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Adaptive Remediation of the Space Debris Environment using Feedback Control

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Abstract

This work presents a source-sink debris evolutionary model of the Low Earth Orbit (LEO) with a proportional control on Active Debris Removal (ADR). The model is based on a set of first order differential equations, which describe the injection and removal rates in several altitude bands within the LEO. Explosions and collisions generate fragments via the standard NASA breakup model, while Post Mission Disposal (PMD) and ADR are the removing mechanisms. Drag, the only natural sink mechanism, is computed through a piecewise exponential model of the atmospheric density, assuming that all objects have circular orbits. The model also includes a feedback controller on ADR where the number of removals is proportional to orbital population. The proposed control mimics the human-driven corrective actions arising from the review and adaptation of debris mitigation policies. The model is validated and then preliminary results are reported. They highlight that a synergy of PMD and ADR can reduce the number of removals needed for the current population to be maintained over a 200-year timeframe.

Keywords: Space Debris Model, Source-Sink Debris Model, Feedback Control, Adaptive Remediation, Active Debris Removal, Post Mission Disposal

1 Introduction

Satellite-based services pervade everyday life and generate a worldwide economy worth more than $320 billion per year through science, remote sensing and telecommunication [1]. Within this context, space debris represents an increasing threat: an orbital object smaller than 1 centimetre can damage, disrupt, or even destroy a satellite, resulting in loss of services and potential costs of hundreds of millions of dollars [2]. Since the beginning of the space age, the number of orbital debris has steadily increased, accounting now for more than 90% of the current Low Earth Orbit (LEO) catalogued population [3,4]. Moreover, even without ongoing launch activities, new explosions and collisions are likely to result in a continuing degradation of the environment, posing a growing menace to future space activities. To confront this threat, the Inter-Agency Space Debris Coordination Committee (IADC) was established in 1993; in 2002, its members reached an agreement on common guidelines for the reduction of space debris, later revised in 2007 [5]. Satellite manufacturers and operators are gradually implementing these measures, but the lack of a legally binding framework limits their widespread adoption.

Models of the current space environment have been built to analyse the current situation, predict possible future scenarios and test the actual or proposed mitigation guidelines, together with their real or predicted level of compliance.

The objective of this work is then to gain a better understanding of the effects and limitations of debris control strategies and to identify and evaluate rules based on specific object types and characteristics. These strategies are indeed related to different objects classes. For example, prevention measures can focus on the reduction of rocket body explosions or limit the release of Mission Related Objects (MROs). Mitigation and remediation strategies can act on intact objects with respectively Post Mission Disposal (PMD) and Active Debris Removal (ADR).

In the past, several space agencies, public and private institutions have developed their models, using different approaches, for example:

- the space around Earth can be modelled as mono [6–12], or multi-dimensional [13,14];
- a model could be limited just to a single zone, e.g. LEO [15,16] or Geosynchronous Earth Orbit (GEO)

[17] or can simulate more regions (e.g. from LEO to GEO) [13,18,19];

- a deterministic or semi-deterministic [20,21], stochastic [19], probabilistic [22] or even a mixed approach [23] can be used for determining, launches, orbital propagation, collisions and other parameters.

Three-dimensional (semi-) deterministic models, propagate orbits of all the objects in their databases, add in new launch traffic, compute collision probabilities and generate fragmentation debris when indicated. Examples of these models are: Semi-Deterministic Model (SDM) [20], Debris Environment Long-Term Analysis (DELTA) [18], Low Earth orbit to geosynchronous Earth orbit environment debris model (LEGEND) [13], Long-term Utility for Collision Analysis (LUCA) [24], and Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) [14].

To provide reliable statistics on the outcome, these complex models must be run multiple times with a Monte Carlo based approach. The drawback of this method is that the results obtained in a single Monte Carlo run only depend on the particular set of hypothesis and initial conditions used, and on the stochastic events happening during each simulation. Therefore, the results from dozens or hundreds of these simulations are joined into probability density functions of the key parameters. From the computational point of view, these evolutionary models are very demanding and therefore they are usually not suitable to quickly test a wide selection of scenarios.

In the early debris models (developed in the 1980's and 1990's), when the available computer power was a much stricter condition, a different approach was used. These simple discretised propagation models used a Eulerian [22,23,25] or Lagrangian [26,27] mesh of the Earth atmosphere, with altitude and mass discretisation, and did not propagate individual objects. In these works, simple first-order differential equations describe source and sink mechanisms in the Earth orbital environment. In the 1990's, several authors used this approach [7,8,26] sometimes referred to as Particle In a Box (PIB) due to the utilisation of the gas-derived collision law [28].

Despite the exponential increases in computer power, this same approach has continued to be used more recently. Based on Talent's works, in 2009, Lewis et al. created a new model called Fast Debris Evolution (FADE) [15], while other models were recently published in 2011, 2014 and 2016 [29–31].

