Evolutionary Predictive Model of the Space Debris Environment

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Abstract

In recent years, the exponential growth of space debris has become evident. To mitigate debris problem, a precise model for predicting the space debris environment is necessary. This research project tackles this challenge of space debris modelling, through adopting the continuum approach. In the continuum approach a space debris cloud is treated as a fluid. As a novel aspect, the model will include a detailed uncertainty analysis. The challenge here is to find a unified approach to deal with the different uncertainty sources. The analysis will help to identify the largest uncertainty sources and will aid in developing a more precise model. To find a balance between robustness and computational time high performance computing will be employed. Furthermore, the effect of mitigation measures and newly launched missions will be investigated through the combination of historical data with economic forecasting methods, making it possible to make informed decisions for sustainable space operations.

Introduction

In the last 10 years the landscape of space flight has changed drastically. Historically, only national and supranational agencies like NASA [1], ESA [2], Roscosmos [3] were able to put a satellite into space. With companies like SpaceX [4] offering rocket starts commercially, space has become increasingly accessible. In 2021, the start-up sector in space saw a significant increase in funding. Relative to 2020, capital investment grew by 82% [5]. This offers several opportunities, but it also means that the number of players and the number of objects in the popular regions of space like the low-earth orbit and the geostationary orbit is increasing rapidly. Mega-constellations for commercial use by companies such as SpaceX, Amazon [6] and OneWeb [7] further contribute to the rising number of satellites. This sharp increase can be seen in Fig. 1. The number of objects is growing exponentially.

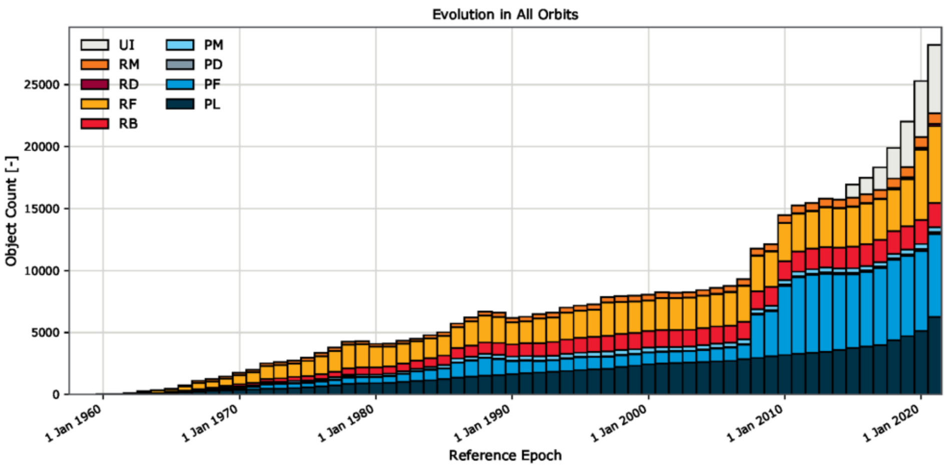

Fig. 1: Evolution of the number of objects in all orbits [8]

As a consequence, space debris has become an increasingly relevant topic. Space debris refers to any artificial object in space that is no longer functioning. This also includes fragments and any parts thereof. Space debris poses a risk to active satellites, since even small fragments could cause fatal damage [9]. In 2009 a catastrophic collision occurred between the non-functioning satellite Cosmos 2251 and the operational satellite Iridium 33. This collision created a large number of fragments, that span multiple altitudes. The collision was caused by lack of knowledge about the position of the Cosmos 2251 satellite [10]. In the worst-case scenario, collisions like these could cause a chain effect, where the fragments created by one collision collide with other objects and so on. This is called the Kessler syndrome [11]. To keep space usable for future generations, space debris has to be mitigated and collisions have to be avoided. For this purpose, an accurate model of the space debris population has to be developed.

This research is part of the GREEN SPECIES project, funded by the European Research Council on the “Robust control of the space debris population to define optimal policies and an economic revenue model for sustainable development of space activities” and aims at developing a highly accurate and robust space debris model, including an uncertainty analysis.

State of the Art

The modelling of space debris is usually separated into two main approaches: A deterministic and a statistical approach. In the deterministic approach each space debris object is tracked and propagated individually. This approach is widely used and assesses the biggest collision risks [12] Fragments smaller than 10 cm are usually neglected in these simulations, since the computational cost associated with modelling each small fragment is exceedingly high. The growing number of objects in space and the increasingly high traffic neglecting centimeter or sub-centimeter debris results in underestimating the actual threat for safe in-orbit operations. Therefore, a comprehensive model of these smaller fragments is necessary for safe and sustainable use of space.

Instead of deterministic models, a continuum approach can be adopted for these smaller fragments. The continuum approach treats the small space debris objects as a debris cloud, which is modelled through a density function. This density function can be propagated using the equation of continuity [13]

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{f}) = \dot{n}^{+} - \dot{n}^{-}$$

where n is the phase space density, $\boldsymbol{f}$ represents the forces that account for the orbital dynamics and orbit perturbations and $\dot{n}^{+}$and $\dot{n}^{-}$ account for the sources and sinks of space debris objects, respectively. Solving this equation is not trivial, since it represents a Partial Differential Equation (PDE).

