PROBABILISTIC ORBIT LIFETIME ASSESSMENT WITH OSCAR

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ABSTRACT

ESA's space debris mitigation policy has come into force in March 2014 and adopts the space debris mitigation technical requirements from the ECSS adoption notice of ISO 24113. Those requirements include recommendations on the disposal of systems that have reached the end of their useful life, and were driving the development of OSCAR (Orbital SpaceCraft Active Removal). Specifically, OSCAR is the component of DRAMA designed to address disposal manoeuvres at end-of-life and assess the compliance of the later stages of a mission with the mitigation requirements, where mission planners have to decide on their implementation at early stages in the project (typically around SRR/PDR).

In its current version, published and freely available within the DRAMA software suite, OSCAR allows for the analysis of the orbit evolution subject to different possible future scenarios for solar and geomagnetic activity, which are the main drivers in the estimation of the residual lifetime for a specific orbit.

Based on standardised and widely accepted methods for the prediction of those scenarios, the remaining orbit lifetime is computed via a semi-analytical propagation taking into account all relevant perturbations.

However, long-term forecasts of the orbit evolution are very sensitive to several quantities, most of them very difficult to forecast, including the solar and geomagnetic activity, the objects cross-section, its attitude state and mass, the drag and solar radiation pressure coefficient of the object, as well as physical model limitations. Moreover, the uncertainties in the injection manoeuvre transferring the spacecraft into its disposal orbit and uncertainty in the disposal epoch cannot be neglected.

With OSCAR being used in the compliance verification process with respect to the mitigation requirements, the current approach to also assess the uncertainty associated with a lifetime estimate shall be discussed. By accounting for the various sources of uncertainty, OSCAR will allow for a more probabilistic and thus more realistic estimate, which is beneficial in the compliance analysis.

This paper will give a brief overview on the core functionalities of OSCAR and then focus on the uncertainties considered for the upcoming upgrade of OSCAR. The propagation of the uncertainties results in a probabilistic assessment of the orbit lifetime. For example, the 25-year-rule compliance can then be based on an assessment in how many cases the orbit lifetime would be below or above 25 years.

***Index Terms*—** DRAMA, OSCAR, Mitigation, Space debris, Policy, Lifetime, Uncertainty

1. INTRODUCTION

The time span from where an object is injected into its orbit until the re-entry into Earth's atmosphere, is referred to as the orbit lifetime. While several object properties and environmental conditions affect the decay of an orbit and thus make it very difficult to estimate the orbit lifetime, it is still a very important quantity to characterise a space mission.

The orbit lifetime needs to be computed to assess the compliance with current space debris mitigation guidelines. Those guidelines typically define a so-called *25-year-rule* for the Low Earth Orbit (LEO) region. Space mission designers have to define a mission plan that guarantees their compliance with that rule, which means that after the end of operations, the spacecraft burns up in Earth's atmosphere within 25 years.

The Orbital Spacecraft Active Removal (OSCAR) tool within the European Space Agency's (ESA) Debris Risk Assessment and Mitigation Analysis (DRAMA) software suite allows to compute the remaining lifetime for a given orbit.

The obtained result can be compared to the 25-year limit in the mitigation guidelines. However, this approach does not take into account any uncertainties associated with such a lifetime estimate. In this paper, sources of errors in the estimation of orbit lifetime are analysed. This is a first step towards a probabilistic assessment of orbit lifetime that is envisaged as a goal for a future upgrade of OSCAR.

1.1. Mitigation guidelines

In March 2014, ESA's space debris mitigation policy [1] has come into force. It adopts the space debris mitigation technical requirements from the European Cooperation for Space Standardization (ECSS) adoption notice [2] of ISO 24113 [3].

For spacecraft that are designed with ESA's space debris mitigation policy applicable, the project is required to provide a *space debris mitigation plan*. An essential part of this plan for LEO missions is the assessment of the remaining lifetime after the end of nominal operations.

The French Space Operations Act (FSOA) [4], which came into force in France in 2010, can be regarded as an example on national level, which renders the 25-year-rule as applicable.

The computation of the orbit lifetime is thus an essential step in the early phases of a space mission project and, depending on the envisaged orbit solution, is one of the drivers of the design of the spacecraft and the mission.

