EVALUATION OF THE DEBRIS ENVIRONMENT IMPACT OF THE ESA FLEET

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ABSTRACT

A possible quantitative approach to space sustainability is the assessment of the impact of a mission on the space environment through a risk metric. In particular, we apply a debris index that quantifies the probability that a spacecraft is involved in a fragmentation and the effect of this fragmentation on operational satellites. Aggregates of such assessment give a historical and future perspective on the utilisation of the space environment as a resource leading to the notion of the space environment capacity. This capacity can then be linked to the contribution of each mission to a potentially (un)stable space debris environment.

Such an indexing approach is applied here to evaluate a set of missions operated by ESA in Low Earth Orbit since its inception, looking at the cumulative risk associated to the ESA fleet, its variation over time, and the historical context, highlighting the positive trend associated to the progressive adoption of mitigation measures. Firstly, the debris environmental impact of the different satellites is computed based on the mission plan, retrieving as much as possible historical data on disposal plans and assumed success rates. For already concluded missions, this value is then compared to the actual achieved performance; for on-going missions, the value will be compared with the one computed with the latest available data (e.g. with updated operational lifetime, in case of mission extensions). In addition, the assessment is carried out also considering all the mission objects, i.e. including for example the fragmentation risk associated to the upper stages used to insert the spacecraft in orbit and to any released mission related object.

Planned missions will be also analysed highlighting which aspects appear to be the most effective in reducing the overall mission impact on the space environment. Such considerations are formulated to show the applicability of risk metrics in assessing the impact on the environment at large, and, therefore, their potential contribution to the promotion of behaviours in line with the sustainable use of outer space.

Keywords: sustainability; debris mitigation; impact assessment.

1. INTRODUCTION

Ever since the start of the space age, there has been more space debris in orbit than operational satellites. Whereas the issue of space debris was initially not clear to operators, it has become nowadays a routine aspect in the operations of satellites to ensure the mitigation of the risk associated to it. A major milestone in this perception shift is represented by the publication in 2002 of Space Debris Mitigation Guidelines by the Inter-Agency Space Debris Coordination Committee [1], which have since served as a baseline to technical standards and contributed to build a common understanding of the required mitigation tasks.

One way to assess the impact of space operations on the debris environment is therefore to look at whether a mission is compliant with debris mitigation guidelines. While this is a necessary first step, one also has to be aware that the landscape changed over the last years. Recent phenomena, such as the change in launch traffic to the Low Earth Orbit, driven by large constellations and small satellites, have accompanied the publication by the United Nations on the guidelines for the Long-term Sustainability of Outer Space in 2018 [2], where the concept of *long-term sustainability of outer space activities* has been notionally defined as

> the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.

By looking at this definition, one can see that current guidelines are not fully linked to the objective of sustainable space flight. For example, the effect of mitigation measures (and of different level of compliance) is usually assessed by using models of the long-term evolution of the environment, where the different scenarios are evaluated by looking at the number of objects or number of catastrophic collisions. If one analyses different scenarios only based on the number of objects in orbits, one may have only a partial representation of the situation as the criticality of scenarios with the same number of objects

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may be very different, depending on the type of objects, where the objects are located, and which is their manoeuvrability status. The same reasoning applies when looking at the predicted collision rate, instead of number of objects, on-orbit over time.

Another point that is not captured by the guidelines is the dynamic evolution of the environment. In LEO, the number of satellites launched in a year has reached in the last years around four times the level of 10 years ago, and even a larger increase with respect to the year (2003) when the IADC guidelines were published [3]. In addition, the satellites that are launched are very different from 10-20 years ago, with roughly half of the satellites launched in the last four years having a mass smaller than 10 kg. This change in traffic is also related to a shift towards a more commercial exploitation of LEO and a diversification of the operators. All these elements (traffic volume, type of satellites, type of actors) are important to keep in mind when we look at the level of compliance to mitigation guidelines and at whether these guidelines will work in the next 20 years of space activities.

Finally, guidelines do not prescribe how to achieve compliance, so different approaches are possible. For example, in LEO, the compliance to the end-of-life disposal guideline may be achieved either manoeuvring a satellite to an orbit with a lower orbit or by deploying a device (such as a sail) to augment the cross-sectional area of the spacecraft and accelerate its decay. While both approaches may result in the mission being compliant, they may also be not equivalent in terms of the impact on the environment [4]. More in general, one may want to be able to compare (in quantifiable manner) different mitigation strategies.

