ASSESSING UNCERTAINTIES IN THE ESTIMATION OF THE ORBITAL LIFETIME

A. Operti[(1)], **V. Braun**[(2)], **S. Lemmens**[(3)], **and S. Corpino**[(4)]

[(1)] *Politecnico di Torino, 10129 Torino, Italy, Email: andrea.operti@gmail.com*
[(2)] *IMS Space Consultancy GmbH at Space Debris Office (OPS-GR), ESA/ESOC, 64293 Darmstadt, Germany, Email: vitali.braun@esa.int*
[(3)] *Space Debris Office (OPS-GR), ESA/ESOC, 64293 Darmstadt, Germany, Email: stijn.lemmens@esa.int*
[(4)] *Politecnico di Torino, 10129 Torino, Italy, Email: sabrina.corpino@polito.it*

ABSTRACT

The European Space Agency's (ESA) space debris mitigation policy intends to avoid the creation of more space debris. Among other metrics, the orbital lifetime needs to be computed in order to assess the compliance with the current space debris mitigation requirements for individual space objects. However, a deterministic assessment of the orbit decay and lifetime prediction is not likely to be a suitable approach, while a probabilistic assessment, which takes into account also the associated sources of uncertainty, would be more realistic. This paper focuses on assessing the uncertainties correlated with the estimation of the orbital lifetime and addresses the question whether or not a present bias in the lifetime estimate could be reduced by the introduction of a constant correction factor for the atmospheric density.

Key words: DRAMA, OSCAR, Mitigation, Space debris, Lifetime, Uncertainty.

1. INTRODUCTION

Since a spacecraft is exposed to the risk of collision with space debris and operational satellites throughout its launch, early operations, operational and end-of-life phases, the estimate of the orbital lifetime is extremely important to characterize a space mission. Moreover, a non-negligible risk exists during crossings or nominal operations within the Low Earth Orbit (LEO) region. ESA's space debris mitigation policy implements the space debris mitigation technical requirements from the ECSS adoption notice of ISO 24113:2011 [5], intended to minimize debris generation and risk associated with space debris. These requirements are addressed to space mission planners, designers, manufactures and operators to ensure that spacecraft and launch vehicle orbital stages are designed, operated and disposed in a manner that prevents them to generate debris through their orbital lifetime. The requirements define the so called 25 years rule for the LEO region, meaning the spacecraft has either to de-orbit (and burn up in Earth's atmosphere) or to re-orbit to an orbit above the protected region within 25 years from the end of operations. The Orbital Spacecraft Active Removal (OSCAR) tool within the ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) software suite allows to compute the remaining orbit lifetime for a given orbit and to compare the result with the guidelines to assess the compliance.[1] However, deterministic solutions of the orbit decay and lifetime prediction are likely to be not suitable approaches, due to the sensitivity of the long-term forecast to several quantities that introduce uncertainties into that estimate. Those include the solar and geomagnetic activity, the stochastic nature of the thermosphere, the complexity of drag modeling, the attitude of the object and its physical properties, such as mass and average cross-sectional area [2]. Therefore, a probabilistic assessment of the orbital lifetime, which takes into account also the associated sources of uncertainty, would be more realistic. The assessment of those uncertainties and the investigation on possible methods to correct the eventual bias in the orbit lifetime constitute the main topic of this paper. The orbital lifetime is by definition the elapsed time between the point where an object is injected into its orbit and the re-entry into Earth's atmosphere [5]. A clear distinction has to be made between the orbital lifetime as defined by ISO and the one computed with the OSCAR tool for the purpose of this paper. The former allows to include the operational phase into that figure, while the latter will consider the natural decay at the end-of-life of a satellite.

1.1. Study Objectives

The work presented in this paper originates from a research initiated by the Space Debris Office at the European Space Operations Centre (ESOC), in order to provide a probabilistic assessment of the orbital lifetime that would represent a future upgrade of OSCAR [1]. Therefore, the objective of this paper is assessing the uncertainties correlated with the orbital lifetime estimation. This would involve looking at the inherent uncertainties of cur-

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

rently used atmosphere models and the propagation of those uncertainties, as well as quantifying other errors relevant in the interaction with the atmosphere, e.g. initial conditions of the spacecraft, mass and cross-sectional area. In addition, the drag correction coefficient analysis is intended to answer the question whether or not a global constant correction is able to reduce the bias in the orbit lifetime estimates. This work is intended to be of value to the long-term re-entry predictions, since accounting for the various sources of uncertainty, will allow for probabilistic and therefore more realistic estimates.

