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LONG-TERM SIMULATIONS TO ASSESS THE EFFECTS OF DRAG AND SOLAR SAILS ON THE SPACE DEBRIS ENVIRONMENT

Camilla Colombo[1], Alessandro Rossi[2], Alessandro Francesconi[3], Florio Dalla Vedova[4], Juan Luis Gonzalo[1], Vitali Braun[5,6], Benjamin Bastida Virgili[6], Holger Krag[6]

[1] Politecnico di Milano, Dep. of Aerospace Science and Technology, Milano, Italy, camilla.colombo@polimi.it;
[2] IFAC-CNR, Sesto Fiorentino, Italy;
[3] University of Padova - DII/CISAS, Italy;
[4] LuxSpace Sarl, Luxembourg;
[5] IMS Space Consultancy, Germany;
[6] European Space Agency (ESA), Germany.

This paper is focused on the long-term simulation part of a study, funded by the European Space Agency, aimed at assessing the net effect of using sails for passive deorbiting at the end of life on the future debris population around the Earth. The aim of the "environmental feedback" task of the study was to perform simulations on the overall debris population considering the cases in which solar and drag sails are used for deorbiting. This is done in three steps, first the requirements in terms of sail area for deorbiting in a desired time are found, and then these requirements are compared with the current capabilities of sail technology. As a third step the revised sail area, considering technological constraints, are used for each spacecraft employing a sail in the debris simulation in SDM. The paper discusses the results of the long-term simulations.

I. INTRODUCTION

This paper is focused on the long-term simulation part of a study, funded by the European Space Agency, aimed at assessing the net effect of using sails for passive deorbiting at the end of life on the future debris population around the Earth. In principle, indeed, these attractive technologies [1][2][3] will support the compliancy to post-mission disposal guidelines, for small missions. However, the increased cross section also increases the collision risk. The whole study presented in [4] answered the following questions: what will happen in case of collisions with deorbiting satellites using these techniques? When will a catastrophic collision take place and how can it be modelled? How will the debris population around the Earth evolve in the future when more and more satellites will use these technologies to deorbit? Is it possible to perform collision avoidance manoeuvres when a sail or a tether are employed? In particular, when focussing on solar and drag sails, their increased cross-sectional area will decrease the deorbiting time; however, it will also increase the collision risk over the deorbiting phase with respect to a standard satellite. In case a sail is involved in a collision, a new fragmentation model was devised, which considers also large and soft appendages to characterise the resulting fragments distribution. The results of long-term simulation of the whole space object population environment with the Space Debris Mitigation (SDM) tool [5] are used to show the net effect of using these strategies.

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As a third step the revised sail area, considering technological constraints, are used for each spacecraft employing a sail in the debris simulation in SDM.

The paper is organised as follows: Section II describes the way the sail requirements were computed both from a dynamical and an operative point of view. Section III explains the way the sail was involved into the simulations. Section IV is dedicated to the environmental effects of solar and drag sails. First the sail requirements for a given orbit are derived and its size is compared with current technological limits. Simulations involving sails are then presented together with their results. A separate paragraph (Section V) is dedicated to discussion, while Section VI contains a summary and the future work.

II. SAIL REQUIREMENTS

The sail requirements are defined by specifying a desired deorbiting time for the spacecraft using a solar sail or a drag sail. As the sail requirements must be specified for many spacecraft and initial conditions to be considered in the long-term simulations, a matrix of orbit altitudes a-R_E (a being the orbit semi major axis and R_E the radius of the Earth) and inclinations i has been defined. This is the indicative of the operational orbit where the satellite deploys a sail once the deorbiting phase is initiated.

For each initial condition and desired deorbiting time $T_{\text{deorbiting}}$ the required drag or solar+drag sail is numerically calculated. This consists in finding the effective area-to-mass ratio to deorbit, namely $A/m\,c_R$ or $A/m\,c_D$, where A is the cross area exposed to the solar radiation pressure or to drag, m is the mass of the spacecraft plus the deorbiting kit, and c_R and c_D are the reflectivity and drag coefficient, respectively. For these simulations a reflectivity coefficient of 1.8 [6] and a drag coefficient of 2.1 [7] are used.

Given a value of the effective area-to-mass ratio x and an initial orbit condition $[a, e, i, \Omega, \omega, M]_0$ the orbit evolution is propagated with the semi-analytic propagator PlanODyn [8], considering solar radiation pressure, atmospheric drag with a Jacchia 77 exponential model with exospheric temperature of 750 K and no solar flux variation as described in [9], and the effect of zonal harmonics up to order 6. The orbit evolution is computed until deorbit is reached below an altitude of 70 km. The required effective area-to-mass ratio to deorbit in the desired deorbiting time $T_{\text{deorbiting}}$ is computed via a bisection method on x so that the two constrains are satisfied:

1. The minimum perigee $r_{p,\min}$ achieved during the orbit evolution is below the critical perigee $r_{p,crit}$ = 120 km: $r_{p,\min} = \min r_p(t) \leq r_{p,crit}$
2. The deorbiting time is within the desired deorbiting time with a tolerance of ± 20 days.

The required effective area-to-mass is stored in matrix form so that, for each initial a, e and i, the required sail area can be computed. The simulation set-up is shown in Tab. 1; the initial right ascension of the ascending node and anomaly of the perigee for the simulation are set to 0. Even though in [6] it was shown that the initial orbit orientation with respect to the Sun position makes a difference in the requirements in terms of sail area in case only solar radiation pressure and the Earth's oblateness (represented by the J_2 parameter) are considered, this is not true anymore here, as when drag is considered and deorbiting happens in more than 5 years, the effect of drag smooths out the effect of solar radiation pressure; therefore, the initial orbit orientation is not anymore a driving parameter for the simulation. This was demonstrated in [4], where maps showing the area-to mass requirement for deorbiting in 25 years with an initial eccentricity of 0.001 for two initial right ascension of the ascending node were shown.

Note that, for the debris propagation in SDM in Section IV the most conservative case between using a drag sail and a drag+solar sail is considered, i.e., the one that requires the longer time to deorbit. For the debris simulation involving sails, two options will be considered:

- Below h_{limit} = 800 km: 50% of satellites (with mass < 1000 kg) use sail to deorbit, rest do not use it.
- Above h_{limit} = 800 km: 100% of satellites (with mass < 1000 kg) use sail to deorbit.