However, these models have in some cases a simplistic approach to the problem and are not able to capture all the behaviours of the more complex evolutionary models. Nevertheless, their simplicity significantly reduces computational times, while capturing at the same time fundamental trends. Moreover, in 2016, Kessler highlighted that current long-term models tend to be over-complex, and their long run-times are a handicap that produces an unnecessary accuracy not needed for determining event probabilities, such as orbital collisions [32].

In 2014, White and Lewis found that an adaptive strategy, based on a simple feedback control, was more efficient compared with a fixed ADR rate when the objective was to maintain the current debris population in a 200-year time span [33]. This strategy however dealt only with the total number of debris, while many other objectives can be set (e.g. minimising the total mass or the number of collisions). These and other parameters can be used either individually or together to create a better control loop in the model.

The investigation of the effectiveness and influence of guidelines and mitigation measures, such as passivation, PMD and ADR, plays a key role in the understanding of the human interaction with the space environment, both in the short and in the long-term.

The choice of developing this new model, instead of using an existing one, allows full control of every single aspect of the modelling process concerning both the debris environment and the controller. Using the PIB approach has many advantages. First of all, it is very fast. It requires seconds or minutes compared to hours needed for an evolutionary model to have a single run, saving hundreds of hours for each test campaign. Furthermore, it reduces (or even removes) the need for executing several Monte Carlo runs to capture basic descriptors of the future environment maintaining, at the same time, a small error compared to the average values of evolutionary models [15]. As said before, this approach is indeed more time efficient than evolutionary models when there is the need to capture fundamental trends for populations or collision activity. Conversely, it is not suitable for in-depth investigations that require detailed information of the debris populations, for which evolutionary models are well suited.

A way to improve our knowledge of the space debris problem is to have a model that better reflects (via a controller) the real life iterative process of reviewing and upgrading the guidelines throughout the years, basing such reviews on the current estimates of future population growth.

The innovation in this work is the use of a feedback controller as a key element for the model that will extend previous works [33,34], where only one single adaptive strategy was tested.

This paper presents the source and sink model, currently in development. Material and methods are reported respectively in sections 2 and 3. The model governing equations are listed in sub-section 3.3, and the controller is described in 3.4.

The model is validated against the IADC comparison study of 2013 [35] in section 4. Preliminary results, produced with simplified assumptions, are listed in section 5 and then discussed in section 6. Finally, section 7 reports conclusions and future work.

2 Material

2.1 Initial population

Some of the data used in the model, such as initial populations and object type average values, were derived from the European Space Agency (ESA) Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) database of LEO crossing objects created (in October 2013) by the Institute of Aerospace Systems, Technische Universitaet Braunschweig.

The initial population is valid for epoch 1/1/2013 for objects equal or larger than 10 cm and with perigee in LEO. However, since the actual model does not account for orbit eccentricity, a subset of 15,778 objects is extracted from the total of 19,630. These have a semi-major axis less than Earth radius plus 2000 km (i.e. an equivalent circular height less than 2000 km) and will be further referred as LEO-residing objects.

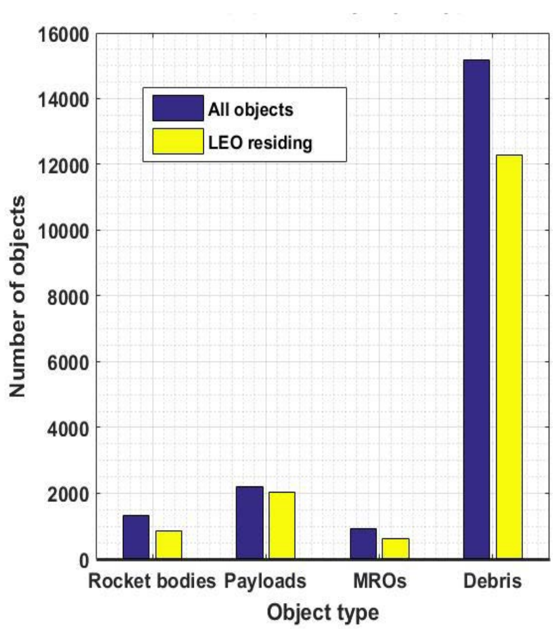

Figure 1. Total and LEO-residing object in the initial population by object type.

Four types of objects are present in the database: rocket bodies, payloads (both active and inactive), MROs and debris, as can be seen in Figure 1. Table 1 lists some average values for these objects. The biggest and heaviest ones are the rocket bodies with an average mass of 1,374.7 kg and 3.42 m diameter. Following these are payloads (both active and inactive) with about half the average mass (698.77 kg) and an area slightly less than half the average rocket body diameter (1.98 m). Much smaller are both the MROs and the debris that have a comparable average area of 0.59 m^2 but very different average masses, about 6.16 and 46.53 kg respectively for debris and MROs.

