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ScienceDirect

Advances in Space Research 58 (2016) 1255–1274

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Assessment of breakup severity on operational satellites

Francesca Letizia [a,*], Camilla Colombo [a], Hugh G. Lewis [a], Holger Krag [b]

[a] Astronautics Research Group, University of Southampton, Southampton SO17 1BJ, UK
[b] ESA Space Debris Office, ESOC, 64293 Darmstadt, Germany

Received 9 February 2016; received in revised form 13 May 2016; accepted 17 May 2016
Available online 27 May 2016

Abstract

In the past years, several methods have been proposed to rank spacecraft and space debris objects depending on their effect on the space environment. The interest in this kind of indices is primarily motivated by the need of prioritising potential candidates of active debris removal missions and to decide on the required reliability for disposal actions during the design phase. The index proposed in this work measures the effect of the catastrophic fragmentation of the analysed spacecraft in terms of the resulting collision probability for operational spacecraft. The propagation of the debris cloud generated by the fragmentation and the estimation of the collision probability are obtained by applying an analytical approach based on the study of the density of the fragment cloud. The dependence of the proposed severity index on the mass of the spacecraft and on its semi-major axis and inclination is investigated. The index was computed for the objects in the DISCOS database and its results were compared to other formulations proposed in literature. A discussion on the results and on the comparison is presented.

Keywords: Space debris; Environmental index; Debris cloud

1. Introduction

The long term evolution of the space debris environment appears to be highly affected by fragmentations of massive objects, such as intact large spacecraft and rocket bodies (Rossi et al., 2015b). For this reason, different metrics have been proposed to rank spacecraft depending on the consequences of their fragmentation on the space environment. The purpose of these analyses is twofold. First, one objective is to obtain a better insight on the critical parameters that have the largest influence on the space debris evolution. Second, the output of these rankings could lead to the identification of potential candidates for active debris removal missions: in such a scenario, it would be important to decide which spacecraft should be removed first to have the largest global beneficial effect.

Several authors have proposed different approaches to the problem and highlighted the relevance of having a quantitative measure of the environmental effect of an object in orbit, depending on its orbital parameters and physical characteristics (Utzmann et al., 2012; Bastida and Krag, 2013; Lang et al., 2013; Rossi et al., 2015b). Rossi et al. (2016), for example, simulated different fragmentations, considering locations and targets representative of the distribution of intact objects in orbit. For each scenario, the number of objects present in orbit in the 200 years following the fragmentation was studied and used to measure the effect of the fragmentation. Alternatively, Rossi et al. (2015b) introduced a *criticality* index, which depends on the background debris density, the object residual lifetime, the mass, and its orbital inclination. Similar parameters were identified also by Utzmann

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[*] Corresponding author.
E-mail addresses: f.letizia@soton.ac.uk (F. Letizia), c.colombo@soton.ac.uk (C. Colombo), h.g.lewis@ac.uk (H.G. Lewis), Holger.Krag@esa.int (H. Krag).

http://dx.doi.org/10.1016/j.asr.2016.05.036

et al. (2012). In these case, no simulation is performed, and the indices collect what are identified as the most relevant factors to provide an immediate measure of the criticality of the studied object. A different approach was presented by Lewis (2014), where the proposed environmental index is computed considering the spacecraft orbital region, the implementation of mitigation measures for the spacecraft and the long term effect of the selected measure.

These examples show how the proposed environmental indices focus on different aspects of the space debris environment, ranging from the likelihood of the breakup to happen to the evaluation of the long-term changes in the whole debris population. In the ECOB index (Environmental Consequences of Orbital Breakups) proposed in this work, only the effects of potential breakups, of spacecraft and rocket bodies, are studied. For this reason, ECOB is indicated in the following also as a *severity index* to stress that it does not consider the likelihood of breakups to happen, but only how dangerous they can be for other space objects. In particular, the effect of a breakup is measured by the resulting collision probability for a set of target spacecraft with the breakup fragments over time. A grid in semi-major axis, inclination, and mass is used to define possible initial conditions of the breakup. For each case, the evolution of the produced debris cloud is modelled applying an analytical method, which describes how the cloud density changes under the effect of atmospheric drag. Given the fragment density, the collision probability of the target is obtained applying the analogy with the kinetic theory of gases. Once the value of the index is know for any point in the grid, a simple interpolation can be used to compute the value of the index for any object.

The article is organised as follows. Section 2 will describe the debris cloud propagation method and Section 3 will introduce the structure of the proposed environmental index. Some preliminary results are presented in Section 4 and they will be used in Section 5 to specify the index computation. More detailed results will be presented in Section 6 and the comparison with other proposed environmental indices will be discussed in Section 7.

2. Debris cloud propagation method

According to the NASA breakup model (Krisko, 2011), for each trackable object produced by a fragmentation there are millions of objects in the size range between 1 mm and 5 cm. Considering these numbers, even low intensity fragmentations can easily produce some thousands objects, whose individual propagation would make the simulation prohibitive in terms of computational resources (i.e. time and RAM). Evolutionary studies on the debris population usually deal with this issue by setting a cut-off fragment size at 10 cm, so that only objects larger than this threshold are included in the simulations. However, especially when the impact of a single breakup is analysed, it could be relevant to include all objects that have the potential to interfere with other spacecraft, decreasing the threshold down to 1 mm. This change in the scope of the analysis can be achieved by abandoning the evaluation of the single fragments' trajectories and studying the fragmentation cloud globally.

The propagation method CiELO (debris Cloud Evolution in Low Orbits) was developed with this aim: within this approach, the fragmentation cloud is described in terms of its spatial density, whose evolution in time under the effect of drag is obtained by applying the continuity equation. A detailed description of the method can be found in Letizia et al. (2015b), whereas only a brief overview of the approach is provided here, focussing mostly on the new improvements with respect to Letizia et al. (2015b).

The simulation of a fragmentation event starts with the modelling of the breakup. The NASA breakup model (Johnson and Krisko, 2001; Krisko, 2011) is used for this purpose. The evolution of the fragment cloud from this time instant is affected both by the dispersion of the energy among the fragments and the effect of orbit perturbations. Considering only the case of fragmentations in LEO, the Earth's oblateness spreads the fragments to form a band around the Earth. Once the band is formed, the atmospheric drag can be considered as the main perturbation and the continuity equation can be applied to obtain the cloud density evolution, following the approach firstly proposed by McInnes (1993).

Compared to formulation by McInnes (1993), where the debris density is function of the radial distance from the Earth (r) only, the method was extended to express the cloud density as function of semi-major axis (a) and eccentricity (e) (Letizia et al., 2015d). This extension results into an increase in the method applicability: whereas the description with the distance only can be applied to fragmentations starting from circular orbits between 800 and 1000 km, the formulation in a and e can be used also for orbital altitudes between 700 and 800 km. This means that the analytical method can be employed for the whole region where the majority of fragmentations occurred (Orbital Debris Program Office, 2014).

2.1. Density-only formulation

As briefly mentioned at the beginning of this section, the continuity equation is applied once the band is formed because only in that moment the hypotheses required to obtain an analytical solution hold. This means that alternative modelling techniques are required to describe the transition to the band. In Letizia et al. (2015b) this was done by numerically propagating the trajectory of the fragments for the months required to form the band. In the new version of the model used in this work this is done by applying a method similar to the one embedded in the continuity equation, which does not involve integrating the fragments' trajectories. When the continuity equation is solved with the method of characteristics, the value of the solution at a certain time is obtained by *reshaping* the initial condition