This choice is due to the fact that there are not many satellites that will benefit of passive sail deorbiting for orbit altitude above 800 km, since few satellites are placed where a sail small enough, i.e., within the technological limit, can deorbit a s/c in the desired $T_{deorbiting}$. Fig. 1 shows two examples of orbit evolution for two different initial conditions and values of the effective area-to-mass ratio. It is visible the decrease of the semi-major axis due to drag and the oscillation in the eccentricity vector, and therefore in the magnitude of the perigee, due to solar radiation pressure; these two effects overlap.

Tab. 1. Sail requirements numerical simulation set-up.

Variable	Value
Initial time	2013/01/01
r_p [km]	[500:25:1000, 1100:100:2500, 3000:500:10000, 11000:1000:15000]
e	[0.001:0.001:0.01, 0.02:0.01:0.05, 0.1:0.1:0.3]
i [deg]	[0.00001, 2.5:2.5:130]

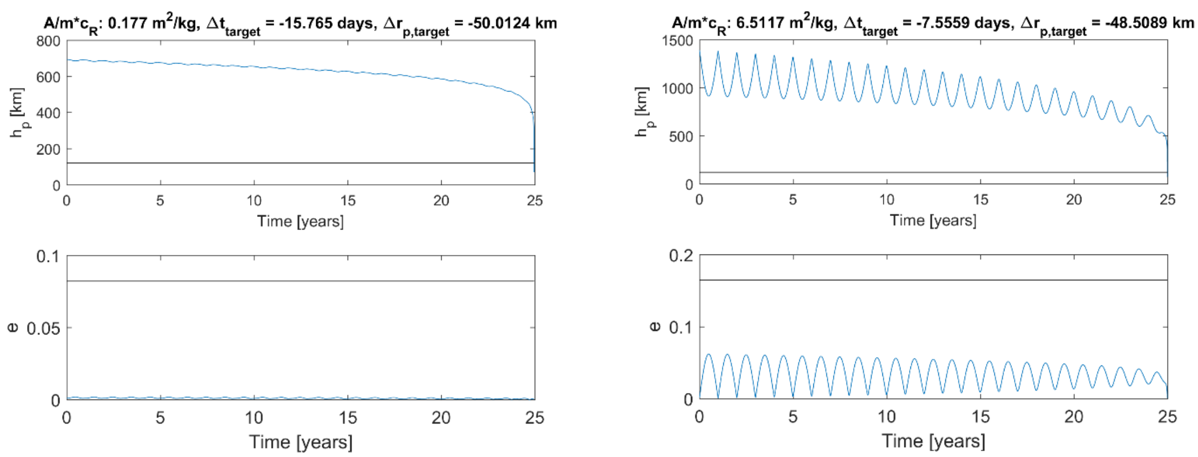

Fig. 1. Deorbiting due to drag, solar radiation pressure and Earth's oblateness for two initial conditions and two values of the area-to-mass. Δt_{target} and $\Delta r_{p,target}$ correspond to the threshold used in the zero-finding algorithm to compute the required area to deorbit in a desired time.

Once the required effective area-to-mass ratio is defined based on the desired deorbiting time, we need to estimate which additional mass shall be considered for each satellite planning to use a drag or solar sail for its deorbiting. In this perspective, the drag or solar sail are conceived as a module to be added/integrated onto the given satellite before launch or during disposal. Although several configurations exist for drag or solar sail modules, the typical box-shaped modules storing and then deploying a square sail made of four sail segments are used as reference for what follows. A sketch of this typical sail module is shown in Fig. 2.

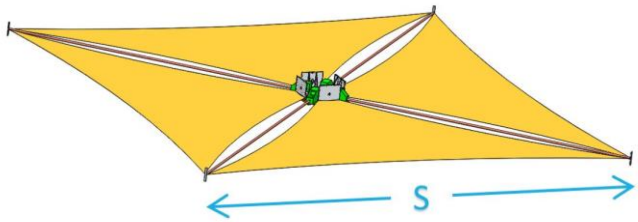

Fig. 2. Sketch of a typical sail module.

For such drag sail modules, the following technical parameters can be defined:

- Sail side length (S): the (ideal) side length of the square sail
- Ideal Sail Area (A^*) = S^2
- Actual Sail Area (A): the real sail area considering the void surfaces existing by design between sail segments (areas) and extended booms, (areas) = $\eta.A^*$ with η< 100%
- Mass of the complete Drag and Solar Sail (DRS) module (m_{DRS})
- Ideal Sail Assembly Loading (SAL*) = m_{DRS}/A^*
- Actual Sail Assembly Loading (SAL) = m_{DRS}/A
- Mass of satellite (without DRS Module) at time of disposal ($m_{\mathrm{S/C}}$)
- Total Mass to be deorbited with the Drag sail (m) = $m_{\mathrm{S/C}} + m_{\mathrm{DRS}}$

Using these parameters, it was possible to derive which DRS module (mass) ensures the required deorbiting by complying to the A/m requirement (i.e. a constant) resulting from the use case under investigation. Indeed, for a given satellite and a given starting orbit, the A/m requirement "Req(constant)" can be substituted by:

$$\frac{A}{m} = \mathrm{Req(constant)}$$

$$\frac{\eta A^*}{m_{s/c}+m_{DRS}} = \mathrm{Req(constant)}$$

$$\frac{\eta S^2}{m_{s/c}+m_{DRS}(S)} = \mathrm{Req(constant)}$$

With the imposed A/m requirement "Req(constant)", the resolution of this equation necessitates the knowledge of (1) the sail areal efficiency η and (2) how the drag and solar sail module mass relates to its side length. In [4] we showed the sail module mass to be a linear functions of the sail side lengths. So, the results of the sail requirement matrix are revised to check whether the technologic limits are satisfied.

III. SAIL IMPLEMENTATION IN SDM

Given a starting orbit within 2000 km of altitude, the effective area-to-mass of the sail needed to deorbit within either 10 or 25 years were pre-computed and stored in ad-hoc matrices. Whenever a satellite reaches its end-of-life, if it is orbiting within 2000 km of altitude (i.e., perigee below 2000 km), and it is not naturally re-entering within the desired time span, the code looks into the proper matrix for the size of the needed sail. Then the "opening" of a sail is simulated by increasing its cross-sectional area up to the level read from the matrix.

