A DEBRIS RISK ASSESSMENT TOOL SUPPORTING MITIGATION GUIDELINES

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ABSTRACT

The Debris Risk Assessment and Mitigation Analysis (DRAMA) tool, developed by a European team under ESA contract, has been designed to enable space programmes to assess their compliance with the European Code of Conduct for Space Debris Mitigation. DRAMA is composed of five individual software applications collected under a common graphical user interface. The individual applications have been designed and developed to address different aspects of debris mitigation — collision avoidance manoeuvres, collision flux and damage statistics, disposal manoeuvres at end-of-life, re-entry survival and re-entry risk analysis. These tools provide the DRAMA user with numerical and graphical results suitable for determining the debris risk posed to their mission and assessing the effectiveness of their end-of-life strategy. The tool also provides a basic compliant / non-compliant answer, in respect of the European Code of Conduct, for the operational and disposal phases of a mission. This paper demonstrates the capabilities of the ESA DRAMA model, describing its concept and purpose, and providing an overview of the individual software tools and graphical user interface that form DRAMA.

1. INTRODUCTION

It is well recognised within the space debris scientific community, and increasingly within the space industry as a whole, that debris mitigation is a necessary component of a space programme. Space debris mitigation guidelines and standards, being developed by national and international space agencies and forums, address measures to protect space assets and preserve the orbital environment. They consider mission-related object limitation, explosion prevention, collision protection (spacecraft shielding and collision avoidance) and manoeuvring objects at end-of-life (including re-entry into the Earth's atmosphere). Such measures need to be addressed at all stages of a space programme, including management, design and operation, in order to be applied effectively.

Within Europe, the need to provide consistent and accurate guidance on debris mitigation to the space industry has been appreciated for several years. To this end, the European Code of Conduct for Space Debris Mitigation has been drafted by ESA and national space agencies in Europe, and represents a vital step in attempts to preserve the near Earth orbital region for future use. It presents fundamental safety and mitigation recommendations related to space debris, providing current mitigation measures that represent best practice. In parallel with this document, the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool has been developed over the past two years. The purpose of this software tool is to enable space programmes to assess their mission in respect of the recommendations contained within the European Code of Conduct. The development of DRAMA has been performed by a European team, comprising QinetiQ (UK), DEIMOS Space (Spain), eta_max space (Germany), HTG (Germany) and ESA/ESOC.

An overview of the DRAMA software is given in the following section. The full functionality of the model is then demonstrated by assessing the debris risk for example mission profiles in Sections 3 and 4. The results of this analysis are discussed in the context of mitigation guidelines within these sections, before a summary is provided in Section 5.

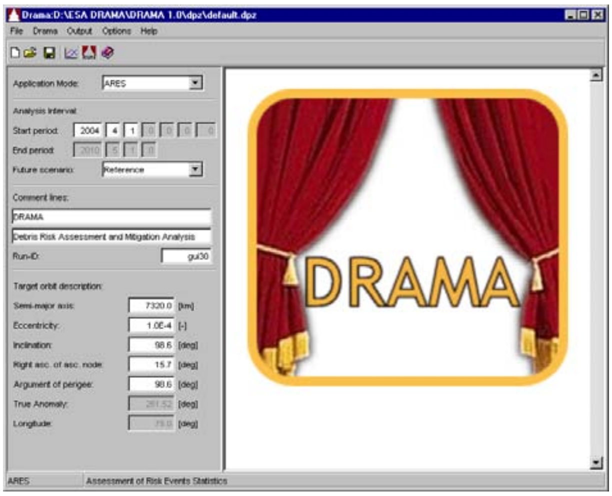
2. THE DRAMA TOOL

The requirements of the DRAMA tool were established by considering the role it needed to play in support of the European Code of Conduct (Martin, 2004). While there are only a limited number of quantitative criteria that can be directly assessed by the software, the requirements were derived to ensure that DRAMA had