2.2 Launch traffic

The Institute of Aerospace Systems, also produced a list of objects launched from 1st January 2005 to 31st December 2012. This database identifies in total 793 objects launched in this 8-year interval (see Table 2) of which 537 are LEO-residing ones, with an average value of 67.125 per year. The majority of LEO-residing objects (67%) consist of payloads (equal to 45.125 per year), as listed in Table 2. Therefore, for every payload launched, 1.4875 other objects reach orbit on average. The model uses these yearly average values as a reference for launch traffic and new objects released per launch.

3 Method

3.1 Model description

The model developed is a multi-bin and multi-species deterministic source-sink model for LEO [28] (see Figure 1). It uses discrete time and a system of first order linear equations to describe the population evolution of three object types in a custom number of bands in LEO, from 200 to 2000 km.

The current model uses a constant launch traffic (computed as the average of an 8-yr cycle, see section 2.2) as well as a fixed yearly explosion rate. Collisions are calculated via the gas-derived laws [28,36], and with the proportion among catastrophic and damaging collision presented in [37]. The fragments generated during both explosions and collisions are computed a priori via the revised NASA break-up model [38,39]. Drag is the only sink mechanism and is calculated via a piecewise exponential model of the Earth's density with an average value of the solar activity [40,41].

Table 1. Statistics on LEO-residing objects by type in the initial population.

Object class	Object count	Average mass [kg]	Average diameter [m]	Average area [m^2]	Average area/mass [m^2/kg]
Rocket bodies	845	1,374.70	3.4218	10.5370	0.010334
Payloads	2,031	698.77	1.9776	4.8523	0.011947
MROs	627	46.53	0.5666	0.5904	0.014265
Debris	12,275	6.16	0.2840	0.6301	0.093425
Total	15,778	170.21	0.6813	1.7026	0.075341

Table 2. Statistics on object launched by type in period 2005-2008.

	All Objects			LEO-residing		
Object Type	**Total**	**Yearly average**	**Type [%] ***	**Total**	**Yearly average**	**Type [%] ***
Rocket bodies	238	29.750	30.01	101	12.625	18.81
Payloads	387	48.375	48.80	361	45.125	67.23
MROs	168	21.000	21.19	75	9.375	13.97
Total	793	99.125	100.00	537	67.125	100.01

* Percentages may not total 100 due to rounding.

The model can handle three types of objects in a custom number of circular altitude bands in LEO: intact objects, explosion fragments, and collision fragments (see Figure 2). It is also capable of handling PMD with a custom residual lifetime and level of compliance, and ADR with either a fixed value or the automatic proportional controller.

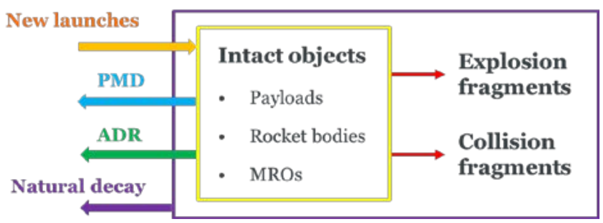

Figure 2. Schematics of object types and source and sink mechanism.

3.2 Model hypothesis

To simplify the problem, the model does not take into account external factors such as the economy (i.e., the cost of remediation measures), politics (i.e., legal responsibility and ownership) or possible future technology.

The actual model uses several hypotheses, such as all objects have circular orbits and no solar activity. Therefore, the results can be applied only to a limited range of scenarios where these conditions hold. Drag is also the only perturbation included in the model, as solar radiation pressure, Earth's oblateness and other third-body perturbations are not taken into account. One can argue that the lack of these perturbations will produce unrealistic results. However, the model itself does not need to focus on the accuracy of the generated numbers but on the capabilities of the controller to act on the populations and their evolution, and the ability to capture underlying trends, eventually to be further analysed afterwards with other, more complex, models.

3.3 System governing equations

The model uses a system of coupled non-linear first-order differential equations to handle the population derivatives. It uses three different equations to simulate better the addition or removal of each object type based on their nature (intact objects, explosion fragments and collision fragments). In a scenario without any explosions, the same equations can also be used to investigate existing intact objects, existing fragments, and new collision fragments.