2. STUDY APPROACH

In order to assess the uncertainties in the estimation of the orbital lifetime, the orbit dynamic of the predicted lifetime has to be compared to the observed orbit decay of the object in question, which represents the *reference orbit*. In his work, Braun [1] already identified all the intact satellites (or payloads, P/L) and rocket bodies (R/B) that orbited the Earth in the LEO region for at least 1 year. For the purpose of this study, this data set is herein considered and extended in order to account also for the objects that had resided for at least 1 year in High Elliptical Orbits (HEO) region and for the class of small satellites (e.g. CubeSats). In particular, an orbit has been classified as HEO if the apogee altitude is above 2000 km, while the perigee altitude is at several hundred kilometers.

ESA's Database Information System Characterising Objects in Space [2] (DISCOS) was used to retrieve all the objects available that meet the following requirements:

- re-entry has occurred in the past,
- it has not been associated to manned spaceflight
- it has to be a P/L or a R/B
- the altitude of perigee has to lie between 400 km and 2000 km for near-circular orbits or, whenever the perigee finds itself below 400 km, then the eccentricity has to be greater than 0.2 in order to include high eccentric orbits which still experience a relevant interaction with the atmosphere in the regions close to the perigee.

The result is an initial data set comprehensive of 1144 objects, which includes 607 rocket bodies and 537 payloads in LEO and HEO. The identification of the small satellites imposed a further constraint applied on the spacecraft mass, which has to correspond to an order of magnitude of 10 kg or below. For this particular class, it has been considerate appropriate to include in the data set also the missions with an orbital lifetime below 1 year. This led to an initial data set comprehensive of 77 small satellites.

[2]https://discosweb.esoc.esa.int

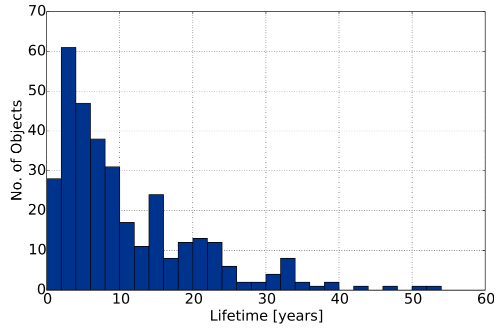

Figure 1. Real orbit lifetime of the payloads in LEO and HEO used for the analysis.

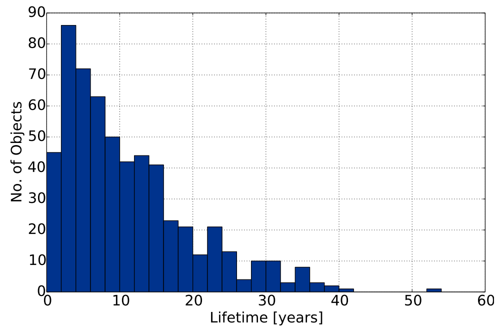

Figure 2. Real orbit lifetime of the rocket bodies in LEO and HEO used for the analysis.

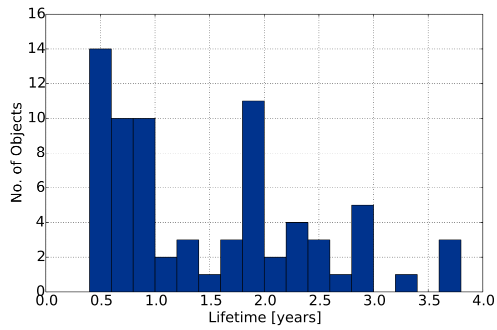

Figure 3. Real orbit lifetime of the small satellites in LEO used for the analysis.

The reference orbit required the knowledge of the orbit information for those objects and USSTRATCOMs Two Line Elements (TLE) were considered appropriate for the present study. Figures 1, 2 and 3 report the true orbital lifetimes of the selected objects. For the identified reference orbits, orbit lifetime estimations are computed with OSCAR. This requires to know the initial states, which is retrieved from several TLEs for each object. While for the estimation of the ballistic coefficient, DISCOS was used to retrieve information about the physical properties of the objects (mass, shape, average cross-sectional area).

