RE-ENTRY ANALYSIS COMPARISON WITH DIFFERENT SOLAR ACTIVITY MODELS OF SPENT UPPER STAGE USING ESA'S DRAMA TOOL

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Abstract

The goal of the paper is to investigate the influence of different methods for solar activity forecasts on the simulation of residual lifetime of upper stages in GTO. For this study the OSCAR software from the ESA DRAMA tool suite was used to perform an orbital decay simulation for an Ariane 4 upper stage (1997-016-C) from 1997 to 2012. As a reference, the orbital decay of the rocket body has been compared to TLE data available from Space-Track. For the simulation, it was possible to select between a best-guess scenario (including best case and worst case scenarios), constant equivalent solar activity, ECSS standard cycle or any user-selected historic cycle and solar activity sampled through a Monte Carlo approach. In addition, the evolution of the orbit has been analysed taking orbit perturbation into account (Drag, Geopotential, Third Bodies effect). Finally a sensitivity on the mass and cross-section area of the upper-stage have been performed in order to understand which parameter may influence the residual life in GTO.

Keywords: Ariane; De-orbit; OSCAR; DRAMA; GTO;

1. Introduction

1.1. Requirements regarding space debris mitigation

Since 2008, the French Space law imposes requirements on launchers in order to reduce the growth of space debris [11]. Those are also covered in the ESA Space Debris mitigation [5] requirements, which aim to adopt the standard ISO 24113 [8]. The UN Space Debris Mitigation Guidelines (SDMG) [16]) also include recommendations on the disposal of systems that have reached the end of their useful life. The following key requirements induced by the legislation [11] directly influence the design of launchers in Europe.

- Spacecraft crossing the LEO region shall re-enter Earth's atmosphere within 25 years after the end of the operational phase.
- Spacecraft operating in GEO shall be disposed of in such a way that they never interfere with the GEO region.

While the so called 25-year rule is easy to understand, the implementation poses some difficulties. This is mainly due to the fact that the orbital lifetime strongly depends on future solar and geomagnetic activity, both quantities lacking satisfactory long-term predictions. Furthermore, in high eccentricity orbits like the geotransfer orbits (GTO) the orbital lifetime is strongly sensitive with respect to the initial conditions. The key requirements, especially those of the SDMG, were driving the development of the upgraded version of the *OSCAR* tool.

1.2. OSCAR overview

The software tool OSCAR is currently being redeveloped under ESA contract by TU Braunschweig and DEIMOS Space S.L.U. within the upgrade of the ESA DRAMA tool suite. Being one of five individual tools for specific mitigation related analysis in DRAMA, OSCAR allows the investigation of various end-of-life disposal strategies. Another key feature of *OSCAR* is the compliance assessment of the disposal phase of a mission wrt. the SDMG. In its current version, *OSCAR* allows for the analysis of different possible future scenarios for solar and geomagnetic activity, all based on currently available standards, which are the main drivers in the estimation of the residual lifetime for a specific orbit. The *OSCAR* software has been developed focusing on:

- Assessing the remaining orbital lifetime of a user-defined satellite, wholly or partly orbiting in LEO, to identify if any action is required to ensure an acceptable duration for disposal.
- Taking into account different options for the future modeling of solar and geomagnetic activity by using widely accepted forecasting methods.

- Allowing the incorporation of up-to-date solar and geomagnetic data.
- Allowing the investigation of re-orbit and de-orbit requirements (e.g. Δv , propellant mass fraction and manoeuvre duration) for chemical as well as electric propulsion systems.
- Allowing the investigation of the use of an electro-dynamic tether system for the de-orbit of circular LEO spacecraft.
- Allowing the investigation of the use of a drag augmentation system for the de-orbit of LEO spacecraft.
- Assessing the compliance with the SDMG for a user-defined disposal strategy.

Besides the new possibility of drag augmentation system analysis, the main features within the upgrade are the compliance assessment based on the SDMG, as well as the solar and geomagnetic activity forecast, based on current standards, which will be described in Sec. 3.1.

1.3. Goal of this study

The goal of this study was to get a better understanding of the orbital decay of upper stages, especially in high-eccentricity orbits, taking into account different standardized approaches for future solar and geomagnetic activity forecasts. For that purpose, an Ariane 4 upper stage in a GTO was selected. A better understanding of the underlying orbital mechanics in GTO allow for a more sophisticated upper stage design prior to mission start in order to be compliant with the SDMG. Another goal was to compare the orbit evolution by applying different recommended solar activity forecast models with available TLE data. In a first part, the selected Ariane 4 upper stage will be presented. Then the method used to perform the calculation will be elaborated. In Sec. 3.1 the different available standards for solar and geomagnetic activity forecasts will be elaborated. At last, a sensitivity analysis has been performed on different parameters to understand how orbital decay is affected by the selected initial conditions.