1.2. OSCAR

OSCAR is the component of DRAMA designed to address disposal manoeuvres at end-of-life and assess the compliance of the latter stages of a mission with the mitigation requirements. In its current version, published and freely available within the DRAMA software suite[1], OSCAR allows for the analysis of the orbit revolution subject to different possible future scenarios for solar and geomagnetic activity, which are the main drivers in the estimation of the remaining lifetime for a specific orbit.

The OSCAR software has been developed focusing on:

- Assessing the remaining orbital lifetime of a user-defined spacecraft, wholly or partly orbiting in LEO, to identify if any action is required to ensure an acceptable duration for disposal.
- Predictions of solar and geomagnetic activity based on methods recom-mended by current standards from ECSS [5] and ISO [6].
- Allowing the investigation of re-orbit and de-orbit requirements (e.g. Δv, propellant mass and manoeuvre duration) for chemical and electric propulsion, electrodynamic tethers and drag augmentation devices.
- Assessing the compliance with ESA's space debris mitigation requirements including both protected regions for LEO and Geostationary Earth Orbits (GEO).

A semi-analytical method is used to predict the evolution of the orbit based on the input solar and geomagnetic activity scenario, as well as object properties. The Fast Orbit Computation Utility Software (FOCUS) propagator considers the following perturbations:

- The geopotential with full zonal and tesseral terms up to $(n, m) = (8, 8)$, including Kaulas theory with J_2^2 terms,
- Atmospheric drag based on a Gauss-Legendre quadrature of the perturbation equations including the thermosphere model NRLMSISE-00,
- Luni-solar gravity attraction, and
- Solar radiation pressure (SRP) with a cylindrical Earth shadow

An Adams-Bashforth/Adams-Moulton Predictor/Corrector method is used to integrate the singly averaged elements in time steps of up to two days. The lifetime estimates provided by the propagation are subject to an ISO-recommended margin for semi-analytical methods of 5% [6]. The compliance verification for GEO disposal manoeuvres is performed with an SRP coefficient of at least 1.5, which is recommended by [7].

1.3. Study objectives

The goal of this paper is to present the preliminary results of a larger on-going internal study at ESA with its main objective being to upgrade OSCAR with a capability to assess orbital lifetime in a probabilistic way.

The first step to achieve this goal is to identify the sources that contribute to the uncertainties in the lifetime estimate. Second, the individual sources are analysed with respect to the observed variations in the identified quantities and how the probability density functions (PDFs) of the initial quantities combine and finally project on the PDF for the orbit lifetime.

In this paper, the effects of errors in thermosphere models, the modelling of the attitude of the satellite and its drag coefficient as well as the sensitivity of the lifetime estimate on changes in the disposal epoch and uncertainties in the orbital elements are analysed.

The results obtained herein shall serve as an input for further analyses in the future.

1.4. Related work

The characterisation of lifetime assessment uncertainties and analysing the sensitivity to various parameters was the subject of several recent studies.

In general, the evolution of uncertainties has been studied by many authors over the last few decades.

However, in the context of orbit lifetime assessment, there are only a few publications: The study by Dell'Elce et al. [8, 9] resulted in two papers, where the authors characterised the quantities that contribute to the uncertainties in orbit lifetime. They used their result to compute the PDF for the orbit lifetime estimate for a satellite in LEO.

A statistical lifetime assessment analysis for Geosynchronous transfer orbits (GTO) was performed by Le Fèvre et al. [10]. The authors recommend to use a Monte Carlo approach to obtain a probabilistic assessment of the orbit lifetime for objects on high-eccentricity orbits, as the initial parameters are very sensitive to even small changes.

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[1] `https://sdup.esoc.esa.int`

In order to achieve the goal of obtaining a probabilistic lifetime assessment in OSCAR, the analysis of [8, 9] served as a very valuable input and was extended to include a larger set of objects in LEO and thus study the effects in-depth.

2. STUDY APPROACH

In order to study the impact various uncertainties in the initial conditions have on drag-affected orbits, a source of reference, or an objective *truth* was required, the orbit lifetime computations can be compared with.

For this purpose, all intact satellites and rocket bodies have been identified, that had been resident in the LEO region for at least 1 year.

