DRAMA 2.0 – ESA's space debris risk assessment and mitigation analysis tool suite

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9 authors, including:

Christopher Kebschull
OKAPI:Orbits Gmbh

Noelia Sánchez-Ortiz
Arribes Enlightment

Joaquim Oliveira
Aurora Technology

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DRAMA 2.0 - ESA'S SPACE DEBRIS RISK ASSESSMENT AND MITIGATION ANALYSIS TOOL SUITE

Vitali Braun[a], J. Gelhaus[a], C. Kebschull[a], N. Sánchez-Ortiz[b], J. Oliveira[b], R. Domínguez[b], C. Wiedemann[a], H. Krag[c], P. Vörsmann[a]

[a] *Institute of Aerospace Systems, Technische Universität Braunschweig , Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany*
[b] *DEIMOS Space S.L.U., Ronda de Poniente 19, 2°2, Tres Cantos, Madrid, 28760 Spain*
[c] *ESA/ESOC (Space Debris Office), Robert-Bosch-Str. 5, 64293 Darmstadt, Germany*

Abstract

In order to support mission designers in all sort of space debris related problems, a software called DRAMA (Debris Risk Assessment and Mitigation Analysis) was developed in the past and was now upgraded under ESA contract by TUBS and DEIMOS, to include additional components, increase the performance of existing tools and incorporate current mitigation standards. The DRAMA tool suite in its upgraded version delivers five individual components, which shall support the verification of the compliance of space missions with mitigation guidelines and recently published standards. The existing tools ARES (Assessment of Risk Event Statistics) and MIDAS (MASTER-based Impact Flux and Damage Assessment Software) have been upgraded, using the MASTER-2009 model now. The covariance data used by ARES was updated and it is now possible to select covariances as per TLE, CSM, scale them or provide external covariance data. The number of orbit groups and the population size division has also been reviewed. MIDAS allows for additional ballistic limit equations to be defined by the user. SARA (incl. SESAM and SERAM) is used for the analysis of satellite re-entry and the related risk on-ground has been maintained, while a new component called CROC has been developed to calculate the cross-section of complex bodies. The cross-section can be generated for a user defined aspect angle, for an aspect angle plus a defined rotation axis and for a randomly tumbling body. OSCAR (Orbital Spacecraft Active Removal) has been completely redesigned. Several new features are now available. Designers planning to de-orbit the spacecraft by drag augmentation devices can now use OSCAR to do first simulations. For the estimation of orbits with a specified orbital lifetime (e.g. 25-year-rule), different scenarios for future solar and geomagnetic activities can be selected, which are in line with the current ISO and ECSS standards.

This paper will give an overview over the work done during the ESA/ESOC project "Upgrade of ESA's Space Debris Mitigation Analysis Tool Suite". The most important upgrades will be explained, focusing on the redesigned OSCAR tool. The key features of OSCAR will be pointed out to show users how OSCAR can support mission planning.

Keywords: ESA; DRAMA; space debris; risk assessment; mitigation; de-orbit; impact risk; removal; cross-section computation;

I INTRODUCTION

The DRAMA software tool suite has been designed to support space mission planners in the analysis of all kinds of debris related problems in the course of a satellite mission. Several distinct tools are provided to enable the assessment of debris mitigation strategies for the operational and disposal phases of a mission as well as the estimation of the risk caused by debris during the mission or by objects surviving a re-entry of the spacecraft. The following tools are available within DRAMA and can also be operated independently, e.g. via the command line interface:

- ARES: Assessment of Risk Event Statistics
- MIDAS: MASTER(-based) Impact Flux and Damage Assessment

Email address: v.braun@tu-braunschweig.de (Vitali Braun)

- OSCAR: Orbital Spacecraft Active Removal
- CROC: Cross Section of Complex Bodies
- SARA: (Re-Entry) Survival and Risk Analysis

An additional tool is CSTATE, which has been implemented in the new DRAMA version and is thought to be an auxiliary tool for the other programs. It performs the conversion between different formats of orbit data. These tools can be controlled via the command line interface, but it is recommended to use the re-developed graphical user interface (GUI). The GUI allows the user to create multiple DRAMA projects for a more flexible use of the software suite.

In this paper, first an overview will be given, showing the key features of the new DRAMA version and presenting the major changes in all of the individual tools. While a preliminary overview on the whole project was given in [7] and some aspects of the GUI were presented in [11], in this paper the focus shall be on the redevelopment of the OSCAR tool (in Sec. III), as the main author was primarily responsible for the implementation of this tool.

I.1. Key features of DRAMA 2.0

The upgrade of the DRAMA tool suite consisted of minor modifications and model revisions up to a complete redevelopment of individual tools like OSCAR or the GUI. The most significant changes as compared to the former DRAMA version are given in the following list:

- A new graphical user interface has been developed.
- An auxiliary tool CSTATE was added, which is used for time and coordinate system conversions.
- ARES now uses MASTER-2009 for flux computations.
- ARES implements a customizable radar equation to simulate any catalog system performance.
- The catalog uncertainties available in ARES for TLE (Two-line elements) or CSM (Conjunction summary message) types can be selected, alternatively ARES also accepts user-defined data.
- For ARES the uncertainties associated with TLE and CSM data have been obtained from a detailed analysis of historical data.
- In MIDAS user-defined BLEs can be provided and flux computations are now performed using the MASTER-2009 model.

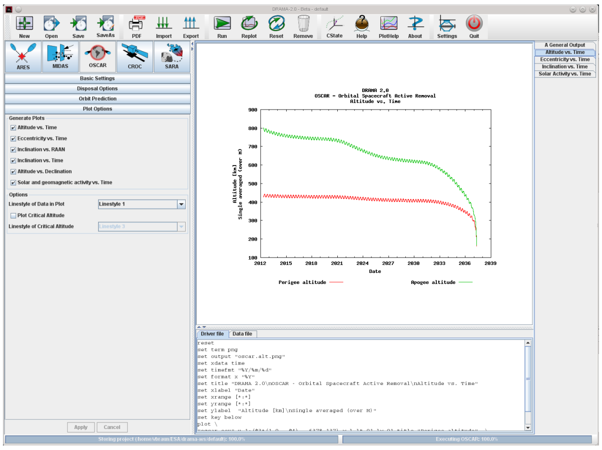

Fig. I: The graphical user interface of DRAMA.

