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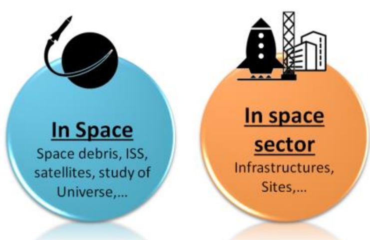

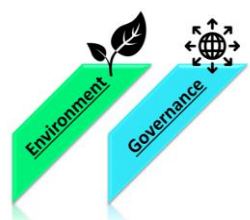

Eco-labelling for spacecraft: a debris index

Based on the example of eco-labelling for household appliances, an index for spacecraft is proposed to reflect its environmental impact in terms of space debris. The index is based on measuring the effect of a potential in-orbit fragmentation on operational satellites. The proposed formulation distinguishes spacecraft by considering their mass, their operational orbits, and the implementation of disposal strategies at the end of their missions. Such an index could be applied in the framework of spacecraft licensing and insurance, and promote awareness for a more sustainable access to space.

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Eco-labelling for spacecraft: a debris index

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Background

The space around the Earth is populated by an increasing number of objects and most of them are not operational ones. According to ESA[1], out of the 23000 catalogued objects, only around 1000 are operational satellites whereas the rest is composed by spent satellites, mission related objects and, mainly, fragments produced by explosions and collisions.

The analysis of the evolution of these numbers over time has suggested the adoption of measures to limit the growth of the debris population such as the passivation of rocket bodies (to limit the risk of explosions) and the definition of protected orbital regions that should be left clear at the end of a mission. However, the efficacy of these measures is still under discussion. In the recent years, a greater awareness of the threat posed by space debris to the future access to space is emerging and initiatives such as ESA Clean Space actively promote the idea of a sustainable use of space. From this point of view, the guidelines for space debris mitigation may take inspiration from the ones developed to create a more sustainable use of resources on Earth to limit global warming.

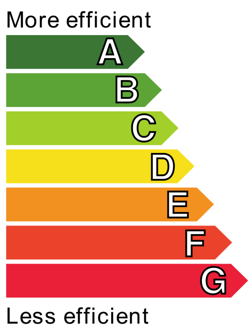

Figure 1: Energy label.

Among different indicators that have been developed to measure the sustainability of our way of life (e.g. CO_2 footprint), the labelling of large household appliances appears to be a successful example, able to shift the market towards more efficient and more environmental friendly products. The European energy label was introduced in 1994 for cold appliances (e.g. freezers, refrigerators), and then extended in the following years to washing machines and dishwasher [Mills and Schleich, 2010]. In the years since its adoption, the seven-level coloured scale has become a well known indicator of energy efficiency, applied (unofficially) also to cars, buildings, and planes.

The labelling of appliances was introduced to fill the so-called *energy-efficiency* gap [Heinzle and Wüstenhagen, 2012], i.e. the fact that consumers were not aware of the consumption of their appliances. This had a direct impact both on the *private* level in terms of the cost of bills, and on the *society* level in terms of the energy demand and the environmental consequences. The eco-labelling contributed to orient the market towards more efficient products, with an increase of the market share of A-level appliances [Heinzle and Wüstenhagen, 2012, Sammer and Wüstenhagen, 2006]. It also helped to define a required minimum level of efficiency, for example with the ban of new refrigerators with classes D to G [Mills and Schleich, 2010]. Finally, it contributed to create awareness in consumers and producers, so that now energy efficiency is among the drivers in the choice of a product [Sammer and Wüstenhagen, 2006]. This work analyses a similar approach that could be applied to tackle the space debris issue.

Description of the idea

The task to define a *debris label* for spacecraft should start from the analysis of the main differences with respect to the case of household appliances. The first important difference is that the labels for appliances are targeted to the final users to orient their decision while buying. For satellites this approach is not feasible as currently missions are developed *ad-hoc* to provide specific data and services. For this reason, labelling a spacecraft should address mostly the spacecraft operators, for example with respect to their interface with space agencies and external organisations.