The concept of *impact on the space environment* can be translated, in practice, into the quantification of two aspects: how detrimental is a mission to other operators? how likely is a mission to contribute to the Kessler syndrome in the long-term? In past works [5], we have developed a risk metric to perform this type of assessment at mission-level.

The proposed metric is a risk indicator with general expression

$$\text{Risk} = \text{Probability} \times \text{Severity}, \tag{1}$$

where the Probability term (p) captures the likelihood that an object is involved in a fragmentation event and the Severity term e quantifies the consequences of such an event. In particular, the term p represents the probability of collision with objects large enough to trigger a catastrophic collision, whereas the severity term quantifies the effect of such fragmentations on operational satellites. This is done by defining a set of representative objects of the population of operational satellites and computing the collision probability for these objects due to the simulated fragmentations.

Equation 1 is evaluated along the mission profile of an object

$$I = \int (p_c \cdot e_c)\, dt = \int \hat{I}(t)\, dt \tag{2}$$

to capture two key elements: the implementation of disposal strategies at the end of mission and the evolution of the environment in the time frame when the object is in orbit. The first aspect is addressed by considering the possible paths of evolution of the trajectory depending on the success rate of the disposal strategy (α), so that Equation 2 becomes

$$I = \int_{t_0}^{t_{\text{EOL}}} \hat{I}\, dt + \alpha \underbrace{\int_{t_{\text{EOL}}}^{t_f} \hat{I}\, dt}_{\text{Disposal}} + (1-\alpha) \underbrace{\int_{t_{\text{EOL}}}^{t_f} \hat{I}\, dt}_{\text{No disposal}}\,. \tag{3}$$

The approach can be extended to analyse all the objects in orbit and scenarios coming from long-term simulations of the environment [6]. This can be done to assess whether the level of space activity is in line with the environment capacity [7], intended as the number and type of missions compatible with the long-term stability of the environment. The introduction of the concept of *environment capacity* implicitly treats outer space (and, in particular, the ability of operating in it) as a limited shared resource and space environment impact assessments, such as the one applied in this study, represent a quantification of which portion of such resource is used and can be applied in a framework of resource allocation [8].

For the current study, the approach summarised in Equation 2 was applied to the evaluate the spacecraft in the fleet of spacecraft developed by ESA, considering both existing and future missions, and focussing on the *Science* and *Copernicus* missions as represented in Figure 1.

2. EXISTING MISSIONS

The analysis of existing missions was performed considering all the spacecraft in LEO for which ESA is a launching state and that operate above 400 km of altitude. The

Figure 1. Representation of ESA-developed Earth observation missions. © ESA, CC BY-SA 3.0 IGO

Table 1. Parameters used for the analysis of existing missions. Italics is used to indicate estimated values for the PMD strategy, whereas non-italics values derive from requirements.

COSPAR	Name	Launch year	Mass [kg]	Operational altitude [km]	Planned OLT [years]	EOL	PMD rate	PMD target
1991-050A	ERS-1	1991	2141	778	3	2000	*0.5*	*570 km*
1995-021A	ERS-2	1995	2494	784	3	2011	*0.5*	*570 km*
2001-049B	Proba-1	2001	94	587	2		0	
2002-009A	Envisat	2002	8110	784	5	2012	*0.5*	*700 km*
2005-043E	SSETI Express XO-53	2005	77	695	2	2006	*0.5*	*-50 km*
2009-059A	SMOS	2009	658	759	3		*0.5*	*-50 km*
2009-059B	Proba-2	2009	130	722	2		*0.5*	*-50 km*
2010-013A	CRYOSAT 2	2010	720	719	3		*0.5*	*-50 km*
2012-006K	*AVUM (Vega)*	*2012*	-	-	-	-	-	-
2013-021A	Proba-V	2013	138	816	2.5		*0.5*	*-50 km*
2013-067A	Swarm-B	2013	473	495	4			
2013-067B	Swarm-A	2013	473	495	4			
2013-067C	Swarm-C	2013	473	495	4			
2014-016A	Sentinel-1A	2014	2157	696	7		0.9	(25-year)
2015-028A	Sentinel-2A	2015	1130	789	7		0.9	(25-year)
2015-070A	(LISA Pathfinder)	2015	-	-	-			
2016-011A	Sentinel-3A	2016	1130	803	7		0.9	(25-year)
2016-025A	Sentinel-1B	2016	2157	696	7		0.9	(25-year)
2017-013A	Sentinel-2B	2017	1130	789	7		0.9	(25-year)
2017-064A	Sentinel-5P	2017	818	827	7		0.9	(25-year)
2018-039A	Sentinel-3B	2018	1130	803	7		0.9	(25-year)
2018-099AL	ESEO	2018	45	581	3	2020		
2019-092B	CHEOPS	2019	276	704	3.5		0.9	(25-year)
2019-092F	OPS-SAT	2019	7	520	3			

