UPGRADE OF THE ESA DRAMA OSCAR TOOL: ANALYSIS OF DISPOSAL STRATEGIES CONSIDERING CURRENT STANDARDS FOR FUTURE SOLAR AND GEOMAGNETIC ACTIVITY

V. Braun(1), N. Sánchez-Ortiz(2), J. Gelhaus(1), C. Kebschull(1), S. Flegel(1), M. Möckel(1), C. Wiedemann(1), H. Krag(3), and P. Vörsmann(1)

(1)*Institute of Aerospace Systems, Technische Universität Braunschweig , Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany, Email: v.braun@tu-braunschweig.de*
(2)*DEIMOS Space S.L.U., Ronda de Poniente 19, 2°2, Tres Cantos, Madrid, 28760 Madrid, Spain*
(3)*ESA/ESOC Space Debris Office, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany*

ABSTRACT

In 2008 the UN General Assembly adopted resolution 62/217, endorsing the space debris mitigation guidelines (SDMG) of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS). These guidelines contain recommendations for satellite operators to implement measures for various mission phases in order to reduce the further accumulation of space debris in space and especially within the protected regions. These are defined within the SDMG as being the LEO region (up to 2,000 km altitude) and the GEO region (± 200 km in altitude around the GEO altitude and ± 15 degrees latitude).

In the first version of ESA's DRAMA tool suite, OSCAR (Orbital SpaceCraft Active Removal) was designed as a tool to allow users the analysis of different disposal stragies for spacecraft in the LEO and GEO region. The upgrade of the ESA DRAMA tool suite by TUBS and DEIMOS under ESA/ESOC contract included the development of a renewed version of the existing OSCAR tool, allowing in its current version the consideration of different future solar and geomagnetic activity scenarios and besides the already known disposal systems (chemical and electric propulsion, as well as electrodynamic tether) the analysis of the orbital evolution using drag augmentation devices. One of the primary goals was to implement techniques recommended by current standards. The recommendations from the SDMG were used for the definition of the critical regions as well as compliance criteria, the user may check his disposal strategy against. For satellites operating in GEO, the ISO 26872:2010 (Space Systems - Disposal of satellites operating at geosynchronous altitude) standard was accounted for. For the generation of future solar and geomagnetic activity, the standards ISO 27852:2011 (Space Systems - Estimation of orbit lifetime) and the ECSS-E-ST-10-04C (Space engineering - Space environment) have been considered and recommended modeling approaches were implemented.

In this paper, the OSCAR tool is presented, giving an overview on the future solar and geomagnetic activity scenario generation, the standards involved, as well as the new available disposal option of using drag augmentation devices. Exemplary results are shown, considering the deviations encountered when using methods proposed by different standards, as well as some propagation results obtained with FOCUS-1A, which is the propagation tool used in OSCAR. Further new features will be highlighted, for example the possibility to download up-to-date solar and geomagnetic activity data and use it in OSCAR simulations, as well as the compliance checks provided by OSCAR based on the SDMG.

Key words: ESA; DRAMA; OSCAR; Disposal; End-of-life; Mitigation; Standards.

1. INTRODUCTION

OSCAR is the component of DRAMA (Debris Risk Assessment and Mitigation Analysis) designed to address disposal manoeuvres, using different disposal strategies under consideration of standardized future solar and geomagnetic activity and assess the compliance of the latter stages of a mission with the SDMG.

The modeling of the future solar and geomagnetic activity is the main driver in the estimation of the residual lifetime for a specific orbit. In the upgraded OSCAR tool, forecasts are based on methods as recommended by different standards, e.g. ISO, ECSS, and will be described in more detail in Sec. 2. OSCAR allows for the estimation of the residual lifetime for a given orbit and also checks whether an action is required to be compliant with the SDMG. A new function in OSCAR is to directly download and use available up-to-date solar and geomagnetic data files from ESA as well as CSSI.