Note that the characteristics of the sail (i.e., its area) are dictated by dynamical computations but there is a maximum size allowed by the current technological constraints. In some cases, it is possible that this maximum size, driven by the technological limits, is not able to deorbit a specific satellite within the desired time span (e.g., in 10 year). Nonetheless, it was decided to open a sail as large as possible also in these cases to accelerate the deorbiting. Therefore, it is possible that a sail is going to stay in space for a time span longer than the one listed in the scenario definition (i.e., 25 or 10 years). This choice was made in order to simulate a worst-case scenario with as many sails in orbit as possible. For each sail, besides the total area also the percentage of the size occupied by the booms and by void space are considered to discriminate between different impact scenarios.

As mentioned in [4], five different reference scenarios, summarised in Tab. 2, were simulated. Based on the above reference cases, in this study, four cases where sails are used to deorbit the satellites at their end-of-life were simulated. These sail scenarios are briefly described in the following and are summarised in Tab. 3. All the four sail scenarios were simulated with at least 50 Monte Carlo runs.

Tab. 2. Reference simulation set-up.

Case	Launch	Compliance to Post Mission Disposal (PDM) 25 year	Collision avoidance manoeuvre probability of success	Simulation time span [years]	Large constellation
REF-01	Business as usual (IADC)	60%	90%	100	no
REF-02	Business as usual (IADC)	90%	90%	100	no
REF-03	Business as usual (IADC) + launch traffic 2010-2016	90%	90%	100	no
REF-04	Business as usual (IADC) + launch traffic 2010-2016	60%	90%	200	yes
REF-05	Business as usual (IADC) + launch traffic 2010-2016	90%	90%	200	yes

Tab. 3. Sail scenario set-up.

Case	Set-up	S/c using the sail	Percentage of s/c using the sail	Sail dimension for deorbiting in	Large constellation	Sail/Balloon percentage	Simulation time [years]
SAIL-01	REF-04	< 1000 kg	50% below 800 km 100% above 800 km	25 years	Do not use the sail	90% sail 10% balloon	100
SAIL-02	REF-04	< 1000 kg	100% below 800 km 100% above 800 km	25 years	Do not use the sail	90% sail 10% balloon	200

SAIL-03	REF-04	< 1000 kg	100% below 800 km 100% above 800 km	10 years	Do not use the sail	90% sail 10% balloon	100
SAIL-04	REF-05	< 1000 kg	100% below 800 km 100% above 800 km	10 years	Do not use the sail	90% sail 10% balloon	200

IV. SAIL CASES RESULTS

Fig. 3 shows the effective number of objects in Low Earth Orbit (LEO) in the first three sail cases SAIL-01 to SAIL-03, compared to the background case REF-04, where no sails were used.

Fig. 4 (right panel) shows the effective number of objects in LEO in the case SAIL-04, compared to its background case REF-05. On the shorter time span of 100 years little differences are visible between the scenarios. On the longer term it can be noticed how the use of the sail to deorbit the satellites is beneficial in terms of total number of objects (SAIL-02 scenario, red line). It is worth stressing that the SAIL-02 case is assuming that 100% of the satellites are deorbited with the sail, i.e., considering a full compliance with the 25-year rule, whereas the REF-04 is assuming a 60% compliance. While it could be argued that the comparison is not "fair", it should also be noted that the purpose is to assess the effect of the massive use of sails in space and, moreover, this full compliance is allowed by the fact that the use of sails is not limited by propellant budget considerations, as in the case of traditional thrusters.

For comparison purposes, Fig. 4 (left panel) shows all the sail cases together. Two effects concur to the further reduction of objects in space at the end of the 200-year time span observed in the SAIL-04 scenario: first, the underlying reference scenario for the case SAIL-04 is REF-05, which assumes a 90% compliance to the 25-year rule, and secondly, the residual lifetime is reduced from 25 to 10 years, going from the case SAIL-02 to SAIL-04. The right panel of Fig. 4 highlights the comparison between the REF-05 and the SAIL-04 scenarios. A significant improvement in terms of number of objects can be observed. Again, it has to be taken into account that the comparison is made between a scenario where 100% of the objects with mass lower than 1000 kg and below 1000 km of altitude comply to a 10-year rule with a scenario where the same type of objects follow a 90% compliance to a 25-year rule. It is worth repeating, that the rest of the spacecraft (i.e., mass> 1000 kg or h > 1000 km) follow, in both scenarios, a 90% compliance to a 25-year rule.

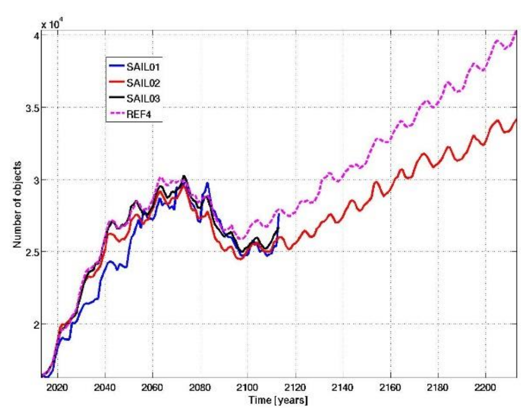

Fig. 3. Effective number of objects larger than 10 cm in LEO for the SAIL-01 to 03 scenarios, compared with the REF-04 case (dashed magenta line).

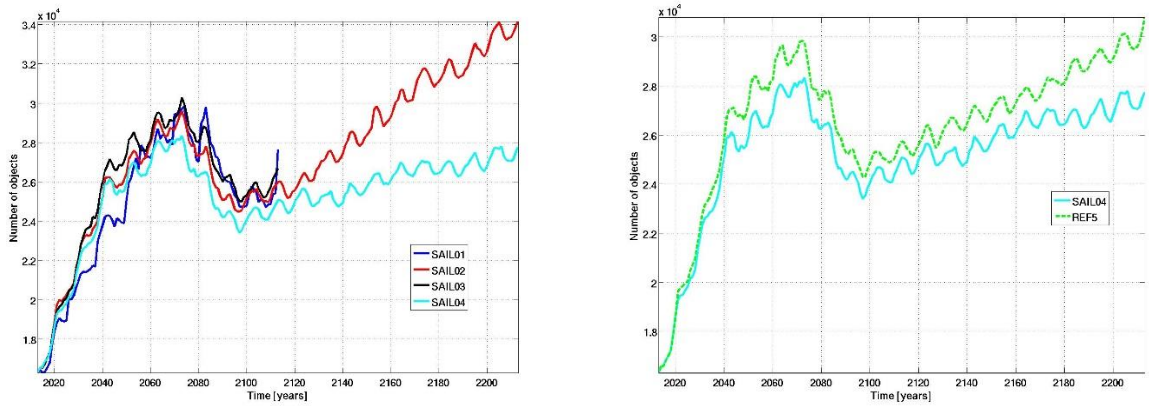

Fig. 4. Left panel: effective number of objects larger than 10 cm in LEO for the four sail scenarios. Right panel: effective number of objects larger than 10 cm in LEO for the SAIL-04 scenario (solid cyan line), compared with the REF-05 case (dashed green line).