Table 1. Data set summary for the objects identified in the LEO and HEO regions.

	P/L	R/B	Small Satellites
LEO	285	226	73
HEO	48	349	-
Total	333	575	73

From the original set of data, a set of objects was filtered by not having orbit information and/or average cross-sectional area, which ultimately resulted in 575 R/Bs, 333 P/Ls and 73 small satellites. In Table 1, a summary of the data set is shown for the LEO and the HEO regions.

3. ORBIT LIFETIME ESTIMATION WITH OSCAR

The orbit lifetime estimation presupposes the selection of an appropriate thermosphere model, which also introduces a source of uncertainty. To account for the atmospheric drag effects, the current available version of OSCAR uses the MSIS-90 atmospheric model. For the study presented in this paper, the more recent NRLMSISE-00 is used, which will be available in the upcoming new version of OSCAR.

Given the solar and the geomagnetic activity, respectively represented by the $F_{10.7}$ proxy and the indices K_P or A_P, the atmospheric model provides the total density as a function of the coordinates of the satellite. The solar and geomagnetic activity quantities have to be forecasted and different approaches exist for the purpose. A description of those implemented in OSCAR and compliant with the ECSS or ISO is available in [1]. For the analysis presented herein the *latest prediction* method have been used. This is one of the two approaches recommended by [4] 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 [6]. For the case study presented, the objects considered for the analysis already re-entered the atmosphere, thus no solar and geomagnetic activity data forecasting is required. This allows to exclude the uncertainties in the orbit lifetime estimation correlated with the solar and geomagnetic activity forecast.

In order to determine whether or not the bias in the orbit lifetime estimation can be minimized with a global constant coefficient, a set of global constant drag correction factors has been identified. The coefficient, indicated with C_C, is applied on the neutral density estimate at the satellite altitude provided by the atmospheric density model. The correction of the force model final output allows to influence in a direct way the orbit lifetime by varying the magnitude of the drag force. For the analysis presented in this paper, the range of the correction factors extends from 0.6 to 1.3, with a spatial resolution of 0.025, for a total of 29 coefficients. This choice follows from the considerations and the results of the studies conducted by Doornbos et al. [3]. In his work, he shows the log-normal statistics of accelerometer-derived over model density ratios for CHAMP and GRACE, comparing various models. It has to be noted that in those studies the mass and the geometry of the satellites were known, which is not the case as for the present study. However, the range from 0.6 to 1.3 has been considered to be broad enough for this first analysis. Each object will then experience a gradual increase in the drag force and the resulting predicted orbit lifetime will be compared with the reference orbit.

4. ADDRESSING UNCERTAINTIES

A comprehensive overview on the different sources of uncertainties in the orbit lifetime computation is provided in [2] and a first analysis has been initiated by Braun et al. in [1]. In particular, this paper presents and describes the effects on the lifetime estimate associated with the uncertainties in the atmosphere models, the attitude, the physical properties and the drag coefficient. The following analysis is subdivided according to the region of the orbit (LEO and HEO), for which each class of objects identified in Section 2 is presented, in order to give a rapid comparison.

4.1. Uncertainties in the LEO region

Figure 4 represents the distribution of the relative error (computed minus observed) in the orbit lifetime estimate for the class R/B, as it is currently in OSCAR, which is referred to as *nominal case*. This would be equivalent to applying a drag correction coefficient C_C equal to 1. For this case, the mean relative error is about -4%, i.e. OSCAR tends to currently underestimate the orbit lifetime for R/Bs in LEO, under the assumption that the object information is correct and the applied attitude motion is randomly tumbling. The median is currently about -8.8% and actually lower than the mean. This is due to the presence of outliers on the right side, which contribute to shift the mean toward the positive direction. The standard de-

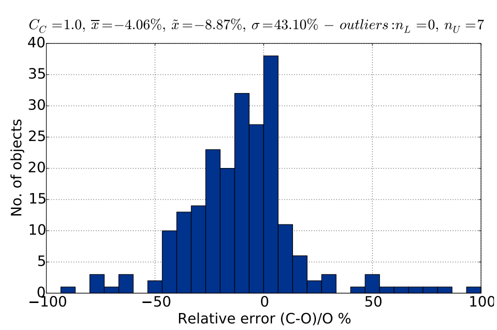

Figure 4. Relative error in the computed orbit lifetime of the R/Bs in LEO, nominal case.