The upgraded version of OSCAR also allows for the analysis of drag augmentation systems, besides the already

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known options of chemical propulsion, electric propulsion and electrodynamic tethers. It is possible to analyse delayed de-orbits with a specified residual lifetime on the final orbit, as well as a re-orbit with an arbitrary re-orbit altitude for the already known disposal strategies, while the drag augmentation system is implemented as a delayed de-orbit strategy, where the time until atmospheric re-entry is computed. Additionally, for chemical propulsion systems, direct de-orbit may be analysed, resulting in a re-entry within the next revolution. Details are described in Sec. 3.

All of the user-defined scenarios are evaluated with respect to the SDMG, which is done via a set of pre-defined non-compliance criteria:

1. Lifetime of LEO crossing spacecraft > 25 years.
2. LEO protected region crossing within 100 years.
3. GEO protected region crossing within 100 years.

All results are provided via ASCII data files. Examples for possible OSCAR simulation results will be shown in Sec. 4.

2. SOLAR AND GEOMAGNETIC ACTIVITY

A completely new feature in the upgraded OSCAR version is the implementation of different methods providing a forecast of solar and geomagnetic activity as recommended by recent standards. For the estimation of orbital lifetime, five different methods may be used to generate future solar and geomagnetic activity data which serves as input for the orbit propagation. The methods are based on recommendations by ISO [13], ECSS [5] as well as a method which has been implemented within the French Space Act [7]. In [2] the deviations in the results for the orbital lifetime estimation obtained by the application of the different methods in OSCAR are discussed in detail. In the following, a short description for each method is given.

2.1. Best guess scenario

The implementation of the *best-guess* method, which is also recommended by ISO 27852 [13], is based on the algorithm as used by the Marshall Space Flight Center (MSFC), which is called the *MSFC Lagrangian Linear Regression Technique* (MLLRT) [15].

A modified McNish-Lincoln method is used [8] to estimate 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 from the smoothed mean cycle. The latter is derived from sampled past cycles 10 through 23 in OSCAR. The individual solar cycles showed varying activity as well as cycle durations. The transformation of all cycles to a common mean duration of 132 months was the first step in the database build up for the historical mean solar cycle, which is available as a data file to OSCAR.

As the atmosphere model in FOCUS-1A, which is the orbit propagation tool used by OSCAR, requires the $F_{10.7}$ value as an input parameter for solar activity, the 13-month smoothed sunspot number $\bar{R}$ is converted to the smoothed solar flux $\bar{F}_{10.7}$ according to [15]:

$$\bar{F}_{10.7} = 49.4 + 0.97 \cdot \bar{R} + 17.6 \cdot e^{-0.035 \cdot \bar{R}} \qquad (1)$$

As the forecast, using this method, is only valid for the current cycle, for subsequent cycles the smoothed mean cycle is assumed. As there is a discontinuity between the start and the end of the smoothed mean cycle, a cubic spline is used to connect subsequent cycles. For that purpose the forecast was replaced by the spline polynomial for an interval starting 24 months prior to the beginning of the next cycle. This guarantees a smooth transition between subsequent cycles.

2.2. Best case / worst case scenario

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. In order to derive the solar activity for a given confidence, one has to find the underlying probability density function for the physical process behind each solar cycle. According to [15], there are strong indications that a gaussian distribution is not applicable to the data set available for the 23 cycles so far. Therefore, the method as recommended in [15], was implemented in OSCAR, using equally spaced quantiles based on available data from 23 solar cycles. An example shall demonstrate, how this method works. Consider the mean solar activity of the first month for each available cycle and sort them in ascending order. As shown in Figure 1 those values (ranging from 68.02 sfu to 72.84 sfu) are then equally distributed between 0 and 100 %. The definition of an

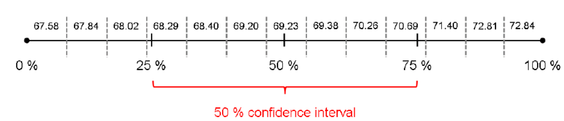

Figure 1. Example for the estimation of solar activity confidence interval values for the first month of the mean solar cycle.

exemplary confidence interval of 50 % now means that the BC is sampled by using the smoothed value at 75 %, while the WC would use the value at 25 %. As the bins defined by the number of sampled cycles do not match with the arbitrary defined confidence interval in general, an interpolation is performed to find the required solar activity. A cubic spline interpolation is used to enable a smooth transition from observation data (no WC/BC) to maximum values specified by the confidence interval, assuming a transition interval of 18 months, the inflection point being the last observed value for solar activity.