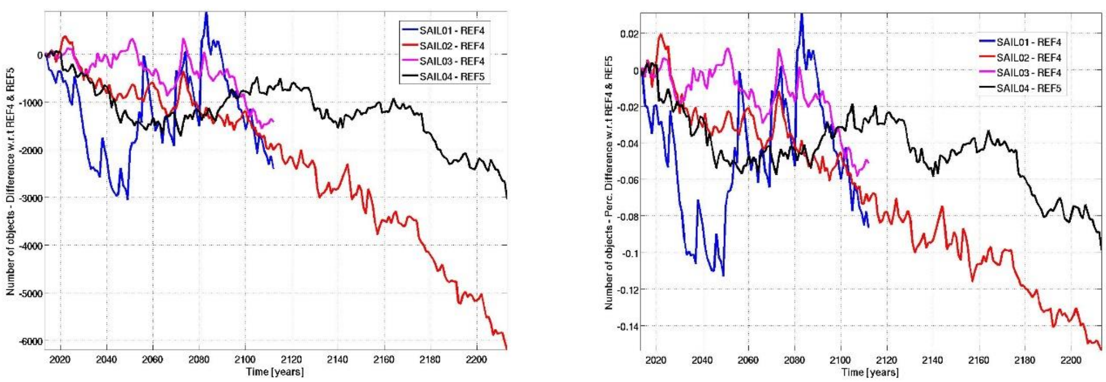

Fig. 5. Difference in the effective number of objects larger than 10 cm in LEO between the SAIL-01 to 03 scenarios and the REF-04 case, and between the SAIL-04 case and the REF-05 case. In the left panel the difference in terms of absolute numbers is shown, while in the right panel the percentage difference is shown (see text for details).

Fig. 5 shows, in the left panel, the difference in the number of objects between the four sail cases and their underlying reference scenarios. The blue, red and magenta lines show the differences between the cases SAIL-01, SAIL-02 and SAIL-03 and the REF-04 scenario, whereas the black line shows the difference between the SAIL-04 case and the REF-05 scenario. The right panel shows the same comparisons but in terms of relative differences, e.g., the red line is showing the quantity:

$$\frac{N(\text{SAIL-04}) - N(\text{REF-05})}{N(\text{REF-05})}$$

where $N(\text{SAIL-04})$ is the number of objects in the SAIL-04 scenario (and similarly for the other cases).

The more jagged pace of Fig. 5, with respect to the plots showing the number of objects as a function of time, is due to the fact that they represent small (absolute or relative) differences between these quantities. Concentrating on the longer time spans, a decrease of about 10-15% is observed in the final population of the sail cases. At difference from the results for the absolute number of objects (Fig. 4), the SAIL-02 scenario displays the largest difference with respect to its underlying reference.

To better understand these results it is worth observing Fig. 6 and Fig. 7. Fig. 6 shows the number of satellites (not belonging to the simulated large constellation) larger than 1000 kg in the REF-04 and in the SAIL-02 cases. As mentioned above, these objects are not implementing a sail device. Hence, they are following the same deorbiting rules. As expected, the two scenarios display a very similar pace, meaning that this population is largely unaffected by the underlying scenario's evolution, apart from a different number of fragmentations that destroy some of them during the 200-year time span (the same is true for the REF-05 versus SAIL-04 scenarios). On the other hand, Fig. 7 shows the time evolution of the number of satellites smaller than 1000 kg (again excluding the constellation satellites). Here a striking difference can be noted between the reference and the sail scenarios. This is related to the fact that in the SAIL-02 and SAIL-04 cases all (100%) the satellites are deorbited at the end-of-life, either in a 25-year or in a 10-year time span, respectively, while in the REF-04 and REF-05 scenarios only 60 % and 90% of these smaller satellites are deorbited at the end-of-life following the 25-year rule. It should be noted how the difference in the smaller satellite population (SAIL-02 – REF-04) is larger than the analogous difference (SAIL-04 – REF-05), due to the different level of compliance in the underlying reference case (i.e., 60 % versus 90%). In light of what was just described, it is easier to understand why, in Fig. 5, the scenario displaying the best relative improvement in the final number of objects larger than 10 cm is indeed the SAIL-02, rightly because of the increased gap in the number of satellites smaller than 1000 kg.

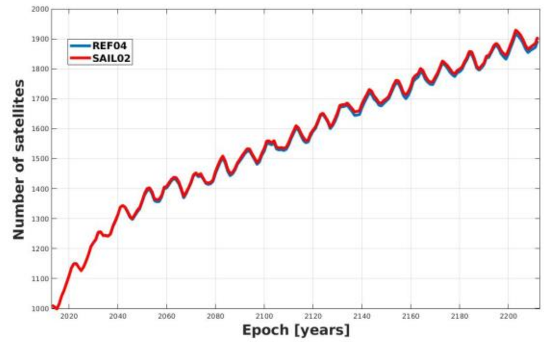

Fig. 6. Number of satellites (not belonging to constellations) larger than 1000 kg in the REF-04 (blue line) and in the SAIL-02 scenarios.

Fig. 8 shows the breakdown of the population in the SAIL-02 and SAIL-04 scenarios in terms of different components. Here there is an additional line (in cyan) showing the number of sails present in space. It can be seen how this number stabilises, after the initial growth, thanks to the balance between new opened sails and re-entering ones. Note that this number also includes stranded sails (i.e., sails damaged by collisions – see later) and sails that, as mentioned above, are staying in space for a time span longer than the one detailed in the scenario definition, due to technological limitations in its actual size.