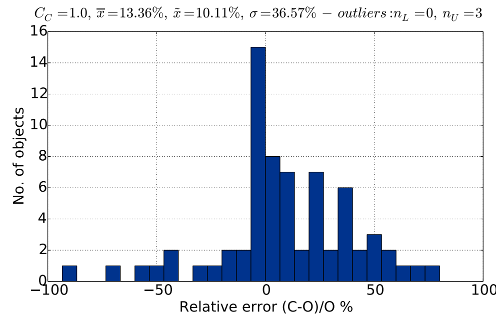

Figure 5. Relative error in the computed orbit lifetime of the small satellites in LEO, nominal case.

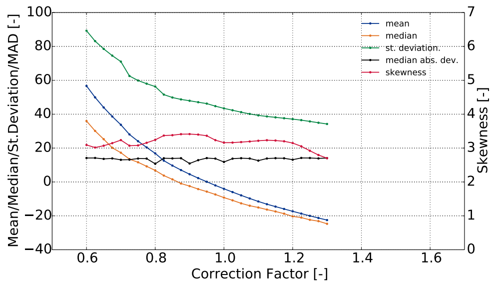

Figure 6. Statistical quantities as a function of the drag correction coefficient,C_C, for the R/Bs in LEO.

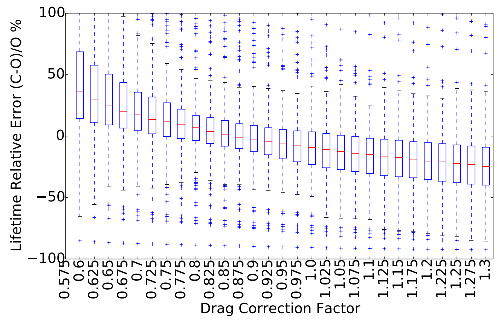

Figure 7. Boxplot showing the trend of the median (in red) and the outliers for the R/Bs in LEO.

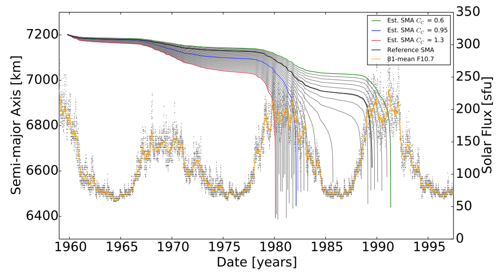

Figure 8. Case study comparing the estimated orbit evolutions, as a function of the correction coefficients, with the reference orbit.

viation is about 40%, which means the data deviates in a non-negligible way from the mean value. The visual upper range limit of the histogram reports a number of 7 outliers, n_U, while no outliers are present on the lower boundary, n_L. In Figure 5, the same results are shown for the small satellies. Interestingly, in this case the mass of the data is concentrated on the right side, with a mean of about 13% and a median of about 10%. The standard deviation for this class does not vary considerably from the previous cases.

In order to analyze the large volume of the data set and its properties, statistical methods are herein used on the orbit lifetime relative error to gather a better understanding of the underlying phenomena and how the propagation of the uncertainties affects the estimate of the orbit lifetime. In this analysis it is chosen to use the *mean*, the *median*, the *standard deviatio*n, the *median absolute deviation* (MAD) and the *skewness*. The MAD is a robust measure of the variability or deviation of a univariate sample of quantitative data, thus more resilient to outliers in a data set than the standard deviation. It is computed as:

$$MAD = median\left(|X_i - median\left(X\right)|\right) \quad (1)$$

Figure 6 presents the R/Bs case. It can be seen that the mean, median and standard deviation have a monotonic decrease as the correction factor increases. In particular, the zero-mean value finds itself in correspondence of a correction factor of about 0.95. This particular case, where the mean assumes the closest value to zero is denoted with C_{C0}. Large values of the standard deviation could be indicative of a predominant role of the actual shape of the rocket body, the solar cycle variations and other minor perturbations. As the drag force fades out, those would become responsible to trigger the orbit evolution. On the other hand, as the correction factor increases, the density effect would play the major role and therefore the orbit lifetime would be influenced merely by the modelling of the perturbation forces and atmosphere dynamics. Figure 7 shows another way to visualize the trend of the median and the outliers for the R/Bs in LEO.

