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Title: Review of Uncertainty Sources Affecting the Long-Term Predictions of Space Debris Evolutionary Models

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Abstract: Since the launch of Sputnik-I in 1957, the amount of space debris in Earth's orbit has increased continuously. Historically, besides abandoned intact objects (spacecraft and orbital stages), the primary sources of space debris in Earth's orbit were (i) accidental and intentional break-ups which produced long-lasting debris and (ii) debris released intentionally during the operation of launch vehicle orbital stages and spacecraft. In the future, fragments generated by collisions are expected to become a significant source as well.

In this context, and from a purely mathematical point of view, the orbital debris population in Low Earth Orbit (LEO) should be intrinsically unstable, due to the physics of mutual collisions and the relative ineffectiveness of natural sink mechanisms above ~ 700 km. Therefore, the real question should not be "if", but "when" the exponential growth of the space debris population is supposed to start. From a practical point of view, and in order to answer the previous question, since the end of the 1980's several sophisticated long-term debris evolutionary models have been developed.

Unfortunately, the predictions performed with such models, in particular beyond a few decades, are affected by considerable uncertainty. Such uncertainty comes from a relative important number of variables that being either under the partial control or completely out of the control of modellers, introduce a variability on the long-term simulation of the space debris population which cannot be captured with standard Monte Carlo statistics.

The objective of this paper is to present and discuss many of the uncertainty sources affecting the long-term predictions done with evolutionary models, in order to serve as a roadmap for the uncertainty and the statistical robustness analysis of the long-term evolution of the space debris population.

*Highlights (for review)

- Evolutionary models depend on many endogenous/exogenous variables
- Many of these variables are partially or completely out of the control of modelers
- Long term projections are greatly affected by uncertain variables
- Uncertain variables widen the envelope of the possible future evolutions of debris

REVIEW OF UNCERTAINTY SOURCES AFFECTING THE LONG-TERM PREDICTIONS OF SPACE DEBRIS EVOLUTIONARY MODELS

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ABSTRACT

Since the launch of Sputnik-I in 1957, the amount of space debris in Earth's orbit has increased continuously. Historically, besides abandoned intact objects (spacecraft and orbital stages), the primary sources of space debris in Earth's orbit were (i) accidental and intentional break-ups which produced long-lasting debris and (ii) debris released intentionally during the operation of launch vehicle orbital stages and spacecraft. In the future, fragments generated by collisions are expected to become a significant source as well.

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Unfortunately, the predictions performed with such models, in particular beyond a few decades, are affected by considerable uncertainty. Such uncertainty comes from a relative important number of variables that being either under the partial control or completely out of the control of modellers, introduce a variability on the long-term simulation of the space debris population which cannot be captured with standard Monte Carlo statistics.

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I. INTRODUCTION

SINCE the launch of Sputnik-I in 1957, human activities in space have led to the production and release of hundreds of millions of objects of various sizes, from particles smaller than 1 mm to non-operational spacecraft measuring many square metres. While in the past, besides abandoned intact objects, i.e. spacecraft and orbital stages, the primary sources of space debris were accidental and intentional break-ups, as well as the intentional release of mission related objects, the growing amount of space debris makes the risk of collision among space objects increasingly likely. In this context, and from a purely mathematical point of view, the orbital debris population in LEO should be intrinsically unstable, due to the physics of mutual collisions and the relative ineffectiveness of natural sink mechanisms above ~ 700 km (cf. Fig. I).

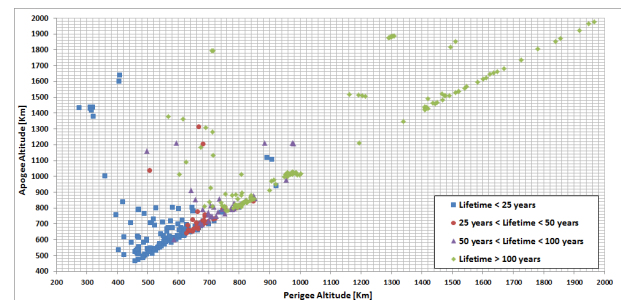


Figure I. - Orbital lifetime as a function of the disposal perigee and apogee altitude for spacecraft and orbital stages residing in the LEO region.¹

Therefore, the real question should not be "if", but "when" the exponential growth of the space debris population were supposed to start. To address such important question, since the end of the 1980's several sophisticated long-term debris evolutionary models have been developed^{2,3,4,5,6}. These tools have grown in complexity and capabilities, incorporating accurate orbit propagators, detailed launch traffic models, all the relevant sources and sinks mechanisms, updated on-orbit explosion/fragmentation statistics, improved break-up models for explosions and collisions (in terms of

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debris number, area, mass and velocity distributions), various methods for collision probability estimation, Monte Carlo statistical methods based on discrete-time Markov chains, etc. Currently these models are frequently used to probe reasonable future scenarios, being very well suited to evaluate the relative effectiveness of mitigation and remediation measures. The predictions done with these models are compared and fine-tuned, for instance in the framework of studies promoted by the Inter-Agency Space Debris Coordination Committee (IADC)⁵.

Unfortunately these predictions, in particular beyond a few decades in the future, rely on our ability to predict and model a series of exogenous (e.g. future solar activity, the nature and magnitude of space traffic activities, etc.) and endogenous (e.g. the number of fragments generated after each collision, the number of future collisions among orbiting objects, etc.) variables, many of which are completely out of the control of modellers. Therefore, the actual predictions done with these models are affected by considerable uncertainty. This uncertainty is higher than that resulting from the analysis of Monte Carlo statistics, as the latter only measures the intrinsic variability in the occurrence of stochastic events modelled in the simulations^{7,8,9,10,11,12,13,14}.

II. UNCERTAINTY SOURCES

Mid-term and long-term projections of the Earth's satellite population performed with actual evolutionary models are affected by several important sources of uncertainty. Some of these uncertainty sources can be considered under the partial control of modellers, while some of them are completely outside their control¹⁵.

Among the variables being under the partial control of modellers we can list:

- Initial debris environment;
- Atmospheric density models;
- Long term trajectory propagation;
- Collision probability estimation;
- Collision energetic threshold for catastrophic break-up;
- Collision geometry leading to catastrophic break-up;
- Collision class leading to catastrophic break-up (debris vs. debris, debris vs. intact, intact vs. intact);
- Break-up models (fragment number, area, mass and velocity distributions);

- Target ranking for active debris removal.

Among the variables being completely outside the control of modellers we can list:

- Future launch traffic and space technology evolution;
- Quality of mitigation measures adopted and overall levels of compliance;
- Viable technological options for remediation measures with active removal;
- Irresponsible deliberate actions endangering the environment (e.g. ill-conceived anti-satellite weapons tests);
- Evolution of solar and geomagnetic activity;
- Evolution of the upper atmosphere of the Earth at satellite altitudes.

All the variables, and the variables on which these variables depend, will have an impact on the way the space debris population surrounding the Earth will evolve on the long-term.

III. REVIEW OF UNCERTAINTY SOURCES UNDER THE PARTIAL CONTROL OF MODELLERS

III.I Initial Debris Environment

The initial debris environment is of paramount importance, as it represents the initial condition from which the long-term evolution of the space debris population will be derived.

The degree of uncertainty affecting the initial debris environment will depend on the minimum debris size considered for the simulation¹⁶. If the attention is focused on the objects driving the long-term collisional evolution of the environment, i.e. those bigger than 10 cm in LEO, the current catalogue could be considered as reasonably complete. In addition, current state of the art models already take into account the catalogue incompleteness¹⁷ (e.g. the Henize factor), limiting the intrinsic uncertainty of the initial debris environment to more than acceptable levels.

III.II Atmospheric Density Models

Numerous atmospheric density models have been developed over the past few decades. These models could be subdivided into two main classes:

- Time varying models developed from the combination of conservation laws and atmospheric constituent models, to build a

physical model (e.g. NRLMSISE-00, JB2008, DTM2013, GOST2004, etc.);

- Static models developed using simplified physical concepts, based on in-situ measurements and satellite tracking data (e.g. Exponential, Harris-Priester, etc).

Actual space debris evolutionary tools usually use time varying atmospheric density models, in order to take into account the effect of the long-term evolution of the solar activity. While such models are affected by substantial local and short-term discrepancies (cf. Fig. II), most models provide a sufficiently good representation of the average Earth's atmospheric density and therefore do not represent a limiting accuracy factor (cf. Fig. III).

To validate the previous affirmation, Fig. III shows the relative difference of the mean semi-major axis evolution, over 50 years, computed with two different atmospheric models, NRLMSISE-00 and DTM78. Fig. II shows instead the relative difference of air density estimated by each of the models. These figures have been computed using the “study case” configuration presented in Tab. 1, with identical solar and geomagnetic activity.