It was required to have access to the orbit information for those objects, where USSTRATCOM's Two-line Elements (TLE) were considered as appropriate for the foreseen study. Also, information on the object's shape was required in order to estimate the cross-sectional area and mass.

In total, 213 rocket bodies (R/B) and 287 satellites (or payloads, P/L) have met the defined criteria. Besides the TLE as an external source of information, ESA's Database Information System Characterising Objects in Space (DISCOS) was used as the primary source to obtain the required object dimensions.

For the identified reference orbits, lifetime computations with OSCAR were performed, based on initial states obtained from several TLEs for each object.

The first analyses quickly revealed that handling payloads posed some challenges. First of all, spacecraft may come with any arbitrary shape in general, where appendages like solar panels, as well as the rather complicated attitude rules make it difficult to work with a convenient model for the ballistic coefficient across the entire propagation span. Moreover, manoeuvres require another step of pre-processing - and even after this step, a satellite on its disposal orbit, which does not perform any attitude control any longer, is difficult to model.

The handling of rocket bodies is less complicated: If present, manoeuvres were only filtered within the very first TLEs, which still allowed to have many objects with long lifetimes in the analysis. Also, rocket bodies are not attitude-controlled, so that a random tumbling motion can be assumed and the information from DISCOS proved to be very consistent in combination with the TLE, after the results of the first test cases were obtained. Only six R/B were filtered , as their relative deviation from the true lifetime was larger than $100\,\%$.

In Fig. 1 the true lifetimes of the selected R/B are shown. It can be seen that by far most of the objects are in the range from 1 years to 10 years. There were also two objects that had true lifetimes between 36 years and 38 years.

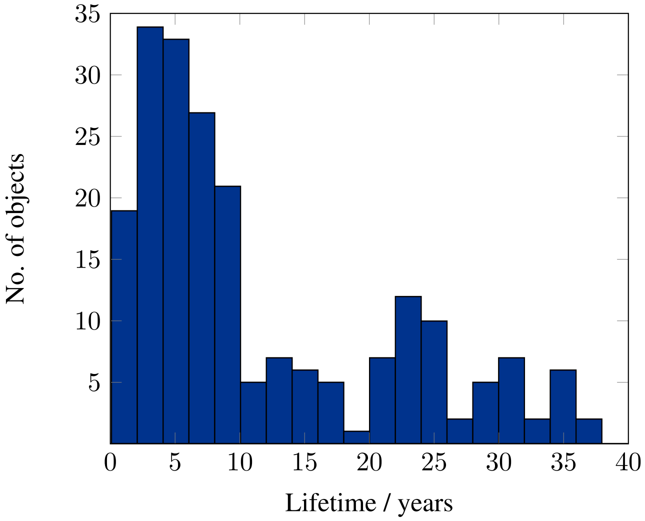

Fig. 1. Real lifetimes of rocket bodies in LEO used in the analysis.

In principle, with about 60 years of space activities, this value would also be the maximum possible reference. In Fig. 2 it can be seen that most of the objects in the analysis were launched between 1970 and 1980.

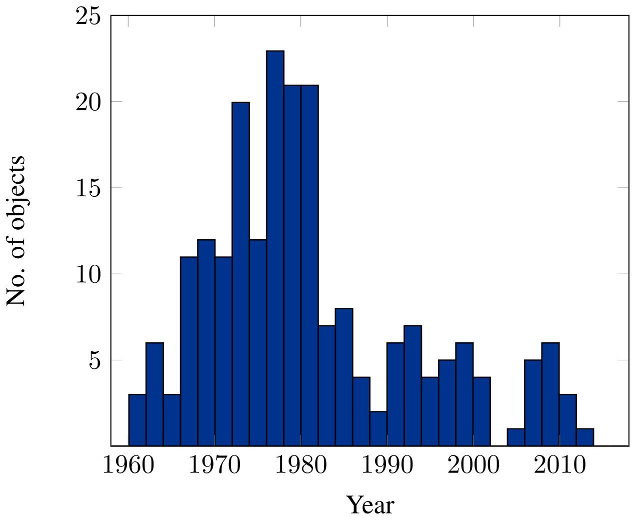

Fig. 2. Launch year of rocket bodies in LEO used in the analysis.