The model uses a discrete time scale, and evaluates the total number of objects at each timestep as the sum of the three components as:

$$N_T(t) = N_I(t) + N_E(t) + N_C(t)\,, \tag{1}$$

where the subscripts T, I, E and C refers respectively to the total number, intact objects, explosions and collision fragments. In the same way, the total derivative is computed as the sum of the three types of derivative:

$$\dot{N}_T(t) = \dot{N}_I(t) + \dot{N}_E(t) + \dot{N}_C(t)\,. \tag{2}$$

The three future states are calculated from the current state with an explicit midpoint method (also known as the modified Euler method). The derivatives of the three object types are computed in each band b with [8,15]:

$$\begin{cases} \dot{N}_I(b,t) = \dot{L}(b,t)n_L \\ \qquad -\dfrac{D(b)}{r_I}N_I(b,t) + \dfrac{D(b+1)}{r_I}N_I(b+1,t) \\ \qquad -\dot{E}(b,t) - 2*\dot{C}(b,t) - \dot{M}(b,t) - \dot{R}(b,t), \\ \dot{N}_E(b,t) = \dot{E}(b,t)n_E \\ \qquad -\dfrac{D(b)}{r_E}N_E(b,t) + \dfrac{D(b+1)}{r_E}N_E(b+1,t), \\ \dot{N}_C(b,t) = \dot{C}(b,t)(f_{CC}n_{CC} + f_{DC}n_{DC}) \\ \qquad -\dfrac{D(b)}{r_C}N_C(b,t) + \dfrac{D(b+1)}{r_C}N_C(b+1,t), \end{cases} \tag{3}$$

where $\dot{L}$ is number of launches per year, n_L the number of objects released per launch, D a decay parameter, r the object radius (for each type), $\dot{E}$ the yearly explosion rate, $\dot{C}$ the collision rate, $\dot{M}$ a mitigation parameter that defines the PMD measures, $\dot{R}$ the ADR rate, n_{CC} and n_{DC} the number of collision fragments generated by catastrophic and damaging collisions, with f_{CC} and f_{DC} the fraction of catastrophic and damaging collisions, assumed equal to 31.87% and 68.13% [42].

In the system of equations (3), the second term of each equation represents the number of objects that have decayed in the lower band due to drag (or removed from the simulation if in the lowest band), while the third term accounts for the objects that have decayed from the upper band. Explosions remove one intact object whereas collisions remove two, while both add the respective amount of fragments to the corresponding object type. Finally, if defined so in the test case parameters, the model can also remove intact objects in response to post-mission disposal measures and ADR.

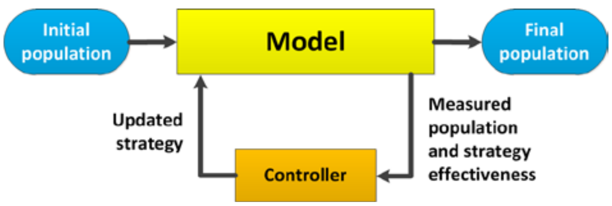

Figure 3. A simple schematics of the model architecture.

3.4 Feedback controller

The need to test the effectiveness of a controller in the space environment drove the model design. As the execution is fast (dozens of seconds), it allows the possibility to run several different scenarios, perform sensitivity analysis and parametric studies on initial conditions, and control methods. Test results can be furthermore used to identify unusual single cases (otherwise removed due to the averaging process on Monte Carlo runs) to be better investigated later with a more complex model for which source-sink models are not well suited.

Many possible control laws can be applied to the model to create an adaptive feedback. The basic idea is to evaluate the current population at a fixed time interval (for example every year) and adapt the strategy to improve its effectiveness.

The dependent variable checked is the total number of objects. However, many other choices are possible, such as the amount of intact object or collision fragments, collisions rates or the previous strategy's effectiveness. Based on the observed values, the controller defines a new strategy to be applied in the following time interval, as depicted in the schematics in *Figure 3*. The current controller acts only on the ADR rate.

Proportional controllers are a form of control loop feedback mechanisms widely used in control systems, where the controller observes an output value $y(t)$ from a system and compares it to a specific set point $r(t)$ The obtained error,

$$e(t) = y(t) - r(t), \tag{4}$$

is then used to compute a control $u(t)$ that is passed to an actuator that interfaces with the system.

In this model, the plant is the space environment itself (see Figure 4) and the outputs are the populations of the three object types (plus the total one), as well as other useful variables such as the collision rates.

As it can be seen from the model schematics, depicted in Figure 4, the output of the controller, $u(t)$, is defined as

$$u(t) = k_P e(t), \tag{5}$$

where k_P is the proportional gain and $e(t)$ is the error on the total number of objects between the current measure $N(t)$ and the set point $N^*(t)$, representing a population target:

$$e(t) = N(t) - N^*(t). \tag{6}$$

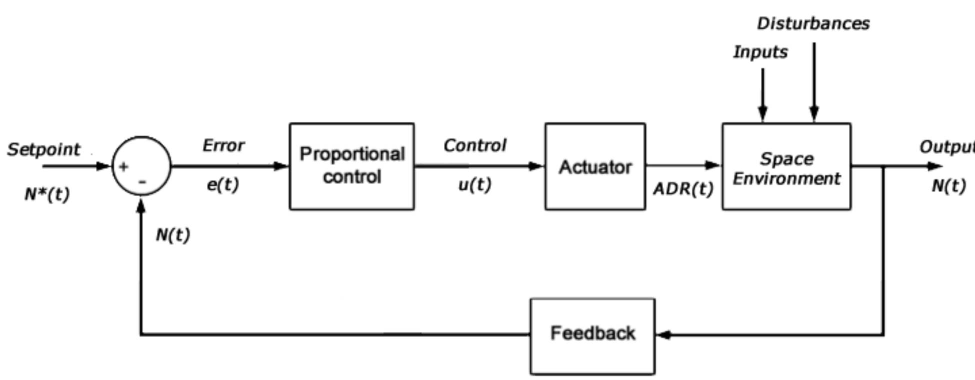

Figure 4. Schematics od a proportional controller for the space environment.

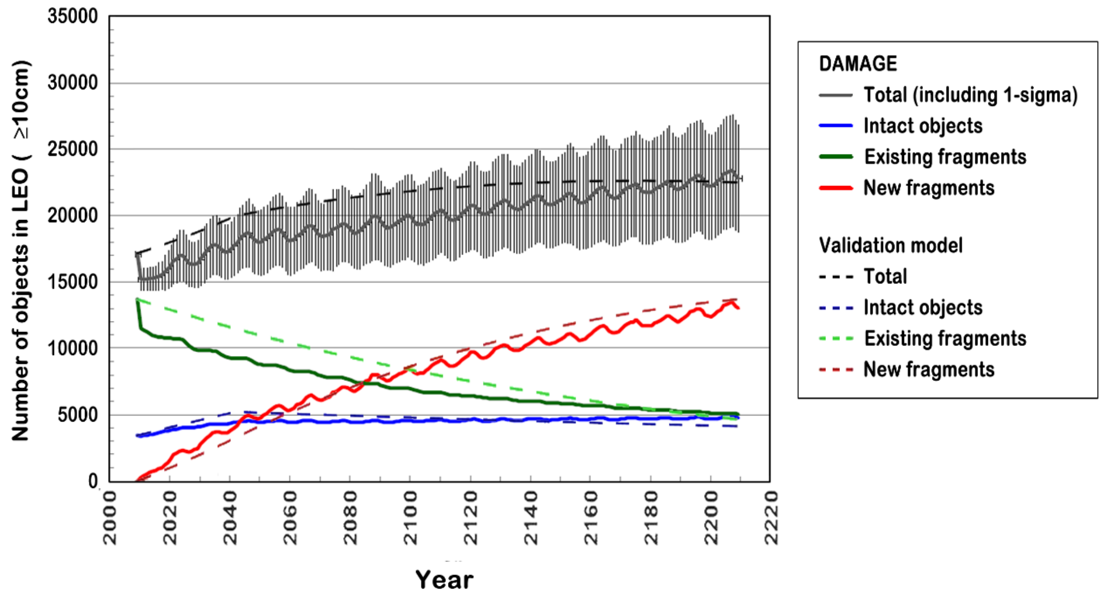

Figure 5. The plot depicts the comparison of the LEO population projection for DAMAGE (solid lines) [35] and the validation model (dotted lines). The grey vertical lines indicate 1-sigma standard deviation on DAMAGE results.

Table 3. Comparison of the numerical results obtained with DAMAGE (and presented in [35]) with the model results.

		DAMAGE		Validation Model		
Object Type	**Initial population**	**Final population**	**Change [%]**	**Initial population**	**Change [%]**	**Difference [%]**
Intact objects	3,410	4,540.18	+ 33.14	4,134.42	+ 21.24	- 8.94
Existing fragments	13,697	4,978.52	- 63.65	4,651.46	- 66.04	- 6.57
New fragments	0	11,060.32	-	13,670.37	-	+ 23.60
Total	17,107	20,579.02	+ 20.30	22,456.25	+ 31.27	+ 9.12

The proportional gain is defined as follows:

$$\begin{cases} k_P = 0 & \text{if} \quad e(t) \le 0 \\ k_P = \dfrac{u_{\max}}{e_{\max}} & \text{if} \quad 0 < e(t) < e_{\max} \\ k_P = u_{\max} & \text{if} \quad e(t) \ge e_{\max} \end{cases} , \quad (7)$$

with $e_{\max}$ the maximum error possible above which the maximum control $u_{\max}$ is used. This simple proportional law is used to determine a removal rate from a minimum value of zero with a linear law up to the selected maximum value $u_{\max}$. This maximum value for the removal rate ensures that a realistic limit can be modelled and a fixed (but custom) amount of removals per year can be reached. Without this limit, the controller would have the possibility to reach unrealistic (and limitless) high values for yearly removals.