missions are listed in Table 1 where OLT indicates the operational lifetime, EOL the End-of-Life of the mission, and PMD refers to the Post-Mission-Disposal.

The assessment of a missions includes also the risk coming from associated objects, such as, for example, upper stages used for the insertion of the satellite. For this reason, the launch with COSPAR ID 2012-006 is included as ESA is the launching state for the AVUM (Vega) object; for the same reason, LISA Pathfinder is listed as the upper stage used for the launch was left in LEO. In the case of ride-share launches, the risk associated with the upper stage is distributed across the payloads in proportion to their mass, as a first order approximation of the risk.

The data on spacecraft and related orbits were retrieved from DISCOS[1]. For what concerns the adoption of mitigation measures, performance is considered to be time-dependent. ESA performed its first collision avoidance manoeuvre in May 1997 to reduce the risk associated to a conjunction between ERS-1 and the Cosmos-614 satellite (1973-098A)[2]. With respect to this first manoeuvre, several operational aspects changed [9] and, most notably, the quality of the space surveillance data used for collision avoidance activities, especially with the introduction of CSMs (Conjunction Summary Message) and CDMs (Conjunction Data Message) [10]. For the current analysis, this is translated into a different level of risk mitigation achieved through collision avoidance activities, which are considered to be available only for manoeuvrable satellites. For earlier missions, where a dedicated analysis was not always executed and large discrepancy could exist based on the access to surveillance data, this level is set to 50%, as a general estimate for the risk reduced and applied for activities until 2015. At latest with the advent of CDM and CSM data by space surveillance providers, a dedicated methodology has been used to quantify the risk reduction and the value targeted is systematically set at 90% [11]. For what concerns post-mission disposal planning, it is assumed that missions launched before 2014 (the formal introduction of an ESA policy on space debris mitigation applicable to all missions) considered only a best-effort disposal, reflected both in the lower PMD success rate reported in Table 1 and in a target disposal orbit that may result in a lifetime longer than 25 years. As there were no strict requirements on the disposal targets and success rates, these values are to be considered as coarse estimates (that can be outperformed for missions still active). These values are indicated in italics in Table 1 where a value in km is provided, which refers either to the mean altitude of the disposal orbit or, in case of negative number, to the targeted altitude reduction.

[1]The data from DISCOS can be accessed from its web-based frontend DISCOSweb.

[2]Personal communication, Xavier Marc, 11 February 2021

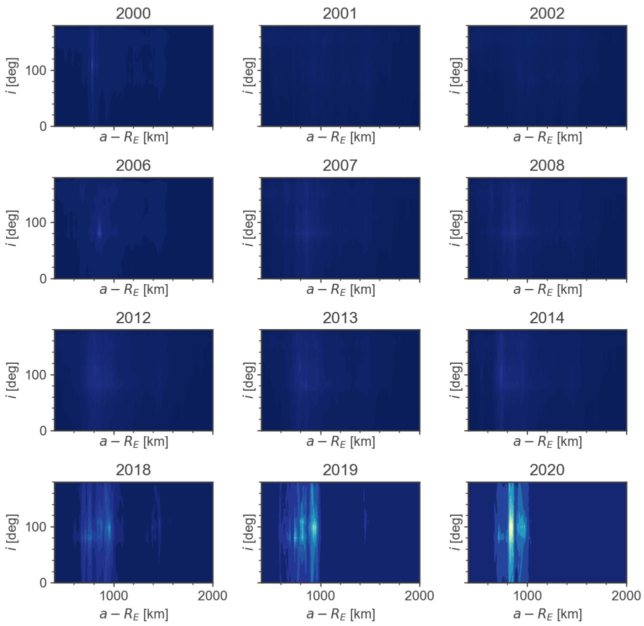

Figure 2. Flux from the background debris population as extracted from MASTER.