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

the capability to provide analysis results that allow users to understand the implications of the more qualitative recommendations. DRAMA essentially consists of several tools collected under a graphical user interface (GUI), pictured in Fig. 1, enabling an assessment of mitigation strategies for the operational and disposal phases of a mission. To provide the user with a means to assess the different aspects of debris mitigation, the tools within DRAMA are:

- ARES (Assessment of Risk Event Statistics) to assess collision avoidance manoeuvres.
- MIDAS (MASTER (-based) Impact Flux and Damage Assessment Software) to assess collision flux and damage statistics.
- OSCAR (Orbital Spacecraft Active Removal) to assess disposal manoeuvres at end-of-life.
- SESAM (Spacecraft Entry Survival Analysis Module) to assess the re-entry of a system into the Earth's atmosphere.
- SERAM (Spacecraft Entry Risk Analysis Module) to assess the risk posed by any objects that survive to ground.



Application Mode: ARES
Analysis interval
Start period: 2004 4 1 0 0 0 0
End period: 2010 5 1 0
Future scenario: Reference
Comment lines:
DRAMA
Debris Risk Assessment and Mitigation Analysis
Run-ID: gui30
Target orbit description:
Semi-major axis: 7320.0 [km]
Eccentricity: 1.0E-4 [-]
Inclination: 98.6 [deg]
Right asc. of asc. node: 15.7 [deg]
Argument of perigee: 98.6 [deg]
True Anomaly: 281.52 [deg]
Longitude: 75.0 [deg]

Figure 1. The DRAMA graphical user interface.

Each of the tools has been designed to provide a fast, well-founded assessment of a user-defined mission and provide a basic compliant / non-compliant answer in respect of the European Code of Conduct recommendations. The algorithms used do not greatly over or under-estimate any output and the results provided can be used to support a space debris mitigation plan.

2.1. Collision Avoidance Manoeuvres (ARES)

ARES allows the DRAMA user to assess the statistical probability of collision between an operational spacecraft and the tracked objects orbiting the Earth, and the possible requirements for collision avoidance manoeuvres (N. Sánchez-Ortiz, 2004, 2005). Although the risk of collision in the current environment is not prohibitive, the threat is recognised and some missions allow for avoidance manoeuvres within their propulsion budget. For a mission, the decision to perform an avoidance manoeuvre is determined by comparing the collision probability considered acceptable, to the risk associated with a given encounter — a function of the geometry of the encounter, the collision cross-section and the orbit uncertainties.

The four main functions implemented within the ARES software allow the computation of:

- The annual collision probability due to the whole population larger than 10 cm in size (provided by the MASTER'2001 model), and due to the catalogued population.
- The mean number of avoidance manoeuvres and features of the defined avoidance criteria, including false alarm rate, risk reduction, residual risk and remaining risk.
- The delta-velocity for an avoidance manoeuvre rate.
- The propellant mass fraction for an avoidance manoeuvre rate.

Collectively, they support the definition of an appropriate avoidance strategy for a mission.

2.2. Collision Flux and Damage Statistics (MIDAS)

The risk of collision with smaller objects and the damage such collisions may cause, is assessed within DRAMA using the MIDAS software, which has been derived from the ESA MASTER'2001 Standard Application (Bendisch, 2002). MIDAS provides debris and meteoroid flux analysis for a given target orbit, particle size range and analysis interval. The damage caused by particles impacting on spacecraft surfaces is evaluated using one of four damage (ballistic limit) equations: Cour-Palais thin plate equation, Whipple shield equation, ESA triple wall equation (for aluminium honeycomb sandwich panels) or Cour-Palais glass target equation (for solar cells).

With MIDAS the DRAMA user is able to determine the collision probability and number of impacts, the failure flux, number of penetrations and the probability of no penetration for their mission.