2. The Ariane 4 upper stage

Ariane 4 is one of the most successful European launchers, built and launched between 1988 and 2004. With a total number of 116 launches (including 3 failures), 182 payloads have been placed into orbit. The rocket architecture design is based on a ”building-block” philosophy. Six versions were available using a three-stage core vehicle but different combinations of boosters [1].
The Ariane 4 upper stage H10 (cryogenic with a propellant mass of 10 tons) went through several evolution steps. The last version, H-10 III has been introduced after the 70th flight (see Table 1). The tank architecture was slightly modified, which allowed a higher propellant loading of up to 11.9 tons. This version was used until the last Ariane 4 flight. [15]

It is one tank of this upper stage that re-entered the Earth's atmosphere after an end-of-life phase of 15 years in February 2012 and impacted in a village in Brazil. The A4 (1997-016C) has been launched on April 16th, 1997 from Kourou. The launcher was a 44LP with an H-10 III upper stage. The mission delivered BSAT 1a und Thaicom 3. For the simulation in this study, the orbital parameters (from TLE data, Space-track) and further characteristics (mainly from ESA's DISCOS database) are shown in Table 2. The H-10 III properties are shown in Table 1.

Table 1: H-10 III properties

Parameter	Value
Length	11.05 m
Diameter	2.6 m
Launch (wet) mass	13,223 kg
Dry mass	1,240 kg
Propellant loading	11,982 kg
Mixture ratio	4.87
Engine	HM-7B
Thrust	64.8 kN
Specific impulse (vacuum)	445 m/s
Burning time	780 s

The design of the next European launcher is currently being discussed and should be settled in 2014. This will be the first rocket that should be totally compliant with the space debris mitigation requirements. Therefore it is important to understand the orbital behaviour of former upper stages.

Table 2: Characteristics of A4 upper stage orbit and geometric parameters

Parameter	Value
Orbit altitude	250 km × 36,260 km
Inclination	7.0°
RAAN	9.8°
Argument of Perigee	178.0°
Mean Anomaly	188.0°
Cross-sectional area	21.7 m^2
Drag coefficient C_d	2.2
Reflectivity coefficient C_r	1.3

3. Methods

As described in Sec. 1.2, different standardized modeling approaches for solar and geomagnetic activity forecasts have been implemented in the new version of *OSCAR*. This study consisted of the following steps:

- Analyse A4 orbital evolution based on TLE data from 1997 to 2012.
- Perform *OSCAR* simulations for Scenarios 0 to 4 (as defined in Table 3).
- Plot the results and compare orbital evolution with the true trajectory given via TLE data.
- Perform a sensitivity analysis based on various relevant initial parameters.

Table 3: Solar and geomagnetic activity forecast models associated with the defined scenarios.

Scen.	Model	Reference/Standard
Ref.	-	TLE
0	Observed activity	-
1	Constant equiv. activity	French Space Law [6]
2	Sample solar cycle	ECSS-E-ST-10-04C [4]
3	Monte Carlo sampling	ISO 27852:2011 [9]
4	Best-guess	ISO 27852:2011

In order to study the orbital decay, the evolution of the keplerian parameters will be represented. The main characteristic of the GTO is the high eccentricity, which leads to a perigee altitude well within the Earth's atmosphere and an apogee near the geosynchronous altitudes. Due to the low inclination (7°), the sum of the right ascension of ascending node (RAAN) and the argument of perigee (AoP) gives the orientation with respect to the sun, which is a key information to explain the orbital evolution.
The sensitivity analysis is based on the two main geometric parameters regarding the upper stage, i.e. mass and cross-sectional area, in order to understand how the object design may influence the residual orbital lifetime. The sensitivity of the initial line of nodes (RAAN) has been performed in order to interpret any correlation of the residual orbital lifetime with the starting date. To be precise, the combination of RAAN and AoP should be studied, but due to the near-equatorial orbit and the AoP being about 180° it sufficed to look at RAAN only.

3.1. Solar and geomagnetic activity forecast in OSCAR

For the prediction of solar and geomagnetic activity, the following methods have been investigated and then implemented in *OSCAR*:

1. Constant solar flux and geomagnetic activity
2. Sample solar cycle
3. Monte Carlo sampling
4. Best-guess scenario, including best-case / worst-case estimation given an arbitrary confidence interval

A possible approach is to define *constant solar flux and geomagnetic activity* levels, which in fact are *equivalent constant* values, thus not being dependent on the end of the satellite's mission. The actual values for both parameters are found in a tuning process, which is described in [6] and was developed in the frame of the French Space Act. The authors derived an analytical formulation relating the equivalent constant solar flux to the satellite's ballistic coefficient $(A \cdot C_d)/m$ and the initial apogee altitude h_a:

$$F_{10.7} = 201 + 3.25 \cdot ln\left(\frac{A \cdot C_d}{m}\right) - 7 \cdot ln\left(h_a\right) \qquad (1)$$

The estimated constant flux is related to a 25-year orbital lifetime and basically says that by using that constant equivalent flux, the re-entry date will be 25 years ahead with a 50% probability level. Solar activity data from five past solar cycles were used to find the above formulas within an iteration process. The initial date, which is equal to the mission end, was placed at the beginning, in the middle and at the end of a solar cycle. From an initial apogee altitude of 800 km the perigee altitude was iterated to find the orbit, which leads to a 25-year orbital lifetime in 50% of the simulated scenarios.