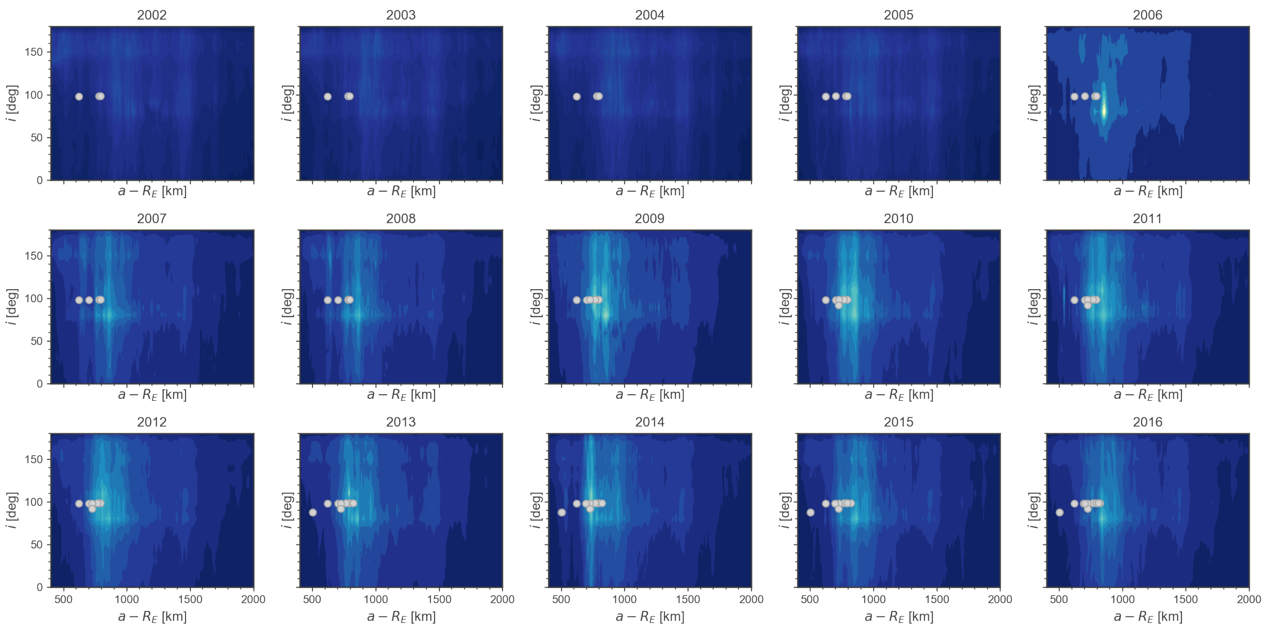

Figure 3. Flux from the background debris population as extracted from MASTER. The grey markers indicate the location of ESA missions.

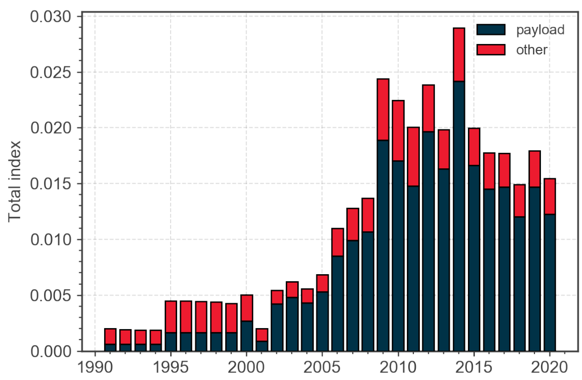

Figure 4. Total index for the existing ESA-developed missions over time.

The distribution of the background debris objects is retrieved from MASTER, selecting the population corresponding to the year of analysis up to 2016, which is the reference population in the current MASTER version [12].