2.3. Constant cycle scenario

The computation of the orbital lifetime strongly depends on the solar and geomagnetic activity. The simulation results may show notable deviations, depending on the position of the simulation start within the solar cycle. Also, the cycle level (high, medium, low activity) and the duration may have a significant impact on the results. Therefore, a method to use a constant equivalent solar flux was proposed in [7]. The authors derived an analytical formulation relating the so called *equivalent constant solar flux* to the satellite's ballistic coefficient $m/\left(A \cdot C_d\right)$ and the initial apogee altitude h_a:

$$F_{10.7} = 201 + 3.25 \cdot ln\left(\frac{A \cdot C_d}{m}\right) - 7 \cdot ln\left(h_a\right) \qquad (2)$$

This function was derived, taking into account different solar cycles and different start epochs and fitting the parameters in such a way, that in 50 % of the simulations the orbital lifetime was lower than or equal to 25 years. Therefore, using Equation 2 results in an equivalent constant solar flux which provides an orbital lifetime on the disposal orbit according to the SDMG. For the geomagnetic activity A_p a constant value of $A_p = 15$ was defined. In OSCAR, Equation 2 may be used along with the possibility of defining an own equivalent constant flux. This needs to be done, for example, in those cases where Equation 2 can not be applied. A different formulation would be required for high eccentricity orbits, for example.

2.4. Repeated solar cycle scenario

The method to repeat a standardized cycle is proposed by the space environment standard of the European Cooperation for Space Standardization (ECSS) from 2008 [5]. Besides other environmental issues, that standard provides so-called *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. For a given propagation time frame, that cycle is repeated for an appropriate number of times. OSCAR also takes into account the position within that cycle at simulation start, which is derived on historical information on solar cycle minima.

2.5. Monte Carlo sampled cycle scenario

The Monte Carlo sampling method is one of the two approaches for long-term solar flux forecast recommended by the ISO 27852:2011 standard [13]. The method itself was investigated in [16] and is based on the sampling of a randomly drawn solar cycle out of available observed data from five preceding solar cycles in OSCAR. 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. 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 third order lagrange polynomial.

An example for the solar cycles 24 and 25 is shown in Figure 2 for the different modeling approaches. The constant solar cycle is not shown, as that would result in a horizontal line depending on the spacecraft orbit. It can

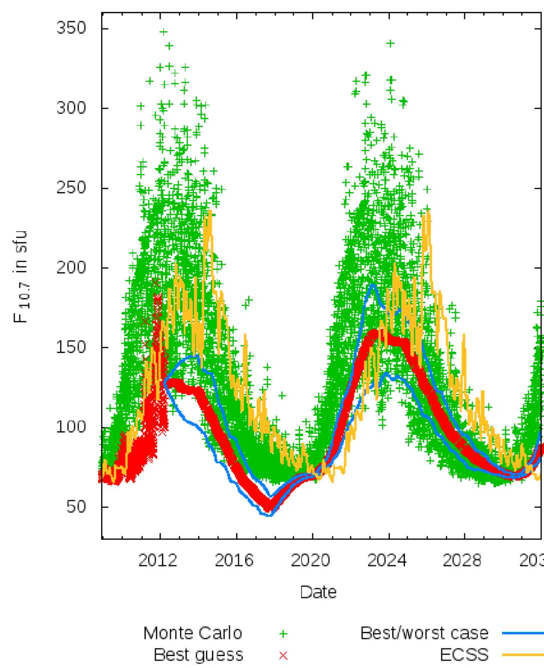

Figure 2. Example for an OSCAR solar activity forecast in solar cycle no. 24 for the different modeling approaches.

be seen that observed data in the best guess scenario is available until mid-2012 when forecast starts. This point in time is also the inflection point for the best case and worst case scenarios, defined by a confidence interval of 40 %. The Monte Carlo as well as the ECSS cycle both show a higher activity in cycle 24, as they are based on previous cycles which showed a significantly higher activity than is observed for the current 24^{th} cycle. Also, the repeated ECSS cycle shows a drift which is due to the 140 month duration compared to about 132 months for the other scenarios. A more detailed comparison of the different scenarios was done in [2].