4 Validation

The model was validated against the IADC comparison study of 2013 [35,43], which used very optimistic hypotheses: it assumed no new explosions (passivation effectiveness equal to 100% and old debris objects did not explode) and 90% of satellites decayed in 25 years after an operational lifetime of 8 years. The initial population was from ESA's MASTER 2009 database, with a reference epoch of 1 May 2009 and was then projected forwards for 200 years.

Among the several models used in [35], the UK Space Agency's model DAMAGE was selected for this validation. Table 3 lists the results of both DAMAGE results and the model, while Figure 5 depicts a visual comparison.

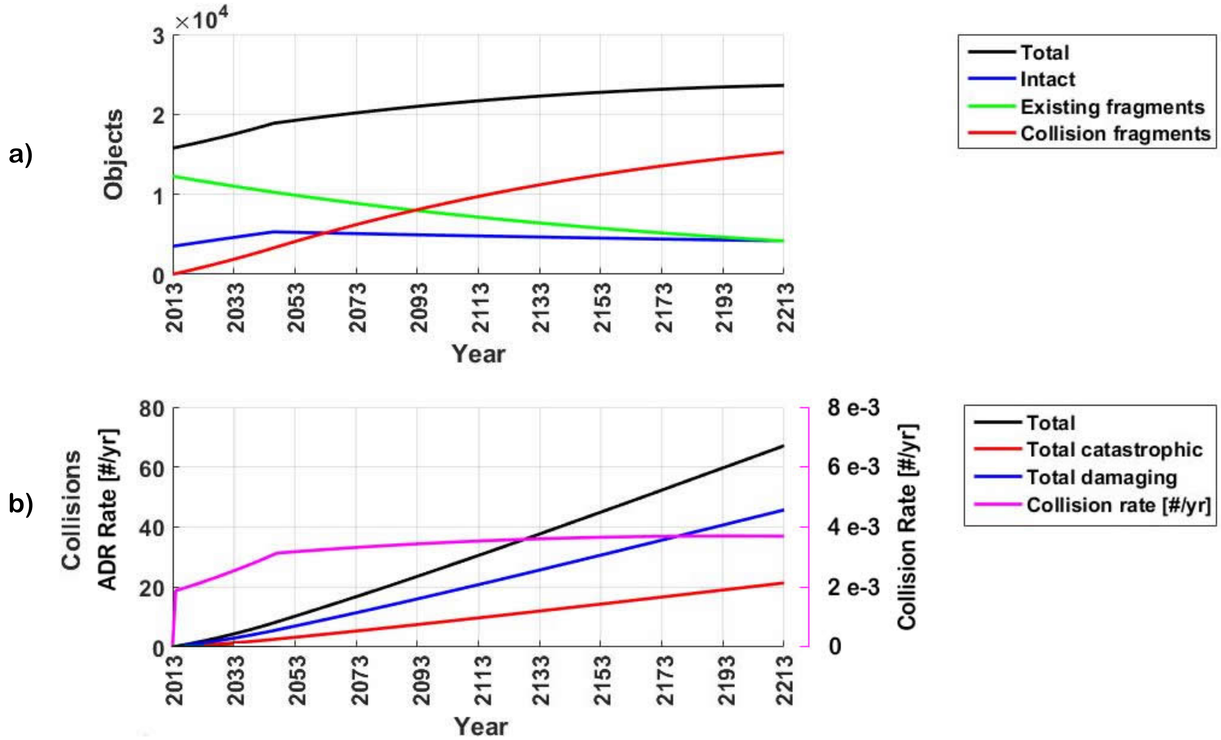

Figure 6. LEO population projection with population breakdown (top image), and evolution of collisions, and ADR rate (bottom image) in the optimistic mitigation scenario

The validation analysis uses the same initial population as the original IADC study (MASTER 2009). However, the average physical characteristics for the object types and launch traffic are derived from the available dataset (i.e. MASTER 2013, see Sections 2.1 and 2.2).

As the original IADC work was performed before the publishing of [39], DAMAGE (and the other models in [35]) used the uncorrected formula for generating collision fragments [38]. In order to ensure consistency, the same wrong formula was then utilised to compare the numerical results.

For this test, the model was set to a single band mode with a decay coefficient obtained from [8] and equal to $D = 5.4 \cdot 10^{-3} yr^{-1}$, with a time step equal to 1 year.

Collision-related values were computed using the same group of object types used in the original work: rocket bodies, payloads and MROs are grouped as intact objects, while debris are existing fragments. Since there are no explosions, the model's second governing equation in (3), can be used to test existing intact objects that are only affected by drag. The new fragments are all the objects generated during the simulation (discounting newly launched objects); but, since there are no explosions, they represent only the new collisions fragments. For this reason, the equation can be effectively used to compute the newly generated collision fragments.