Connected to this point, it should be observed that the *private* cost of operating a spacecraft with a high *debris index* is less direct than the case of bills for a household. For example, putting spacecraft in a congested orbit could increase the operational cost due to the need of performing more collision

[1] `http://www.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris`, last access 15/06/2016

avoidance manoeuvres. On the other hand, the decision to dispose a spacecraft at the end of its mission may not bring a direct economic benefit to its operator. This observation suggests that a *debris label* would make sense only if implemented within processes such as licensing of the spacecraft before the launch, insurance, or provision of collision avoidance services by external providers.

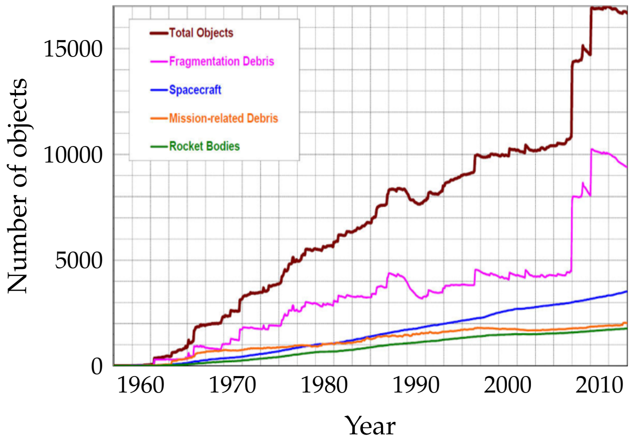

Figure 2: Growth of the catalogued population of objects in Earth orbit[IADC Steering Group, 2013].

Another important decision to make for such an index is what should be measured. It was observed that the long term evolution of the space debris environment is highly affected by the fragmentation of large intact objects. Fig. 2 shows the evolution of the number of objects in orbit with time and one can observe the effect of the fragmentation of Fengyun-1C and of the Iridium-Cosmos collision. A fragmentation can be caused by explosion (for example due to a failure on-board) or by a collision with another object. In both cases, a cloud of fragments is generated: the cloud, initially dense and localised, spreads under the effect of different forces, so that a fragmentation is able to affect objects in different orbital regimes.

A way to measure the severity of the consequences of these fragmentation is to look at the increase in the collision risk for operational satellites. It is very important to underline that this is only one possible option; alternative approaches may be based on the analysis of the fragments still in orbit after a certain time period or the increase in the collision risk for the whole population (so considering not only operational satellites, but also spent satellites and rocket bodies). The reason why this work suggests to look at the effects on operational satellites is because this can be more easily connected to the cost to operators due to fragmentations (*private* cost). In addition, the collision risk for operational satellites may also be seen as an indicator of the availability of future access to space (*shared* cost) because the orbital regions with most operational satellites are the ones that offers a privileged point of view for Earth observation. For example, this is the case of sun-synchronous orbits, which allows the Earth to be observed with constant illumination conditions. Therefore, they are expected to be an important asset also in the future.

For these reasons, the proposed index is based on the evaluation of the consequences of fragmentations on operational satellites. In addition, the likelihood of these fragmentations to happen should be considered. For explosions, the probability can be estimated starting from historical data on fragmentations in orbit, whereas the probability of collisions depends on the orbital region where the spacecraft operates. In summary, the index will have the following structure

$$\text{Index} = p_e \cdot e_e + p_c \cdot e_c \tag{1}$$

where p_e is the probability of an explosion happening, e_e measures the effects of the explosion on operational satellites, p_c is the probability of a collision happening, and e_c measures the effects of the collision on operational satellites.