3. DISPOSAL OPTIONS

The OSCAR tool can be used to estimate key parameters as the required Δv or fuel mass for the disposal maneuver, which transfers the spacecraft to an orbit with the desired properties consistent with the SDMG recommendations. Such a maneuver can be performed by different means. In OSCAR, the user may analyse the following disposal options:

- Chemical propulsion system (CP)
- Electric propulsion system (EP)
- Electrodynamic tether system (ET)
- Drag augmentation system (DA)

Having the system defined it is necessary to specify the disposal strategy. In OSCAR, the following strategies can be used:

- Direct de-orbit (CP)
- Delayed de-orbit (CP, EP, ET, DA)
- Re-orbit (CP, EP, ET)
- None

While a delayed de-orbit is an option available for any disposal system selected, the other options are only viable for specific systems, given in parantheses in the above listing. For example, a direct de-orbit is a strategy, where the perigee of the orbit is adjusted to 60 km, which can only be accomplished by a chemical propulsion system and results in an atmospheric re-entry within the next perigee pass in OSCAR. Also, a re-orbit is not possible with drag augmentation systems, as these systems are assumed to be deployed only to accelerate the orbital decay. The option "None" allows for the analysis of the initial orbit of the spacecraft. In such a scenario, OSCAR would not perform any maneuver and only compute the orbital evolution for the given trajectory. This is useful, for example, if one wants to know the remaining lifetime on the current orbit as it may be possible, that no action needs to be performed to comply with the SDMG. In the following sections the single disposal systems are described in more detail.

3.1. Chemical propulsion system

The CP system in OSCAR is represented by its specific impulse only. The user thus only needs to provide this single value for the simulations, in which it is assumed that thrust is provided instantly at a given position within an orbit. Thus, OSCAR does not account for problems associated with finite maneuver duration, thrust characteristics, multiple starts, etc. A propulsion database is available to select a CP engine by its name, e.g. Cold gas, Solid Motor, Monopropellant, etc. It is also possible to define new engines or alter the existing ones.

For de-orbiting from an initially circular or elliptical orbit, a chemical engine is fired impulsively at the apogee in a direction opposite to the velocity vector, having the effect of lowering the object's perigee. For delayed deorbit manoeuvres OSCAR applies a bisection iteration technique to find the required perigee altitude for the given apogee altitude of the initial orbit to achieve a deorbit within (a) the lifetime limit specified by the SDMG (which is 25 years), and (b) a user-specified time period (which has to be defined and can have any arbitrary value > 0). The natural orbital evolution using FOCUS-1A and hence an estimate of the remaining orbital lifetime of the new orbit is determined.

The Δv required to manoeuvre a spacecraft from its initial trajectory to the orbit with the estimated perigee altitude is then computed and from the Δv the required fuel mass is obtained from the Tsiolkovsky rocket equation, given the spacecraft dry mass.

The re-orbit is another option for spacecraft especially in higher LEO altitudes and in GEO in order to get spacecraft out of the protected regions with significantly lower effort than would be the case for a de-orbit option. In the upgraded OSCAR version it is possible to specify any arbitrary value for the re-orbit altitude, which will always result in a circular orbit after the application of a series of two-burn Hohmann maneuvers. Therefore, it is also possible to analyse re-orbit strategies in GEO with several intermediate orbits, e.g. as recommended by [12]. However, if the re-orbit altitude given by the user does not comply with the SDMG, OSCAR will generate an appropriate warning according to the compliance criteria as given in Section 1. The required re-orbit altitude in GEO is computed using the IADC equation:

$$\Delta H = 235 + 1,000 \cdot c_r \cdot \frac{A}{m} \tag{3}$$

3.2. Electric propulsion system

The EP system in OSCAR is represented by its specific impulse, the thrust and the thruster lifetime. This data triad is given for any thruster selectable from the propulsion database in OSCAR, while new engines can also be defined by the user. In OSCAR it is assumed that a constant thrust is provided during operation. This may be different in real operations, as the thrust may be interrupted due to the spacecraft moving in and out of eclipse and the battery storage not being sufficient to supply the necessary power during these periods. Subsequently, this would result in extended transfer times, which should be taken into account by the user when evaluation OSCAR results.