- OSCAR was completely redeveloped and now offers the possibility to select between different standardized methods (ISO, ECSS) to generate forecasts of future solar and geomagnetic activity.
- OSCAR allows for the simulation of drag augmentation devices as a new disposal system.
- OSCAR performs a compliance evaluation with respect to the recommendations of the Space Debris Mitigation Guidelines [16].
- A new tool called CROC has been developed for the computation of the cross-section of complex bodies for different aspect angle conditions.
- Each tool within DRAMA writes its own gnuplot driver files.

I.2. The Graphical User Interface (GUI)

The new graphical user interface of DRAMA was designed in Java and can thus be used for Windows, Linux and Mac operating systems. It allows for a fast access to the input and output data of the individual tools. The input is provided via the sidebar which is shown on the left side in Fig. I. The selection of the individual tools is done via a toolbar, which is integrated in the sidebar and can be found on top of it. The topbar consists of several buttons for quick access to general tasks like, for example, creating a new project, starting the execution, etc. The results of each tool are presented in the results window, as shown in Fig. I for an altitude vs. time plot as computed by OSCAR in this example. All generated plots are selectable via a tabbed pane on the right of the results window. In the shown example, there are five different outputs which have been generated by OSCAR.

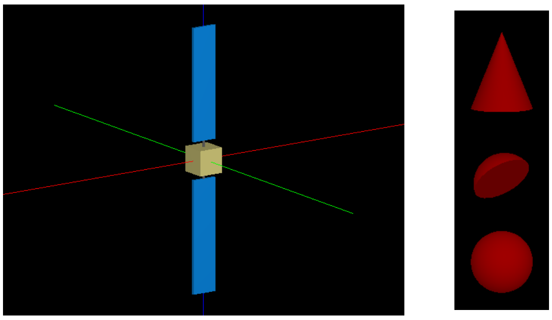

Fig. II: Satellite model as designed with CROC *(left)* and additional shapes available in CROC *(right)*.

Component	Type	Dimension	Position
Satellite bus	Box	$100 \times 100 \times 100$	$0, 0, 0$
SA connector	Cylinder	5×200	$0, 0, -100$
Solar array 1	Box	$100 \times 10 \times 450$	$0, 0, 300$
Solar array 2	Box	$100 \times 10 \times 450$	$0, 0, -300$

Tab. I: Element definition for the example satellite in CROC (dimension and position in cm).

II WORKING WITH DRAMA

In this section, the individual tools of DRAMA are presented, highlighting the major features of the new version. The redeveloped OSCAR tool will be looked at in more detail in Sec. III. The tools are presented from a mission planner's point of view, who will start with the design of the satellite by specifying its dimensions and shape using the CROC tool. Various debris related problems can then be analysed, using ARES for the assessment of risk event statistics, MIDAS for the estimation of impact and damage flux and finally SARA for the evaluation of the re-entry strategy when the spacecraft is disposed of. The auxiliary tool CSTATE is used to provide the right orbit data format based on the selected orbit by the mission planner.

II.1. Creating a satellite model with CROC

The tool CROC allows for the geometrical definition of complex satellites built from basic elements, which are boxes, cylinders, spheres, sphere caps and cones. In the example in this paper, however, the design of the satellite shall be kept very simple. The satellite bus shall be of the size of one cubic meter. Two solar arrays shall be attached to the satellite each of the size $1.0 \times 4.5\ m^2$. The connection shall be realized by a cylindrical bar of 5 cm in diameter allowing to have a spacing of 50 cm between the solar arrays and the satellite bus. As an overview the design of the satellite is given in Tab. I. The model as it is represented in the DRAMA GUI is shown in Fig. II.

	DISCOS	CROC
Min. cross-section (m^2)	20.250	22.023
Avg. cross-section (m^2)	63.034	65.062
Max. cross-section (m^2)	99.034	106.402

Tab. II: Cross-section for ENVISAT as estimated by CROC with 12 elements, compared to the data from ESA's DISCOS database [15].

After the design has been finished, CROC can be executed and the cross-section is calculated for an aspect angle specified by $\theta = 0°$ and $\varphi = 0°$, which is the along-track direction. For the given example, the computed cross-section with respect to the aspect angle is $10.05\ m^2$.

To have a more realistic comparison the values for a model of ENVISAT are shown in Tab. II for the function F3 (randomly tumbling satellite) and compared with the information given by ESA's DISCOS database. A more detailed description on CROC can be found in [15].

II.2. Assessment of Risk Event Statistics (ARES)

After the definition of the satellite geometry the impact of the debris environment during the planned mission shall be analysed. Therefore the DRAMA software suite provides two tools. In this section, the ARES component will be used to assess collision avoidance manoeuvres. In Sec. II.3, the MIDAS tool will be used to assess collision flux and damage statistics. In order to do so, both tools require the definition of the satellite's orbit. For this example it is assumed that the satellite is located on a Sun-synchronous orbit. The mean keplerian elements of this orbit are given in Tab. III.

In addition, ARES does require the satellite radius. Therefore the computed cross-section by CROC can be used with the assumption of a spherical body:

$$r_{Sat} = \sqrt{\frac{A_{CROC}}{\pi}} \tag{1}$$

For the computation of the annual collision probability (Functionality F1) ARES makes use of a radar equation. The parameters of this equation have to be provided

Epoch	2009-05-01
Semi-major axis	$7,160.0\ km$
Eccentricity	0.001
Inclination	98.6°
RAAN	38.0°
Arg. of Perigee	0.0°
True anomaly	0.0°

Tab. III: Orbit definition for example satellite, to be used for the tools ARES and MIDAS.

	Branch 1 (Radar)	**Branch 2 (Telescope)**
Ref. diameter (m)	0.32	0.7
Ref. altitude (km)	2000.0	36,000.0
Exponent	2.0	−0.5

Tab. IV: Parameters for the definition of the radar equation as used in the example.

	Detectable population	**Total population**
Flux ($1/km^2$/year)	$0.1972 \cdot 10^2$	$0.1910 \cdot 10^3$
Annual Coll. Prob.	$0.3013 \cdot 10^{-3}$	$0.2042 \cdot 10^{-2}$

Tab. V: Results of ARES for the flux and the annual collision probability of the example satellite with the total population being all objects larger than 1 cm.

by the user. Thus the user can define the sensitivity of a surveillance system to split the whole population, as provided by MASTER-2009, internally into known (detectable) and unknown objects:

$$D_{min}(h) = D_{ref} \cdot \left(\frac{h}{h_{ref}}\right)^{exp} \qquad (2)$$

The parameters, which have been used for the example in this paper are shown in Tab. IV. The resulting annual collision probability (ACP) for the detectable and the whole population as well as the related flux is shown in Tab. V. The ACP for the whole population (only objects larger than 1 cm have been considered) is nearly one order of magnitude larger than for the detectable population.