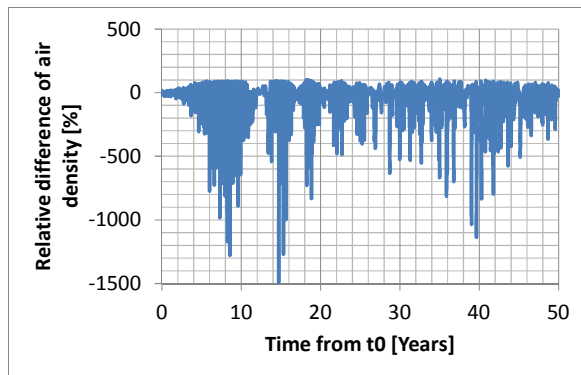


Figure II. - Relative difference of air density computed with NRLMSISE-00 and with DTM78 atmospheric models.

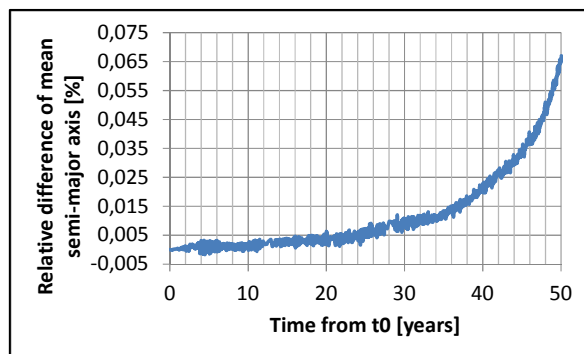


Figure III. - Relative difference of mean semi-major axis computed with NRLMSISE-00 and with DTM78 atmospheric models.

Initial Epoch	01/01/2000 00:00:00/000 UT
Semi-Major Axis [Km]	7128.14
Eccentricity	0.01
Inclination [deg.]	98.391
A/M [m²/Kg]	0.012
C_D	2.2
F10.7 [sfu]	150
Geomagnetic Index (A_p)	8

Table 1. – “Study Case” configuration

III.III Long-Term Trajectory Propagation

Trajectory propagation, in particular at short-term scales, is one of the variables that can be considered under a relative good control by modellers, as in principle there is no intrinsic limitation to reach any appropriate level of accuracy with suitable physical mathematical models, proper software tools and adequate computational resources.

Nevertheless, up-to-date models and applications are concerned by two main problems:

- Computational time: The increase on accuracy of the models used for trajectory propagation is most of the times linked with an increase of the computational burden. As a consequence, and depending on the application, such increase may not be justified. To overcome this limitation, analytical¹⁸ and semi-analytical¹⁹ orbital propagators have been developed, in order to account for the main perturbations affecting the orbital propagation, while the computational time is kept at reasonable levels. Fig. IV shows the very good coherence between the fully numerical model, implementing a quite complete dynamical model (GRIM4S4 = 36 × 36 geopotential harmonics, third body perturbation, atmospheric drag and solar radiation pressure with eclipses), and the STELA¹⁹ model. Nevertheless it is obvious that there is a significant difference in accuracy between the SGP4¹⁸ model and both the numerical and semi-analytical models, when propagating a typical LEO object in the long term. While this difference is justifiable by the fact that the SGP4 model has been developed for short-term applications, Fig. IV highlights the possible consequences of using, for long term propagations, a model that has not been conceived to do so.

In terms of computation time, the 50 years orbital propagation with the numerical model

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took 1200 times more computational effort when compared with SGP4, while the propagation with STELA took 16 times more computational time than SGP4.

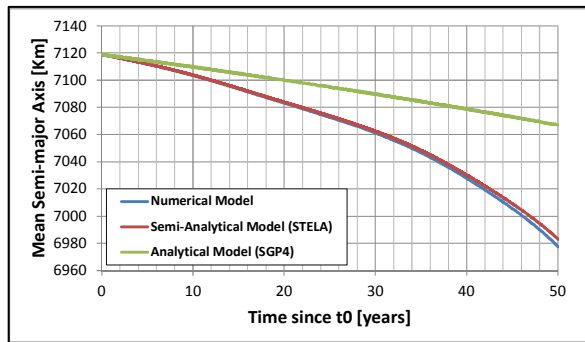


Figure IV. - Mean semi-major axis evolution computed with Tab. 1 parameters and with a fully numerical propagator (blue), with the STELA¹⁹ semi-analytical propagator (red) and with the SGP4¹⁸ fully analytical orbit propagator (green).

- Un-Modelled and Chaotic Dynamics: Among the dynamical error sources affecting the long-term orbital propagation of space objects, the following have to be highlighted:
 - Roto-Translational Coupling: The roto-translational coupling accounts for the coupling between the motion of the space object on its orbit and around its centre of mass. This coupling affects the non-operational objects (i.e. space debris), as the operational objects are most of the time controlled in attitude.

This effect is of key importance for objects with high area-to-mass ratios and relatively slow tumbling motions compared with the orbital periods, as their effective drag and reflecting area, even though averaged along an orbit, could change considerably as a function of their attitude evolution, generating a variation of the non-conservative perturbing accelerations by the same factor. Most of the up-to-date orbital propagators used for long-term debris modelling do not take into account such coupling. To quantify this error with a known satellite, Fig. V presents the geometry of a SPOT-like satellite. As a function of the attitude of the satellite, the exposed drag area could vary from 8.0658 m² to 22.259 m². If this satellite were considered as randomly tumbling, its mean exposed drag area would be of

16.904 m². Fig. VI shows the evolution of the mean semi-major axis over 100 years, as a function of the exposed drag area of such SPOT-like satellite

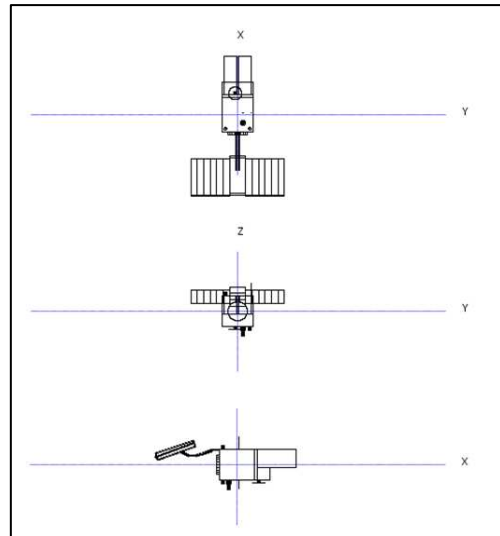


Figure V. - Geometry schema of a SPOT-like satellite.

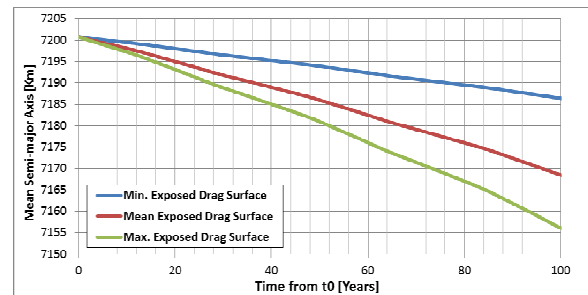


Figure VI. - Semi-major axis evolution depending on the exposed drag area for a SPOT 5 like orbit.

- Resonant Effects: In particular high eccentric orbits have complex dynamical properties due to their high eccentricity and the wide range of inclinations and semi-major axis covered. Especially third body perturbations may lead to resonant effects with strong influences on the orbital parameters evolution²⁰. Some theoretical considerations about the dynamical properties of highly elliptic orbits are provided in references 21 and 22. As an example, Fig. VII shows the semi-major axis evolution of a geostationary transfer orbit at low inclination, typical for Ariane launches, in which the various curves were obtained by varying of 0.1% the area-

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to-mass ratio of the object (the same outcome would have been obtained by maintaining the area-to-mass ratio constant and changing instead, by a small amount, the predicted solar activity). In this example, the semi-major axis evolutions were reasonably similar for about 15 years, but the ensuing occurrence of a resonance condition led to significant further evolution discrepancies, depending on very small and basically unpredictable differences in the conditions at resonance entrance.

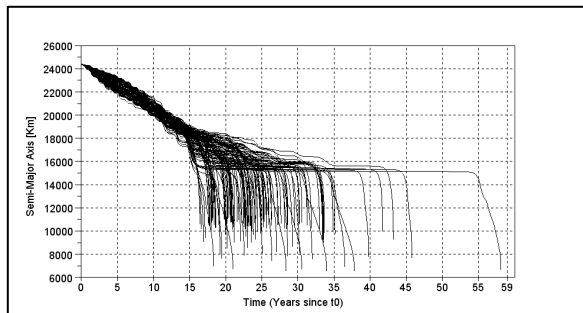


Figure VII. - Semi-major axis evolution of a geostationary transfer orbit at low inclination in which the various curves were obtained by varying of 0.1% the area-to-mass ratio of the object.