4.1 Validation discussion

The model can achieve a similar trend and behaviour compared to DAMAGE results for all object types. In both models, intact objects and existing fragments tend to stabilise to a similar value, while new collision fragments became the dominant population after 2100. The total population increases up to 20,579 in DAMAGE and 22,456 in the validation model. In this latter, the trends seem to flatter toward the end of the simulation. However, the numerical value is still inside the 1-sigma standard deviation band (see Figure 5).

DAMAGE results present some periodic ripples in all the population trends, as depicted in Figure 5. These ripples are up to about 10% compared to the mean value and are caused by the periodic effect of the solar activity: approaching a solar maximum Earth's atmosphere expands and so more objects decay; conversely after about 11 years, corresponding to low solar activity, the atmosphere shrinks and fewer objects decay in the same time interval. Currently, the model does not implement the solar cycle and therefore these ripples were not present.

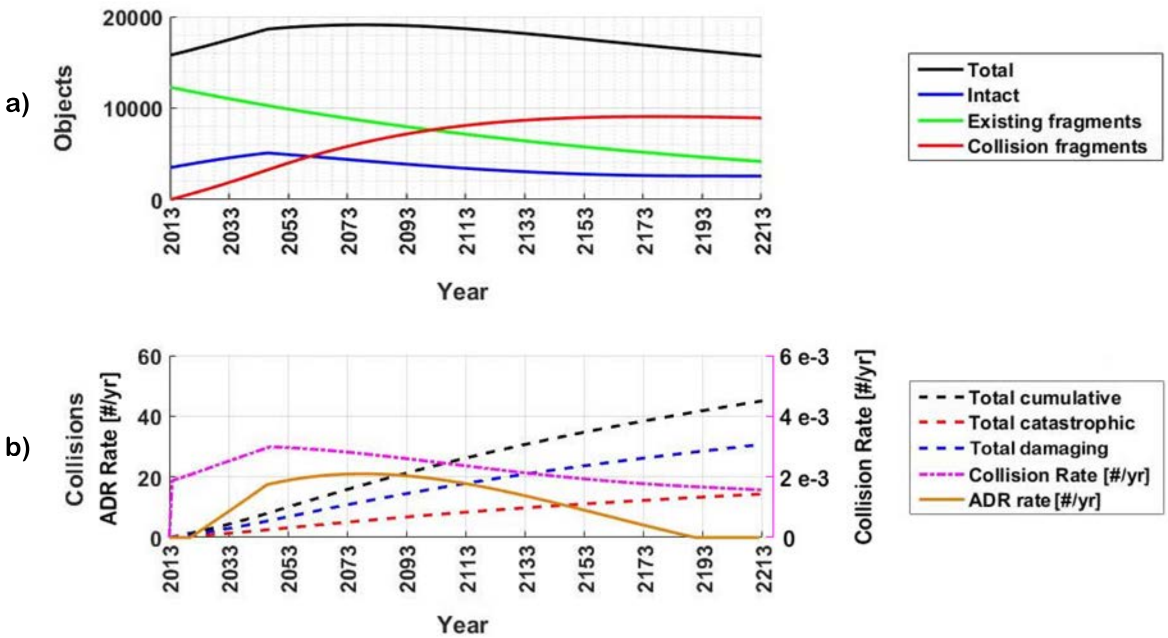

Figure 7. LEO population projection with population breakdown (top image), and evolution of collisions, and ADR rate (bottom image) using the proportional control on ADR

From the numerical point of view, the final populations were slightly different, with the collision fragments more numerous in our model (refer to Table 3). The total number of catastrophic collisions was also in good agreement: 67.37 compare to 63.37 for DAMAGE.

5 Results

5.1 Validation scenario with revised break-up model

A test similar to the validation one was performed using the same settings, except for the collision fragments that were now computed with the proper implementation of the breakup formula that corrects for the kinetic energy of the impacting objects [39]. These results are listed in Table 4.

Table 4. Results obtained with the revised formula of the NASA breakup model. The last column refers to the validation results listed in Table 3.

Object Type	Initial population	Final population	Change [%]
Intact objects	3410	4,123.05	+ 20.91
Existing fragments	13,697	4,651.46	- 66.04
New fragments	0	16,894.06	-
Total	17,107	25,668.57	+ 50.05

5.2 Optimistic mitigation scenario

The analysis presented in this section is similar to that one performed for the validation, but uses more recent data; the projection starts in 2013 and spans 200 years.

The initial population of LEO-residing objects and the launch traffic was taken from the MASTER 2013 database (see sections 2.1 and 2.2). This study used as well the revised version of the break-up model by Krisko [39]. Table 5 lists the test results, while Figure 6 depicts the orbital population, collisions and ADR rate.

Table 5. Results obtained in the optimistic mitigation scenario test.