2.3. Disposal Manoeuvres (OSCAR)

The removal of large objects from the protected low Earth orbit (LEO) and geosynchronous orbit (GEO) regions is recognised as the most effective space debris mitigation measure — the mass / area in the most crowded orbital regions is reduced and the probability of collision lowered. It is the purpose of the OSCAR tool to enable users to assess the latter stages of their mission in relation to the recommended debris mitigation practices. Thus it enables investigations into the orbital and system requirements for a variety of disposal manoeuvres (Cheese, 2004).

Specifically the OSCAR software provides the DRAMA user with an assessment of:

- The remaining natural orbital lifetime of systems orbiting wholly or partly in LEO, to determine whether an active disposal manoeuvre is required.
- Chemical propulsion disposal manoeuvres: a direct (or immediate) de-orbit, a delayed de-orbit, or a re-orbit from the LEO / GEO protected region.
- Electric propulsion disposal manoeuvres: a delayed de-orbit, or a re-orbit from the LEO / GEO protected region.
- Electrodynamic tether disposal manoeuvre: a delayed de-orbit.

In each case, the delayed de-orbit manoeuvre is performed in a user-defined time interval ≤ 25 years. A re-orbit from the LEO protected region manoeuvres the system to an orbit altitude ≥ 2,000 km, while that from the GEO protected region is done in accordance with the recommendation of the Inter-Agency Debris Co-ordination Committee (IADC). The delta-velocity, propellant mass and manoeuvre duration required to complete the manoeuvre are provided by the tool.

2.4. Re-entry Survival and Risk Analysis (SESAM, SERAM)

A considered analysis of the dynamics of re-entry of an object into the Earth's atmosphere is essential to complete the assessment of debris mitigation measures. The SESAM and SERAM tools within DRAMA allow system designers and operators to analyse the risk of controlled and uncontrolled re-entry events, due to the possible impact of surviving objects on ground.

The SESAM tool uses an object-oriented method, analysing only individual parts of the spacecraft, due to the efficiency of this method in terms of computational effort. The spacecraft is defined using a set of non-shadowing components specified by their shape (sphere, cylinder, flat plate or box), size and material. Two break-up altitudes are coded within the software: solar panel break-off at 95 km, and spacecraft break-up at 78 km. Using this approach, the SESAM tool considers re-entry trajectory dynamics, aerodynamic, aerothermo-dynamic and thermal analysis. The output of this survival analysis — the mass, velocity, incident angle and impact location of the surviving fragments — serves as input to the casualty risk assessment performed by SERAM (Klinkrad, 2004).

The risk analysis software provides the DRAMA user with both a low- and high-resolution result. The low-resolution computation is based on the initial entry orbit and casualty cross-section, while the high-resolution calculation is based on the full results of the analysis performed by SESAM. The two results allow the user to assess the probability of casualty due to components surviving re-entry at different stages of mission planning and operation. The casualty probability is determined using casualty cross-section, impact probability and population density. SERAM uses world population data that are adjusted for the user-defined analysis epoch by assuming an exponential growth, which doubles the population levels within 40 years.

The SESAM and SERAM tools provide the user with the total mass, geometric and casualty cross-section of objects surviving entry into the Earth's atmosphere, and the casualty probability for the re-entry event. There is currently no consideration of the risk of fatality within SERAM.

2.5. User Interface

The DRAMA tool is structured as illustrated in Fig. 2; the five individual tools are collected under a common user interface. To simplify this interface, the re-entry survivability and risk assessment tools (SESAM and SERAM) are combined into a single option within the GUI known as SARA. It is important to note that there is no exchange of information between the OSCAR tool and SARA — the DRAMA user is required to enter the state vector at the re-entry interface for the SARA / SESAM tool.