In addition to the comparison with true orbits, the implementation of a Monte Carlo (MC) engine for OSCAR was initiated. The first results are shown in this paper, where the uncertainties in the disposal epoch were mapped on the lifetime estimate.

3. LIFETIME ESTIMATION WITH OSCAR

The estimation of orbit lifetime presupposes selecting an appropriate thermosphere model. In the currently available version of OSCAR, the MSIS-90 model is used. For the analysis in this paper, the more recent NRLMSISE-00 model was selected.

Both models have in common that they provide the total number density as a function of the coordinates of the satellite as well as several quantities that describe the solar and geomagnetic activity. The K_p or A_p indices for geomagnetic activity and the $F_{10.7}$ proxy for the solar activity have to be forecasted. While there are no physical models available to provide reliable predictions of those quantities, one can use one of several different approaches to obtain the required predictions for spans of several decades ahead.

Four different methods which are individually compliant with either the ECSS or ISO standards [6, 5], have been implemented in OSCAR.

The **latest prediction** method is one of the two approaches recommended by [6] and uses latest available data of the current solar cycle to predict the future evolution of the solar and geomagnetic indices, a method described in [11].

This approach also provides best-case and worst-case estimates for a user-defined confidence interval. The duration of a solar cycle is 3954 days, which is compliant with [6].

The **repeated solar cycle** method is an approach recommended by [5]. The tailoring guidelines of that standard describe the future predictions based on a repetition of the 23^{rd} solar cycle. The cycle duration is fixed with 140 months à 30 days.

The **Monte Carlo sampling** approach is the second method compliant with [6]. It is based on a random draw approach for a data triad consisting of the daily $F_{10.7}$ and the averaged $\bar{F}_{10.7}$ index, as well as the geomagnetic index A_p. Daily data from up to six past solar cycles is used to generate an instance of a future series of cycles. All of them have been transformed to a fixed duration of 3954 days.

The fourth method is based on a **constant equivalent solar and geomagnetic activity**. It is derived from a method developed in the frame of the French Space Operations Act [10], which is said to be compliant with ISO 27852 due to the random construction of future solar cycles based on data from past cycles.

4. ADDRESSING UNCERTAINTIES

A comprehensive overview on the different sources of uncertainties in the lifetime computation is provided in [9]. In general, the following sources were identified:

- Atmosphere model errors (including errors in the prediction of solar and geomagnetic activity)
- Attitude and drag coefficient
- Disposal orbit injection errors, which result in an uncertainty of the initially planned orbital elements
- Uncertainties in knowing the disposal manoeuvre date or, for non-manoeuvreable satellites, the launch epoch date in advance.

4.1. Uncertainties introduced by the interaction with Earth's atmosphere

An advantage in the comparison with past orbits is the fact, that the important atmosphere model inputs, namely the solar and geomagnetic activity indices, are known and thus do not introduce additional errors. One can thus assume that the resulting deviations are a combined result from the force model errors, the initial state and the shape and attitude motion of the object. However, one has to keep in mind, that also atmosphere models are calibrated only for a limited time span and do not cover the entire span from 1960 onwards by their underlying data.

The first results were obtained for the nominal solar and geomagnetic activity, which are accessible via the latest prediction method in OSCAR. It can be seen in Fig. 3 that the mean relative error (computed minus observed) is about -10%. This means that OSCAR tends to underestimate lifetimes in LEO. In [6], it is recommended to add a margin of 5% to compensate for force model errors. This would compensate in some way for the observed deviation. The standard deviation is about 20% and, interestingly, corresponds to the generally assumed value when atmospheric uncertainties are assessed.