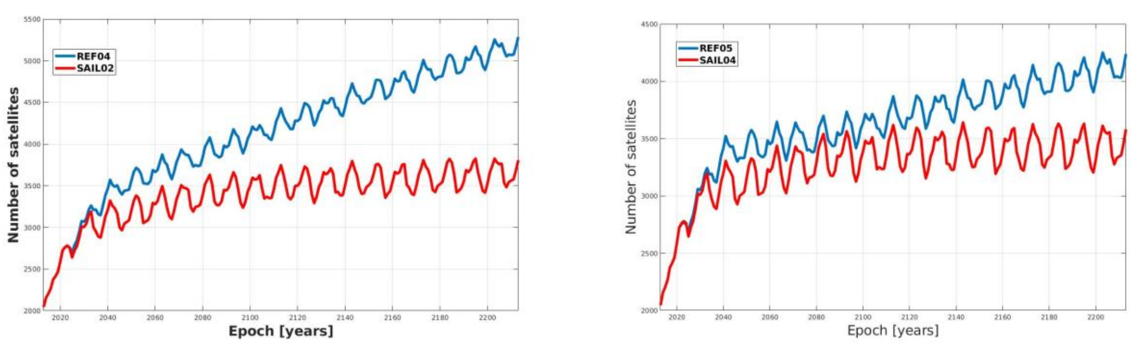

Fig. 7. Left: number of satellites (not belonging to constellations) in the REF-04 (blue line) and in the SAIL-02 scenarios. Right: number of satellites (not belonging to constellations) in the REF-05 (blue line) and in the SAIL-04 scenarios.

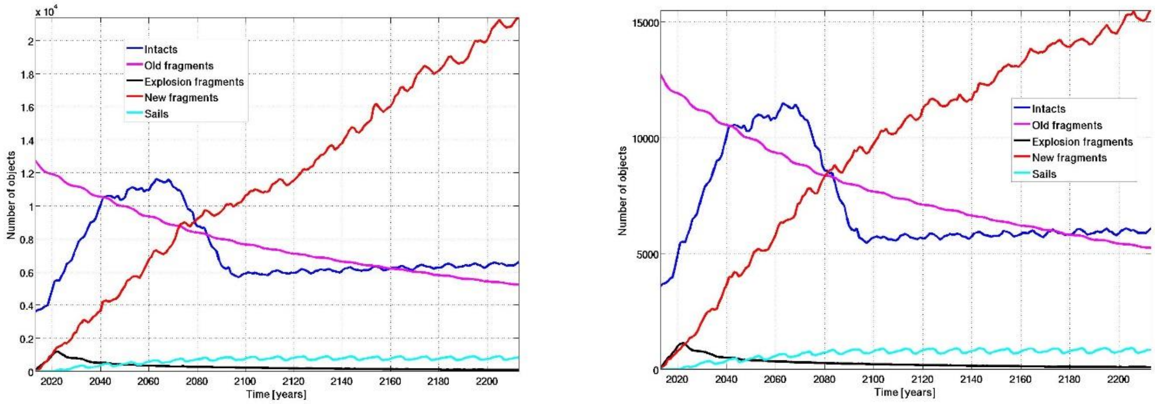

Fig. 8. Breakdown of the number of objects in LEO in the SAIL-02 (left panel) and SAIL-04 (right panel) scenarios.

The figures from Fig. 9 to Fig. 12 contain information on the collisional activity going on in the sail scenarios. First, Fig. 9 shows the cumulative number of catastrophic and non-catastrophic collisions for the four sail cases, compared with the two underlying reference scenarios. It can be noticed how, differently from the plots showing the number of objects, a significantly increased collision activity is observed in the scenarios where the sails are used. This is clearly related to the increased cross-sectional area in orbit (see Fig. 13). Nonetheless, the increased number of collisions involving the sails is not generating large fragment clouds and thus is not significantly contributing to the overall debris population. To highlight the different collisional processes happening in the presence of the sails, it is worth noting, from the right panel of Fig. 9, how, differently from the reference scenarios, the number of non-catastrophic collisions exceeds the number of catastrophic ones in the sail cases. This is further highlighted by Fig. 9 and Fig. 10 showing how the number of events (in the long-term cases SAIL-02 and SAIL-04) is increased by about 80% and 250% for the catastrophic and non-catastrophic collisions, respectively. Note also how the percentage difference is higher in the SAIL-04 case, due to the significantly reduced collision activity of the REF-05 case (see [4]).

Fig. 11 and Fig. 12 show the altitude distribution of the catastrophic and non-catastrophic collisions. The 50 km bins show the average number of events for each Monte Carlo run. The red line outlines the distribution of all the collisions of a given type, while the blue line outlines the distribution of only the collisions which involve at least one sail. It can be seen how the satellites carrying a sail are involved in most of the events above about 1000 km.

A further question that is worth answering is the possible interaction of the deployed sails with the planned mega-constellations. In the SAIL-02 scenario there are, on average, 30.1 collisions in each Monte Carlo run involving uncontrolled constellation satellites: 16.8 are catastrophic fragmentations and 13.2 are non-catastrophic collisions. Within these about 30 collisions, 10.1 involve sails: 9.3 are non-catastrophic collisions and 0.74 are catastrophic fragmentations. In the SAIL-04 scenario there are, on average, 28.9 collisions in each Monte Carlo run involving uncontrolled constellation satellites: 15.6 are catastrophic fragmentations and 13.3 are non-catastrophic collisions. Within these about 29 collisions, 10.7 involve sails: 9.76 are non-catastrophic collisions and 0.94 are catastrophic fragmentations.