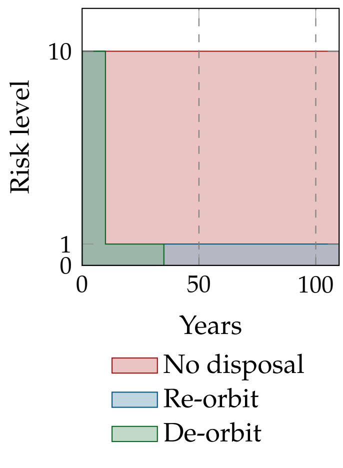

Figure 3: Debris index for different disposal profiles.

This index should be evaluated on a mission profile to distinguish between spacecraft that do and do not implement end-of-life disposal. When a disposal strategy is implemented, the spacecraft leaves its slot at the end of the mission and it is either moved towards higher altitudes or towards the Earth to re-enter in the atmosphere and burn up. Fig. 3 shows an example of the evaluation of the index along the mission profiles for three possible disposal strategies. For simplicity, it is assumed that the operational orbit has a debris index ten times larger than any other orbit. In the first case, no disposal is performed, so the level of the debris index stays constant indefinitely. In the second case, the spacecraft is re-orbited to a less critical region. In the last case, the spacecraft re-enters in the Earth atmosphere 25 years after the end of its mission.

These three scenarios can be compared by looking at the area enclosed by each profile in Fig. 3. This analysis is of course affected by the time-window considered. A short time window (e.g. less than 50 years) will give more relevance to the *private* cost associated to space debris, whereas a large time window (e.g. 100 years) would shift the focus on the *shared* cost among all operators. For this reason, the choice of the time window should be carefully selected and tested to ensure that the debris index is able to distinguish among the three options in Fig. 3, while keeping a good balance between short and long term effect of space debris.

Realistic implementation

The proposed debris index is based on the assessment of the effect of potential fragmentations on operational satellites and the likelihood of these fragmentations to happen.

To assess the effect on operational satellites, a set of representative targets is defined. This is done to avoid having to propagate the trajectories of all operational spacecraft and to build a reference set that is robust to the variation of some elements in the population. In this way, there is no need to regenerate the results after each new launch. A way to define this representative set is to look at the distribution the cross-sectional area of operational satellites, as shown in Fig. 4 for satellites in orbit between 700 and 1000 km. The reason why the cross-sectional area is considered is because it can be seen as an indicator of the vulnerability of a certain orbital region to collisions. Alternatively, the distribution of mass or number of objects may be used. In any case, Fig. 4 shows clearly that operational satellites are concentrated in specific orbits. For example, in Fig. 4 fifteen cells (indicated with a grey marker) collect 90% of the total area distribution. For each cell, a representative target is defined, with mass and area equal to the average values among the object in the cell, and orbital parameters equal to centre of the cell.

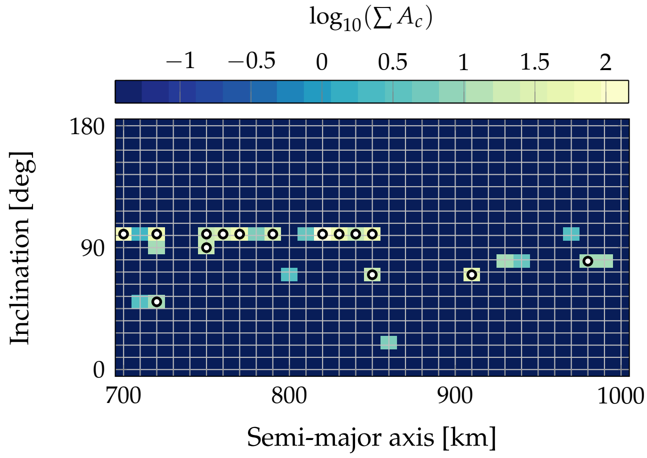

Figure 4: Distribution of the cross-sectional area of spacecraft launched in the last 10 years, in orbit between 700 and 1000 km [Letizia et al., 2016].

Once the target set is defined, the effect of fragmentations can be evaluated. A key point of the suggested approach is not to compute the index only for specific objects, but rather to study its dependence on parameters such as orbit altitude, inclination, and the spacecraft mass.