The collision risk reduction is related to the number of avoidance maneuvers. The decision on whether to perform a collision avoidance maneuver in a close encounter depends on the collision risk of that particular encounter, and on the fuel available for maneuvering. ARES functionality allows computing the annual average risk reduction as a function of the ACPL (accepted collision probability level), as well as the DeltaV and fuel required to achieve such risk reduction. It can be done by using the functionality F4 (Required Propellant), which comprises all the other ARES functionalities (Annual Collision Probability, Avoidance Schemes Assessment and Required Delta-V). The orbit uncertainties of the potentially impacting objects are based on CSM data for this example and it is assumed that the event is predicted one day before it would occur. The uncertainties in the initial spacecraft position are set to 200 m along-track, 100 m cross-track and 75 m in radial direction. The results are computed for ten different *Accepted Collision Probability Levels* (ACPL) as a

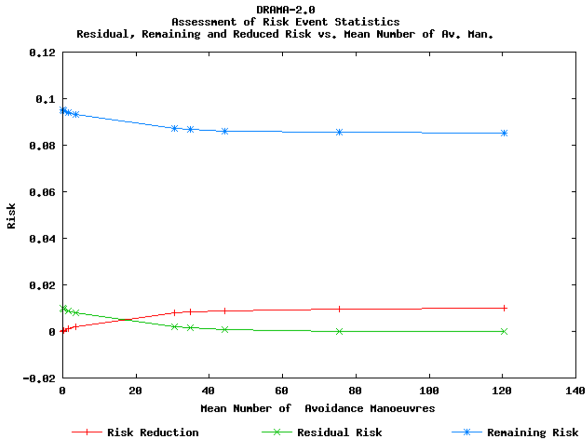

Fig. III: Residual, remaining and reduced risk as a function of the mean number of avoidance maneuvers per year.

function of the number of revolutions between the maneuver and the time of the predicted event. For an allowed minimum distance of 1.5 *km* the risk as a function of the mean number of avoidance maneuvers (per year) is shown in Fig. III. The remaining risk is the risk associated with objects which are not cataloged. It is the amount of risk which can not be diminished by the avoidance strategy. The residual risk is the risk which is accepted by the operator through the ACPL. The number of avoidance maneuvers is a direct consequence of the ACPL, as it indicates the threshold for raising a warning event. The smaller the ACPL, the more maneuvers are required to keep the spacecraft over the selected ACPL. ARES provides the DeltaV required for collision avoidance maneuvers assuming either a cross-track maneuver, or along-track maneuvers performed a number of orbit revolutions before the close encounter. Fig IV shows that, the sooner the maneuver is performed, the lower the fuel consumption. More details on ARES can be found in [8] and [3].

II.3. Assessment of Impact and Damage Flux (MIDAS)

The impact and damage risk due to smaller debris particles can be assessed with MIDAS. The upper limit for the object size is set to 5 cm, the lower limit to 100 μm assuming that smaller particles would lead only to a degradation of the surface. All debris sources out of the Business-as-Usual (BAU) scenario are considered and the analysis time interval is from May 1st, 2009 to May 1st, 2016 for a seven year lifetime of the satellite. The analysis made for this example shall be limited to the leading surface only. The number of particles shall be estimated, which are likely to impact and penetrate the surface. Therefore the surface will be designed as a double wall with two identical plates of aluminium with a thickness of 5 mm. The shielding effect of this surface shall

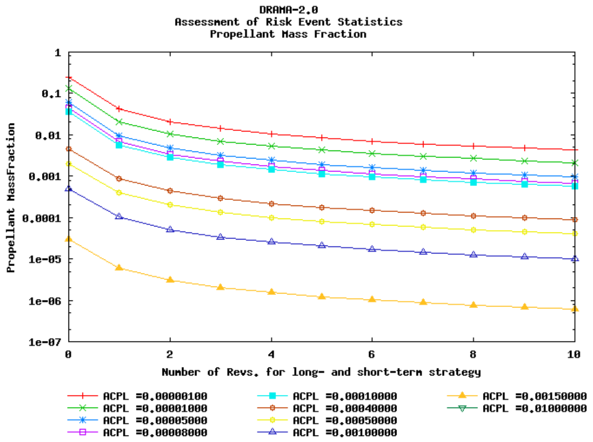

Fig. IV: Propellant mass fraction as a function of the number of revolutions between the time of the maneuver and the time of the predicted event, for different ACPLs.

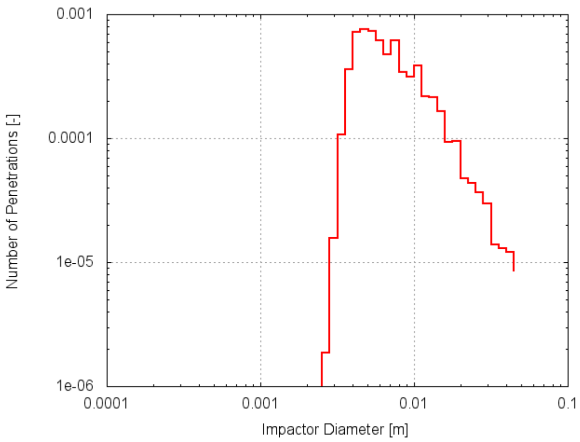

Fig. V: Number of penetrations as a function of the impactor diameter.

be analysed with the spacing between the two walls being 5 cm. The ESA triple wall damage equation has been used. This is one of four implemented damage equations (two for single walls and two for multiple walls) that can be applied to calculate the limiting particle diameter. Particles of larger diameters would penetrate the surface. The general equation for multiple walls is

$$d_{p,lim} = \left[\frac{t_w + K_2 \cdot t_s^{\mu} \cdot \rho_s^{\nu_2}}{K_1 \cdot \rho_p^{\beta} \cdot \rho_w^{\kappa} \cdot \rho_s^{\nu_1} \cdot v_p^{\gamma} \cdot \cos^{\xi} \alpha_p \cdot S^{\delta}} \right]^{\frac{1}{\lambda}} \qquad (3)$$

with the parameters for the *ESA triple wall* equation as given in Tab. VI. For the impactor diameter as the independent variable, the number of penetrations and the probability of no penetration for the given example are shown in Fig. V and Fig. VI. It can be seen in the figures that the number of impacts decreases for increasing impactor diameter, which can be expected due to the