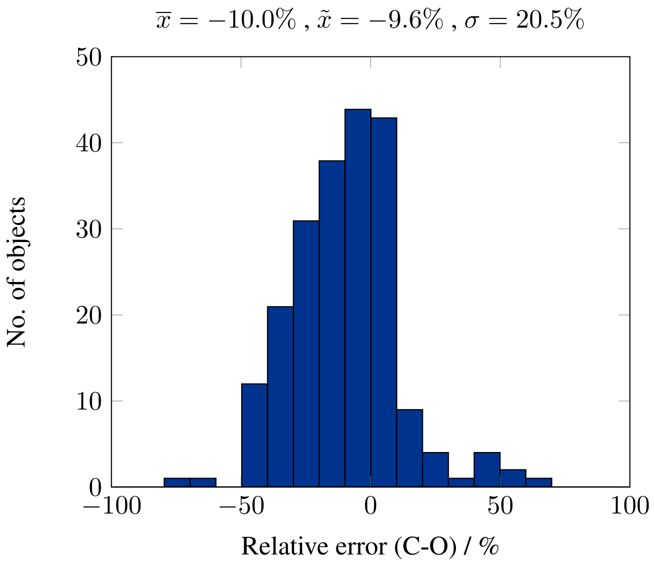

Fig. 3. Relative error in the computed lifetimes for the nominal case, compared to true lifetimes for rocket bodies in LEO.

In Fig. 4, the same results are shown for the ECSS-recommended repeated solar cycle. The past solar and geomagnetic activity was replaced by a repeated 23^{rd} cycle. The surprising result is that the deviations are significantly reduced when compared with the nominal case in Fig 3. The standard deviation, however, is increased to about 25%. The reason for this can be found by looking at Fig. 2: most objects in this analysis were launched in the years between 1970 and 1980. The orbits of those objects were thus affected by solar cycle 21 or even cycle 22, both showed a higher solar activity than cycle 23, which is the basis for the ECSS scenario.

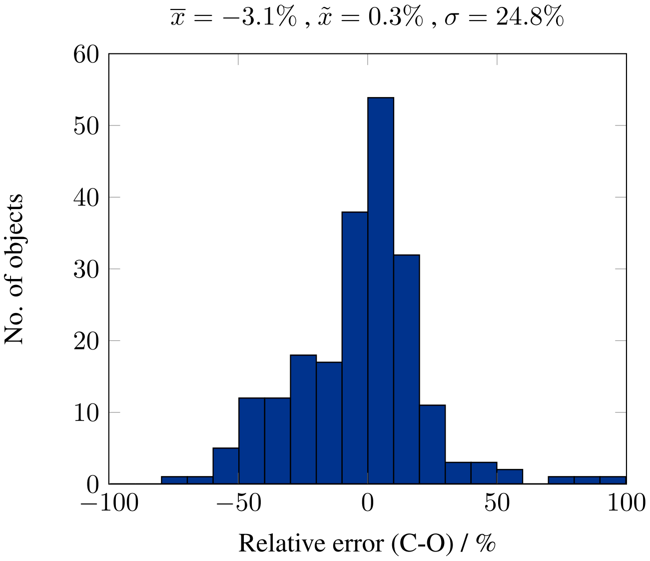

Fig. 4. Relative error in the computed lifetimes for the ECSS repeated cycle, compared to true lifetimes for rocket bodies in LEO.

The next case was analysed for the ISO-recommended MC method. The result is shown in Fig. 6. It can be seen that the deviation to the reference is greater than for the nominal case, with the mean error being about -17%. The standard deviation is at 22%.

The MC method as recommended by ISO demands for sampling a full triad of A_p, $F_{10.7}$ and the 81-day averaged $\bar{F}_{10.7}$ for each day of a cycle from any of the five preceding cycles. It is counter-intuitive to do this for the averaged data, as this could be, in principle, obtained from the sampled daily values in a post-processing step.

Therefore, another analysis was performed, where $\bar{F}_{10.7}$ was obtained from the sampled daily $F_{10.7}$ data. The result is shown in Fig. 6. One can see that the mean and median error are both reduced by about one percentage point, while the standard deviation declines slightly. While one could argue that the results are better with the post-processing step included, the difference is not that significant. It is thus difficult to prefer one method over the other - at least the ISO-