For initially circular orbits, the low thrust transfer using an EP system is simulated by the application of analytical relationships, e.g. as given in [17]. For orbits with considerable eccentricity, those analytical formulations can not be applied anymore. As it could be interesting to investigate electric thrusters also for objects on high eccentric orbits, e.g. geotransfer orbits (GTOs), an algorithm was implemented to simulate the orbit evolution under the influence of continuous low thrust using the Gauss variational equations. As long as the thrust is on the order of magnitude of a perturbative effect, which is limited to a maximum of 1 N in OSCAR, these equations provide the expected results.

For a delayed de-orbit option, OSCAR will search for the altitude which has to be reached in order to provide the specified residual lifetime. This is similar to the procedure already described in Section 3.1. The transfer time, fuel mass and Δv required to perform the transfer to that orbit are computed by OSCAR.

OSCAR also estimates the minimum (delayed de-orbit) or maximum (re-orbit) altitude the thruster is capable of to achieve within the given thruster lifetime. Also the Δv and fuel mass are computed for this capability scenario.

3.3. Electrodynamic tether system

The feasibility of a conductive tether de-orbit mission was demonstrated in previous theoretical studies and limited flight experiments [9, 10, 11]. For this reason, a simple software module was already included in the initial version of OSCAR to allow an assessment of the de-orbit of a circular LEO satellite using a conductive tether. In the upgraded version, OSCAR uses the same algorithm, which was already decribed in [14] and uses a simplified equation for circular orbits in LEO taken from [9].

3.4. Drag augmentation system

As the orbital decay is governed by atmospheric drag, the increase of the drag force acting on a satellite would result in lower orbital lifetimes. Therefore, several authors have proposed systems to increase the drag-effective cross-section of a spacecraft. This can be done by using inflatable structures, e.g. balloons, or mechanisms to deploy surfaces in velocity direction. In the upgraded OSCAR version, the simulation of drag augmentation systems is new. Besides the estimation of the de-orbit duration for a user-defined DA, OSCAR also computes the required cross-section which is compliant with the SDMG. An example is shown in Figure 3 for different initial altitudes in LEO and taking into account two different solar and geomagnetic activity scenarios, best guess and the ECSS standard cycle. It can be seen that in its initial configuration, a drag augmentation system would be required for altitudes above 600 km, depending on the solar and geomagnetic activity scenario. As the disposal phase in this example began in 1997 and the spacecraft thus experienced mainly the solar cycles 23 and 24, there is a difference between repeating cycle 23 two times - as is the case for the ECSS cycle - and having the lower activity cycle no. 24 following cycle 23. Therefore, in the best guess scenario one will always obtain a higher cross-section requirement. A satellite in a typical sun-synchronous altitude of about 800 km altitude would require a cross-section of about 100 m^2 in this example, meaning a cross-section augmentation by a factor of 10. If an inflatable balloon would be used, this would result in a sphere with required diameter of about 11.3 m. Also, the required cross-section in the best-guess scenario is about 30 % higher when compared to the ECSS cycle in this example.