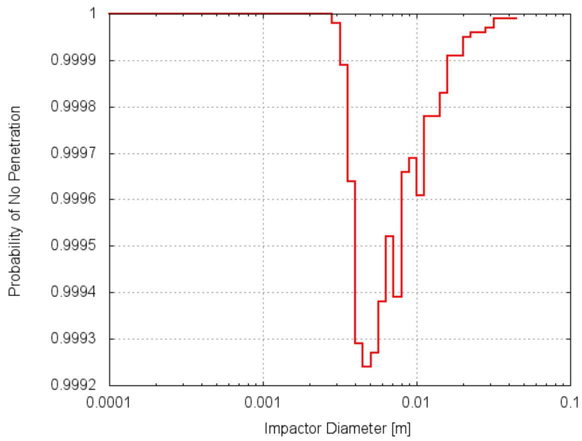

Fig. VI: Probability of no penetration as a function of the impactor diameter.

decreasing number of impacting objects with increasing diameter in the MASTER-2009 population. The number of penetrations has its maximum at about 4 mm, which results in a minimum for the probability of no penetrations in Fig. VI. For smaller impactors the number of penetrations quickly decreases, as these particles are not able to penetrate the shield.

Besides the *number of impacts* and the *probability of no penetration* also the *failure flux* as well as the *probability of collision* are computed by MIDAS. The results are also provided as a function of time and impactor mass in differential, cumulative and reverse-cumulative plots.

The user is also able to define additional ballistic limit equations matching the parameterized forms of the implemented single and multiple wall equations based on [12] (see also [8]). It is possible to define up to ten surfaces, each either *Earth Oriented*, *Sun Fixed* or *Inertial Fixed* surfaces. While the impact flux is also given in the *Damage Analysis* mode for an one square meter sphere as reference, it is possible to perform only the *Impact Analysis* for a sphere or randomly tumbling plate of an arbitrary cross-section.

II.4. Re-entry analysis with SARA

The SARA tool can be used for the simulation of the re-entry into the Earth's atmosphere. A detailed knowledge about the satellite components (shape, size, mass, material) is required in order to get good results. Thus, the example satellite is assumed to be in line with the default settings of the SARA component [13]. The satellite model comprises of 36 objects (27 boxes, seven cylinders, one plate and one sphere) out of four different materials, defined by their density, specific heat capacity, melting temperature, specific heat melting and the emission coefficient. For the initial orbit the parameters as

ESA triple wall	K_1	K_2	λ	β	γ	κ	δ	ξ	ν_1	ν_2	μ
$v_n < 3\ km/s$	0.3875	0.6458	1.056	0.5	2/3	0.0	0.0	2/3	0.0	0.0	1.0
$v_n > 7\ km/s$	0.2556	0.0	1.5	0.5	1,0	0.0	−0.5	1.0	2/3	0.0	0.0

Tab. VI: Parameters of the ESA triple wall BLE.

Epoch	2016-05-01 06:00 UTC
Semi-major axis	$6,470.0\ km$
Eccentricity	0.001
Inclination	98.6°
RAAN	0.0°
Arg. of Perigee	0.0°
True anomaly	0.0°

Tab. VII: Initial orbit for re-entry analysis.

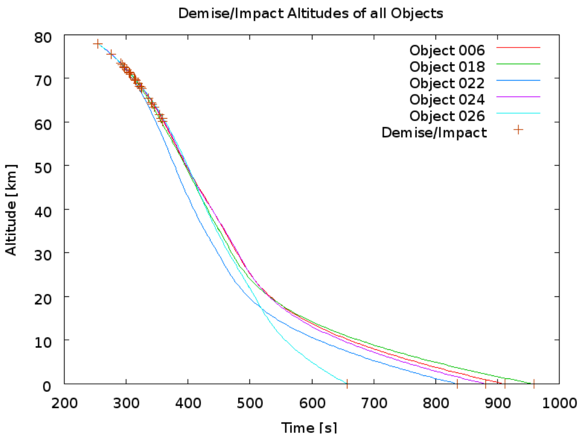

Fig. VII: Demise and impact altitude of all objects.

given in Tab. VII have been chosen based on the orbit used for the operational life time of the satellite (compare Tab. III) As shown in Fig. VII five of the included 36 objects are impacting on ground. These impacts occur between 660 s and 960 s after the start of the re-entry simulation. Within about five minutes the objects are impacting along the ground track. The distance between the first and the last impacting object is about 600 km.

The global casual probability as computed by SARA is shown in Fig. VIII. For a defined world population of about 7 billion people the risk is significantly higher in the northern hemisphere because of the higher population density in that area. The maximum probability of nearly $3 \cdot 10^{-6}$ is still below the threshold of 10^{-4} as adopted by several space agencies for the risk of any personal casualty due to a single re-entry event [12].

The ground track of the impacting objects is shown in Fig. IX. All objects are impacting into the Pacific Ocean at half the distance between Hawaii and the east coast of the Asian continent.

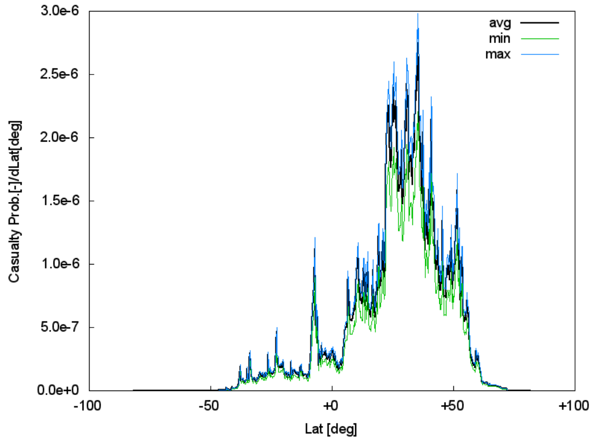

Fig. VIII: Global casualty probability.