III.IV Collision Probability Estimation

Many algorithms exist for the computation of the probability of collision between two orbiting objects. Their nature and formulation mainly depends on the problem to which these algorithms are going to be applied.

If one is interested in the computation of the short-term probability of collision between two orbiting objects, which is done for example in the context of operational conjunction assessment, algorithms are used to integrate the probability density function, defining the on-orbit uncertainties of the two orbiting objects, on a sphere of radius equal to the hard body radius^{23,24,25}. This approach may only be used when we have a relatively good knowledge of the on-orbit positions and uncertainties of the objects for which we are computing the probability of collision.

On the contrary, when we are interested in the computation of the probability of collision among the objects of a system over long time scales, which is the case when we analyse the long-term evolution of the space debris population, averaged approaches are preferred^{26,27}. Such approaches, by the uniform sampling of the problem in time and by the representation, either explicit or implicit, of the space

debris population in terms of spatial densities, make use of the kinetic gas theory conceptual framework to compute the mean probability of collision by unit of time for any space object in the population. Such averaged approaches have the advantage of drastically reducing the computation time when compared with the explicit collision probability computation approaches. However, as we are only interested in the mean collisional behaviour of our system, these methods do not allow to draw conclusions on particular objects.

III.V Collision Energetic Threshold for Catastrophic Break-up

The Energy-to-Mass (EMR) threshold for catastrophic collisional break-up is usually assumed to be 40,000 J/kg. Such threshold has been estimated via on-ground hypervelocity tests and analysis carried out in the past²⁸.

The real EMR threshold for catastrophic collisional break-up might be more complex, due to basic structural differences between colliding space objects. However, having determined its right order of magnitude, the exact range of values of the critical EMR for catastrophic break-up might not be so crucial, in particular for LEO regime simulations.

This conclusion is supported by many studies that have been done on this topic since the 90's^{29, 30, 31}. In particular Ref. 29 extensively investigates the effect of the catastrophic EMR on the long term evolution of space debris > 1 mm. This study concludes that the abundance of objects larger than 1cm is comparable for the 10.000, 20.000 and 30.000 J/Kg EMR thresholds. On the other hand, a value lower by one order of magnitude (4500 J/Kg) would lead to a much larger number of catastrophic collisions, which engender a higher number of small particles. References 30 and 31 arrive to fairly similar conclusions.

III.VI Collision Geometry Leading to a Catastrophic Collision

The collision geometry leading to a catastrophic collision can be seen as directly linked with the EMR threshold for catastrophic collision. This relationship comes from the fact that in general real on-orbit collisions are not centre-of-mass vs. centre-of-mass collisions. As a consequence, object shapes with loose structures or appendages, like solar panels, antennae and booms, play a critical role, often transforming potentially catastrophic events in minor accidents, as far as the long-term evolution of the space debris population is concerned.

This effect can be justified by the analysis of the 4 accidental collisions recorded so far with EMR >

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40,000 J/kg³². From these 4 collisions, only one (Iridium 33 vs. Cosmos 2251) resulted in a truly catastrophic break-up. In addition, this collision could have been avoided with a proper operational conjunction risk assessment process. The other 3 events (Cosmos 1934 vs. #13475, Cerise vs. #18208 and Thor Burner R/B vs #26207) released 9 catalogued fragments in the environment, while the straightforward application of the standard NASA break-up model, ignoring the impact geometry, would have predicted the release of more than 1000 additional catalogued objects. Consequently, the critical impact cross-section leading to a catastrophic collision, for any event involving an intact satellite, might be significantly smaller than the overall impact cross-section.

Some of the current evolutionary models could in principle address this problem, because the effective collisional cross-section leading to a catastrophic breakup can be set differently from those used for atmospheric drag and radiation pressure computations. However, this potentiality is not able, at present, to eliminate the uncertainty, due to the lack of statistically relevant experimental data, of detailed studies and of a specific wide consensus in the community. As a matter of fact, most, if not all, of the published long-term evolutionary analyses, including those involving the comparison of several models, did not explicitly mention the use of specific cross-section reduction factors for collision modelling, either agreed or not.

Since the catastrophic collision fragments act as feedback impactors, leading to further catastrophic collisions and dominating after a few decades, according to the evolutionary models, the evolution of the environment, any uncertainty in the expected number of catastrophic collisions would have important consequences on the long-term debris environment predictions.

III.VII Break-Up Models

Currently the standard NASA break-up model^{33,34} is the most used for the analysis of on-orbit fragmentation consequences, either due to collisions or explosions. This empirical model was developed from 1980's on-orbit satellite break-ups and the Satellite Orbital Debris Characterization Impact Test (SOCIT), executed on ground in early 1990's.

Even if the analysis carried out by NASA, comparing the model with on-orbit collisional break-ups, showed that the slope of the cumulative size distribution for debris larger than a few millimetres was in reasonable agreement with available observations, the changes in spacecraft design and materials since the 1990's could be at the origin of not negligible discrepancies between model and

reality. Hopefully, undertakings as DEBRISAT³⁵ will help to limit such discrepancies in the near future.

In any case, and even once that DEBRISAT's results will be used to update the model, discrepancies will always exist between model and reality, concerning the number of fragments generated by a break-up, their area-to-mass ratio distribution, as well as their delta-V distribution.

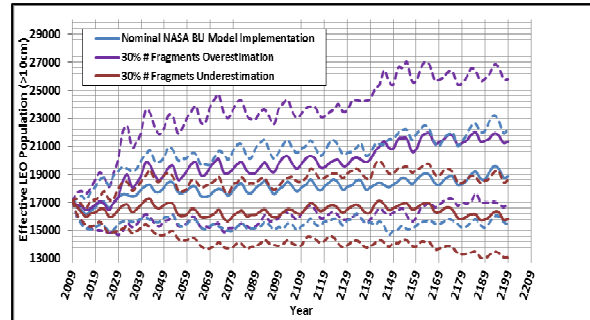


Figure VIII. - MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of the NASA BU Model considered error⁷. The thick curves are the arithmetic means from 40 Monte Carlo projections. The dotted curves represent the 1- σ standard deviation.

In order to give an idea of the effect that an error in the number of generated fragments would have on the long-term evolution of the space debris population, Fig. VIII shows that the over/under estimation, by a reasonable factor, of the number of debris produced after each collision would have an important impact on the long-term projections derived with our evolutionary models, as the generated fragments fuel the collisional process.

III.VIII Target Ranking for Active Debris Removal

When dealing with Active Debris Removal (ADR), the potential long-term benefits should depend on the order in which the abandoned intact objects (i.e. spacecraft and orbital stages) are taken away from the environment. As can be clearly seen from simulation results³⁶, not all the abandoned objects represent the same danger for the environment, being the potential hazard proportional to their probability of collision with debris able to induce a catastrophic fragmentation and to their mass, i.e. the latent source of new fragments.

The first parameter (i.e. the probability of catastrophic collision) will depend on the orbital region in which the object is placed, being this probability directly proportional to the spatial density of potentially lethal impactors, typically with sizes of 10 cm or larger. As a consequence, intact objects placed in orbits between 700 and 1100 km, characterized by average residual lifetimes in between

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50 and 2000 years³⁶, should be preferred to objects outside this altitude shell (cf. Figs. I and XVII).

The second parameter accounts for the danger that the objects pose to the environment as “reservoirs” of potential fragments after a collision. Their number, in fact, directly depends on the mass of the colliding objects³³ as follows:

$$N(L_c) = 0.1 M^{0.75} L_c^{-1.71} \quad [1]$$

where $N(L_c)$ represents the number of collision fragments of a given characteristic size L_c (in metres), or larger, and M , for catastrophic collisions, represents the combined mass (in kg) of the colliding objects.

However, different ranking schemes based on equally reasonable assumptions may produce quite different priority lists and it is not straightforward to check their relative long-term effectiveness, even disregarding the intrinsic stochastic nature of the debris environment long-term evolution.

This ambiguity concerning the identification and ranking of ADR targets, as well as the evaluation of the long-term benefits of a given ranking scheme, come from the fact that our models have been built to analyse the mean behaviour of our system over long-time scales, not to study the deterministic effects that some particular objects would have on the environment, if any could be discerned in a jungle of stochastic events.

IV. REVIEW OF UNCERTAINTY SOURCES COMPLETELY OUT OF THE CONTROL OF MODELLERS

IV.I. - Future Launch Traffic and Space Technology Evolution

Future launch traffic and space technology evolution can be reasonably assessed for no more than a few decades. Many market, regulatory, technological, political and financial factors affect the launch traffic and space technology long-term developments³⁷.

