridors, makes the results obtained with the sails even closer to those obtained with a large $\Delta V$ of 200 m/s. This picture clearly highlights the benefits given by the resonant corridors with respect to a standard procedure based on a single impulsive maneuver aimed at lowering the perigee.

Moving to the results of the simulations performed using a launch traffic displaced by 500 km upward, the left panel of Fig. 6 shows the number of objects as a function of time for 4 scenarios where, similarly to Fig. 4 only impulsive maneuvers to lower the perigee are performed. Namely:

1. the blue line (almost coincident with the orange one) shows the number of objects in the case where an impulsive maneuver with $\Delta V = 100$ m/s is performed in order to lower the perigee;
2. the orange line refers to the case similar to the one of the blue line (impulsive maneuver with $\Delta V = 100$ m/s), where the launches are also displaced in inclination towards the resonant corridors (allowing for a maximum displacement in inclination up to $50^\circ$);
3. the yellow line (almost coincident with the purple one) refers to a case similar to the one described above in 1)
with a $\Delta V = 200$ m/s maneuver;

4. the purple line refers to a case similar to the one described above in 2) with a $\Delta V = 200$ m/s maneuver.

Here again, since no sails are used, the solar radiation pressure resonances are very faint. Therefore, only the effects due to the doubling of the $\Delta V$ from 100 to 200 m/s are noticeable.

The right panel of Fig. 6 shows the results of six different scenarios where the area augmentation devices are used at the end-of-life and a small $\Delta V$ of either 10 or 20 m/s is applied to reach the closest resonant corridor. At difference from the previous figures, here three cases with different launch traffic are considered for each $\Delta V$:

1. the launches are only displaced 500 km in semi-major axis;

2. the launches are displaced 500 km in semi-major axis and by a maximum of 5° in inclination towards the closest resonance corridor;

3. the launches are displaced 500 km in semi-major axis and by a maximum of 50° in inclination towards the closest resonance corridor.

Looking at the difference between the blue and the orange (and yellow) lines (referring to the $\Delta V = 10$ m/s cases) it can be noticed how the increased use of the corridors (allowed by the ad-hoc displacement in inclination by the launches) allows a significant decrease (about 10 %) in the final number of objects left in orbit. A similar difference is observed for the $\Delta V = 20$ m/s cases.

Finally, Fig. 7 shows again a comparison between the scenarios with and without the use of sails. Whilst the very high orbits considered make the quite standard $\Delta V = 100$ m/s not effective to remove the spacecraft at the end-of-life, we note that the use of the area augmentation devices allows a significant reduction of the final number of objects. A comparable disposal efficiency can be attained by using only an impulsive strategy to lower the pericenter, without exploiting a sail, with a $\Delta V$ about one order of magnitude higher than the one needed by using also a sail. The very high orbits considered in this set of simulations cause a slower, delayed re-entry of the objects in the cases where the sails are considered. Nonetheless, most of the re-entry are actually reached within the usual 25-year time span. Note also that in these scenarios all the MROs are de-facto cumulating in space for all the simulation time span due to the high semi-major axis.
5. CONCLUSIONS

The simulations described in this work show how the de-orbiting corridors, identified by the ReDSHIFT project in the LEO region and associated to the coupled effect of SRP and Earth’s oblateness, can be very effective in removing the majority of objects within 25 years from the end of the operational life. The results show in particular how the exploitation of these trajectories contributes to the stabilization of the space debris environment. In the high LEO region, which might become more populated in the near future, to reach the same level of compliance as the one that can be obtained following the resonant corridors, it is required to apply one impulsive maneuver that is higher of about 1 order of magnitude.

It is worth stressing that, moving the traffic launch towards higher altitudes and towards different inclinations (aiming at the resonant corridors) represents a “thought experiment”. The purpose of the simulations was to highlight the possible benefits of the “de-orbiting highways” in facilitating the disposal of the spacecraft at the end-of-life. In other words, to enhance the signal coming out from the simulations, the displacing of the launch traffic was adopted. Nonetheless, in this way the use of the natural perturbation to help stabilize the environment was proved to be effective and time is ripe to think about the disposal phase of the spacecraft at the early stage of the definition of the operational goals of a mission. A slight change in the initial orbital parameters (e.g., in terms of inclination or semi-major axis) might sometimes guarantee the original mission purposes while paving the way to more effective and cheaper de-orbiting strategies. I.e., the possible changes in the mission design should be properly leveraged against the advantages encountered at the end of the operational life enabling a better compliance with the de-orbiting guidelines. This should represent a new paradigm in mission planning, where the whole lifecycle of the spacecraft, including disposal, has to be considered from the very beginning of the design.

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Figure 6: Left panel: number of objects as a function of time for the different scenarios with the launches displaced upward by 500 km. The left panel refers to cases where no sail is used while the right panel compares cases with and without the use of sail (see legend and text for details).

ReDSHIFT.

References

Figure 7: Number of objects as a function of time for the 6 different scenarios identified in the legend and described in the text.