Figure 8 reports the orbit evolution in terms of semi-major axis for a rocket body in the data set. No manoeuvres were performed during the permanence in orbit and there is no attitude control, so that a random tumbling motion was assumed for ballistic considerations. The effects of the global constant drag force corrections are directly visible: the difference in the orbital lifetime estimates between the two outer values, $C_C = 0.6$ and $C_C = 1.3$, is approximately 12 years, which corresponds to a full solar cycle. This example depicts very well how uncertainties in the atmospheric and drag force model can influence the orbit evolution.

In Figure 9, the same quantities are shown for the case of the small satellites. Although the trend of those is similar to the case presented for the R/Bs, the same cannot be asserted for what concerns the factor C_{C0}. From this first analysis, it assumes a value of about 1.2, with respect to the 0.95 of the R/Bs. This means that actually OSCAR over-predicts the orbit lifetime of the small satellites, under the same assumptions also made for the rocket bod-

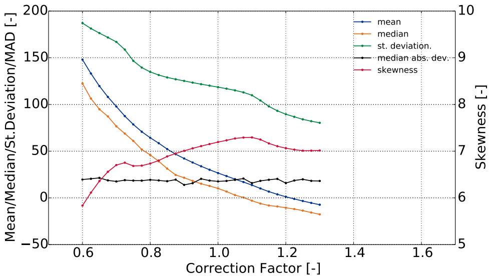

Figure 9. Statistical quantities as a function of the drag correction coefficient, C_C, for the small satellites in LEO.

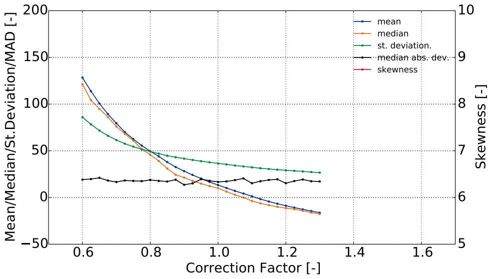

Figure 10. Statistical quantities of the small satellites in LEO as a function of the drag correction coefficient, C_C, excluding the outlier satellite.

ies. To explain the reason of this non-negligible deviation, an in-depth analysis aimed to detect the outliers in the data and any eventual source of erroneous input, i.e. physical properties and drag coefficient. A small satellite exhibited a large deviation of the estimated orbit from the reference orbit, therefore it was classified as an outlier, removed from the data set and the statistical quantities have been re-evaluated. The results are presented in Figure 10. The mean curve shifts downwards the y-direction corresponding to a decrease in the value of about 25%. As consequence, the correction factor that best approximate the orbit lifetime on a global scale is now $C_{C0} = 1.1$. For what concerns the standard deviation, this quantity also decreases in a considerable way, with respect to the previous analysis. However, the drag correction coefficient, C_{C0}, is still larger than the one obtained for the R/Bs. Therefore, an in-depth investigation is conducted on the neutral thermospheric density resulting from the atmospheric model and on the variation induced by the solar and geomagnetic activity simultaneously. As already mentioned, the almost totality of small satellites were launched during the solar cycle 24. This cycle is characterized by a strikingly low solar extreme-ultraviolet irradiance during the solar minimum, which occurred between 2008 and 2010. As consequence, studies have revealed the thermospheric density was lower with respect to the previous solar cycles minima [8]. On the other hand, comparison among the atmospheric density models during the solar activity maximum in the 23th solar cycle (1999-2002) had shown all models overestimate the thermospheric density below an altitude of 500 km [7]. One could possibly shift this conclusion also to the current 24th solar cycle in order to explain the reason