In many evolutionary models, future launch traffic is defined on the basis of past space activity. This is justified by the fact that even if the yearly number of launches has been so far quite variable (cf. Fig. IX), reflecting the above mentioned motivations, the yearly number of net objects added to circumterrestrial space over the past five decades can be rather accurately fitted with linear trends, resulting, on average, in 123 new net objects per year, distributed as follows¹⁵:

- 68 payloads;
- 8 mission related objects associated with payloads;
- 33 rocket bodies;
- 14 mission related objects associated with rocket bodies.

Nevertheless, with the eruption of the commercial space market and the emergence of additional space actors, the reliability of future launch traffic predictions based on past space activity is more than questionable.

Concerning the long-term evolution of the space debris population, many simulations done on this topic^{12,13,38} showed that any change on the future launch traffic would have a very relevant impact.

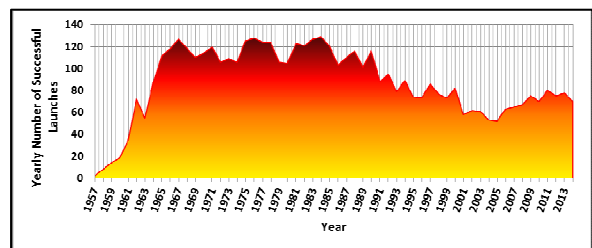


Figure IX. - Yearly number of successful orbital launches.

IV.II. - Quality of Mitigation Measures and Overall Levels of Compliance

The fear that future environment growth might be dominated by collisions, rather than by launches and explosions, motivated the development of numerous mitigation procedures, including the IADC Space Debris Mitigation Guidelines³⁹, the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Mitigation Guidelines⁴⁰, the International Organization for Standardization (ISO) Space Debris Mitigation Standards⁴¹, and a multitude of other national and international documents, with others being still in the making to limit the expected growth of the debris population.

However, the quality of the mitigation measures adopted and the overall level of compliance are depending on national and international laws, guidelines and standards in addition to socio-economical, geopolitical and technological factors.

Figures X, XI and XII present the worldwide level of yearly compliance with the IADC mitigation guidelines, in LEO and in the Geostationary (GEO) protected region.

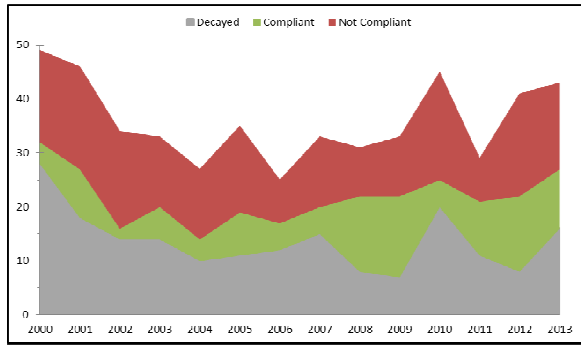


Figure X. – Absolute number of LEO spacecraft compliant with the IADC mitigation guidelines, between 2000 and 2013⁴².

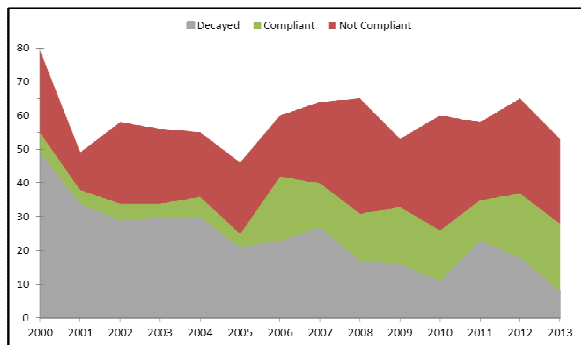


Figure XI. – Absolute Number of LEO orbital stages compliant with the IADC mitigation guidelines, between 2000 and 2013⁴².

As can be observed in Figs. X and XI, approximately 60% of spacecraft and upper stages are currently compliant with the 25 years residual lifetime rule in LEO. It is important to highlight that most of the compliant objects achieved this result due to the action of natural perturbations (i.e. without the need to perform a de-orbitation manoeuvre) and that there was not a clear trend of improvement over the years concerning the rate of compliance.

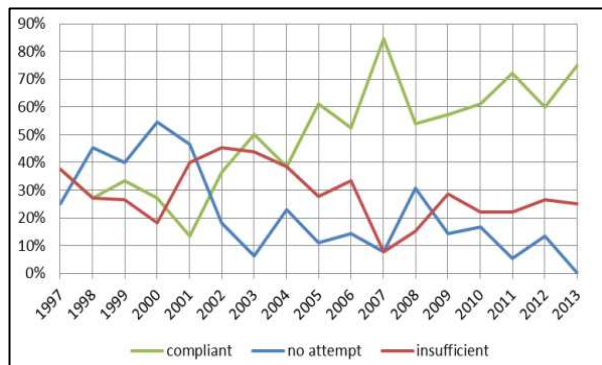


Figure XII. - Percentage of GEO spacecraft compliant with the IADC mitigation guidelines⁴³.

From Fig. XII we may highlight that currently 2/3 of the GEO spacecraft are re-orbited at the end of life

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in order to be compliant with the IADC mitigation guidelines. We can also observe a clear trend of improvement over the years.

Concerning the reduction in the number of on-orbit explosions, there is still an effort to be done (Fig. XIII). Since the 1980's, substantial developments have been implemented by manufacturers and space operators to reduce the number and the magnitude of on-orbit break-ups, nevertheless we are still recording events of this kind, affecting both spacecraft and rocket bodies.

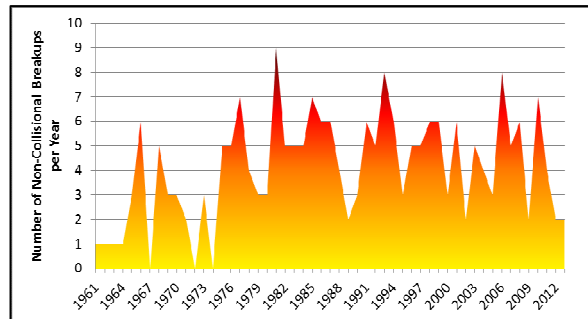


Figure XIII. - Number of non-collisional break-ups per year.

As found in many studies^{7,44,45,46}, the quality of the mitigation measures and the overall levels of compliance will have a major impact on the long-term evolution of the space debris population, as shown in Fig. XIV.

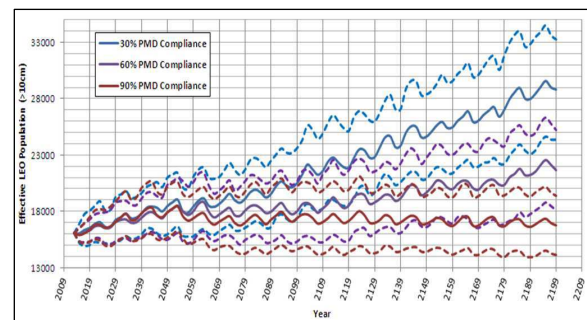


Figure XIV. - MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of the Post-Mission Disposal (PMD) compliance rate. The thick curves are the arithmetic means from 40 Monte Carlo projections. The dotted curves represent the 1-σ standard deviation⁷.

In addition to the above mentioned mitigation measures, which are performed at the end of the operational mission, the operators may implement routine conjunction assessment, in order to minimize the probability of collision between the manoeuvrable operational spacecraft and the catalogued objects. As in the case of the other variables, more or less questionable assumptions have to be done concerning the percentage of the operational population

performing routine conjunction assessment, in order to analyse the effectiveness of such measure regarding the long-term sustainability of space activities. However, the studies carried out so far^{36,47} concluded that operational conjunction assessment would be quite ineffective in maintaining under control the long-term growth of decimetre sized space debris if not coupled with other mitigation techniques.

IV.II. – Viable Technological Options for Remediation Measures with Active Removal

The use of remediation techniques, as active debris removal (ADR), for the long-term stabilisation of decimetre sized space debris, constitutes a very active field of research nowadays. These researches are carried out in two main fields: space debris long-term modelling to assess the relative effectiveness of different approaches, and the development of the specific technologies needed to make ADR a reality.

Concerning the long-term evolution of the debris population, some of the main questions to be addressed are the following:

1. How many intact objects have to be removed from the environment, per unit of time, in order to stabilize over the long-term the decimetre sized space debris population? (cf. Figs. XV and XVI.)
2. Which are the objects that have to be removed with the highest priority?
3. Which will be the consequences of ADR failed missions?
4. Which will be the perceived short and long-term cost-benefit ratio of doing ADR?