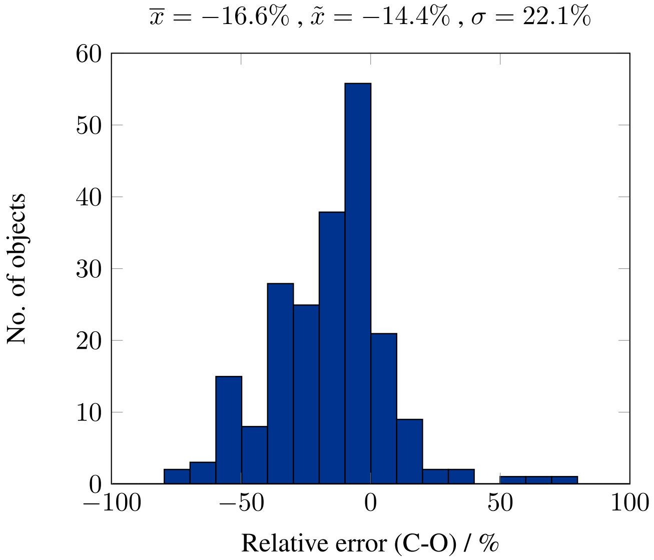

Fig. 5. Relative error in the computed lifetimes for the ISO-MC approach, compared to true lifetimes for rocket bodies in LEO.

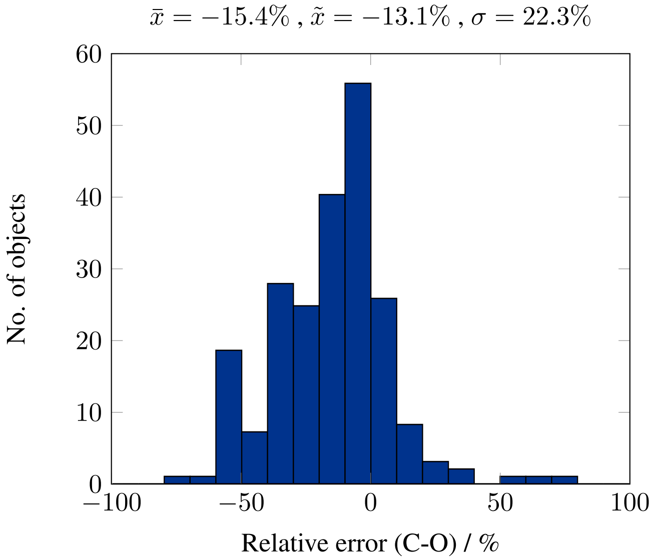

Fig. 6. Relative error in the computed lifetimes for the MC approach, which uses averaging (as opposed to the ISO recommended method to randomly draw averaged values for $\bar{F}_{10.7}$), compared to true lifetimes for rocket bodies in LEO.

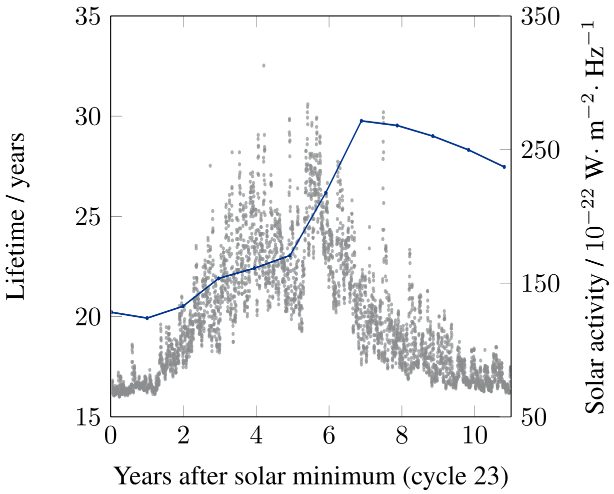

Fig. 7. Lifetime estimates (blue markers, connected with lines) for the same initial conditions, altering only the state vector epoch. Variation shown for solar cycle 23 (daily values for $F_{10.7}$ with gray markers).

recommended approach is simpler implementation-wise.

4.2. Disposal manoeuvre date

The assessment of orbital lifetime has to occur already at a very early project phase. The space debris mitigation plan (SDMP), which is required according to ESA's space debris mitigation policy, has to be delivered by the System Requirement Review (SRR) already. It contains the design of the disposal phase and as such the designed disposal orbit. Considering typical project durations, eventual delays, extensions of the nominal mission, etc., it is very difficult to narrow down the epoch of the disposal manoeuvre significantly.