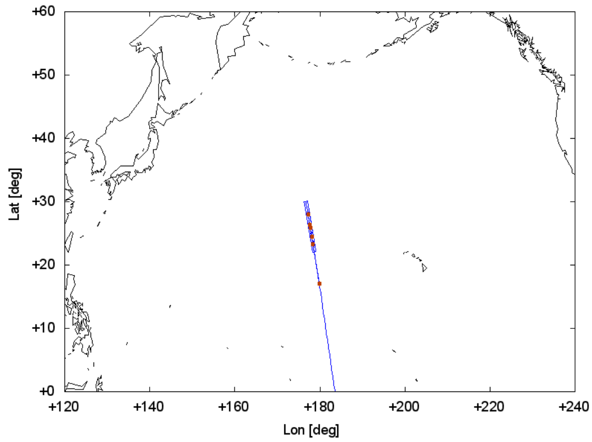

Fig. IX: Ground track of fragments.

III THE REDEVELOPED OSCAR TOOL

After an overview has been given, presenting the key features of the new DRAMA GUI, the tools ARES, MIDAS, SARA and the new developed tool CROC, in this section, the redeveloped tool OSCAR shall be presented in more detail, due to the main author's responsibility in the implementation of this tool.

OSCAR is a dedicated tool for the analysis and evaluation of different disposal strategies after the end of a satellite mission. It is focusing on missions within the protected regions in LEO and GEO, as defined in [16], but also offers the possibility to analyse high eccentricity orbits, e.g. GTO, or other orbits, which even do not have

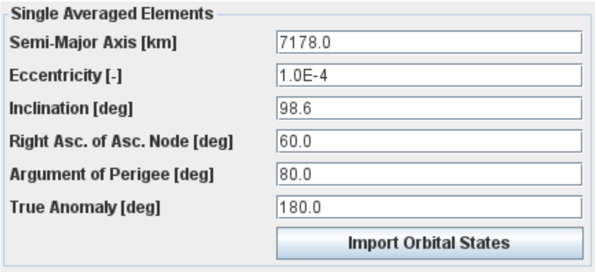

Fig. X: DRAMA GUI showing the orbit input fields for OSCAR and the *Import Orbital States* button, which calls CSTATE.

	Disposal option		
Disposal system	DirD	DelD	Reor
Chemical propulsion	×	×	×
Electric propulsion		×	×
Electrodyn. tether		×	×
Drag augmentation		×	

DirD = direct de-orbit DelD = delayed de-orbit
Reor = re-orbit

Tab. VIII: Available disposal systems and options as well as their allowed combinations in OSCAR.

to interfere with any of the protected regions, for example navigation satellites with an orbit period of about 12 h.

In the Sec. III.2, de-orbit analysis using OSCAR shall be highlighted, while Sec. shows examples for re-orbiting spacecraft in GEO. In general, OSCAR evaluates the user-defined strategy by checking the compliance with the SDMG [16]. The derived criteria which have been implemented in OSCAR are described in Sec. III.4.

III.1. Input

First of all, the user has to provide the orbit of the spacecraft at the beginning of the disposal phase, which is likely to be the orbit the satellite has been operated in so far. For the computation of the orbit evolution, which is e.g. required to check the compliance of the disposal orbit with the SDMG, the tool FOCUS-1A is used. It expects single averaged (over mean anomaly) kepler elements as input and this is also the reason why OSCAR directly demands for the satellite state as being provided in that format. If single averaged elements are not available, the tool CSTATE may be used to convert from TLE, for example, which can easily be done within the GUI via the *Import Orbital States* button, as shown in Fig. X.

After the definition of the orbit and the begin date (e.g. equal to the date when the disposal phase starts), one has to define the disposal strategy. A *disposal system* and a *disposal option* have to be defined. The possible combinations are shown in Tab. VIII. The new OSCAR tool also allows for the analysis of drag augmentation devices which have been proposed for delayed de-orbit of satellites in LEO. While the already known disposal systems from the former OSCAR version all support delayed de-orbit and re-orbit, only a chemical propulsion system is capable of providing a direct de-orbit, which results in a re-entry into the Earth's atmosphere within the next perigee pass.

Besides the options shown in Tab. VIII, it is also possible to use OSCAR for the estimation of the remaining lifetime when specifying the option *none*. In this case, the orbit propagator uses the defined orbit and computes the orbit evolution for the given propagation span.

III.2. De-orbit

The de-orbit after the end of the mission is recommended for all satellites interfering with the LEO protected region. While a direct de-orbit is interesting for satellites which have to be disposed of in a controlled manner, e.g. if the casualty risk is higher than 10^{-4} as described in Sec. II.4, another possible option is the delayed de-orbit. For the latter, it is recommended in [16] to perform the maneuver in a way, which results in the spacecraft being transferred to a trajectory with a remaining lifetime of less than 25 years. The orbit decay depends on the density of the Earth's atmosphere. In order to estimate the remaining lifetime one thus has to determine the density along the trajectory of the spacecraft, which ultimately results in the prediction of solar and geomagnetic activity both being input parameters to atmosphere models.

III.2.1. Solar and geomagnetic activity forecast

In OSCAR, the solar and geomagnetic activity are represented by the parameters $F_{10.7}$ and A_p, respectively. As there is no realistic model available for long-term forecasts of both parameters, it is essential to define a method in a consensus approach within the international community, as there are many different algorithms available. While there is no recommendation in the SDMG of which method to use, all methods as recommended by current standards related to space debris have been considered for the implementation. The final OSCAR version offers five different methods for the generation of a future forecast for solar and geomagnetic activity, as shown in Tab. IX. The *latest prediction* method is the only one of the implemented method, which takes into account latest data of the current solar cycle. It is envisaged that up to date predictions will be provided by ESA/ESOC and can be downloaded directly from the DRAMA GUI. It is also possible to provide a user-defined solar and geomagnetic activity forecast, which

Method	Reference
Latest prediction	ISO 27852 [10]
Best & worst case	based on [10],[14]
Constant	based on FSOA* [6]
Repeated	ECSS-E-ST-10-04C [4]
Monte Carlo	ISO 27852 [10]

* FSOA = French Space Operations Act

Tab. IX: Available methods for future forecasts of solar and geomagnetic activity.

OSCAR will then apply for the given propagation span. If there is not enough data available to cover the complete propagation span, OSCAR performs its own predictions by applying a Modified McNish-Lincoln algorithm as described in [14].

The *Best & worst case* (BC and WC, respectively) 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. The mean value is provided by a latest prediction approach, while historical solar cycles are used to find the solar and geomagnetic activity levels for the specified confidence interval.