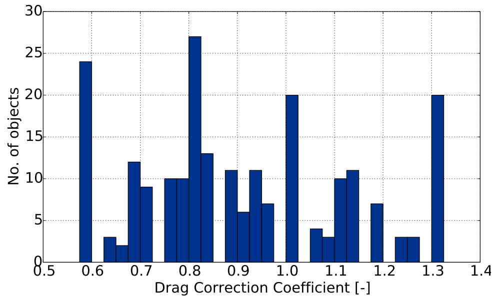

Figure 11. Drag correction coefficients that best approximate the reference orbit of the cylindrical R/Bs in LEO.

why the drag correction coefficient for small satellites is $C_{C0} = 1.1$. Since the R/Bs data set was able to cover a time span of 5 solar cycles, the effects of the bias in the thermospheric models is most likely to be averaged out during such long-term analysis. On the other hand, since small satellites are concentrated in one solar cycle (24th) and this presents a minimum in the solar activity, the correction to apply to the drag force would increase the force experienced by the satellite. It could be that, even if the thermospheric model over-predicts the density, this is still not sufficient to match the reference orbit and an increase in the drag force is necessary. However, it could also be possible that the over-prediction of the density causes errors which accumulate during the long time span for the R/Bs case and this would ultimately results in the necessity to decrease the drag force. Therefore, in order to make solid statements, more data for the small satellites data set is required, especially where the orbit lifetime covers the time period of the solar minimum. Also, the atmospheric model used, namely the NRLMSISE-00, is calibrated for a period of time which does not cover the last solar cycle.

Drag correction coefficient analysis

In order to investigate the underlying physics of the drag correction coefficients, a new quantity is herein introduced: denoted with $C_C{}^*$, it represents the correction factor that for each object allows the orbit lifetime estimation to best approximate the reference orbit, in the sense of the relative error with respect to the re-entry epoch. Figure 11 provides the distribution of the $C_C{}^*$ for the 214 R/Bs of cylindrical shape identified in DISCOS. Other shapes were also present, but those were very few and therefore not sufficient to derive a statistical meaningful data set from them. Multiple modes can be seen in the distribution. In particular, four coefficient are most frequent, for values around 0.6, 0.8, 1.0 and 1.3. In particular, an in depth-analysis was carried on the $C_C{}^*$ and analyzed different types of R/Bs. In this paper, the *Cosmos 3M second stage (S3M)* is used as a case study, since it's the one that presented the greatest number of objects in the data. The following features have been investigated: mass, cross-sectional area and initial state. It has been found that there are two different values in DISCOS for the *mass* and three different values for the *average cross-sectional area*. In particular, Figure 12 shows the $C_C{}^*$ for the 41 objects reporting 1421 kg and 12.91 m^2, while

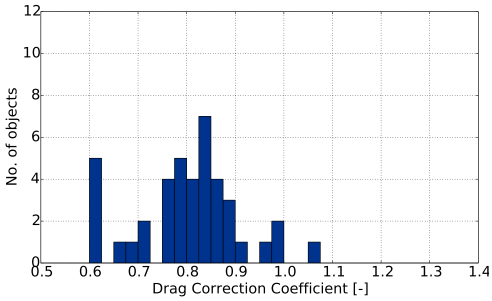

Figure 12. Drag correction coefficients that best approximate the reference orbit for 1421 kg and 12.91 m^2.

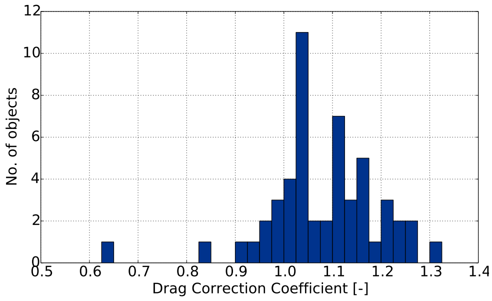

Figure 13. Drag correction coefficients that best approximate the reference orbit for 1434 kg and 10.17 m^2.