The space environment standard of the European Cooperation for Space Standardization (ECSS) from 2008 [4], recommends using a *sampled solar cycle*. Besides other environmental issues, that standard provides *tailoring guidelines* stating that the 23^{rd} solar cycle shall be used for future predictions of the solar activity. Minimum, mean and maximum daily and 81-day averaged values are provided for each month of the 23^{rd} cycle. The mean values of the ECSS cycle are very well representing the 81-day centered average of the 23^{rd} cycle, however, an offset can be observed, which is about eight months. Shifting the ECSS cycle by that value shows a good match between 81-day centered average of the observed data and the ECSS data.

Another approach is to derive future solar and geomagnetic activity data through a *Monte Carlo sampling* method, which is one of the two approaches for long-term solar flux forecast recommended by the ISO 27852:2011 standard [9]. The method itself was investigated in [13] and is based on the sampling of a randomly drawn solar cycle out of available observed data from five preceding solar cycles. The ISO standard defines the cycle length to be 3,954 days, which does not match with the lengths of the cycles 19 through 23, of course. For a random draw approach, in which for every day of the sampled cycle, a data triad, consisting of the observed $F_{10.7}$, the mean $\bar{F}_{10.7}$ and the geomagnetic planetary amplitude A_p, is selected from one of the five available cycles, data has to be interpolated. For that purpose, the five available cycles have been transformed to the common duration of 3,954 days and then daily values have been determined using a lagrange polynomial.

The implementation of a *best-guess scenario* is based on the Marshall Space Flight Center (MSFC) Lagrangian Linear Regression Technique (MLLRT) [12]. It implements a modified McNish-Lincoln method [7], estimating the future behaviour of the current sunspot cycle by adding to the approximated 13-month smoothed sunspot number of all past cycles, a correction term which is derived from the current cycle's deviation when compared to the smoothed mean cycle. The smoothed sunspot number was estimated using the solar cycles 10 through 23. The definition of a best- (BC) or worst-case (WC) scenario is based on an arbitrary value for the so-called confidence interval. From the satellite's operator point of view a BC is referred to a shorter lifetime and therefore a high solar activity, while the opposite is the case for the WC. For example, a confidence interval of 100% means that the BC is sampled by using the smoothed value of that solar cycle which has the maximum solar flux value for each month. For a lower confidence interval only those cycles will be considered which are below the specified value. This, however, presumes a to-be-defined distribution, as historical data is given only for discrete points within the confidence interval, while the latter may be chosen arbitrary. Therefore, for each month, the available 14 data points from each cycle are distributed equidistantly along the 0 to 100% axis. An implementation based on smoothed activity data is also recommended by the ISO 27852:2011 standard [9].

A more detailed description of the different methods presented here, including the analysis of some specific implementation issues as well as some comparisons for LEO orbits can be found in [3].

4. GTO perturbations

GTOs have a very high eccentricity, resulting in perigee altitudes between 180 km and 250 km and apogees near geosynchronous altitudes of about 36,000 km. They are subject to several different perturbations, all of them having complex interactions. First, due to the high eccentricity, the gravitational effects of the Sun and the Moon, called third-body effects, are acting especially in higher altitudes and have to be carefully considered. Then due to the low perigee altitude, the atmospheric drag has also a significant impact on the orbit. At last, the Earth's geopotential creates a secular drift mainly due to Earth's flattening. The interactions of these perturbations with the spacecraft are highly sensitive to the initial conditions after launch as well as modeling errors in the orbit propagation techniques. This may result in very exotic results for the orbital evolution and thus poses a great challenge for the estimation of the required 25-year residual lifetime orbit. For more information please refer to the detailed analysis of those effects in [10]. In that matter, the following parameters are influencing the evolution of the orbit and consequently the orbital lifetime:

- Orientation of the sun wrt. the projection of the line of apsides.
- Secular change in semi-major axis due to the effect of drag near the perigee.
- Precession of line of nodes and line of apsides due to the geopotential.

4.1. Effect of atmospheric drag

It is hard to predict the effect of atmospheric drag, as the atmospheric density may vary by up to two order of magnitudes depending on the solar activity level. When the solar activity is high, the density in higher altitudes as well as drag increases. Even more complexity is added through the fact that the spacecraft passes all altitudes relevant for atmospheric perturbations down to about 150 km. For the orbit propagation in *OSCAR* the tool *FOCUS-1A* is used. The *NRLMSISE-00* [14] model is applied and the atmospheric drag is a function of the drag coefficient C_d, the cross-sectional area, the mass and the velocity of the spacecraft. The quantity m $/C_d \cdot A$ is called the ballistic coefficient (in kg/m^2).