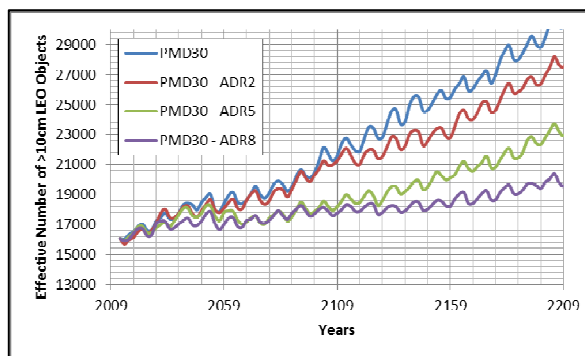


Figure XV. - MEDEE simulated LEO debris population (objects 10 cm and larger) for a 30% PMD compliance rate as a function of the number of yearly removed objects by ADR, starting in 2020. The curves are the arithmetic means from 40 Monte Carlo projections.

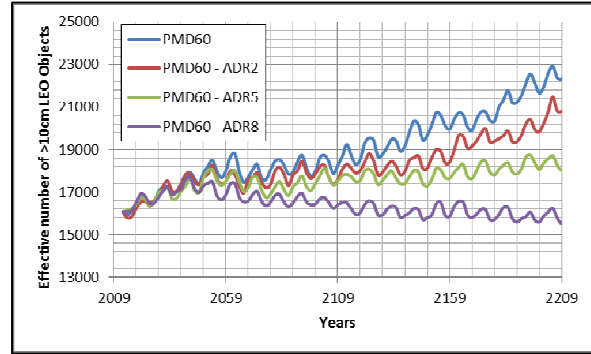


Figure XVI. - MEDEE simulated LEO debris population (objects 10 cm and larger) for a 60% PMD compliance rate as a function of the number of yearly removed objects by ADR, starting in 2020. The curves are the arithmetic means from 40 Monte Carlo projections.

Regarding the development of ADR technologies, several options are being evaluated, as contact (e.g. harpoons, tentacles, grappling arms, etc...) or contact-less (e.g. lasers, ion beams, nozzle exhausts, etc...) methods to establish a manageable physical interaction with the objects to be removed. However, other critical technical problems have to be solved, as how to approach and perform safe proximity operations on a non-cooperative target, possibly tumbling in a more or less convoluted way.

In addition to all the operational and technological problems that have to be addressed prior to performing ADR, even leaving aside its economic viability, there are several non-technical challenges that can transform a technical feasible solution in an impracticable one, due to legal or political reasons⁴⁸. This means that in addition to technical considerations, legal and political aspects would play an important role when deciding about:

- The objects to be removed;
- The country/entity in charge of a removal;
- The military/non-friendly implications of ADR activities;
- The technologies used for ADR.

As a consequence, available technological solutions will have to be coupled with geopolitical and socio-economical aspects in order to be able to perform ADR.

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IV.III. – Irresponsible Deliberate Actions Endangering the Environment

Irresponsible deliberate actions, as the testing or use of anti-satellite weapons leading to the generation of a substantial amount of long lasting debris, are unpredictable and cannot be a priori anticipated. The consequences of such deliberate actions, even if sporadic, can be severe for the environment, eventually neutralizing the benefits of decades of mitigation efforts (cf. Tab. 2 and Fig. XVII).

	SOLWIND (1985)	DELTA-180 (1986)	FENGYUN-1C (2007)	USA-193 (2008)
Target	Solwind P78-1 Mt=878 Kg	Delta-180 2nd Stage Mt = 1455 Kg	Fengyun-1C Mt=880Kg	USA - 193 Mt=1815 Kg
Projectile	Sub-Orbital MHV KV Mp=13.6 Kg	USA-19 Sub-Orbital KKV Mp=725 Kg	Sub-Orbital KKV vehicle Mp=600 Kg	Sub-orbital LEAP vehicle Mp=102 Kg
Impact Date	13 Sep. 1985	5 Sep. 1986	11 Jan. 2007	21 Feb. 2008
Impact Altitude [Km]	525	218	863	249
Impact Velocity [Km/s]	6.7	2.9	9.4	9.8
EMR [J/Kg]	3.48×10^5	2.06×10^5	3.01×10^7	2.7×10^5
Catalogued Debris	~300 debris ≥ 10 cm generated (285 Still in Orbit)	~800 debris ≥ 10 cm generated (16 still in orbit)	3391 catalogued debris still in orbit	~300 debris ≥ 10 cm generated (174 still in orbit)

Table 2. – Recorded on-orbit intentional collisions¹⁵

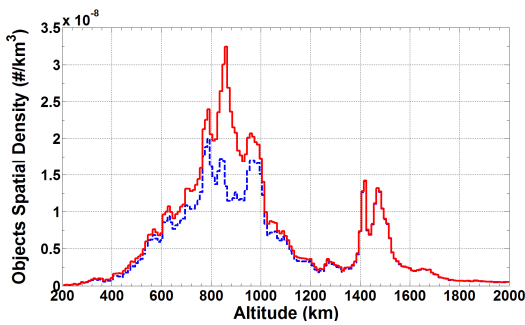


Figure XVII. – Catalogued debris spatial density in LEO before and after the anti-satellite weapon test carried out in January 2007. Since then, another 1400 fragments associated with the break-up have been catalogued.

As an example, Fig. XVII shows the sudden increase of the space debris population in LEO following the anti-satellite weapon test carried out in January 2007, in which the satellite Fengyun-1C was destroyed⁴⁹. To give a rough idea of the impact of such events on the circumterrestrial environment, it is sufficient to realize that this anti-satellite test alone, in numerical terms, increased the number of catalogued orbital debris by an amount comparable to the previous 22 years of space activity combined.

IV.IV. – Evolution of Solar and Geomagnetic Activity

Solar activity drastically affects the dynamics of the space debris population in LEO. Due to the large

variations in solar activity over the time, empirically determining future solar activity is not possible, except in the near term. Predictions become less accurate farther into the future, and because the evolution of the orbital debris environment is highly dependent on the decay rates of the objects over the time, the long-term prediction of orbital debris is highly linked to future solar activity modelling. Figs. XVIII and XIX show the strong dependence between long-term evolution of space debris and solar flux.

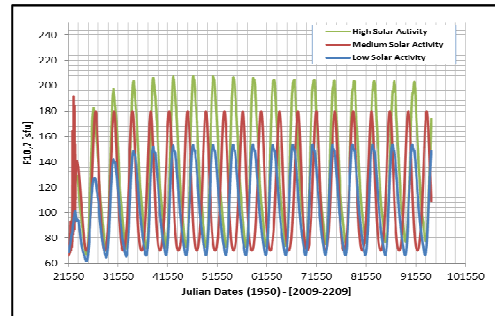


Figure XVIII. - High, medium and low solar flux projections. The F10.7 proxy is given in standard flux units ($sfu = 10^{-22} Wm^{-2}Hz^{-1}$)⁷.

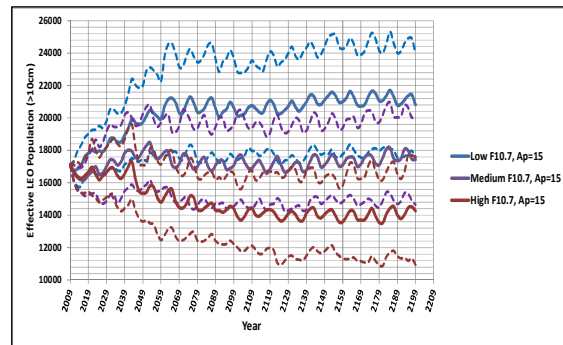


Figure XIX. - MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of the solar flux at 10.7 cm. The thick curves are the arithmetic means from 40 Monte Carlo projections. The dotted curves represent the 1- σ standard deviation.⁷

In addition to the solar flux at F10.7 cm, which is the proxy modelled by most of the existing solar flux models, there is the geomagnetic activity proxy (Ap/Kp), which also has a non-negligible effect on the long-term evolution of the space debris population (cf. Fig. XX) and which is quite unpredictable even in the short-term (cf. Fig. XXI). In Fig. XX Ap=15 represents the mean Ap value for the past 5 solar cycles, while Ap=8 represents the median value.