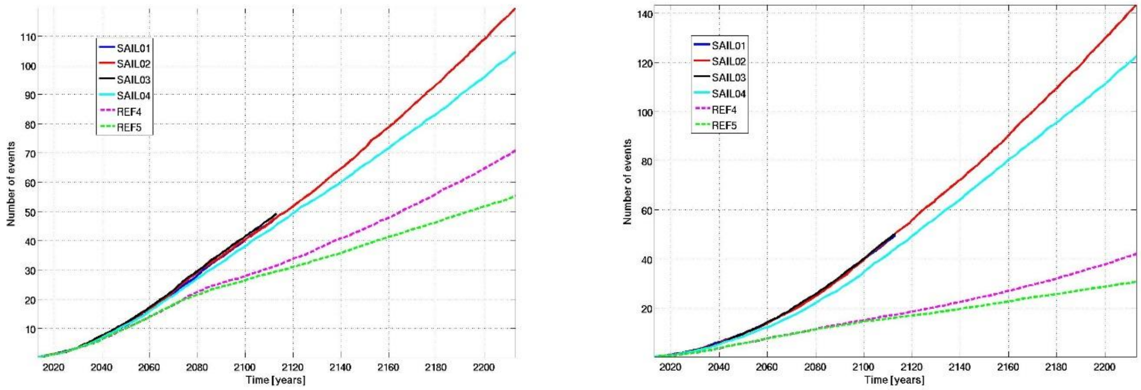

Fig. 9. Cumulative number of catastrophic (left panel) and non-catastrophic (right panel) collisions in the four sail cases, compared to the REF-04 and REF-05 scenarios.

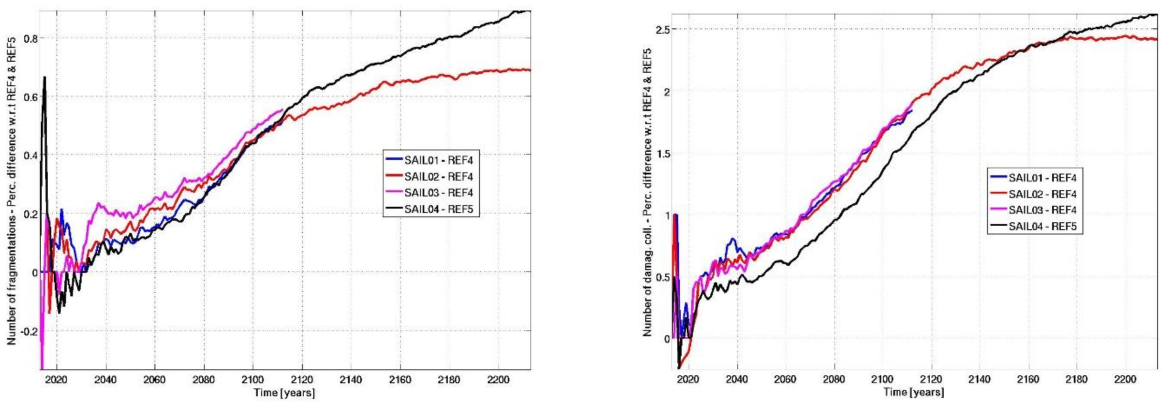

Fig. 10. Relative difference in the cumulative number of catastrophic (left panel) and non-catastrophic collisions (right panel) in the four sail cases with respect to the REF-04 scenario (for the SAIL-01 to 03 cases) and with respect to REF-05 scenario (for the SAIL-04 case).

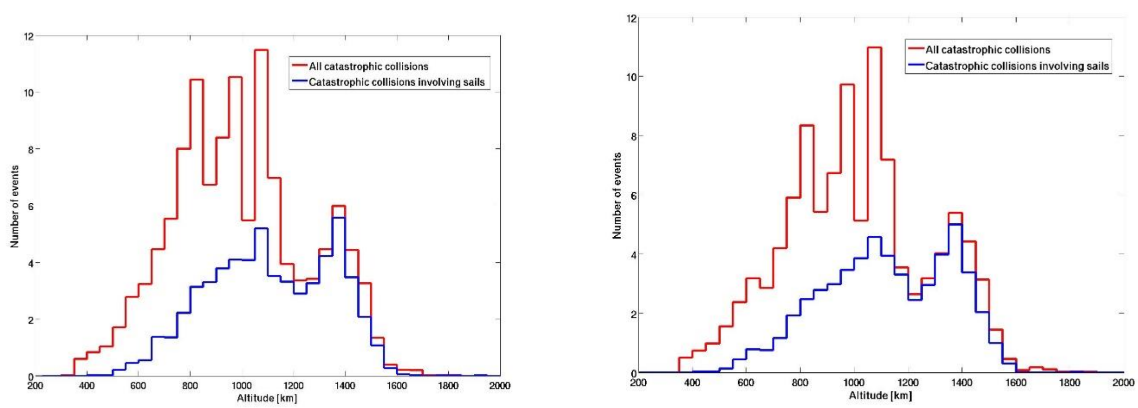

Fig. 11. Altitude distribution of all the catastrophic collisions (red line) compared with the collisions which involve at least one sail (blue line). The left panel shows the results for the SAIL-02 case and the right panel for the SAIL-04 case.

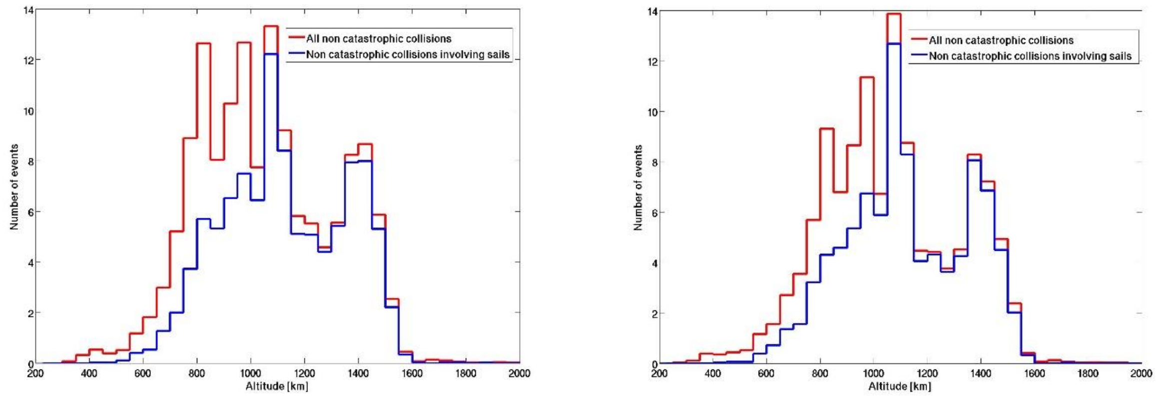

Fig. 12. Altitude distribution of all the non-catastrophic collisions (red line) compared with the collisions which involve at least one sail (blue line). The left panel shows the results for the SAIL-02 case and the right panel for the SAIL-04 case.