Object Type	Initial population	Final population	Change [%]
Intact objects	3,503	4,188.26	+ 19.56
Existing fragments	12,275	4,168.56	- 66.04
New fragments	0	15,253.53	-
Total	15,778	23,610.35	+ 49.64

5.3 Proportional control on ADR

Using the same initial conditions and values for the parameters, as defined in the optimistic mitigation scenario (section 6.2), an analysis is performed using a control on the number of actively removed intact objects. The proportional law presented in equations (5) and (7) was used, with the starting year, 2020, and 25 removals per year as a maximum value. This maximum value is used when the total number of objects is more than 120% of the value in the starting ADR year.

In this test, rocket bodies, payloads and MROs were grouped as intact objects, while existing debris was classified as old fragments. Table 6 lists the test results, while Figure 7-a and Figure 7-b depict the evolution of the LEO populations grouped by object types, the cumulative collisions, the collisions rates and the removal performed.

Table 6. Results of the test with proportional control law on ADR.

Object Type	Initial population	Final population	Change [%]
Intact objects	3,503	2,574.24	- 26.51
Existing fragments	12,275	4,168.56	- 66.04
New fragments	0	8,922.50	-
Total	15,778	15,665.29	- 0.71

6 Discussion

6.1 Validation scenario with revised break-up model

In this test, the final number of intact objects was similar, as expected, to the validation case. Collision fragments were expected to rise, and increased by 23.6%.

The number of existing fragments in the final population was identical in the two tests. This behaviour is due to some limitation of the current model that does not remove objects due to collisions in the second equation of (3). Moreover, the decay coefficient was currently equal for all the object types, and the existing fragment radius was kept constant in all simulations, so the percentage change in existing fragments was always the same. These limits are known and will be addressed in a future version of the model.

6.2 Optimistic mitigation scenario

The same general trends of section 6.1 are found for this mitigation scenario. The total number of objects increases of a similar percentage (+50.05 % and +49.64, see Table 4 and Table 5) despite only LEO-residing objects were taken into account. Intact objects continue to increase in number throughout the 200-year time span. Conversely, existing fragments decrease, reaching, at the end of the simulation, a similar population to the intact one (4,169 compared to 4,188). Collision fragments are the dominant term in the final results, as listed in Table 5.

In general, this test demonstrates that even using very optimistic mitigation measures, such as 90% compliance with PMD, the future population is governed by collision fragments and is likely to increase. However, the trend is reduced to a linear growth instead of a quadratic (or exponential) one, characteristic of a non-mitigated scenario. The number of intact objects is also steady after an initial rise, as depicted in Figure 6, thanks to the adoption of the end of life disposal measure. PMD rules indeed act on the spacecraft starting from 2046, i.e. equal to the starting date, 2013, plus 8 years of operative lifetime and 25 years before the object decay.

6.3 Proportional control law on ADR

As expected, the ADR rate directly influences the number of intact objects and also the number of collision fragments while existing fragments are not affected by the active removal but only by atmospheric drag.

The controller actively removed in total 2,263 objects (11.3 per year on average), reducing the total number of collisions to 45. In this scenario, the proportional control on ADR is able to obtain a total number of objects very close to the original one (15,665 vs. 15,778). Indeed, as listed in Table 6, the final population decreases of -0.71% compared to the initial one. For this reason, the ADR rate is automatically turned off at the end of the simulation by the control law (see eq(7)).

Toward the end of the simulations, the trends for each object type tend to flatten asymptotically, as well as the collision rate (see Figure 7-b).

As clearly visible in see Figure 7-a, the number of integer objects change its trends when the PMD measures start to act in 2046. However, it is only thanks to the additional benefits of the ADR strategy that the new collision fragments slowly reduce their rise up to a stable value around 9,000 (see the red lines in Figure 6-a and Figure 7-a). The ADR rate reduces its positive slope in correspondence of the start of the PMD measures as well, making possible not to saturate the controller.

Therefore, these preliminary results highlight that a synergy of both PMD and ADR measures is needed in order to reach the stability of the LEO population. However, in order to be effective, it should be possible to perform a high number of ADR per year and PMD measures should be widely adopted (i.e. have a high level of compliance).

7 Conclusions and future works

A simplified model of space debris population in LEO has been created. It was validated against the IADC 2013 study [35,43] and is able to produce quantitative results consistent with other similar works in the literature. It also includes PMD and a proportional controller on ADR, allowing to test a broad set of scenarios. Preliminary results show the potential synergy of PMD and ADR in stabilising the LEO population, indicating also the validity of this approach.

However, there are many areas where the model could and should be improved. In particular, governing equations and decay coefficients will be revisited to better represent the real physic behaviour. New classes of objects type, area, and mass will be introduced to improve the modelling of average object physical characteristics. Future works include the overcoming of the current model limitations and the extension of the controller to a more complex one.

Lastly, to decrease even more the model run time, lookup tables will be used for drag coefficients and for the number of fragments generated by the break-up model.

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