Figure 13 provides the 52 objects with 1434 kg and 10.17 m^2. Only one object, not shown in the Figures, has been identified to have 1434 kg and 9.29 m^2. Even for the same R/B, different values of mass and cross sectional area are able to shift the $C_C{}^*$ distribution, which ultimately lead to variations in the orbit lifetime estimates. Larger mass and smaller cross-sectional area would result in a smaller drag force exerted on the R/B. As consequence, correction factors assume larger values in order to match with the reference orbit. The reasons for the presence of different values in the physical properties could be explained assuming that different versions of the launcher type have been used, or residual propellant has been included in the dry mass estimates. At this point, it should be noted the aforementioned analysis has been performed using a constant C_D of 2.2, which represents a source of uncertainty and could be responsible for the deviation of the computed orbit lifetime from the true value in a more or less large scale.

In Figure 14, the same results are reported for the small satellites case. Frequent occurrences are visible for values around 0.6, 1.0 and 1.3.

4.2. Uncertainties in the HEO region

Figure 15 shows the nominal distribution of the relative error (computed minus observed) in the orbit lifetime estimate for the R/Bs in the HEO regions. For this case, the mean relative error is about 56%, i.e. OSCAR tends to currently overestimate the orbit lifetime for satellites

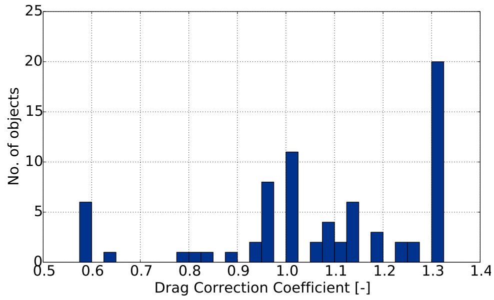

Figure 14. Drag correction coefficients that best approximate the reference orbit of the small satellites in LEO.

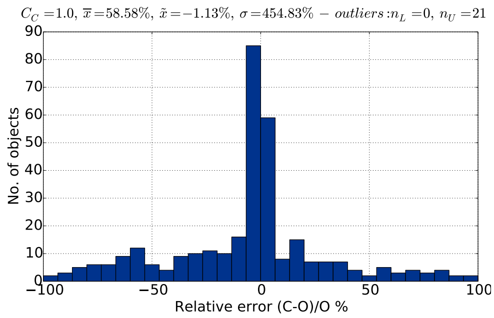

Figure 15. Relative error in the computed orbit lifetime of the R/Bs in HEO, nominal case.

in HEO. The median is currently about -1% and the standard deviation about 454%, which correspond to a large deviation in the data with several objects having a relative error greater than 100%. Figure 16 provides the statistical quantities for the R/Bs that resided in the HEO regions. The mean value of the relative error in the orbit lifetime estimation presents decreasing values as the drag correction coefficient,C_C, becomes larger. However, this trend is not as smooth as it was for the R/Bs in the LEO regions and the curve never intersects the x-axis. In fact, the closest value to zero is for $C_C{}^* = 1.250$. On the other hand, the median is always very close to zero, thus the data distribution is most of the time equally subdivided in objects whose orbit lifetime is over-predicted and in objects whose orbit lifetime is under-predicted. The evolution of the estimated orbit shows that the correction of the drag force with the factor $C_C{}^*$ does not imply the pre-

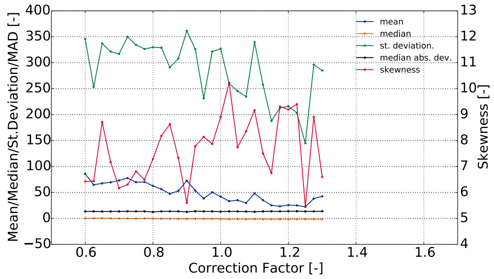

Figure 16. Statistical quantities as a function of the drag correction coefficient,C_C, for the R/Bs in HEO.

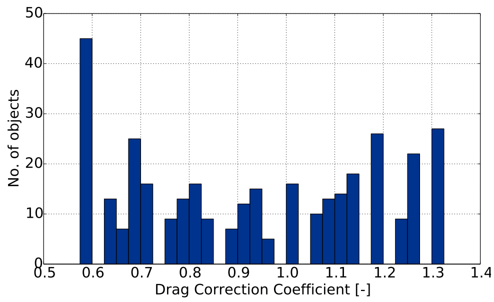

Figure 17. Drag correction coefficients that best approximate the reference orbit of the R/Bs in HEO.

dicted decay will match the reference orbit. Instead, the coefficient is based on the re-entry epoch comparison. In order to overcome this issue, a more complex correction factor algorithm could be implemented to account for the altitude of the satellite.