Fig. 14 shows the location, in the semi-major axis versus inclination space, of the collisions between sail systems and constellation satellites (left panel for the non-catastrophic collisions and right panel for the catastrophic fragmentations. See caption for details). The bulk of the events are clearly happening at the original constellation altitude against uncontrolled (stranded) constellation satellites, but some collisions are also recorded on the disposal trajectory of the constellation satellites (note that a non-controlled disposal trajectory is assumed, i.e., the satellite is supposed to be passivated after the disposal manoeuvre at the end-of-life).

Therefore, as foreseeable, the large number of constellation-related satellites and the large cross section associated to the sails produce a non-negligible interaction. On the other hand, the nature of the collisional events (mostly non-catastrophic) is apparently not responsible for a significant increase in the constellation-related collision activities.

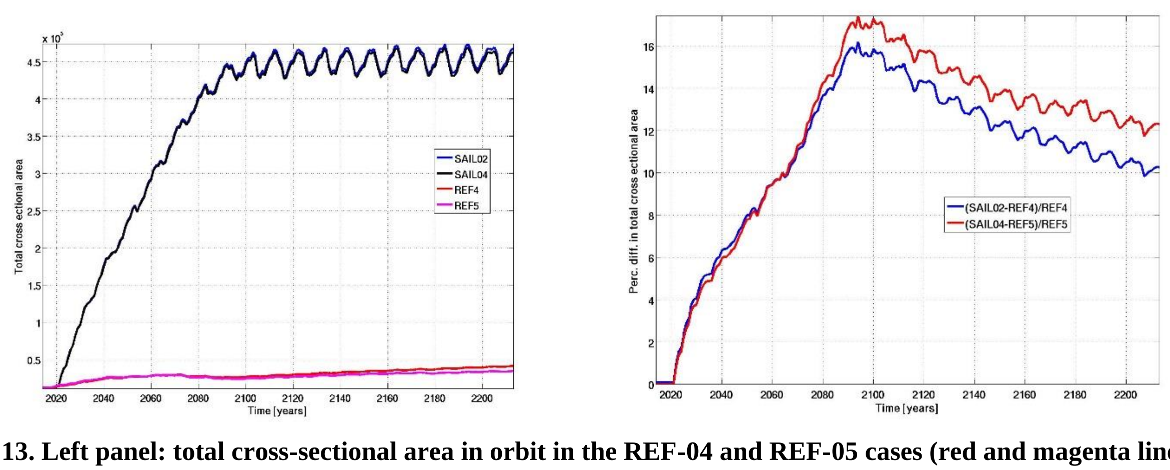

Fig. 13. Left panel: total cross-sectional area in orbit in the REF-04 and REF-05 cases (red and magenta lines, respectively), compared with the cases SAIL-02 (blue line) and SAIL-04 (black line). Right panel: percentage difference between the total cross-sectional area in orbit in the SAIL-02 case with respect to the REF-04 scenario (blue line), and in the SAIL-04 case with respect to the REF-05 scenario (red line).

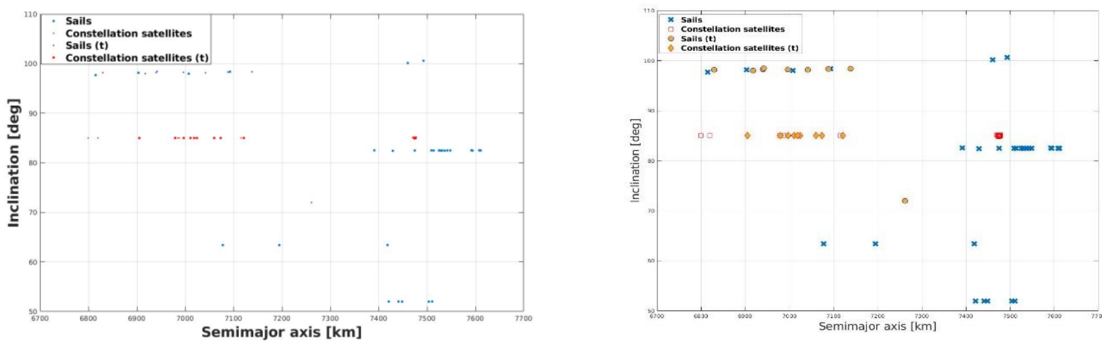

Fig. 14. Left: location of the non-catastrophic collisions involving sails in the SAIL-02 scenario (the (t) means that the sail is the target and the constellation satellite is the projectile). Right: location of the catastrophic collisions involving sails in the SAIL-02 scenario (the (t) means that the sail is the target and the constellation satellite is the projectile).

The left panel of Fig. 13 shows the total cross-sectional area in space in the scenarios SAIL-02 (blue line) and SAIL-04 (black line), compared with the same quantity from the two reference cases (REF-04, in red, and REF-05, in magenta) where no sails are used. There is of course a large increase in the sail scenarios which is responsible for the augmented collisional activity just commented. Note how the absolute values for the SAIL-02 and SAIL-04 cases are similar. In the two scenarios the residual lifetime is different (25 versus 10 years), therefore, in the SAIL-02 there are more sails in space but with a smaller size (because a larger size is needed to deorbit in a shorter time), leading finally to a similar total cross section in orbit. The right panel of the figure is showing the percentage difference with respect to the respective reference cases. An increase in excess of 1000% is observed for both cases.

V. DISCUSSION

Tab. 4 shows the ratio between the values of some interesting quantities recorded in the sail scenario with respect to the values of the same quantity recorded in the underlying reference scenario. In particular, in column 3 there is the ratio between the total cross-sectional area present in space at the end of the simulated time span (shown in column 2), in column 4 there is the ratio between the final number of objects larger than 10 cm, in column 5 the ratio between the total number of collisions, in column 6 the ratio between the number of catastrophic fragmentations and in column 7 the ratio between the number of non-catastrophic collisions.

Tab. 4. Ratios of significant quantities in the SAIL versus REF scenarios.