The reason for this choice can be seen from the plots in Figure 2 and Figure 3, which represent the flux of debris population for different epochs. The scale of the flux is not reported, but within each figure, the plots use consistent colour scale, so that it is possible to compare the populations over time. In Figure 2, in the years after 2016, one can clearly see the presence of a large fragmentation that occurred in one of the future scenarios generated for the production of future populations in MASTER. The fragmentation occurred in one of the simulated scenarios, but it is large enough to be visible also after the averaging process. As such evolution of the environment does not reflect what observed between 2016 and 2020, the reference population is used instead for any year after 2016.

The populations ranging from 2002 to 2016 are shown in Figure 3, together with the location of ESA-developed missions, as indicated by the grey markers. Also in this case it is possible to recognise some fragmentation events, but it is important to specify that the maps were generated using the last day of a year as a reference epoch and, in MASTER, the closest population file to the selected epoch is used. This means, for example, that for the map in 2006, the closest population file is the one in February 2007, which already contains the objects from the Fengyun-1C event. For the same reason, the fragments from the fragmentation of DMSP-F13 (occurred in 2015) appear already in the map for 2014.

For each year of simulation, ranging from 1991 to 2020, the background debris population was updated using the logic described above and it was checked which objects from Table 1 were already in orbit and their operational status. The resulting assessment is shown in Figure 4, where the blue bars indicate the contribution from satellites and the red ones the contribution from the related upper stages and mission-related objects. One can notice how the evolution of the total value is affected by the combined effect of changes in the environment (such as the fragmentations, whose effect is visible in 2006, 2009, and 2014), and changes in the operational status of the objects in the fleet, as visible from the reduction of the risk associated with the disposal of ERS-2 in 2011 and the increase related to the failure of Envisat in 2012.

Another element that affects the index value is the evolution of the trajectories of the uncontrolled objects and the collision risk associated to the orbital regions they are crossing. This is shown in Figure 5, where one can appreciate how the evolution of the risk for Envisat drives the overall assessment in Figure 4.

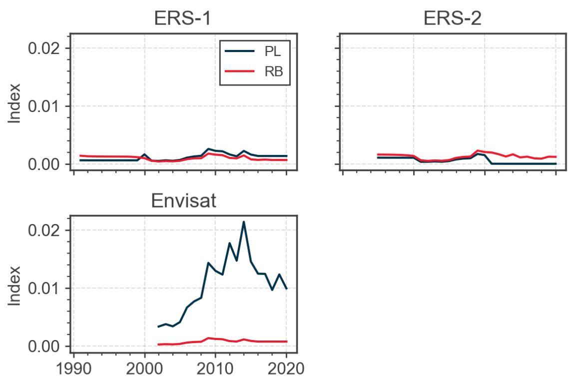

Figure 5. Index for some of the concluded missions.

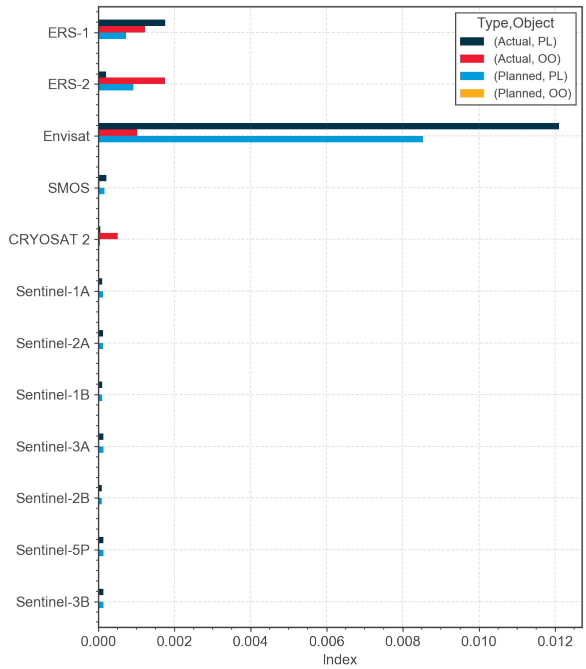

Figure 6. Planned and actual index for the twelve missions with the largest index value, ordered by launch date.