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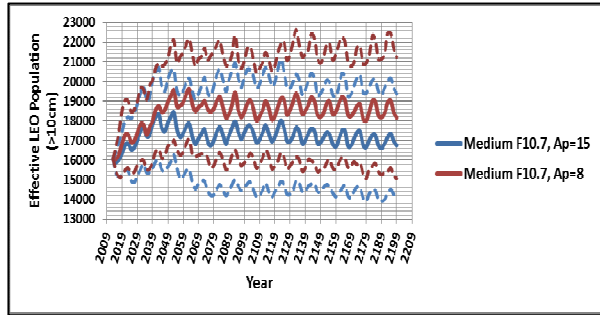


Figure XX. - MEDEE simulated LEO debris population (objects 10 cm and larger) as a function of the geomagnetic index A_p . The thick curves are the arithmetic means from 40 Monte Carlo projections. The dotted curves represent the $1-\sigma$ standard deviation.

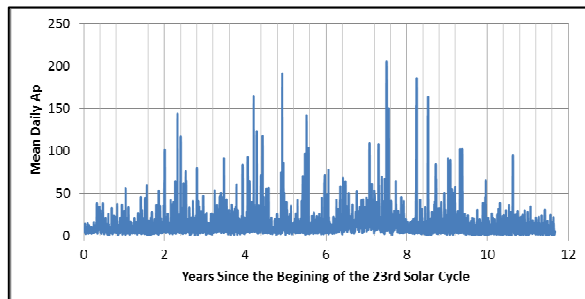


Figure XXI. - Mean daily A_p evolution during the 23rd solar cycle.

IV.V. – Evolution of the Upper Atmosphere of the Earth at Satellite Altitudes

The concentrations of “greenhouse gases” – carbon dioxide and methane in particular – in the middle atmosphere are expected to double by mid-21st century^{50,51}. Such increase on CO_2 levels will result in a cooling of the thermosphere. Modelling studies concluded that the doubling of CO_2 levels will produce an average cooling of the thermosphere of 40–50 K, resulting in a reduction of atmospheric density by more than 40% at a given height.

The consequence of this reduction on atmospheric densities will be longer orbital lifetimes for space objects. As the prediction of the orbital debris environment is highly dependent on decay rates of objects over the time, a variation in orbital lifetimes for satellites and space debris will have a non-negligible impact on the long-term evolution of the orbital debris environment.

The consequences of an increase on atmospheric CO_2 levels and the resulting secular density trend at satellite altitudes have been analysed by Lewis et al⁸. The long-term consequences of such secular trend on the space debris population were estimated to be an increase of 30% in the number of objects ≥ 1 cm and an increase of 10% in the number of objects ≥ 10 cm in one century.

V. CONCLUSION

As described in section II, and explicated on sections III and IV, there are a great number of endogenous and exogenous variables that will have an important effect on the long-term evolution of the future space debris population.

Some of these variables, being of human (anthropogenic) or natural origin, are under the relative control of modellers, while others are completely out of the control of modellers. Whichever their origin and whatever the control that modellers have on them, all these variables must be considered on predictions done with evolutionary models, in order to improve their statistical robustness and the representativeness of the results.

While the proper consideration of variables under the partial control of modellers will imply an intensive work on models related with these variables and probably an increased complexity of such models, the uncertainty linked with variables being completely outside the control of modellers will need to be considered on long term projections, widening the envelope of the many possible futures of the space debris population.