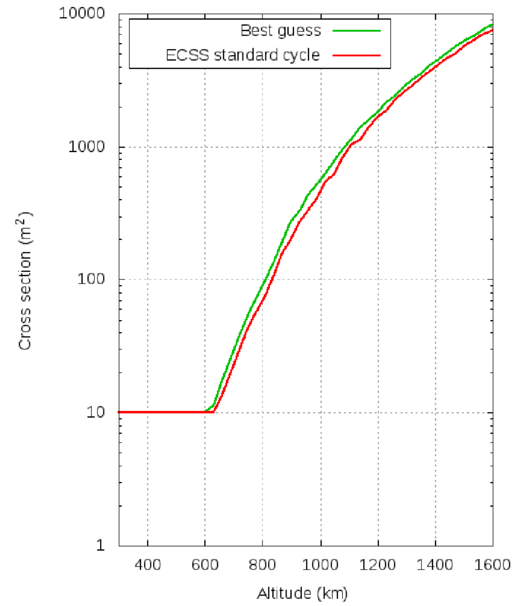

Figure 3. Required cross-section for a drag augmentation system in order to be compliant with the SDMG, for a spacecraft in an initially circular near-polar orbit with a cross-section of 10 m^2 mass of 1,000 kg and drag coefficient $C_D = 2.2$. Results for two solar and geomagnetic activity scenarios are shown.

4. EXEMPLARY RESULTS

In the following some results obtained by the OSCAR software shall be shown and discussed. Two ESA missions in LEO and GEO were selected: The Earth observation satellite Cryosat-2 will be an example for LEO disposal strategies, while Meteosat-10 is a GEO mission.

4.1. Cryosat-2

Cryosat-2 was launched in April 2010. A mission duration of minimum three years after a six month commissioning phase is envisaged. In the following analysis, it is assumed that the mission ends in 01/01/2015 and Cryosat-2 then enters into its disposal phase. The data as shown in Table 1 was used for the following analysis [6]. The Cryosat-2 orbit is assumed to be 710 × 726 km, 92.02 deg inclination. As can be seen from Table 1, Cryosat-2 carries only a limited amount of fuel mainly for station-keeping manoeuvres. The manoeuvres are performed by the low thrust orbit control thrusters (40 mN) based on cold gas.

Table 1. Cryosat-2 data sheet [6].

Parameter	Value
Mass (kg)	743.5
Cross-section min. (m^2)	3.4
Cross-section max. (m^2)	10.4
Specific impulse (s)	72.0
Max. fuel mass (kg)	37.4

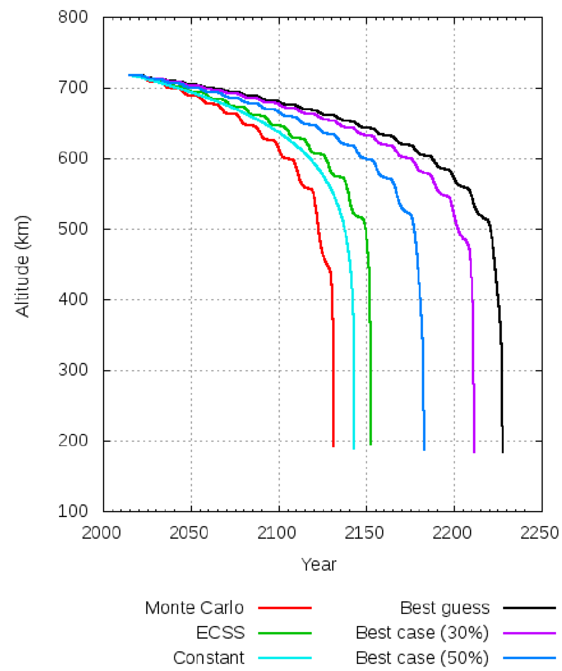

Figure 4. Orbital lifetime of Cryosat-2 for an initial orbit of 710 × 726 km, 92 deg inclination, starting in 2015/01/01. The cross-section was assumed to be 3.4 m^2. Different scenarios for solar and geomagnetic activity were applied.

Residual lifetime on initial orbit

In a first step, the residual lifetime of Cryosat-2 was estimated by OSCAR for the minimum cross-section in flight direction which is a conservative approach. No disposal option is selected at this point. The results are shown in Figure 4 for different solar and geomagnetic activity scenarios starting in 2015. It can be seen that the lifetime estimations provide significantly different results when applying the different solar and geomagnetic activity scenarios available in OSCAR. The minimum orbital lifetime, as provided by the Monte Carlo simulation, is about 115 years, while in the best-guess scenario, Cryosat-2 will stay in orbit for more than 210 years. Even for a confidence interval of 50 %, the orbital decay will last for 165 years. This scenario clearly shows the influence of future solar and geomagnetic activity modeling. Due to the high activity cycle, as provided by the Monte Carlo sampling (see Figure 2) with respect to the best-guess method, and the fact that the satellite experiences at least ten of those cycles, the results may vary by more than 100 years.