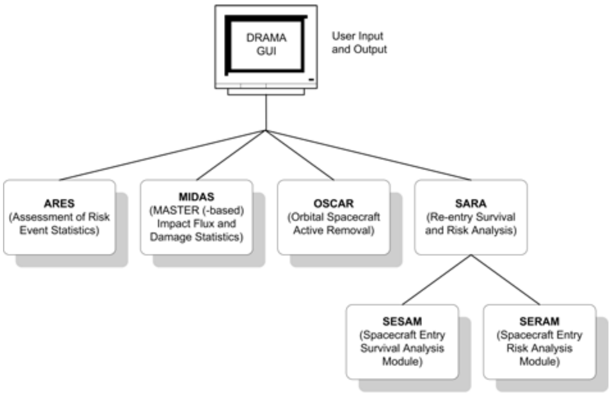
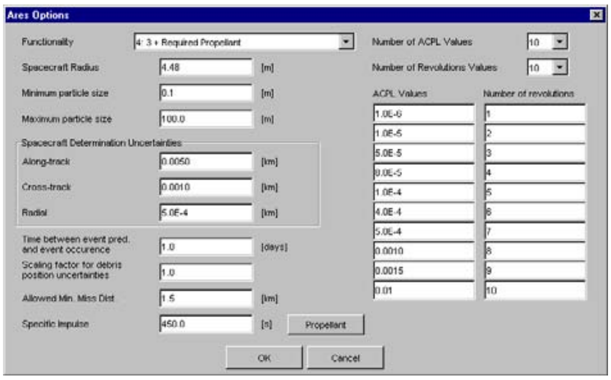


Figure 2. The basic structure of the DRAMA tool.

The graphical interface for DRAMA has been designed to provide a user-friendly means to manage user input and present the results of the analyses in both a textual and graphical format. Overall, the user interface provides:

- Options that enable the user to configure the installation of DRAMA and the behaviour of the GUI.
- Interactive acquisition of user data through input dialogues (as illustrated in Fig. 3).
- Graphical display of analysis results by means of the Gnuplot software package (as illustrated in Sections 3 and 4 of this paper).
- Display of textual analysis results to the user through output dialogues (as illustrated in Fig. 4).
- Error and execution status reports.
- Access to the software user manuals for Gnuplot and DRAMA.


Ares Options

Functionality: 4: 3 + Required Propellant
Spacecraft Radius: 4.48 [m]
Minimum particle size: 0.1 [m]
Maximum particle size: 100.0 [m]

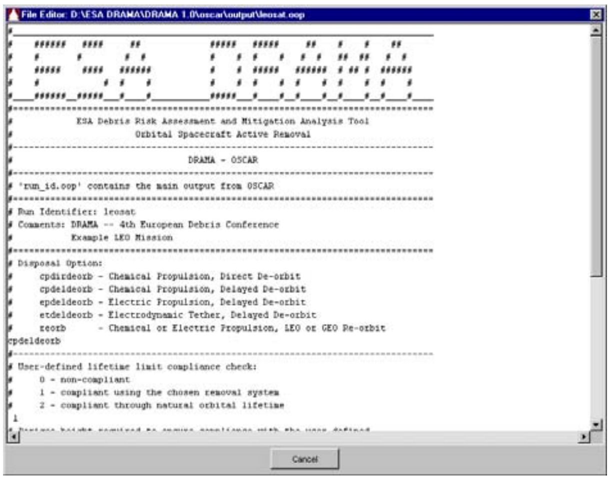
Spacecraft Determination Uncertainties
Along-track: 0.0050 [km]
Cross-track: 0.0010 [km]
Radial: 5.0E-4 [km]

Time between event pred. and event occurence: 1.0 [days]
Scaling factor for debris position uncertainties: 1.0
Allowed Min. Miss Dist: 1.5 [km]
Specific Impulse: 450.0 [s]

Number of ACPL Values: 10
Number of Revolutions Values: 10

ACPL Values	Number of revolutions
1.0E-6	1
1.0E-5	2
5.0E-5	3
8.0E-5	4
1.0E-4	5
4.0E-4	6
5.0E-4	7
0.0010	8
0.0015	9
0.01	10

Figure 3. An example of the user input (for ARES) provided by the DRAMA GUI.