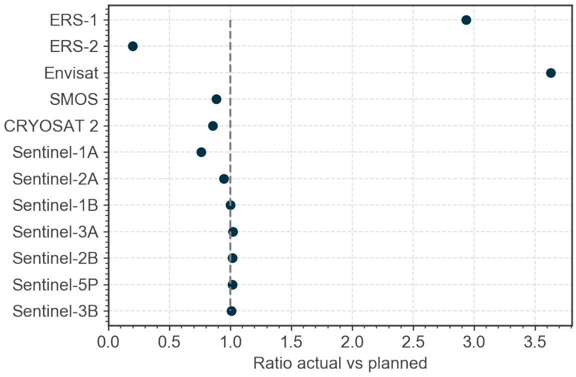

Figure 7. Ratio between the actual index and the planned one for the twelve missions with the largest index value, ordered by launch date.

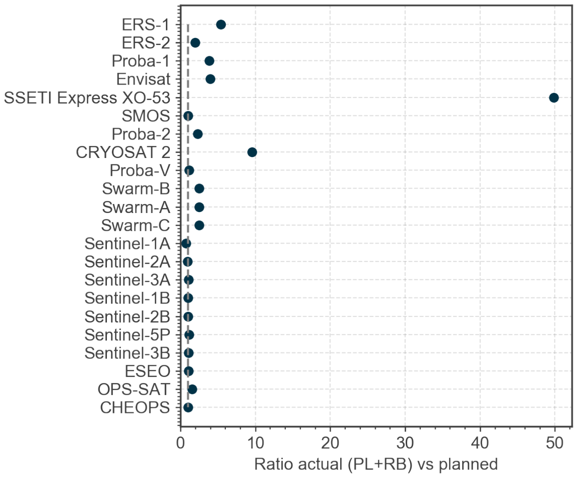

Figure 8. Ratio between the actual index (including the contribution from upper stages and associated objects) and the planned one, ordered by launch date.

One can analyse the contribution from each single mission and compare the planned debris impact and the actual one. We indicate with *planned* the assessment performed at launch year, considering only the contribution from the payload, whereas with *actual* we indicate the assessment at the end of the simulation. The interest in the planned value of the index is to be related to the definition of resource management allocation schemes based on the concept on environment capacity and the assessment on whether a realistic planning is feasible. Figure 6 shows the planned and actual index value for the twelve missions with the largest index value and once can notice how newer missions tend to have a smaller planned impact on the space environment because of their smaller size and because of a systematic adoption of disposal measures.

One can go more in detail in the comparison of the actual and planned impact. There are several reasons why the two can diverge as, for example, subsequent mission extensions or failures in orbit. Figure 7 shows the ratio between the actual index and the planned for the same twelve missions as in Figure 6. There is a clear difference between ERS-2, where the best-effort disposal was successful, and the cases where the satellite failed or was abandoned in orbit. While the real assessment of this ratio can be done only once a mission is concluded, one can see how for the Sentinel mission there is a tendency of going towards a more realistic planning of resources.

The comparison can also be performed considering the contribution from the associated rocket bodies. Also in the case there is a positive trend emerging for more recent missions, where the rate of disposal of rocket bodies is higher.

Another way to look at the assessment of the ESA fleet is to compare it to the trend for the overall environment. The general assessment is performed by using the same approach for the background debris population (and its dependence on the epoch) and retrieving from DISCOS the population for each year, together with the object size and orbital information. The activity status is retrieved from the Union of Concerned Scientists database[3] (available from 2005 onwards) and used as a proxy for manoeuvrability. For the sake of simplicity, a default disposal approach is applied for all the satellites and it consists in lowering the trajectory to a 500x500 km orbit, and simulating the results with different success rates (i.e. 10% and 90%).

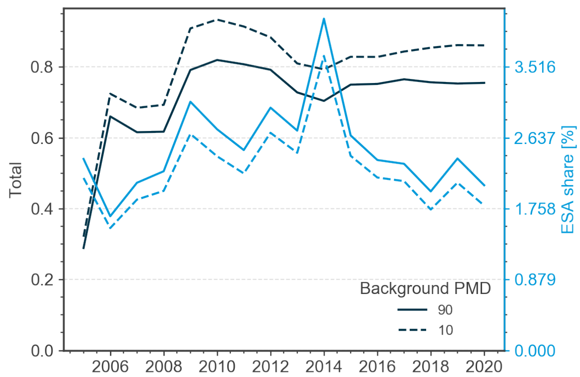

Figure 9. Evolution of the total index for the debris environment and of ESA share.