Drag correction coefficient analysis
Figure 17 shows the distribution of the ${C_C}^*$ for the R/Bs that had resided in the HEO regions. In particular, for this case were considered the objects with a cylindrical geometry, and those whose shape resembles a cylinder plus cone and a cylinder plus sphere. Other shapes were too few to be useful.

5. CONCLUSIONS

The study presented in this paper investigated the influence that combined bias of density values from the thermosphere model, geometry, mass and flow conditions have on the orbit lifetime estimates. These results have been used in order to provide the data and gather the knowledge required to move towards a probabilistic assessment of the orbit lifetime with OSCAR. The results obtained prove that the bias in the orbital lifetime estimate cannot be corrected by a simple global constant correction coefficient. The analysis performed provided a wider and better insight on the phenomena thanks to the large data set available, which included rocket bodies, payloads and small satellites. In particular, the subdivision of the objects according to LEO and HEO orbits demonstrated the different response they have with respect to the drag correction coefficients. The former resulted in a "smooth" propagation, where an increase in the correction factor resulted in a decrease in the orbit lifetime and also in the spread of the data. Moreover, in the LEO region the decay of the estimated orbit approximates closely the reference orbit retrieved from the TLEs. On the other hand, the HEO case is currently being further investigated, as non-negligible deviations from the reference were identified even if the coefficient was able to estimate the re-entry epoch with the smallest relative error. These deviations might come from wrong or deviating initial states or actual maneuvers that put the HEO objects on a de-orbit path. For the small satellites, the evaluation lead to larger global correction factor with respect to the R/Bs case. This has been tentatively linked to the anomalous solar activity of the 24th solar cycle, which present a very low activity with respect to the previous ones. All the small satellites had a quite short orbital lifetime compared to the R/Bs and were concentrated only around the solar maximum. Therefore, it is yet too early for this statement to be conclusive and more data during a low solar and geomagnetic activity would be required. The analysis on the ${C_C}^*$ distribution described the sensitivity of the orbit lifetime estimate to the physical properties used as initial data. Therefore, it states the importance of having good initial data in order to make solid and very precise predictions.

The present study should serve as a base to develop further analysis and research. In particular, a closer investigation should be performed on the physical properties and initial orbits of the objects. Then, the ballistic parameter estimate could be used in order to produce a more complex model than a constant drag coefficient for the drag force. For what concern the drag correction coefficients, the HEO case could be investigated with the use of another approach, for example with an iterator tool which tries to match the orbit and minimize the error in the root mean square sense.

REFERENCES

1. Braun V. et al., (2016). Probabilistic orbit lifetime assessment with OSCAR, *6th International Conference on Astrodynamics Tools and Techniques (ICATT)*, European Space Agency, Darmstadt, Germany
2. Dell'Elce L., Arnst M., Kerschen G., (2015). Probabilistic assessment of the lifetime of low-earth-orbit spacecraft: uncertainty characterization, *Journal of Guidance, Control, and Dynamics*, **38**(5), 900-912
3. Doorbos E., (2016). Evaluation of satellite aerodynamic and radiation pressure acceleration models using accelerometer data, *6th International Conference on Astrodynamics Tools and Techniques (ICATT)*, European Space Agency, Darmstadt, Germany
4. International Organization for Standardization (ISO), (2011). Space systems - Estimation of orbit lifetime, *Tech. Rep. ISO 27852:2011*, Geneva, Switzerland
5. International Organization for Standardization (ISO), (2011). Space systems - Space debris mitigation requirements, *Tech. Rep. ISO 24113:2011*, Geneva, Switzerland
6. Holland R. L. and Vaughan W. W., (1984). Lagrangian least-squares prediction of solar flux, *Journal of Geophysical Research: Space Physics*, **89**(A1), 11-16
7. Pardini C., Moe K., Anselmo L., (2011). Thermospheric density model biases at sunspot maximum. *Report*, Space Flight Dynamics Laboratory, Pisa, Italy
8. Solomon S. C. et al., (2010). Anomalously low solar extreme-ultraviolet irradiance and thermospheric density during solar minimum. *Geophysical Research Letters*, 37