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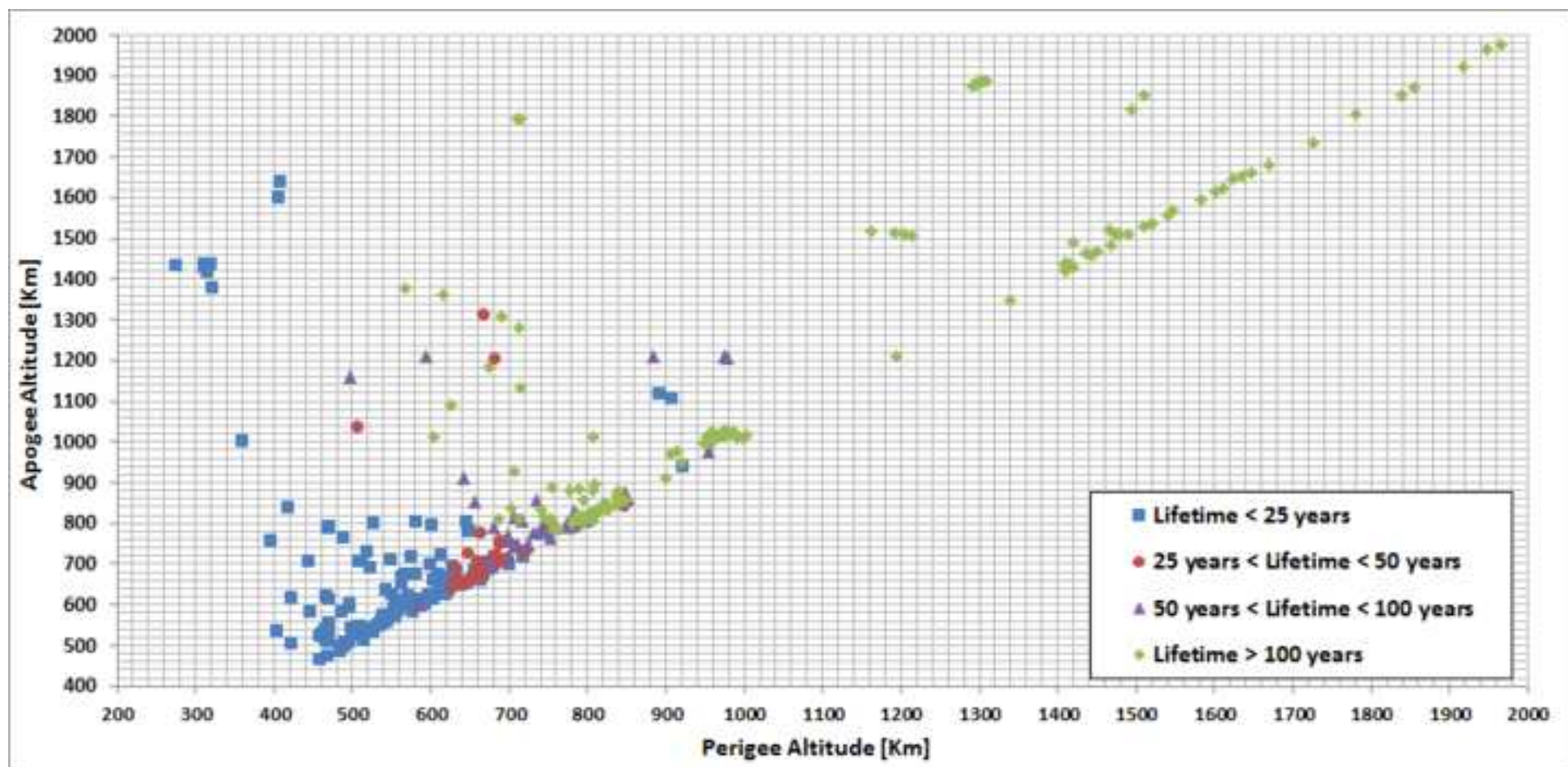
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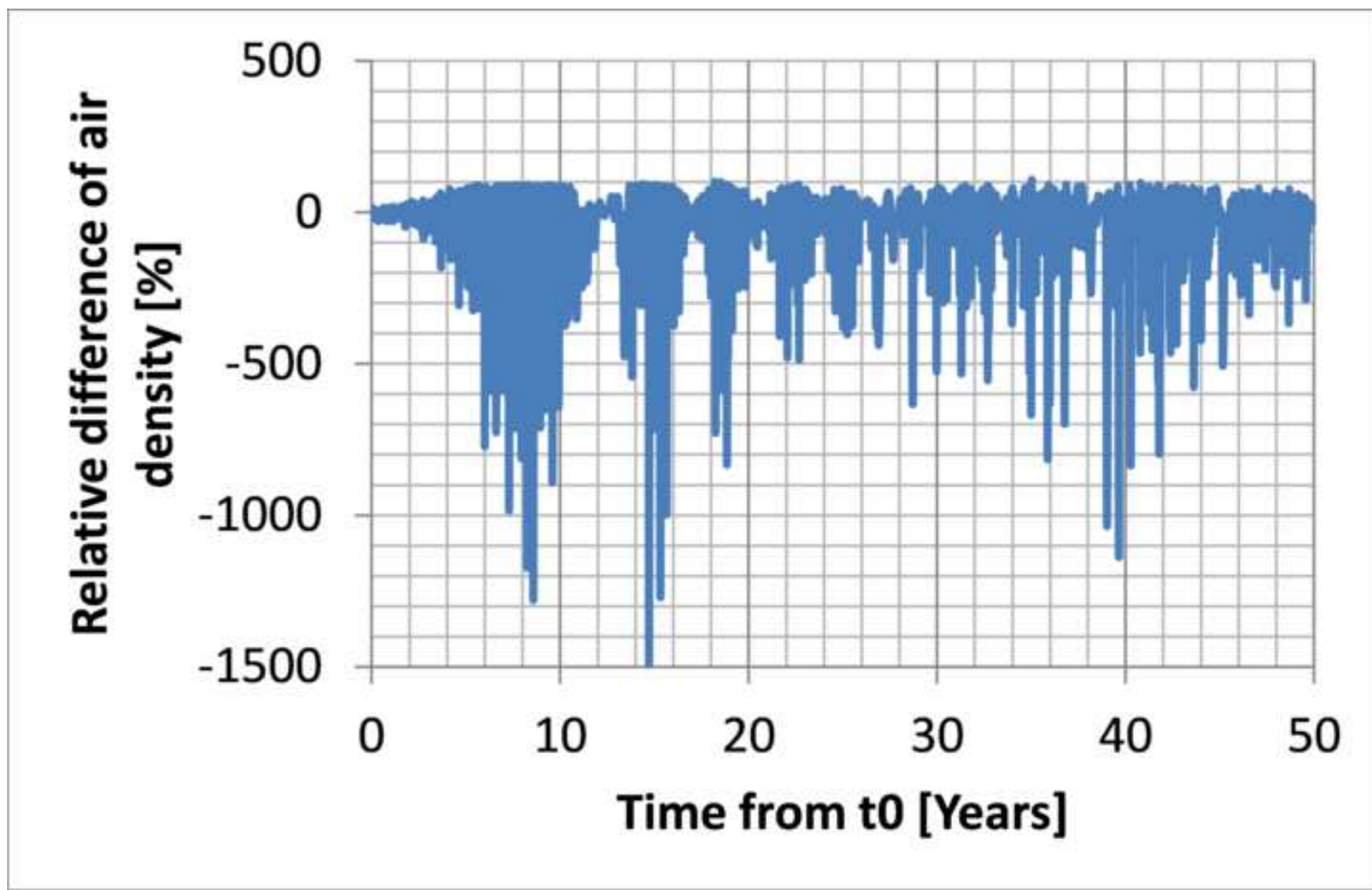
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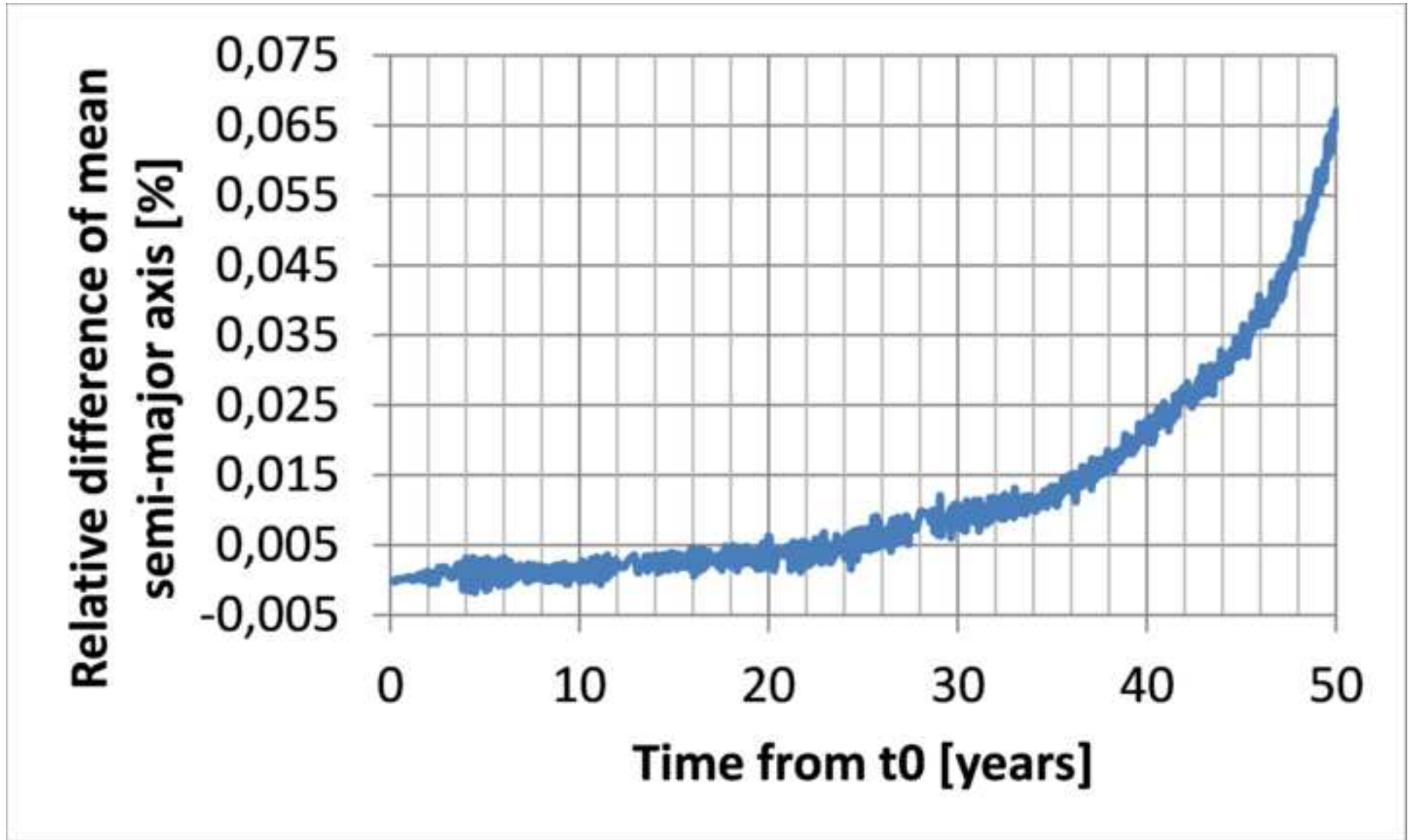