File Editor: D:\ESA DRAMA\DRAMA 1.0\oscar\output\leosat.oop

```
#______________________________________________________________________
#    ######   ####    ##          #####   #####     ##    #   #    ##
#    #        #      #  #         #    #  #    #   #  #   ## ##   #  #
#    #####    ####   ######       #    #  #####   ###### # ## #  ######
#    #           #   #    #       #    #  #    #  #    #  #   #  #    #
#____######_#####__#____#_________#####__#____#_#____#__#___#__#____#___
#======================================================================
#          ESA Debris Risk Assessment and Mitigation Analysis Tool
#                    Orbital Spacecraft Active Removal
#----------------------------------------------------------------------
#                               DRAMA - OSCAR
#----------------------------------------------------------------------
# 'run_id.oop' contains the main output from OSCAR
#======================================================================
# Run Identifier: leosat
# Comments: DRAMA -- 4th European Debris Conference
#           Example LEO Mission
#======================================================================
# Disposal Option:
#     cpdirdeorb - Chemical Propulsion, Direct De-orbit
#     cpdeldeorb - Chemical Propulsion, Delayed De-orbit
#     epdeldeorb - Electric Propulsion, Delayed De-orbit
#     etdeldeorb - Electrodynamic Tether, Delayed De-orbit
#     reorb      - Chemical or Electric Propulsion, LEO or GEO Re-orbit
cpdeldeorb
#----------------------------------------------------------------------
# User-defined lifetime limit compliance check:
#     0 - non-compliant
#     1 - compliant using the chosen removal system
#     2 - compliant through natural orbital lifetime
 1
```

Figure 4. An example of the textual output (generated by OSCAR) provided by the DRAMA GUI.

The exchange of information between the GUI and the individual software tools is handled entirely using ASCII text files, chosen to ensure the portability of DRAMA across different operating platforms. Indeed, DRAMA has been developed to run under the Microsoft Windows, Linux and Solaris operating systems.

3. ON-ORBIT ANALYSIS

The ARES, MIDAS and OSCAR components of the DRAMA tool are applicable to a satellite in its nominal orbit and can therefore be applied to the same mission profile. To demonstrate the functionality of DRAMA, the two example mission profiles detailed in Tab. 1 are considered in this paper.

Table 1. Example mission profiles considered in the on-orbit analysis.

	LEO Satellite	**GEO Satellite**
Orbit Epoch	1-Jan-2004	1-Jun-2010
Semi-major Axis, a (km)	7,160	42,166
Eccentricity, e	0.0001	0.0002
Inclination, i (°)	98.5	0.02
Right Ascension of Ascending Node, Ω (°)	20	40
Argument of Perigee, ω (°)	90	20
True Anomaly, θ (°)	180	270
Cross-section (m^2)	63	42
Mass (kg)	8,100	4,685

3.1. LEO Mission

The first tool to be applied to the LEO mission profile is the ARES tool, assessing the need for avoidance manoeuvres during the mission. The initial functionality of the tool provides the user with the flux levels and annual collision probabilities due to decimetre-sized and larger objects. The results of this analysis are provided in Tab. 2; the difference between the catalogued population and the whole population according to MASTER'2001 is clearly evident. The second functionality of ARES looks at the mean number of avoidance manoeuvres required for a collision probability considered acceptable for the mission (Accepted Collision Probability Level, ACPL). Five different ACPL values, increasing from 10^{-6} to 10^{-2}, are predicted to require a mean number of avoidance manoeuvres per year of 46 down to an almost negligible level for the highest ACPL (Tab. 3). The corresponding reduction in the risk is also provided in Tab. 3 — an ~ 89% reduction is achievable if the mission planners

Table 2. Annual collision probability and flux, due to the whole and catalogued populations ≥ 10 cm, for the LEO mission (provided by ARES).