In the following, it was therefore assumed that the disposal manoeuvre date can be uniformly distributed across a solar cycle with a duration of 11 years. For the results shown in Fig. 7 the lifetime in 1-year-steps was computed. A typical sun-synchronous orbit at $610\,\mathrm{km}$ was simulated. Depending on the year in the solar cycle for which the lifetime is estimated, it can indeed be either below 25 years (and thus compliant with the requirement!) or above. In the example in Fig. 7, the minimum value was about 20 years, while the maximum was 30 years.

One can now count the number of cases where the lifetime is below 25 years and thereby already obtain a more probabilistic assessment of the orbit lifetime taking into account the uncertainties in the disposal manoeuvre date alone. For a cubesat without manoeuvre capability, this date would be equal to the launch (or deployment) epoch.

Fig. 8 shows the cumulated probability, based on the scenario shown in Fig. 7. The 25-year-rule is thus respected in 51% of the cases.

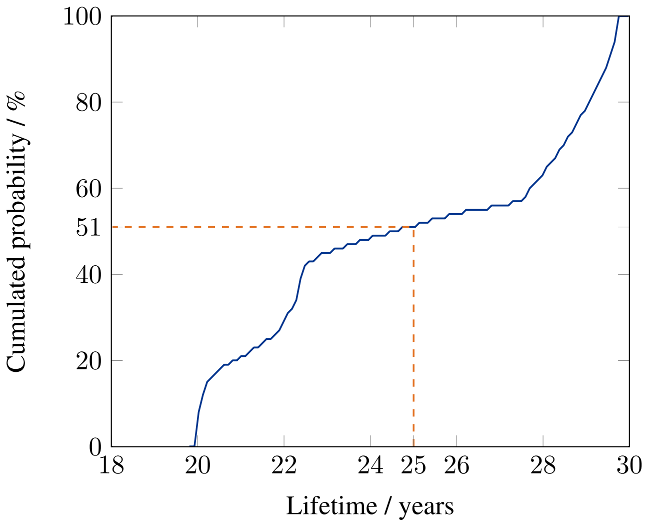

Fig. 8. Cumulative probability assuming a uniform distribution of the initial state vector epoch in the range of one solar cycle. The cumulative probability to obtain a 25-year orbit is shown with the dashed line.

4.3. Lifetime sensitivity due to uncertainties in orbital elements

One goal in the ongoing upgrade activity of OSCAR is to have a MC engine, which allows for parametric studies. An example is shown in Fig. 9, where a Cubesat was analysed, that was deployed in an orbit of 610 km altitude. A typical orbit insertion uncertainty (1σ) of 3 km for the semi-major axis was assumed. The result is shown in Fig. 9. An initial error of 3 km thus maps to uncertainties in the orbit lifetime where the obtained values span from 19.2 years to 20.7 years.

5. CONCLUSION

The goal of this study was to do the first steps towards a probabilistic assessment of orbit lifetime with OSCAR.

The sources of uncertainty in the estimation of orbit lifetime were identified. A subset of rocket bodies, which were on orbit in the past and re-entered Earth's atmosphere, were identified. Their orbits were obtained from USSTRATCOM's TLEs and shape information was derived from ESA's DISCOS.

The orbit lifetime computation with OSCAR was performed for the past orbits and compared to the true orbits in order to be able to assess the general error that results from the combined effects of force model errors, initial state vector and attitude motion errors.

It was shown that the nominal case, based on true solar and geomagnetic activity (via OSCAR's latest prediction method) is biased by about 10% and the combined effects

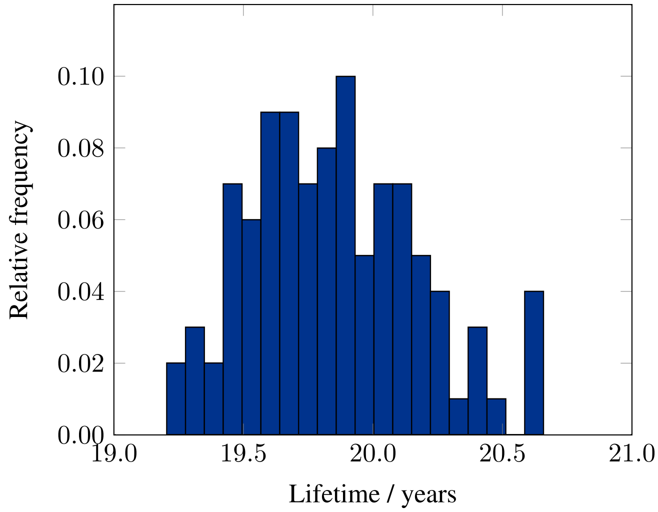

Fig. 9. Distribution of orbit lifetime for a normal distribution in the initial semi-major axis ($\mu = 6988\,\mathrm{km}$, $\sigma = 3\,\mathrm{km}$).