An *equivalent constant* activity can be derived by a statistical approach as described in [6], which was a study performed in the frame of the French Space Operations Act (FSOA). The equivalent constant solar activity is defined in such a manner so that 50 % of the underlying Monte Carlo simulations result in a remaining lifetime of less than 25 years for a given orbit.

A simple method to generate forecasts is to *repeat* a complete solar cycle for the entire propagation span. This is recommended by the ECSS-E-ST-10-04C [4] for the 23^{rd} cycle.

Besides the latest prediction approach, the ISO 27852 also recommends to implement a *Monte Carlo* approach, where for each day in the propagation span, the solar and geomagnetic activity is sampled from up to six different solar cycles (cycles 18-23 in OSCAR) and thus results in different forecasts for each OSCAR run.

In Fig. XI an example is shown for the different methods. OSCAR also generates a plot containing the forecast used for each run. More details about the methods and the implementation can be found in [8] and [1].

III.2.2. Direct de-orbit

For direct de-orbit manoeuvres, which are only possible in combination with a chemical propulsion system, OSCAR estimates the Δv and required fuel mass to lower the spacecraft perigee to 60 km using a Hohmann maneuver, irrespective of the initial spacecraft orbit. It is assumed that positioning the perigee at this altitude will result in an atmospheric burn up on the next perigee pass. Exemplary results are shown in Tab. X and can be compared directly to the results for a delayed de-orbit (see Sec. III.2.3).

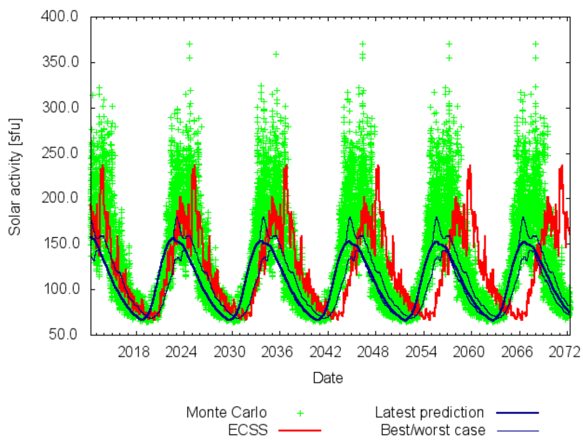

Fig. XI: Example for a solar and geomagnetic activity forecast using different methods .

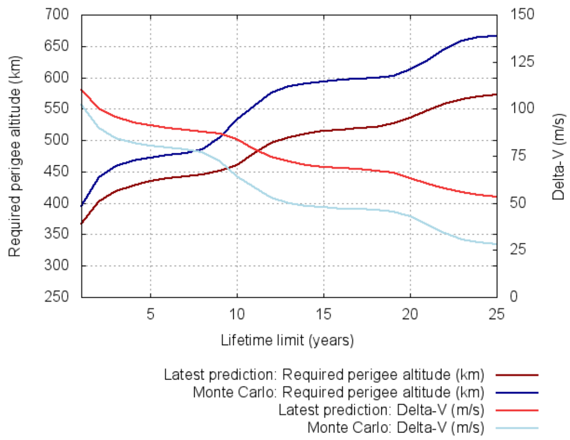

Fig. XII: Perigee altitude and Δv as a function of the remaining lifetime for an initially circular, near-polar orbit at 780 km altitude, showing the latest prediction vs. Monte Carlo forecast scenario.

III.2.3. Delayed de-orbit

For delayed de-orbit maneuvers OSCAR uses a Regula Falsi iteration technique [2] to estimate the altitude to which the spacecraft perigee must be lowered to in order to achieve a de-orbit within (i) the lifetime limit specified by the SDMG (which is 25 years), and (ii) a user-specified remaining lifetime. In Fig. XII the required perigee altitude and Δv are given for two different solar and geomagnetic activity forecasts as a function of the remaining lifetime for an initial circular orbit at 780 km altitude. For this example a specific impulse of 290 s, a mass of 1,000 kg and a cross-sectional area of 20 m^2

Chemical Propulsion System	I_{sp} (s)	Direct De-orbit		Delayed De-orbit		
		Δv (m/s)	Fuel mass (kg)	Perigee altitude (km)	Δv (m/s)	Fuel mass (kg)
Spacecraft cross-section 20 m^2, mass 1,000 kg.						
Solid motor	290	200.4	73.0	566.4	56.9	20.2
Monopropellant (H_2O_2, N_2H_4)	200	200.4	107.6	566.4	56.9	29.4
Bipropellant (O_2 + H_2)	450	200.4	46.4	566.4	56.9	13.0
Spacecraft cross-section 0.5 m^2, mass 100 kg						
Solid motor	290	200.4	7.3	438.7	91.8	3.3
Monopropellant (H_2O_2, N_2H_4)	200	200.4	10.8	438.7	91.8	4.8
Bipropellant (O_2 + H_2)	450	200.4	4.6	438.7	91.8	2.1

Tab. X: Requirements to de-orbit a spacecraft from a circular orbit at 780 km altitude, near-polar inclination, using a chemical propulsion system and assuming a best guess scenario starting in 2008.

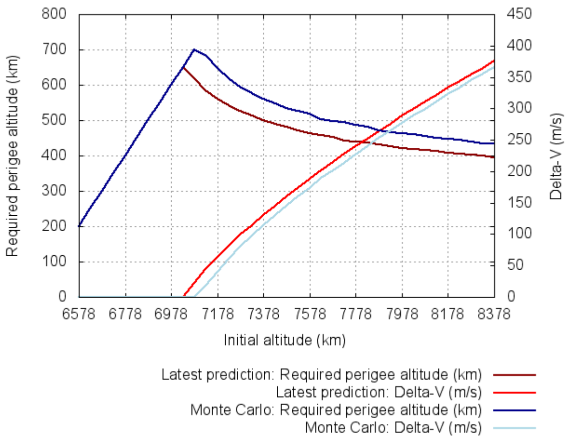

Fig. XIII: Perigee altitude and Δv as a function of the initial altitude. Other parameters as in the example in Fig. XII.

have been defined. It can be seen that the differences can be quite significant, as the latest prediction scenario provides a Δv of about 50 m/s (for a 25 year remaining lifetime orbit), while for a Monte Carlo sampled cycle one would only require about 25 m/s, which is a reduction by about 50 %. This example emphasizes the need for an agreed upon solar and geomagnetic activity forecast method for the estimation of what a 25 year remaining lifetime orbit actually is.