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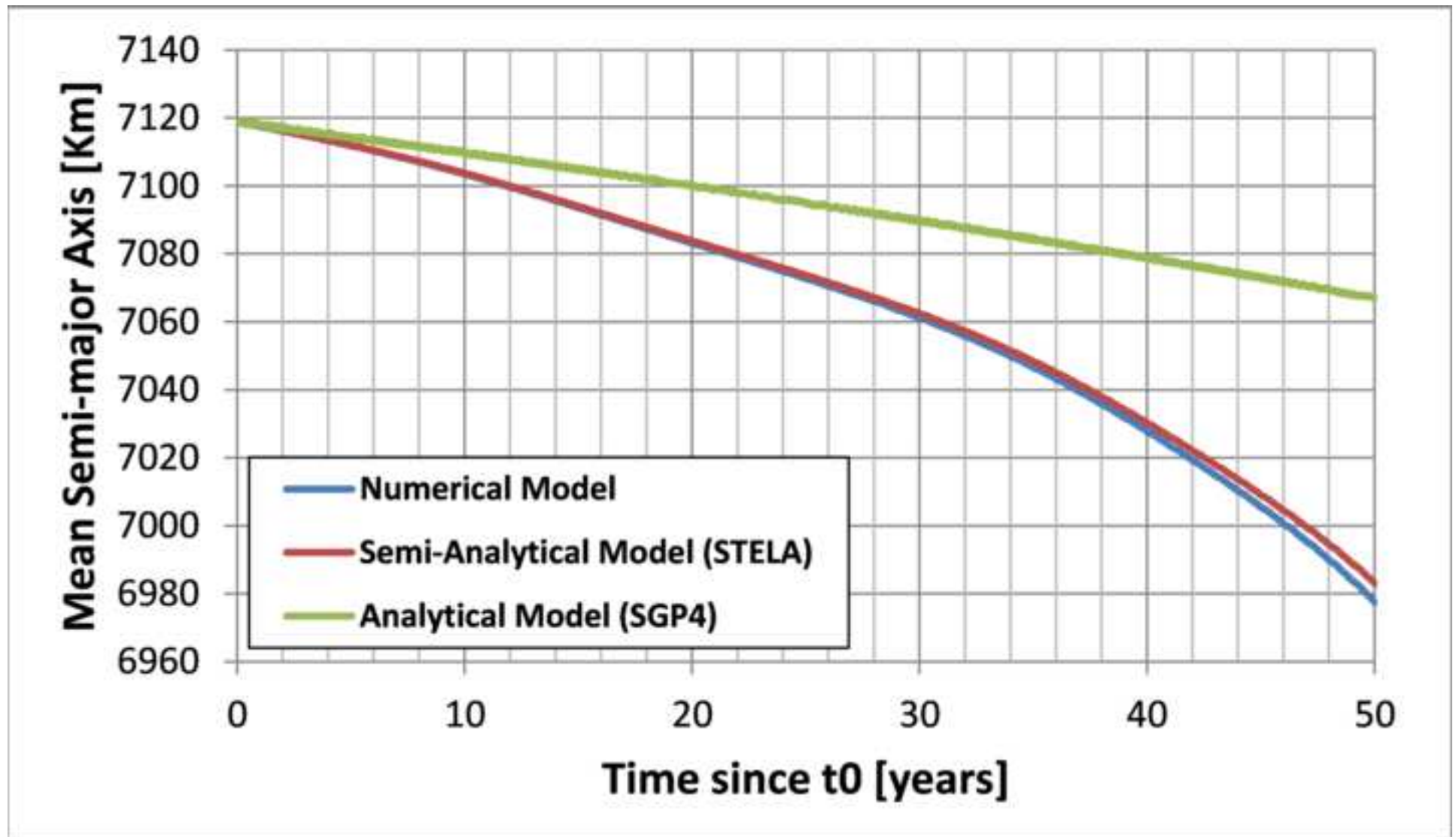
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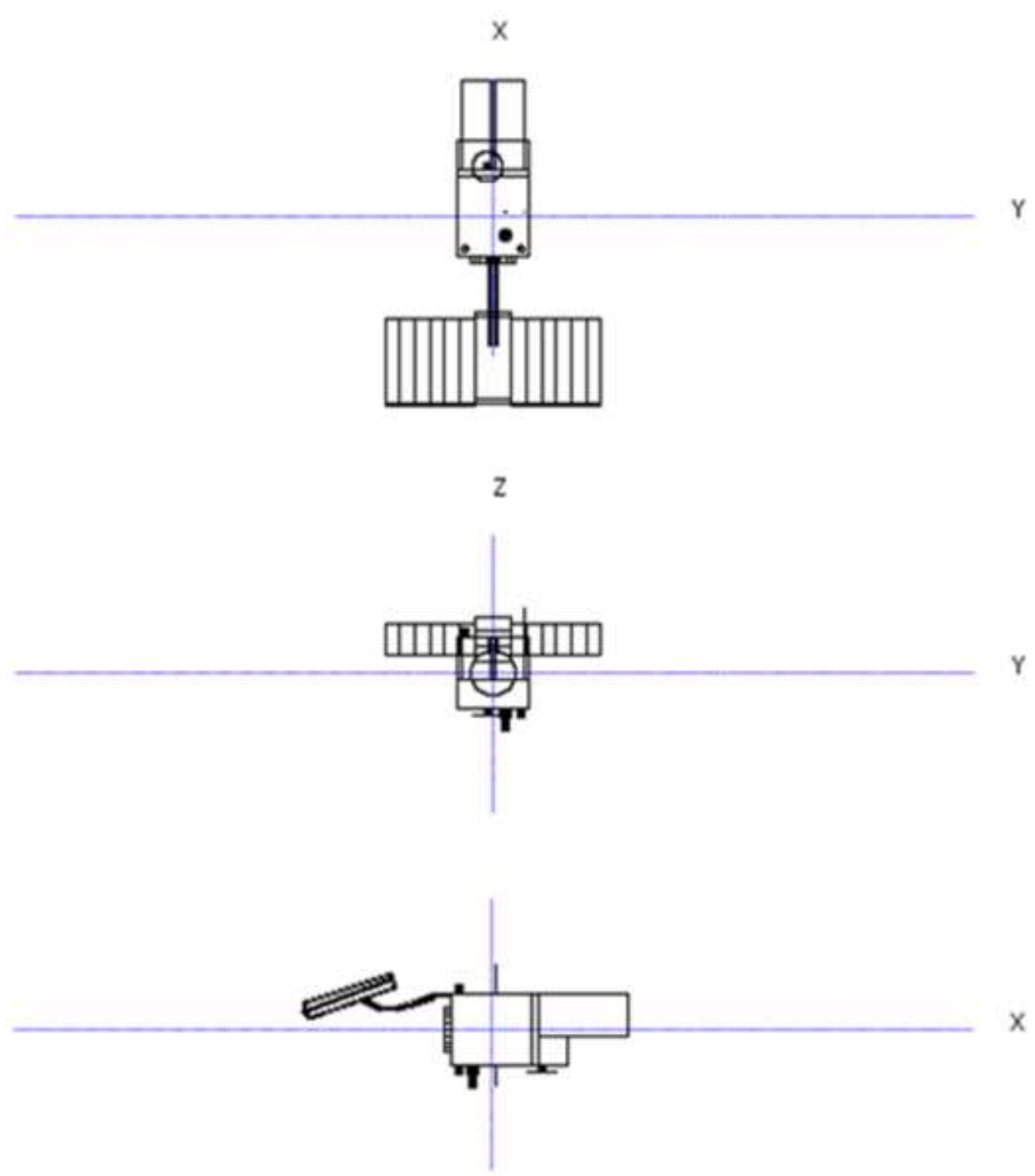
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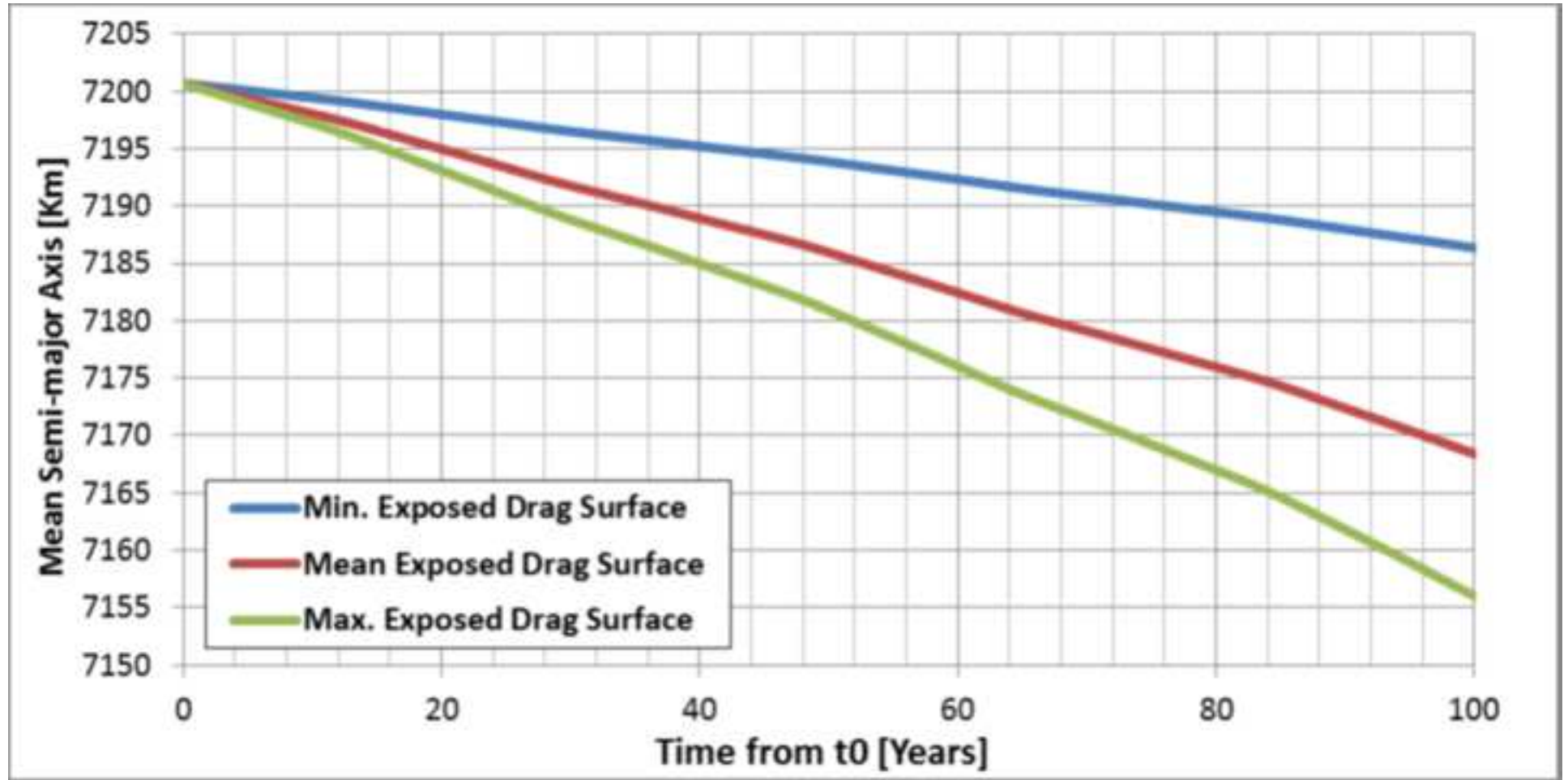


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