The first fully analytical solution for the long-term propagation of debris in Low Earth Orbit (LEO) was presented by McInnes in 1993 [13] based on the Method of Characteristics (MoC). The MoC transforms the PDE into a system of ordinary differential equations and the solution is obtained along characteristic lines. McInnes solved the continuity equation in two dimensions: Time and the radial distance from the center of the Earth. As a perturbation only the atmospheric drag was considered. In recent years, Letizia et al. (2015) [14] has built on the work of McInnes and adopted the approach to model the long-term evolution of a debris cloud generated as a result of a fragmentation event. This method was extended into multiple dimensions (Letizia et al. (2016) [15]). With the work of Colombo et al. (2016) [16] a multi-dimensional approach for the propagation of the global space debris population was presented.

Instead of solving the equation analytically the characteristics can also be numerally propagated. Frey, Colombo et al. (2019) [17] presented the Starling suite, which estimates the non-linear evolution of densities in orbit. A Gaussian Mixture Model (GMM) is applied to the numerically propagated characteristics in order to obtain a simpler, surrogate model. The solution is also extended into the multi-dimensional domain.

In Giudici et al. (2023) [18], the Starling suite was extended to model any non-linear dynamics. Another approach to solve this problem is the finite volume method. This describes the process of discretizing the space into finite volumes and propagating the density using the continuity equation for each of these volumes. The equations are integrated numerically. This has the benefit of immediately achieving the full density [19]. These two models were combined and used to develop COMETA for the long-term propagation of the debris environment in LEO using the continuum approach [20].

To prevent the worst-case scenario of a cascading effect from happening, the space debris environment needs to be well understood. This not only includes modelling the existing space debris environment, but also requires an understanding of how the environment develops in the future. The main goal of this research project is to provide a better understanding of the space debris environment and the uncertainties associated with it. This should also include the effect different events have on it as a whole.

Methodology

In this research, the model of the space debris environment will be extended to include uncertainties to include uncertainties. For this the continuum approach described previously will be adopted. The main research goal of this PhD is to identify and address the biggest sources of influence in the model.

Dolado et. al (2015) [21] presented a classification of uncertainty sources in space debris modelling. This will be built upon to classify uncertainties based on the biggest impact on the space debris environment.

Uncertainties not only stem from numerical modelling, but also from socio-economic and political circumstances. One example of this kind of uncertainty stems from the launch traffic model.

While the actual launch traffic is out of control for the modeler, the model itself can be improved upon. Most models, such as DELTA from ESA [22] or LEGEND from NASA [23] simply repeat the historical launch pattern, while treating constellations separately. This research instead aims to implement a highly adaptable and accurate launch traffic model by combining the study of historical data with economic and financial forecasting models. Additionally, post-mission disposal failures influence the debris environment. Studying these as done in Fernández et. al [24] and quantifying them will help improve the space debris model.

Next to these socio-economic uncertainties, the space debris environment is also highly influenced by physical phenomena such as e.g. solar activity and the atmospheric drag. The strength of the atmospheric drag influences the lifetime of a space debris object in orbit. The solar cycle influences the atmospheric drag, showing that uncertainties in the space debris model are also highly dependent on each other. While for the launch traffic model it was possible to treat it separately from the other uncertainties, here both play a role together. An approach needs to be found that can treat the interacting uncertainties concurrently. For the uncertainty in parameters like the area-to-mass ratio an uncertainty distribution could be defined, which can be treated as a density. The density equation would evolve with a zero derivative. This would allow the uncertainty to be propagated with the continuity equation directly. For the uncertainties of the dynamic equations a more complex approach needs to be defined.

For this purpose, several different uncertainty quantification methods will be investigated. In many applications Monte Carlo methods are used to quantify uncertainties. This could quickly become too computationally expensive for the space debris model. Therefore, other methods such as polynomial chaos expansion or propagating a probability density function directly will be investigated. In Trisolini et. al (2021) [25] the uncertainties of the re-entry dynamics were propagated directly in combination with the dynamics with the continuity equation. It will be investigated whether this approach can also be used for the global space debris environment. This would include extending the current 8-dimensional model to higher dimensions to add the uncertainty as a dimension. Here, this could be either done through the MoC or the FVM approach. Next to the propagation of uncertainties, the model can also be validated using existing data. Horstmann et. al (2019) [26] formulated an error function to classify uncertainties in the deterministic model. To improve computational time surrogate models could also be employed. In the end a balance needs to be found between the computational complexity and the accuracy of the model. Using high performance computing will also be explored. Based on this the best method will be selected.

Conclusions

This research project will give the framework for sustainable use of the space environment. With the inclusion of uncertainties into the space debris modelling, the models can move on from sensitivity analysis to accurate forecasting models. Including the effect of mitigation strategies and newly launched missions will help in guiding future policy decisions and will ensure safe and sustainable space operations in the future.