Fig. 5 shows the variation of the component e_c of the index in function of the orbit semi-major axis and inclination. The grey markers refer to the 15 targets identified from Fig. 4. The colour in Fig. 5 indicates the estimation of the effect of a collision measured as

$$e_c = \sum_{j=1}^{N_T} w_j p_{c,j}, \tag{2}$$

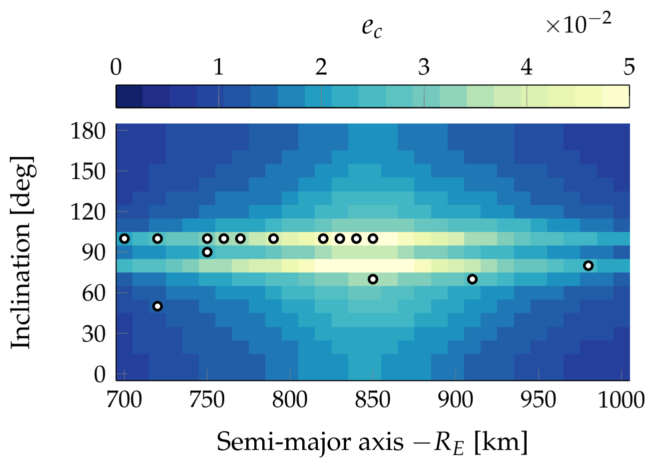

Figure 5: *Reference map*: variation of the term e_c with the orbital parameters [Letizia et al., 2016].

where $p_{c,j}$ is the cumulative collision probability for each representative target and w_j a weighting factor to consider that each cell in Fig. 4 represents a different share of the total area distribution.

One of the advantages of studying the index dependence on these parameters (rather than only evaluating single spacecraft) is that maps such as Fig. 5 show clearly which are the most critical orbits. Observe also that Fig. 5 was obtained simulating always the same fragmentation and changing only its location; in particular, the mass involved in the fragmentation is fixed. It can be shown that if the fragmenting mass is changed, the value of the index changes accordingly following a power law [Letizia et al., 2016]. This follows directly from the equations of the breakup model used to generate the fragments. This behaviour is particularly convenient because it means that no additional simulations are required if one wants to obtain the same map as in Fig. 5 for a different value of the fragmenting mass; it is sufficient to rescale the result already obtained.

In this way, only the reference map in Fig. 5 is needed to compute the index for any specific spacecraft. This only requires to rescale the reference map to the value of the mass of the spacecraft that we want to evaluate and to interpolate the reference map to find the value of the index for the specific orbital parameters of the spacecraft. This means that the process of computation of the index is split into two parts: the generation of the reference map and the actual computation of the index. The generation of the map requires operations that are computationally expensive and that rely heavily on the availability of efficient methods for debris cloud propagation and computational resources. Once the reference map is generated, this can be saved and stored. When the index needs to be computed for some specific objects, this can be done by simply rescaling and interpolating, as explained in the previous paragraph. These operations are fast and can be easily implemented in different programming languages.

In this way, the index can be computed in a matter of seconds for all the objects in a database. This is important because it could be expected that the index may be computed also outside research organisations, for example in companies and institutions with no access to the propagation methods and the computational resources required by the generation of the reference map. All these operations are required to estimate the effect of collisions, so the term e_c in Eq. 1. For the case of explosions, a similar approach can be adopted.

What still needs to be estimated are the two probability terms. The probability of a collision happening (p_c) depends on the orbit where spacecraft operates. Fig. 6 shows the density profile of space debris in Low Earth Orbit as a function of altitude. From this distribution one can derive an estimation of the collision risk for satellites at different altitudes.

The probability of an explosion happening can be estimated by looking at the historical data of in-orbit fragmentations released by NASA, for example through the handbook on the History of In Orbit Fragmentations and the Orbital Debris Quarterly News[2], and used to build a statistical model and estimate p_e in Eq. 1. The value of the index in Eq. 1 is then computed for different points along the mission profile, to obtain a curve such as the ones in Fig. 3 and the final value of the metric is defined by the area enclosed by the risk profile.