4.2. Geopotential

Due to the non-spherical shape of the Earth, the geopotential is expressed in terms of spherical harmonics. The secular drift of the line of nodes is mainly due do the zonal J_2 term of the geopotential:

$$\Delta\Omega_{day} = -9.96^\circ \cdot \frac{(R_E/a)^{7/2}}{1-e^2} \cdot \cos i \qquad (2)$$

4.3. Third-body effects

The gravitational perturbations due to the Sun and the Moon affect the eccentricity, the inclination, AoP and RAAN, while the semi-major axis does not experience any secular trend. The variations in eccentricity thus directly affect the perigee altitude evolution for different orientations of the orbit towards the sun. The perigee altitude increases for the sun direction Θ being at $0^\circ < \Theta < 90^\circ$ and $180^\circ < \Theta < 270^\circ$ wrt. the perigee direction. In other words, the variation of the perigee altitude depends on the orientation of the Sun in an orbit-fixed coordinate system. During the drag affected orbital decay, the combined RAAN and AoP precession may reach sun-synchronous conditions In this case, the orientation of the orbit wrt. the sun remains constant for quite a long time. At this stage, the perigee altitude may experience a strong increase or decrease depending on where the sun actually is. In the case of a perigee decrease a coupling with the atmospheric drag may lead to a quick re-entry. This phenomenon can be called the sun-synchronous resonance effect [2].

5. Analysis

The overall results of the conducted analysis for the defined scenarios are shown in Figures 1 - 3 and will be discussed in the following.

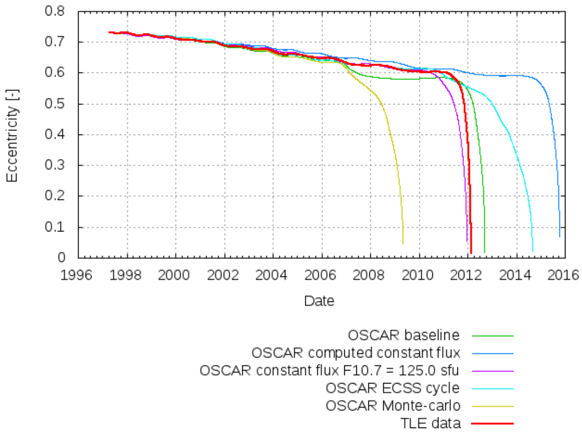

Fig. 1: Eccentricity evolution Scenarios 0-3.

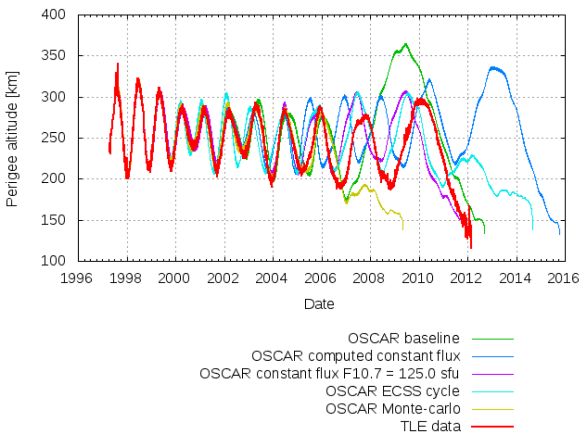

Fig. 2: Perigee altitude evolution for Scenarios 0-3.

5.1. *Reference Scenario - TLE data*

The two line elements (TLE) is a data format which contains all information to describe the orbit of a spacecraft at a distinct epoch using the SGP-4 theory. This format is delivered by USSTRATCOM (US Strategic Command) and TLE data are freely distributed through the Space-Track website. The required TLE data have been downloaded for the object of interest in this paper (Ariane 4, 1997-016C). The TLE data from 1997 until 2012 have been plotted in the different figures (red curves) in order to have a ”truth” reference for the orbital evolution of the upper stage. This case will be used to understand how accurate the different propagation models are in this example.

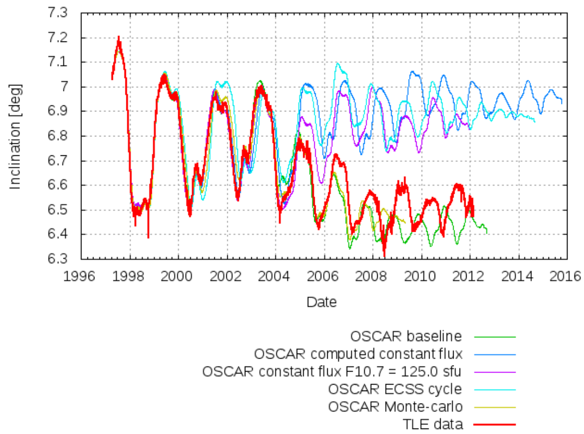

Fig. 3: Inclination evolution for Scenarios 0-3.