For a 25 year remaining lifetime disposal orbit, the required perigee altitude and Δv for the same parameters as in the previous example except for the initial altitude being the independent variable, are shown in Fig. XIII. The spacecraft can be seen to satisfy the mitigation guidelines requirements without need for an active de-orbit manoeuvre for altitudes below 630 km in the latest prediction scenario, as the natural predicted orbit decay will remove the spacecraft within 25 years. In the Monte Carlo scenario the maximum altitude, where a de-orbit maneuver is not required, is higher and at about 660 km. This is due to the higher level of solar and geomagnetic activity within the Monte Carlo cycle. With increasing initial orbital altitude, the spacecraft requires a progressively decreasing perigee altitude to comply with the lifetime limit, thus requiring a progressively increasing Δv and fuel mass.

The approach for electric propulsion (EP) and electrodynamic tether (EDT) systems is similar to the one already described for chemical propulsion, however, one has to take into account low-thrust transfers. For a given remaining lifetime by the user, OSCAR thus computes the required disposal orbit, which is circular for EDT and EP and may also be eccentric for EP. The transition to that orbit is then computed by applying the appropriate models for a low thrust transfer. The required Δv for the EP system is given by Eq. 4,

$$\Delta v_{EP} = \sqrt{\mu} \cdot \left(\frac{1}{\sqrt{a_{new}}} - \frac{1}{\sqrt{a_0}} \right) \tag{4}$$

which then is used to compute the required fuel mass via Ziolkovsky's rocket equation. Finally the transfer time is computed with Eq. 5

$$\Delta t_{EP} = \frac{\Delta m \cdot g \cdot I_{sp}}{T} \tag{5}$$

where Δm is the fuel mass, I_{sp} is the specific impulse of the engine and T is the thrust. These equations, however, are only applicable to circular orbits. For orbits with an eccentricity higher than 0.01 a numerical integration of the orbit is performed using the variational equations for the evolution of the semi-major axis and the eccentricity, while other orbital parameters are assumed to remain constant.

For the EDT system an analytical relationship is used as given by [5]:

$$\Delta t = -\frac{M \cdot R}{12 \cdot L^2 \cdot B_E^2 \cdot R_E^6 \cdot \cos^2 \alpha \cdot \langle \cos^2 \lambda \rangle} \cdot \left[a^6\right]_{a_i}^{a_f} \quad (6)$$

and

$$\langle \cos^2 \lambda \rangle = \frac{1}{16} \cdot \Big(6 + 2 \cdot \cos 2i + 3 \cdot \cos\left[2\left(i - \phi\right)\right] + 2 \cdot \cos 2\phi + 3 \cdot \cos\left[2\left(i + \phi\right)\right]\Big) \quad (7)$$

where M is the total system mass, R is the total resistance of the system, L is the length of the tether, B_E is the strength of the magnetic equator at the surface of the Earth (31 μT), R_E is the equatorial radius of the Earth (6,378 km), α is the angle of the tether relative to the local vertical, λ is the inclination of the spacecraft orbit relative to the geomagnetic reference frame, ϕ is the angle between the Earth's magnetic axis and the Earth's spin axis (11.5°), i is the inclination of the spacecraft orbit in an inertial reference frame and a_i and a_f are the semi-major axis of the initial and final (disposal) spacecraft orbit, respectively.

Finally, a delayed de-orbit can also be accomplished by using a drag augmentation device, which can be done by using inflatable structures, e.g. balloons, or mechanisms to deploy surfaces in velocity direction. In OSCAR, besides the simulation of the user-defined disposal system, also the required cross-section of the drag augmentation system is computed, which would be compliant with the SDMG. An example is shown in Fig. XIV for different initial altitudes in LEO and taking into account two different solar and geomagnetic activity scenarios, latest prediction and the ECSS cycle. A spacecraft with an initial cross-section of 10 m^2, mass of 1,000 kg and drag coefficient of C_D = 2.2 was used in this example. It can be seen that in its initial configuration, a drag augmentation system would be required for altitudes above about 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 latest prediction 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 a required diameter of about 11.3 m. In

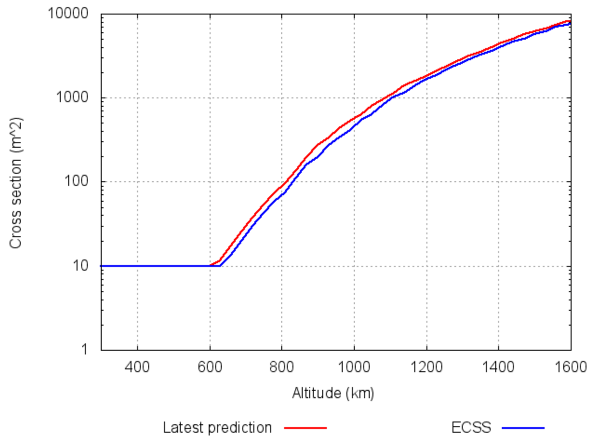

Fig. XIV: Required cross-section for a drag augmentation system in order to be compliant with the SDMG, for a spacecraft in an initially circular near-polar orbit. Results for two solar and geomagnetic activity scenarios are shown.

OSCAR it is assumed that drag augmentation systems are deployed once and can not be retracted. Thus, OSCAR will compute the orbital evolution until the spacecraft burns up in the Earth's atmosphere. Therefore, the delayed de-orbit option does not result in a final orbit where the spacecraft stays for the specified lifetime limit without performing any maneuvers, as is the case for the other disposal systems described earlier.

III.3. Re-orbit

Maneuvering to an orbit outside a protected region is another recommended strategy to dispose of spacecraft at end-of-life, which is mainly used by GEO satellites. In the following, the focus is on GEO objects, but in general OSCAR allows a re-orbit to be performed from any initial orbit to an arbitrary re-orbit altitude.

Typically, satellites are transferred to a graveyard orbit from their assigned GEO slots by means of at least two Hohmann maneuvers. OSCAR reflects such a scenario by allowing the user to specify an integer number of two-burn manoeuvres in order to reach the final re-orbit altitude. In this case, each two-burn manoeuvre raises the spacecraft orbit by an equal altitude increment to an intermediate circular orbit. The spacecraft remains in each intermediate orbit for two and a half revolutions, which is recommended by ISO 26872:2010 for the disposal of GEO spacecraft [9], at which point an engine burn to propel the spacecraft into the next elliptical transfer trajectory takes place.