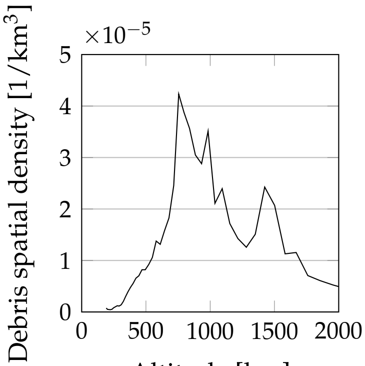

Figure 6: Debris density as a function of altitude. Data from ESA MASTER including all objects larger than 1 mm.

Expected results

The expected output of the proposed debris index is to have a metric able to distinguish space missions on the basis of three main aspects: the mass of the spacecraft, the orbital regime where the spacecraft will operate, and the implementation of end-of-life disposal strategies. The interpretation of the numerical value of this debris index may not be immediate, so a process of normalisation is suggested.

An attempt in this direction was already performed for the classification of the effect of a collision (term e_c). In that case, some severity levels (Tab. 1) were derived from the FMECA (Failure Modes,

[2]`http://orbitaldebris.jsc.nasa.gov/newsletter/newsletter.html`

Table 1: Definition of severity categories [European Cooperation for Space Standardisation, 2009] and possible meaning for the description of the consequences of a breakup.

Severity	Dependability effects	Safety effects	Breakup consequences	Symbol
Catastrophic	Failure propagation	Severe detrimental environmental effects	Subsequent collisions	■
Critical	Loss of mission	Major detrimental environmental effects	Major increase in collision risk	■
Major	Major mission degradation		Increase in collision avoidance manoeuvres	■
Minor	Minor mission degradation		Negligible	■

Effects, and Criticality Analysis) applied during the quality assessment of space missions. The transition between two levels was marked by reference fragmentations.

Fig. 7 shows the classification applied to several missions and, as expected, large missions in sun-synchronous orbits (e.g. Sentinel 3) have larger value of e_c than small missions (e.g. Exactview). A similar approach could be adopted also for the whole index as defined in Eq. 1. The most challenging aspect of the process would be to define levels and reference scenarios to build a scale that enables an immediate understanding as in the case of the labelling of household appliances.

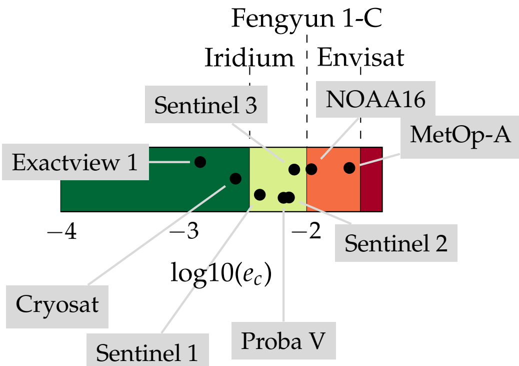

Figure 7: Example of fragmentation severity classification for some representative missions.

Potential risks

A classification of the effects on the space debris environment of a mission is going to be accepted only if all the relevant stake holders are involved in its definition (especially in the formulation of the reference scenarios and the corresponding criticality levels). This means that agencies, operators, manufacturers, and users should be involved in the process. Only in this way it can be avoided that such a classification appears to *blame* specific players.

In addition, such classification should be associated also to a *positive* message. For example, agencies may consider to implement a lean licensing process for *A-level* spacecraft. This would be interesting in particular for small satellites missions that would see a benefit in be more compliant with the guidelines, while now some operators may be tempted to launch their small satellites in a crowded orbital region just because a cheap launch opportunity is available. Similar advantages may be envisioned also in terms of insurance of cost of collision avoidance services provided by external companies. All these measures would enhance the *private* interest of satellite operators to adopt the proposed classification and avoid that it exists only for communication purposes.

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