The observed solar activity is shown in Fig. 4 for daily and averaged (81-day centered) data. The upper stage experienced the 23rd solar cycle as well as the beginning of the 24th cycle. The only solar maximum in that period of time is around the year 2002 within the 23rd cycle.

5.2. *Scenario 0 -* OSCAR *baseline*

As the input for this baseline scenario is taken from available observation data until 2012 (which of course was not known to mission designers in 1997 at the beginning of the disposal phase), the solar and geomagnetic activity is the same in the simulation of the baseline scenario when compared to the TLE data trajectory. It can thus be assumed that the orbital evolution for the baseline scenario (green curves in Figures 1 -3) will deviate from the TLE data due to modeling errors in the propagation routines as well as in the estimated geometric properties of the upper stage. The predicted re-entry is during the last quarter of 2012, which is half a year after the real re-entry. The evolution of the orbital elements are similar to the observed TLE until about 2007, when a sharp decrease in the eccentricity is observed, which severely affects the perigee altitude. As the perigee altitude reaches altitudes of about 170 km, the semi-major axis is significantly reduced through atmospheric drag in this period, which then leads to a completely different behaviour after 2007. Using the *OSCAR* Scenario 0 model we observe that in the beginning, the perigee altitude shows typical oscillations and after reaching a minimum of about 170 km the altitude of the perigee increases sharply up to altitudes of 350 km and then decreases again to finally re-enter Earth’s atmosphere during the last quarter of 2012. This effect can not be observed in the true trajectory and is mainly due to the resonance effect described in Sec. 4. This resonance effect did not occur in reality, as modeling errors in the propagation led to a different orientation of the Sun, which actually was in a quadrant of decreasing perigee while the true trajectory was not.

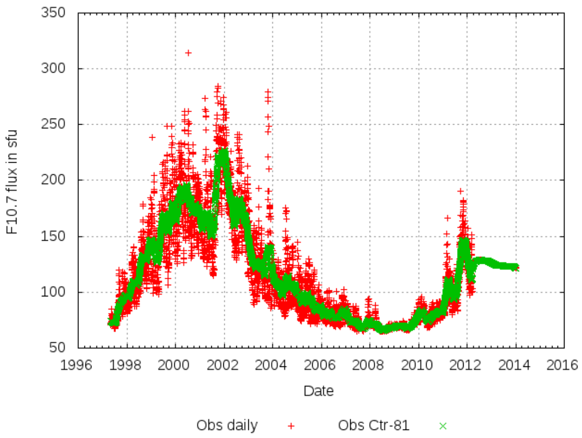

Fig. 4: Solar activity used for Scenario 0.

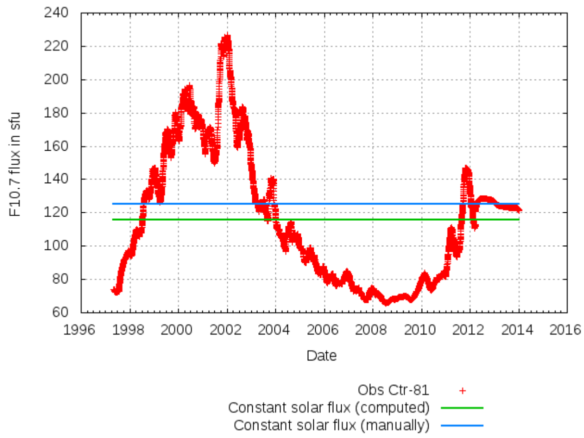

Fig. 5: Solar activity used for Scenario 1.

5.3. *Scenario 1-* OSCAR *constant equivalent flux*

The solar and geomagnetic activity in Scenario 1 is selected to be a constant equivalent solar flux. It is computed according to Eq. 1 and results in a residual lifetime of the spacecraft which is 4 years longer (see dark blue curve in Figures 1 - 3). It can be observed in Fig.3, that in the evolution of the inclination the trend increases (starting in mid-2004) whereas the inclination trend in both, TLE data as well as the baseline scenario, decreases. It has to be mentioned, however, that Eq. 1 was fitted for objects in the sun-synchronous LEO region [6] and the application to high-eccentricity orbits may thus be considered as questionable. For such cases, *OSCAR* allows to specify a user-defined constant equivalent flux. In this analysis, a constant solar activity level of 125 sfu resulted in acceptable results (while the computed value was about 116 sfu). However, in reality one would never know the actual solar activity in the future. Thus, a fitting procedure similar to the one conducted in [6] should be performed for high-eccentricity orbits, taking into account the specific parameters having a strong impact on the computed lifetime.