The results shown above have been obtained for a minimum cross-section, however, which is the approximate cross-section wrt. the flight direction, as given in Table 1. If Cryosat-2 would perform at its end-of-life a pitch manoeuvre in order to have the maximum cross-section pointing in flight direction, it would increase from 3.4 m^2 to about 10.4 m^2. Applying the Monte Carlo cycle in that case results in an orbital lifetime of about 40 years, while for the best-guess scenario the residual orbit lifetime is reduced to about 73 years.

It can thus be said that regardless of the orientation of the spacecraft and the solar and geomagnetic activity scenario, Cryosat-2 will not be compliant with the 25-year rule if no manoeuvre is performed. Therefore, some disposal options shall be looked at in the following section.

Disposal options

For orbital manoeuvering, Cryosat-2 uses 40 mN thrusters (chemical propulsion system) based on cold, low-pressure gas [6] with $I_{sp} = 72\ s$. A delayed deorbit was simulated, as the thrusters are not capable of providing a controlled direct de-orbit manoeuvre. The simulations were performed for the Monte Carlo and the best-guess solar and geomagnetic activity and are shown in Table 2 for minimum and maximum cross-section. For the minimum cross-section, the perigee would have to be lowered by 209 km for the Monte Carlo scenario and 258 km for the best-guess scenario, respectively. Such a manoeuvre would require between 64.3 kg (Monte Carlo) and 79.9 kg (best-guess) fuel mass. As the total fuel mass at begin of life is about 37 kg [6] and only a fraction of that amount will remain for a possible de-orbit manoeuvre in the end, Cryosat-2 will not be able to reach a 25-

Table 2. Cryosat-2: Requirements to reach a 25-year decay orbit using the available chemical propulsion system.

Parameter	Monte Carlo	Best-guess
Cross-section 3.4 m^2		
Perigee altitude (km)	501.2	452.3
Δv (m/s)	58.6	72.1
Fuel mass (kg)	64.3	79.9
Cross-section 10.4 m^2		
Perigee altitude (km)	635.0	559.8
Δv (m/s)	22.3	42.6
Fuel mass (kg)	23.9	46.2

year decay orbit in a minimum cross-section configuration. If it is assumed that Cryosat-2 augments its drag related cross-section by a pitch manoeuvre, for 10.4 m^2 maximum cross-section, the perigee lowering manoeuvre is significantly reduced in its requirements: Only 23.9 kg in the Monte Carlo scenario and 46.2 kg in the best-guess scenario are required. Given the maximum fuel mass of 37 kg, the Monte Carlo scenario figures come close to what is possible.

4.2. Meteosat-10

Meteosat-10 was launched in July 2012 and is a spin-stabilised meteorological satellite in GEO. In this example, a re-orbit shall be performed using a two-burn Hohmann manoeuvre. The data as shown in Table 3 was used for the following analysis. The first step is to determine the required altitude the re-orbit transfer has to provide in order to be compliant with the SDMG, which means that no GEO protected region crossing will occur for the next 100 years. The results for the 100 year orbit evolution are shown in Figure 5 for the disposal orbit with a re-orbit altitude of 36,032 km. It can be seen that the initial orbit will build-up an inclination of up to

Table 3. Meteosat-10 data sheet [4, 3].

Parameter	Value
Mass (kg)	1054.0
Cross-section (m^2)	7.7
Specific impulse (s)	300.0*
Max. fuel mass (kg)	147.7
SRP coefficient	1.14
Orbit	
Semi-major axis (km)	42164.93
Eccentricity	0.00017
Inclination (deg)	1.28
RAAN (deg)	246.48
Arg. of Perigee (deg)	175.55
Mean Anomaly (deg)	127.21

* The specific impulse was assumed according to typical values for 400 N apogee kick motors.