The results of such comparison are shown in Figure 9, where the dark blue curve refers to the overall cumulated value and the light blue curve refers to the value of the ESA share, expressed as a percentage of the total. It is possible to notice how the evolution of the environment appear to be driven mostly by fragmentations events (i.e. Fengyun-1C appearing in 2006, and Cosmos/Iridium in 2009), which can have a different localised effect at operator level (e.g. the peak in 2014 for the ESA share). This result, together with the observation related to the background populations in Figure 2, highlights once more the

[3]Last edition available at https://www.ucsusa.org/resources/satellite-database.

importance for debris impact assessment to be connected with a computational pipeline for the automated routine generation of updated debris populations.

3. PLANNED MISSIONS

For the analysis of planned missions, similar criteria were applied as the ones described for existing missions in Section 2. In particular, the missions planned to be launched until 2030 were included in the analysis and the assumption that no rocket body is left not disposed was applied. The mission parameters were either duplicated from already existing missions (e.g. in the case of the Sentinels) or retrieved from publicly available information[4][13]. The simulation parameters are reported in Table 2.

Current best-practice are assumed for the mitigation actions. For each mission, the nominal case with a 25-year disposal strategy and 90% success rate was simulated together with cases with controlled re-entry and/or increased success rate. The results of this analysis are reported in Figure 10 where the left part of the legend indicates the strategy (i.e. 25y for a 25-year disposal, CR for controlled re-entry) and the right part the PMD success rate.

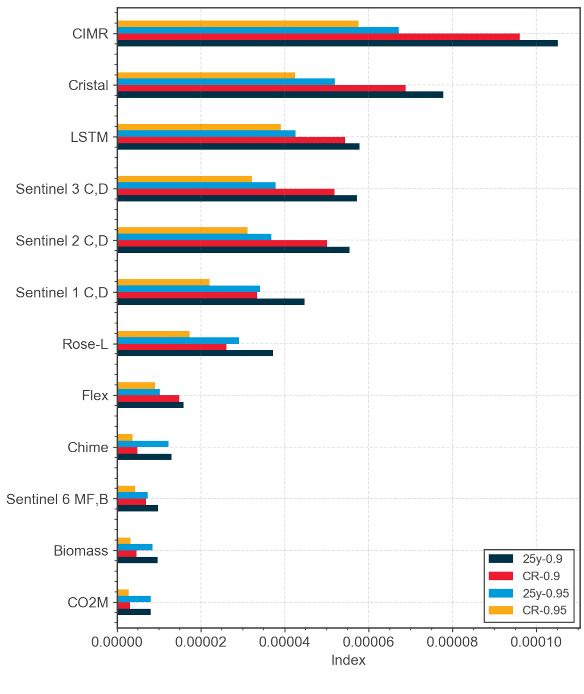

Figure 10. Planned index for future missions, ordered by index value.

[4]The data on Biomass and Flex was retrieved from the corresponding ESA webpage on the Earth Explorers and on eoPortal. Data on the Copernicus Expansion missions can be found on the related ESA webpage and from the press-releases by the manufacturers, as in the case of Airbus.

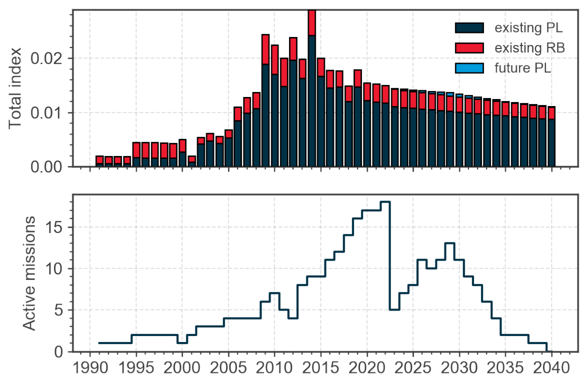

Figure 11. Total index for ESA-developed missions over time, assuming a planned PMD of 90% and successful disposal of all objects.