5.4. *Scenario 2 -* OSCAR *ECSS standard cycle*

The solar and geomagnetic activity in this scenario is based on the ECSS standard cycle defined in [4]. The re-entry of the Ariane 4 upper stage occurs in the end of 2014 (see light blue curves in Figures 1 - 3). In Fig. 6, showing the applied standard cycle, the solar activity seems to be a little bit "delayed" regarding to the observed values, which is due to the definition in [4] as explained in Sec. 3.1. This would explain why the re-entry is slightly later than the observed one.

5.5. *Scenario 3 -* OSCAR *Monte Carlo sampling*

The re-entry of the spacecraft in Scenario 3 occurs in the middle of 2009 (see yellow curves in Figures 1 - 3). In Fig. 7 the solar activity level is always "higher" than

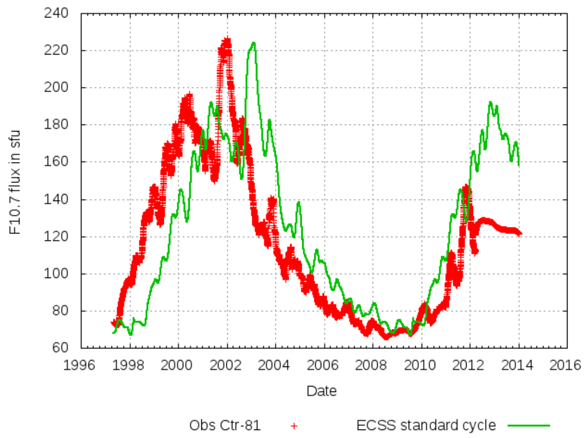

Fig. 6: Solar activity used for Scenario 2.

the observed values, which is due to the fact that solar cycles 19 through 23 are sampled randomly and the cycles 19, 21 and 22 respectively showed higher maxima than the actually experienced by the upper stage 23rd cycle. Therefore the general orbital evolution is similar but the re-entry occurs earlier than the observed one.

5.6. *Scenario 4 -* OSCAR *best-guess scenario*

For this scenario, some modifications were required in order to simulate a best-guess starting from 1997, as *OSCAR* actually has available observed data until 2013 and would start forecasting from this point in time. After having prepared *OSCAR* to do forecasts starting in 1997, the results shown in Figures 8 - 10 were obtained. As explained in 3.1, the best-guess scenario also allows for a best- (in blue) and worst-case(in green) scenario based on an arbitrary (user-defined) value for the confidence interval. A confidence interval of 20 % was selected for this analysis, meaning that the worst-case scenario results in a solar cycle with a solar activity level which corresponds to a historical cycle with about 10 % lower activity. Anal-

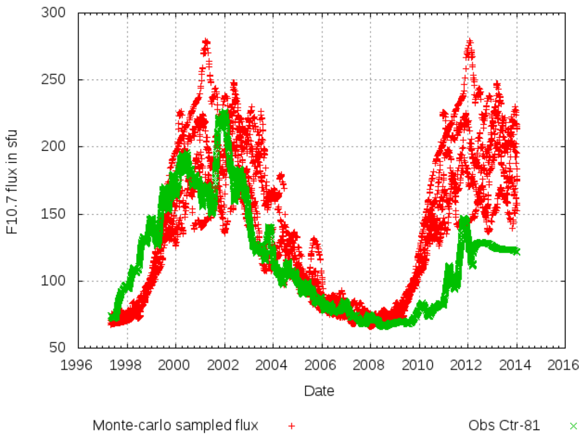

Fig. 7: Solar activity used for Scenario 3.

ogously the best-case scenario is 10 % higher than the mean activity level. We can observe that the three scenarios yield a very similar orbital evolution. However, a very interesting phenomenon is that with a higher solar activity (so called *best-case*) the upper stage has a longer orbital lifetime than with a lower solar activity level (so called *worst case*), which is not the case for a circular orbit [3]. In fact, for the high-eccentricity orbit considered in this analysis, the solar activity is not the main driver of the orbital decay. The evolution is dominated by the eccentricity variations and thus may lead to results, where an effectively higher solar activity ends up in longer orbital lifetimes in the end.