While the re-orbit altitude may be specified to any arbitrary value, for GEO spacecraft OSCAR applies the current IADC formula to estimate the appropriate re-orbit altitude which would be compliant with the mitigation guidelines. This is defined as follows:

$$\Delta H\,[km] = 235 + 1,000 \cdot c_r \cdot \frac{A}{m} \qquad (8)$$

where ΔH is the minimum perigee altitude above the geostationary altitude of 42,164 km, c_r is the radiation momentum exchange coefficient of the spacecraft at the beginning of its life, A is the spacecraft cross-section and m is the spacecraft dry mass. The final re-orbit altitude, Δv and fuel mass required to achieve the overall disposal maneuver for the user-defined re-orbit altitude as well as for a re-orbit compliant with the SDMG, are provided to the user. The total re-orbit manoeuvre duration is calculated by summing the duration of all the individual Hohmann transfers. The duration of each Hohmann transfer is assumed to be half the period of the transfer ellipse (i.e. the time between the first and second burn) plus two times the orbital period of the intermediate circular orbit, which is required for an orbit determination process as recommended in [9].

It should be noted, that for spacecraft in GEO, the eccentricity vector has to be taken into account for the disposal maneuver, as the orientation of the orbit has a major impact on the orbital evolution and thus determines eventual crossings of the protected region which have to be avoided. As OSCAR does not provide the computation of an optimum eccentricity vector, this has to be done by the user before entering the target orbit. The recommended value for any satellite configuration can be obtained, e.g. from [9] and has to be provided for the target orbit before an OSCAR run is performed.

In Fig. XV an example is shown for a GEO protected region violation of a re-orbited satellite. The declination vs. altitude diagram is directly provided by OSCAR and shows a black frame, which is the GEO protected region, while the evolution of the spacecraft orbit for 100 years is plotted to see whether it intersects with that frame or not.

III.4. Compliance evaluation

The user-defined disposal strategy is simulated by OSCAR and key parameters like Δv, required fuel mass and manoeuvre time are determined. While the user-defined scenario does not include any evaluation, OSCAR performs a second simulation for each run taking into account the recommendations from the SDMG. For each run, the user obtains two results: The defined disposal strategy parameters as well as the Δv, fuel mass, manoeuvre time, etc., for a similar scenario which would be compliant with the SDMG.

Each user-defined scenario is thus evaluated and OSCAR adds a comment into the general output file, telling the user about the compliance status of the simulated scenario with respect to the SDMG. In Fig. XVI an example is shown for a scenario which is not compliant.

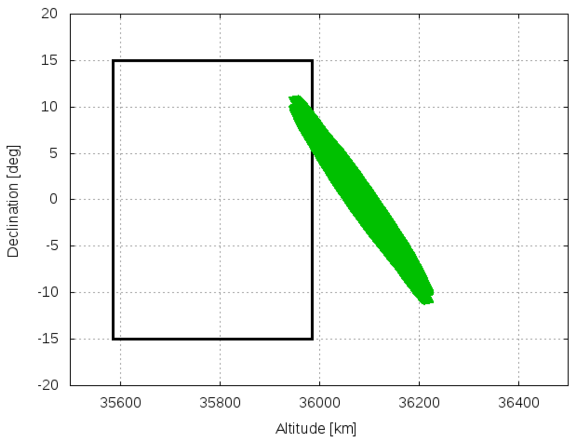

Fig. XV: A visualisation as provided by OSCAR for a GEO protected region violation in a declination vs. altitude diagram for a re-orbited GEO satellite with an eccentricity which is too high.

In the compliance check procedure, which is performed directly before the output is written (after all simulations have been performed), OSCAR checks for five different criteria. The definitions of these criteria are shown in Tab. XI. The first three criteria are directly derived from the SDMG and refer to the crossings of the protected regions in LEO and GEO by the spacecraft. Two additional criteria were defined to account for too short propagation spans, in which case an evaluation of some of the criteria 1-3 would not be possible.

IV CONCLUSION

The upgraded DRAMA software tool suite has been introduced, including the five main tools and the GUI. In general, DRAMA is now much more flexible to the user's needs, which is expected to increase the utilization of the software within the community of space mission analysts and designers. Especially the ARES and OSCAR tools have been upgraded/redeveloped with several new features and the new tool CROC now offers the possibility to estimate the cross-section of a satellite, which is an important parameter for many simulations.

The OSCAR tool has been introduced with all of its major features: the forecast of solar and geomagnetic activity based on most recent standards, the compliance check with respect to the Space Debris Mitigation Guidelines and the new OSCAR version also offers the possibility to analyse drag augmentation systems. More flexibility has been added to the individual disposal options, so that it is also possible to perform re-orbit maneuvers to an arbitrary altitude and do delayed de-orbit maneuvers also with EDT systems, by letting the user decide whether such a maneuver makes sense

```
# - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
#
#  UN Space Debris Mitigation Guidelines compliance check:
#
#  WARNING: Non-compliant as LEO protected region is crossed
#           within the next 100 years.
#
# - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Fig. XVI: Compliance statement example in OSCAR general output file

ID	Criterion
1	Lifetime of LEO crossing spacecraft > 25 years.
2	LEO protected region crossing within 100 years.
3	GEO protected region crossing within 100 years.
4	Criterion 1 could not be evaluated, as propagation time frame < 25 years.
5	Criterion 2/3 could not be evaluated, as propagation time frame < 100 years.

Tab. XI: Compliance criteria as defined within OSCAR.

or not. For each of the user-defined strategy, OSCAR also performs a run which would result in the minimum requirements to be compliant with the SDMG and provides these results in comparison to the results of the user-defined scenario.

The controlling element - the graphical user interface - now provides a direct access to all necessary input data and settings and a comfortable display of the results has been realized. A direct modification of the gnuplot driver files, which are generated by the individual tools, allows for more easily customizable results now.

V ACKNOWLEDGEMENTS

The Upgrade of ESA's Debris Risk Assessment and Mitigation Analysis Software Suite has been under ESA contract 4000104977/11/D/SR. TUBS/ILR as the prime contractor has been responsible for the upgrade of OSCAR, MIDAS and the GUI as well. DEIMOS Space S.L.U. was responsible for the ARES upgrade and the development of CROC. The SARA tool was maintained by ESA/ESOC.

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