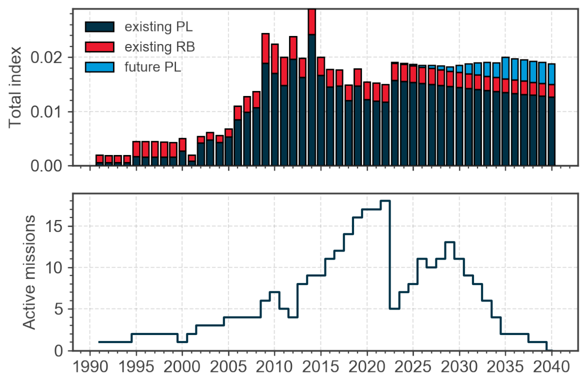

Figure 12. Total index for ESA-developed missions over time, assuming a planned PMD of 90% and no successful disposal.

If we compare the values in Table 2 and the results in Figure 10, we can observe how CO2M, Biomass, Sentinel 2, and Sentinel 3 have a CO2M, Biomass, Sentinel 2, Sentinel 3 have all similar mass but different altitudes (600-800 km) and the fragmentation risk is clearly lower at lower altitudes. Also Chime, Cristal, and CIMR have similar mass values, but again different altitudes (630-820 km): it appears how for mission at higher altitudes, the increase in PMD rate is particularly beneficial because of the higher risk associated with remaining stranded in orbit, whereas at lower altitude a controlled re-entry immediately results in a lower estimated impact on the debris environment.

As already mentioned in the analysis of the existing missions, the results in Figure 10 are dependent on the background debris population, but also modelling assumptions on the description of the fragmentation cloud and on the distribution of operational satellites. This last point has become more relevant in the last years and an automated pipeline is required to perform regular updates of the impact assessments following the actual distribution of active missions.

Table 2. *Sourced parameters used for the analysis of planned missions.*

Name	Launch year	Mass [kg]	Operational altitude [km]	Planned OLT [years]
Sentinel 6MF	2020	1350	1337	7
Biomass	2022	1103	660	5
Flex	2023	430	814	3.5
Sentinel 1C	2023	2157	696	7
Sentinel 2C	2023	1130	789	7
Sentinel 1D	2024	2157	696	7
Sentinel 3C	2024	1130	803	7
Sentinel 2D	2025	1130	789	7
CO2M	2026	1100	602	12
Sentinel 3D	2026	1130	803	7
Sentinel 6B	2026	1350	1337	7
Cristal	2027	1700	760	7.5
Rose-L	2027	2060	690	7
CIMR	2028	1700	817	7
Chime	2029	1640	632	5
LSTM	2029	900	786	12

The results in Figure 10 are also a reminder that debris impact assessments should be performed in addition (and not in substitution) to the application of mitigation guidelines. For example, a very small satellite abandoned in a non-naturally compliant orbit may have a lower associated risk than a large mission properly disposed, but this does not make the first behaviour acceptable. While guidelines ensure that there is a common understanding of which actions are expected from operators, impact assessments can support operators and regulators in measuring the efficacy of such actions.

With this perspective, the analysis presented in this work, and summarised in Figure 11, shows that the ESA fleet can grow significantly in terms of the number of spacecraft, with a limited impact on the overall risk, if the fleet is well managed. The same approach can work for constellations of spacecraft, where the environment drives the design to adopt sustainable strategies and technologies. There is certainly a legacy from past non-disposed missions, but the resulting risk profile is still significantly affected by the choices on the mitigation measures on current and future missions. This can be appreciated if one compares the risk level associated with the fleet in case of successful disposal (Figure 11) with the the case were no spacecraft is successfully disposed Figure 12.

4. CONCLUSIONS

This paper has discussed how the impact of a mission on the debris environment can be quantified with a a risk metric.

The approach was applied to study the fleet of ESA-developed spacecraft, considering existing and future missions. The analysis of existing missions has shown how newer missions tend to have a lower impact on the debris environment thanks to their reduced size and the systematic planning of mitigation actions, including the ones related to the launch vehicles.

The analysis of future missions has shown how the fleet of an operator can grow significantly with a limited impact on overall risk when mitigation actions are implemented. This becomes particularly relevant if we look at space as a limited shared resource as the methodology presented here can support efforts towards its efficient and sustainable utilisation.

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