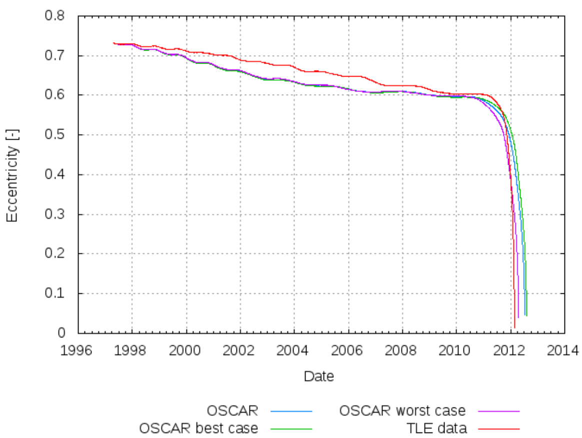

Fig. 8: Eccentricity evolution- Scenario 4

6. Sensitivity analysis

A sensitivity analysis wrt. to the obtained results on the cross-section, mass, RAAN and constant solar flux level was conducted. Exemplary results for the first two parameters will be shown in the following. For each variable, all the parameters of the reference configuration are

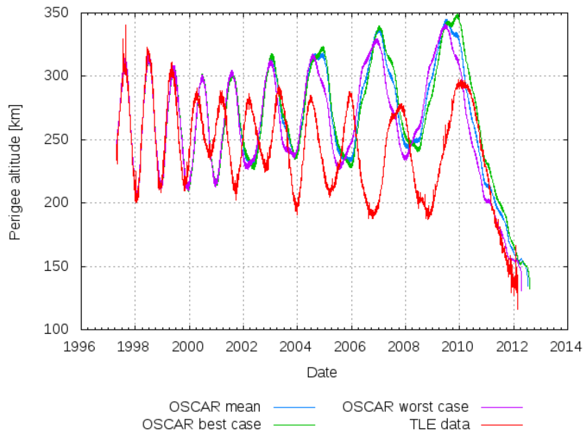

Fig. 9: Perigee altitude evolution- Scenario 4

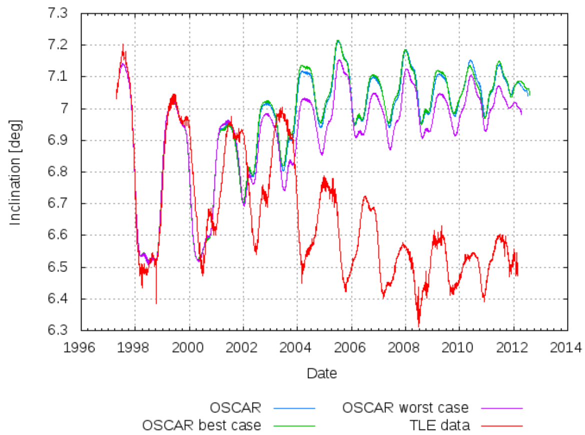

Fig. 10: Inclination evolution- Scenario 4

fixed and only the relevant value is changed. The goal was to see what the influence of these 4 parameters on the orbital lifetime actually is. The initial conditions are depicted in 2.

6.1. Sensitivity of the cross-section and mass

Fig. 11 shows the sensitivity of the cross-sectional area to the orbital lifetime (the blue vertical line representing the baseline). It would be expected that the higher the cross-sectional area, the higher the experienced drag at perigee passes and consequently the lower the orbital lifetime. The overall trend of the curve shows the expected behaviour with decreasing orbital lifetime when increasing the cross-sectional area. The interesting phenomenon is that the curve shows an oscillation with local maxima and minima with an increasing period when the cross section is smaller. In order to understand better the phenomenon, two cases were studied in more detail, namely simulations with a cross-sectional area of 17.5 m^2 (orbital lifetime of about 18 years) and 19 m^2 (orbital lifetime of about 30 years) respectively. It was observed that the 17.5 m^2 scenario resulted in the already decribed resonance effect around the year 2012, while the orbital evolution did not lead to this effect in the 19 m^2 case. This led to a sharp decrease in the perigee altitude for the 17.5 m^2 case, as shown in Fig. 12. In that matter, it can be seen that the orbital lifetime does not continuously decrease with increasing cross-sectional are, as there is an oscillation due to occurrent resonance effects.

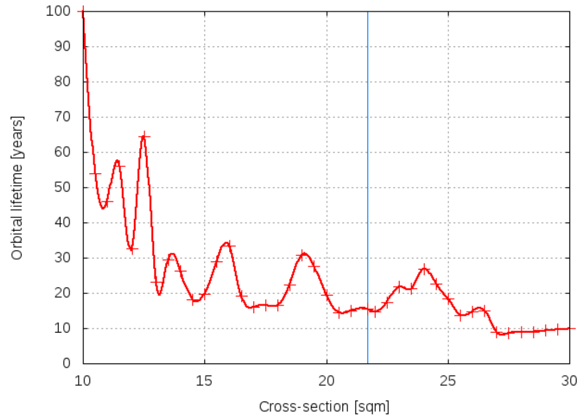

Fig. 11: Sensitivity on the cross section

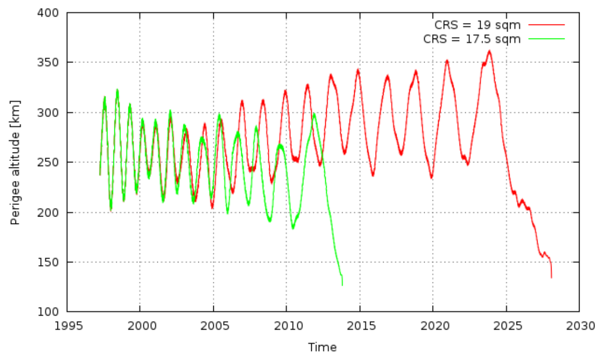

Fig. 12: Sensitivity on the cross section

Fig. 13 shows the sensitivity of the mass to the orbital lifetime. Here, it would be expected that an increasing mass will result in an increased orbital lifetime, as the ballistic parameter is increased. In Fig. 13 the general trend shows the expected behaviour. However, as in 6.1, an oscillation can also be seen, which is due to the same resonance effects as already described for the cross-sectional area sensitivity.