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References

[1] "NASA." Aug. 2023. Accessed: Mar. 13, 2024. [Online]. Available: https://www.nasa.gov/

[2] "ESA." Aug. 2023. Accessed: Mar. 13, 2024. [Online]. Available: https://www.esa.int

[3] "Roscosmos." Mar. 2024. Accessed: Mar. 13, 2024. [Online]. Available: http://archive.government.ru/eng/power/106/

[4] "SpaceX." Aug. 2023. Accessed: Mar. 13, 2024. [Online]. Available: https://www.spacex.com/

[5] Bryce Tech, "Start-Up Space: Update on investment in commercial space ventures," Aug. 2022. Accessed: Mar. 13, 2024. [Online]. Available: https://brycetech.com/reports

[6] "Amazon Mega Constellation Project." Aug. 2023. Accessed: Mar. 13, 2024. [Online]. Available: https://www.aboutamazon.com/news/innovation-at-amazon/what-is-amazon-project-kuiper

[7] "OneWeb." Aug. 2023. Accessed: Mar. 13, 2024. [Online]. Available: https://oneweb.net/

[8] E.S.D Office, "ESA's annual space environment report," 2023.

[9] G. Drolshagen, "Impact effects from small size meteoroids and space debris," *Advances in Space Research*, vol. 41, no. 7, pp. 1123–1131, 2008, doi: 10.1016/j.asr.2007.09.007.

[10] C. Pardini and L. Anselmo, "The short-term effects of the cosmos 1408 fragmentation on neighboring inhabited space stations and large constellations," *Acta Astronaut*, vol. 210, pp. 465–473, 2023.

[11] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of the debris belt," *J Geophys Res Space Phys*, vol. 83, no. A6, pp. 2637–2646, 1978.

[12] S. Flegel *et al.*, "The master-2009 space debris environement model," *European Space Agency, (Special Publication) ESA SP*, vol. 672, Mar. 2009.

[13] C. R. McInnes, "An analytical model for the catastrophic production of orbital debris," *ESA J*, vol. 17, no. 4, pp. 293–305, 1993.

[14] F. Letizia, C. Colombo, and H. G. Lewis, "Analytical model for the propagation of small-debris object cloud after fragmentations," *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 8, pp. 1478–1491, 2015.

[15] F. Letizia, C. Colombo, and H. G. Lewis, "Multidimensional extension of the continuity equation method for debris cloud evolution," *Advances in Space Research*, vol. 57, no. 8, pp. 1624–1640, 2016.

[16] C. Colombo, F. Letizia, and H. G. Lewis, "Spatial density approach for modelling of the space debris population," in *26th AAS/AIAA Sp. Flight Mech. Meet*, 2016, pp. 16–465.

[17] S. Frey, C. Colombo, and S. Lemmens, "Application of density-based propagation of fragment clouds using the Starling suite," in *1st International Orbital Debris Conference (IOC)*, Sugar Land (TX, USA), 2019, pp. 1–10.

[18] L. Giudici, M. Trisolini, and C. Colombo, "Probabilistic multi-dimensional debris cloud propagation subject to non-linear dynamics," *Advances in Space Research*, vol. 72, no. 2, pp. 129–151, 2023.

[19] L. Giudici and C. Colombo, "Space debris density propagation through a finite volume method," Mar. 2023.

[20] L. Giudici, C. Colombo, A. Horstmann, F. Letizia, and S. Lemmens, “Density-based evolutionary model of the space debris environment in low-Earth orbit,” *Acta Astronaut*, vol. 219, pp. 115–127, Jun. 2024, doi: 10.1016/j.actaastro.2024.03.008.

[21] J. Dolado, C. Pardini, and L. Anselmo, “Review of uncertainty sources affecting long-term predictions of space debris evolutionary models,” *Acta Astronaut*, vol. 113, 2015.

[22] B. B. Virgili, “DELTA (DEBRIS ENVIRONMENT LONG-TERM ANALYSIS),” 2016. [Online]. Available: https://api.semanticscholar.org/CorpusID:197866235

[23] J.-C. Liou, D. Hall, P. Krisko, and J. N. Opiela, “LEGEND – a three-dimensional LEO-to-GEO debris evolutionary model,” *Advances in Space Research*, vol. 34, pp. 981–986, Mar. 2004, doi: 10.1016/j.asr.2003.02.027.

[24] Fernández, L. A., Wiedemann, C., & Braun, V. (2022). Analysis of Space Launch Vehicle Failures and Post-Mission Disposal Statistics. Aerotecnica Missili & Spazio, 101(3), 243–256. https://doi.org/10.1007/s42496-022-00118-5

[25] M. Trisolini and C. Colombo, “Propagation and Reconstruction of Reentry Uncertainties Using Continuity Equation and Simplicial Interpolation,” *Journal of Guidance, Control, and Dynamics*, vol. 44, no. 4, pp. 793–811, Apr. 2021, doi: 10.2514/1.G005228.

[26] A. Horstmann, H. Krag, and E. Stoll, “Providing Flux Uncertainties in ESA-MASTER: The Accuracy of the 1cm Population,” in *First International Orbital Debris Conference*, in LPI Contributions, vol. 2109. Dec. 2019, p. 6015.