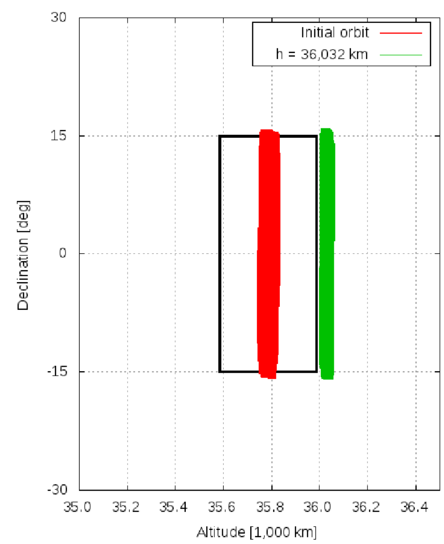

Figure 5. The orbital evolution within 100 years for the initial orbit as well as the recommended altitude given via Equation 3.

about 15 degrees, which is the typically expected maximum value for uncontrolled objects in GEO. Furthermore, the orbital evolution of the disposal orbit above GEO shows, that the GEO protected region is not crossed within 100 years. The re-orbit requirements estimated for the Meteosat-10 example are summarized in Table 4 for a two-burn Hohmann transfer. The manoeuvre duration

Table 4. Meteosat-10 re-orbit requirements for a two-burn Hohmann transfer.

Parameter	Value
Re-orbit altitude (km)	36,032.0
Δv (m/s)	8.9
Fuel mass (kg)	3.2
Duration (days)	2.5

of 2.5 days is due to the recommendations of the ISO 26872:2010 [12], where at least two orbit revolutions are required for orbit determination after each burn. In the example, the apogee will be increased to the specified re-orbit altitude within the first burn, then the orbit is determined within the next two revolutions and finally the perigee is increased to result in a circular orbit sufficiently high above the GEO protected region. The additional 0.5 revolutions are required for the spacecraft to travel from perigee to apogee in order to perform the second burn there.

5. CONCLUSION

The upgraded OSCAR tool within the DRAMA tool suite allows for the analysis of different disposal strategies under consideration of standardized models for future solar and geomagnetic activity. OSCAR performs the orbit propagation in order to evaluate the compliance with respect to the SDMG.

For the modeling of the future solar and geomagnetic activity, four different methods have been implemented: A best-guess method including best case and worst case estimations using a confidence interval, as well as a Monte Carlo method, both methods being recommended by ISO 27852:2011 [13]. A repeatable and standardized cycle, as recommended by the ECSS [5] and an equivalent constant solar flux as applied within the French Space Act [7]. The resulting future solar cycles may be significantly different for the individual methods, which strongly affects the orbit propagation. This was shown for the Cryosat-2 orbital decay, where applying the best-guess method resulted in an orbit lifetime of more than 210 years, while for the Monte Carlo scenario the result was 115 years. This is due to the fact that the current 24^{th} solar cycle shows a very low activity and also the mean solar cycle, which was derived from solar cycles 10-23 for OSCAR's best-guess method, shows a moderate level compared to the five solar cycles 19-23 which are the basis for the Monte Carlo sampling and showed a significantly higher activity.

The new feature of drag augmentation system simulation was shown exemplary for two different solar and geomagnetic activity scenarios. For the practical problem of finding the required cross-section in order to be compliant with the SDMG, simulations were performed. The results show that for a best-guess scenario, the cross-section is about 30 % higher for a typical SSO compared to an ECSS cycle. The examples for spacecraft in LEO show that the best-guess scenario tends to provide conservative estimates as it is based on cycles with lower activity, while the other methods all are based on recent cycles which showed much higher activity. Especially for shorter orbital lifetimes, the best-guess scenario, however, should provide more reliable results, as it is the only method incorporating information for the current 24^{th} solar cycle. As OSCAR was designed to use up-to-date solar and geomagnetic data, one can always update the data files and thus the lifetime estimation process in the best-guess scenario.

For spacecraft in GEO, a new feature in OSCAR is the visualisation of the orbital evolution wrt. the GEO protected region, which was shown in Figure 5. If the black rectangle, representing the protected region, is crossed by the plot, this can be directly seen.

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