7. Conclusion

To conclude, the residual lifetime of an Ariane 4 upper stage in GTO has been studied using different solar activity forecast methods. Table 4 summarizes the different applied scenarios and the resulted orbital lifetimes

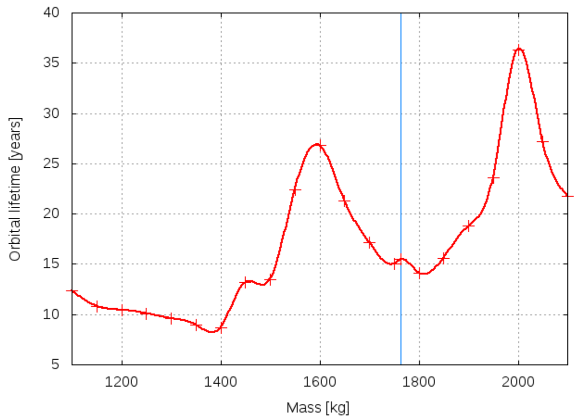

Fig. 13: Sensitivity on the upper stage mass

in the investigated example. We can observe that for the case of an upper-stage launched in GTO, the model with Monte Carlo Sampling is the most optimistic, due to the relatively high solar activities in the sampled cycles. The best-guess scenario provided quite good results, however, it would have predicted a distinctly higher solar activity for the 24th cycle, if the object would have stayed longer on orbit. In that case, deviations might have been significantly higher. The constant equivalent solar activity level

Table 4: Computed orbital lifetimes for the different scenarios.

Scenario	Solar Activity Model	Re-entry date
Ref.	-	Begin 2012
0	Observed activity	end 2012
1	Constant equiv. activity	end 2015
2	Sample solar cycle	end 2014
3	Monte Carlo sampling	begin 2009
4	Best-guess	mid 2012

(computed value of 116 sfu) results in a re-entry in 2015. This is mainly due to the fact that the applied equation was derived for spacecraft staying in sun-synchronous orbits in LEO. However, in this example, a slight increase to a level of 125.0 sfu provided good results. It has to be pointed out, however, that it is difficult to estimate such a constant equivalent flux level a priori. One would have to conduct similar studies for high-eccentricity orbits as done for LEO orbits in [6]. The ECSS sample solar cycle shows a prolonged orbital lifetime which is mainly due to the shift in the solar activity as was shown in Fig. 6. The *OSCAR* baseline is the one that follows the TLE scenario best, as it applies the same solar activity as actually experienced by the spacecraft. It shows that the implemented propagation model is reliable and consistent. However, this is based on observed data after the mission and can not be applied in the orbit prediction for future missions.

On the one hand, while looking for compliance to the

25 years rule, it seems advantageous to have a method which provides longer orbital lifetimes (or is pessimistic), so that we are sure to be within the required period. On the other hand, mission constraints may lead to additional cost in the implementation of the computed orbit solution. The best-guess scenario has in overall the most accurate prediction in terms of the orbital evolution, however, it has to be pointed out, that the applied McNish-Lincoln method requires information on the current cycle in order to estimate the ongoing cycle. If the disposal phase starts at the end of a solar cycle, only a mean cycle will be applied and possible advantages of the McNish-Lincoln approach can not be used.

In order to complete this study it would be interesting to perform the same analysis with other spacecraft in GTO in a first step, also to further broaden the understanding of orbital behaviour in high-eccentricity cases, and then do similar analysis for upper stages in LEO.
The sensitivity analysis shows some exotic results. However, it is clear that all parameters are very sensitive to changes in the initial conditions and can strongly impact the orbital lifetime (even up to years difference for smaller variations). This uncertainty will make it more difficult to predict if an upper stage in GTO will or will not comply with the 25-years rule in some cases. A solution would be to have a perigee low enough to get a maximum drag as soon as possible to avoid sun-synchronous resonance effects. In addition, the position and time of the launch (affecting RAAN) has a high impact on predicted orbital lifetime.

Furthermore, it would be interesting to perform the sensitivity on a wider range to see if the oscillations also occur in a significant manner there. It could be also interesting to analyse, whether there is a (simplified) analytic approach to reproduce the observed sensitivities.

8. References

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