of atmosphere model errors and errors in the attitude motion lead to an underestimation of the orbit lifetimes for the objects analysed.

Other methods, recommended by ECSS and ISO, were also analysed. The surprising result was that the ECSS repeated cycle, used in the propagation with OSCAR, showed the least deviations, where the median error between computed and observed lifetime was only 0.3%. The reason is that most of the analysed objects experienced the higher solar activity of solar cycles 21 and 22 compared with the ECSS repeated solar cycle 23.

For the MC method, it was shown that the deviations are even greater than for the nominal case. It does not seem to be of great importance, whether averaged $\bar{F}_{10.7}$ are sampled randomly, or post-processed from the randomly sampled daily values.

The uncertainty of the disposal manoeuvre date was analysed and for a typical sun-synchronous orbit at 610 km, it was shown that the influence of the epoch is quite significant: While the median value might be close to 25 years, there can be also solutions, where the result is 20 years (close to solar minimum) or 30 years (about 1-2 years after solar maximum). The cumulative probability can be used alongside with the nominal value to provide a more probabilistic estimate of orbit lifetime to assess compliance with the 25-year-rule.

The presented study is currently being continued and shall be extended to also include LEO transient objects (e.g. in GTO), after the MC engine in OSCAR has been fully implemented.

In order to also analyse spacecraft, it would be desirable to extend the information in DISCOS, which would allow for more complex attitude laws over the propagation span.

6. REFERENCES

[1] European Space Agency, ESA Director General, “ESA/ADMIN/IPOL(2014)2 - Space Debris Mitigation Policy for Projects,” 28/03/2014.

[2] European Cooperation for Space Standardization (ECSS), “Space Sustainability: Adoption Notice of ISO 24113: Space systems - Space debris mitigation requirements, ECSS-U-AS-10C,” 10/02/2012.

[3] International Organization for Standardization (ISO), “Space systems - Space debris mitigation requirements,” Tech. Rep. ISO 24113:2011, Geneva, Switzerland, 2011.

[4] French State, “French Space Operations Act no. 2008-518,” 03/06/2008.

[5] European Cooperation for Space Standardization (ECSS), “Space engineering - Space environment, ECSS-E-ST-10-04C,” 15/11/2008.

[6] International Organization for Standardization (ISO), “Space systems - Estimation of orbit lifetime,” Tech. Rep. ISO 27852:2011, Geneva, Switzerland, 2011.

[7] International Organization for Standardization (ISO), “Space systems - Disposal of satellites operating at geosynchronous altitudes,” Tech. Rep. ISO 26872:2010, Geneva, Switzerland, 2010.

[8] Lamberto Dell’Elce and Gaëtan Kerschen, “Probabilistic Assessment of Lifetime of Low-Earth-Orbit Spacecraft: Uncertainty Propagation and Sensitivity Analysis,” *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 5, pp. 886–899, 2015.

[9] Lamberto Dell’Elce, Maarten Arnst, and Gaëtan Kerschen, “Probabilistic assessment of the lifetime of low-earth-orbit spacecraft: uncertainty characterization,” *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 5, pp. 900–912, 2015.

[10] C Le Fèvre, H Fraysse, V Morand, A Lamy, C Cazaux, P Mercier, F Deleflie, and DA Handschuh, “Compliance of disposal orbits with the french space operations act: The good practices and the stela tool,” *Acta Astronautica*, vol. 94, no. 1, pp. 234–245, 2014.

[11] Robert L Holland and William W Vaughan, “Lagrangian least-squares prediction of solar flux,” *Journal of Geophysical Research: Space Physics*, vol. 89, no. A1, pp. 11–16, 1984.