Case	Time span of the simulation [years]	Total cross-sectional area [m^2]	Final number of objects	Number of collisions	Number of catastrophic fragmentations	Number of non-catastrophic collisions
SAIL-01/REF-04	100	15.7	0.99	1.33	1.53	1.18
SAIL-02/REF-04	200	11.3	0.85	2.33	1.69	3.42
SAIL-03/REF-04	100	15.7	0.96	1.57	1.57	2.92
SAIL-04/REF-05	200	13.3	0.90	1.89	1.89	3.98

In the following we are focusing on the 200-year cases, i.e., SAIL-02 and SAIL-04. It can be noticed that in the SAIL-02 case, for an increase in the total area of 11.3 times we have an increase in the total number of collisions (fragmentation + cratering) of 2.33, such that:

11.3/2.33 = 4.9

and in the SAIL-04 for an increase in the total area of 13.3 times we have an increase in the total number of collisions (frag.+crater.) of 2.64, such that:

13.3/2.64 = 5.0

Using the simple proportions, we get that an increase of a factor 10 in the total area leads to an increase of a factor 2 in the number of total collisions. The mean number of collisions c encountered by an object of collision cross-section A, moving through a stationary medium of uniform particle density D, at a constant velocity v, during a propagation time interval Δt is given by:

$$c = v\, D\, A\, \Delta t$$

where $F = v\, D$ is the impact flux (in units of $m^{-2}s^{-1}$).

Considering the SAIL-02 and SAIL-04 cases, the time interval Δt is the same, so the number of collisions should be directly proportional to the area A. On the other hand, we observed that increasing the area by 10 times leads to an increase of the number of collisions (c) of only 2. Therefore, since we can assume that also the mean velocity (v) remains the same, the smaller increase in the final number of collisions must be related to a non-linear dependence of c and D=Number/volume from time. That is, we cannot simply apply the rule Δt *x* Area to compute the effect of the sails on the environment.

Note that the relation is not working also on the opposite way, i.e., it is not possible to extrapolate the expected number of objects from the above relation, since it would be:

$$c_{sail} = v_s\, D_s\, A_s\, \Delta t$$

$$c_{ref} = v_r\, D_r\, A_r\, \Delta t$$

So, since from the simulations we have $c_{sail} = 2\, c_{ref}$ if $A_s = 10\, A_r$

$$v_s\, D_s\, A_s = 2\, v_r\, D_r\, A_r$$

Assuming that the velocities are on average similar ($v_r \sim v_s$):

$$D_s\, A_s \sim 2\, D_r\, A_r$$

$$D_s\, 10\, A_r \sim 2\, D_r\, A_r$$

so we should have:

$$D_s \sim 2/10\ D_r$$

and therefore, since D=(number of objects)/Volume, if a tenfold increase in the cross-sectional area is assumed, a doubled number of collision can be obtained if:

$$N_s \sim 2/10\, N_r = 0.5\, N_r$$

while we observe $N_s \sim 0.9\, N_r$. That is, the final number of objects in our simulations is higher than the number that would lead to a two-fold increase in the number of collisions in a perfect gas system.

One might say that, given the strong simplifying assumptions of the above equations, the disagreement between 0.5 and 0.9 is not so striking. On the other hand, while the non-standard outcome (in terms of fragments produced) of a collision involving a sail might be used as an explanation for the above discrepancy, it is clear that more work is needed to finally parametrize the impact of the massive use of sail systems on the environment.

VI. SUMMARY OF THE SIMULATIONS AND WAY FORWARD

The main results of the long-term simulation involving sails can be summarised as follows:

- With the scenario definition of this study the massive use of sails leads to a decrease in the number of objects in LEO of about 10-15% at the end of a 200-year time span. As mentioned in the text above, it must be stressed that part of the observed improvement is related to the sail scenario definition. Nonetheless, the important message is that there is not a negative effect on the debris environment due to the use of the sails, in terms of number of objects produced.

- Moreover, it should be stressed that the main differences in the final number of objects is due to the satellites smaller than 1000 kg that, in the sail cases, are all (100 %) deorbited quite fast. This is a bit unfair with respect to the "normal" deorbiting procedures simulated in REF-04 and 05 since in those cases only 60 or 90 % of them are deorbited. On the other hand, it is fair to state that this is made possible by the fact that, whereas small satellites tend not to carry propulsion systems able to perform the deorbiting manoeuvres required for disposal of the spacecraft at the end-of-life, a sail system might be added to almost any satellite and can allow, if properly exploited, deorbiting even from quite high orbits. Thus, the apparently unfair assumption (60 versus 100%) can be, at least partly, justified on a technical basis.
- In the opposite direction with respect to this, there is a significant increase (80% and 250% for the catastrophic and non-catastrophic collisions, respectively) in the collisional activity, due to the increased collisional cross section in orbit (in excess of 1000%, see Fig. 13, right panel). On the other hand, not only a collision against a sail is not causing a large cloud if it happens against the membrane of the sail system or the booms, but also, even if the whole satellite is destroyed, only relatively small targets are destroyed (less than 1000 kg) and are not producing very large clouds of fragments, thus not creating long term signatures in the environment.
- While it is true that the global cross section in orbit is increased, in all the additional collisions that involve the sail systems as targets the "fragmentation cross section" (i.e. the cross section that, if hit, generates a large cloud of fragments) is de-facto the same as in the case with no sails because it is the body of the satellite. If the sail system is hit, the large body of the satellite is usually unaffected and therefore no large cloud is created. Similarly, if the sail is acting as projectile, most of the collisions between an object and the membrane-boom system will not result in a fragmentation, hence no large additional clouds are created. These facts explain the observed gain in the environment, despite the largely increased collisional activity.
- Although most of the collisions involving sails do not generate large fragment clouds (hence the actual decrease of the final population), they can represent a nuisance for the active satellites and a significant collision avoidance activity might be needed to properly exploit the advantages represented by the use of sails in LEO. As noted, the significant increase in the orbital cross section leads to an increase of a factor 2 in the total number of collisions in the sail scenarios with respect to the reference ones. This factor 2 can also be interpreted as the expected increase in the number of Collision Avoidance Manoeuvres (CAMs) required in the future. This might be a "worst case" number since also non-damaging collisions against the sail membrane will be avoided. On the other hand, there is no a-priori way to anticipate if a perspective collision against a sail system will result in catastrophic collision or in a negligible damage, therefore any collision should be avoided whenever possible.

The data and percentages mentioned in the above bullets should be appropriately leveraged to produce an indicator of the benefit and criticality of the use of sails. The non-linearity of the processes involved, including non-standard fragmentation events, now prevents a simple parametrisation of the scenarios with a single index. More work on this subject is required in the future

VII. ACKNOWLEDGMENTS

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