Annual collision probability with the catalogued population	1.328×10^{-3}
Annual collision probability with the whole population	2.311×10^{-3}
Flux due to the catalogued population	12.25 $km^{-2}yr^{-1}$
Flux due to the whole population	27.20 $km^{-2}yr^{-1}$

consider a strict ACPL of 10^{-5}. The relative benefit gained by decreasing the ACPL is illustrated in Fig. 5. Here the fractional residual risk is shown to fall by ~ 40% if the ACPL is decreased from 1 in 10,000 to 1 in 1,000,000. However, the remaining risk — which includes the risk due to the untracked, and therefore unavoidable population — is only reduced by ~ 23%. Thus, the un-catalogued decimetre objects should not be neglected when planning an appropriate avoidance strategy.

Table 3. The mean number of avoidance manoeuvres and risk reduction per accepted collision probability level, for the LEO mission (provided by ARES).

Accepted Collision Probability Level	**Mean No. Manoeuvres**	**Risk Reduction**
1.0×10^{-6}	46.17	1.291×10^{-3}
1.0×10^{-5}	18.81	1.186×10^{-3}
1.0×10^{-4}	1.89	7.643×10^{-4}
1.0×10^{-3}	0.063	2.202×10^{-4}
1.0×10^{-2}	0.0029	3.116×10^{-5}

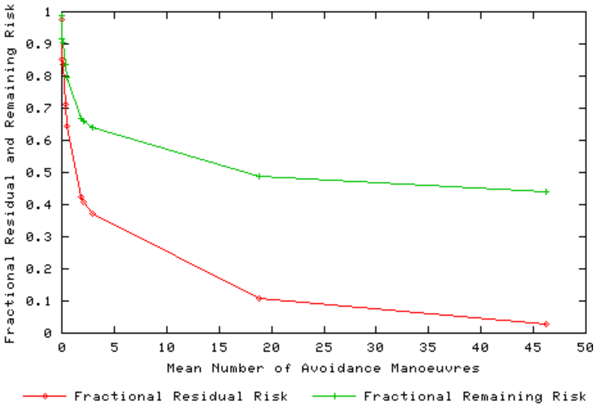


Figure 5. The fractional residual and remaining risk for the LEO mission as a function of the mean number of avoidance manoeuvres (provided by ARES).

By assuming 24 hours between event prediction and event occurrence the delta-velocity, and subsequently the propellant mass, requirements for an ACPL are provided by ARES. The delta-velocity for different avoidance manoeuvre strategies is illustrated in Fig. 6. It shows that long-term manoeuvres (designed to provide an along-track separation between the LEO mission and the object at the time they were expected to collide) are always more efficient than a short-term manoeuvre (designed to provide a radial separation).

For smaller debris size thresholds, the MIDAS tool is applied to the LEO mission. For simplicity, the satellite is modelled as a sphere with the cross-sectional area listed in Tab. 1. A four year analysis interval is chosen from the orbit epoch of 1-Jan-2004 to 1-Jan-2008. Note that these are future epochs in the context of MASTER'2001 and so results are provided for particle sizes larger than one millimetre. Fig. 7 shows the annual collision probability with objects between 1 mm and 1 cm in size, while Fig. 8 provides the number of impacts expected per year. As expected, space debris

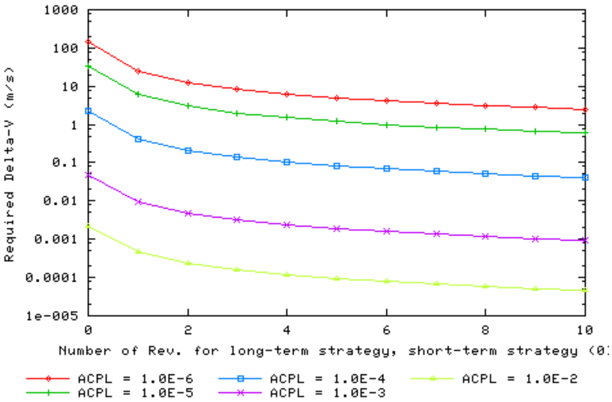


Figure 6. The required delta-velocity for different manoeuvre strategies, per accepted collision probability level, for the LEO mission (provided by ARES).

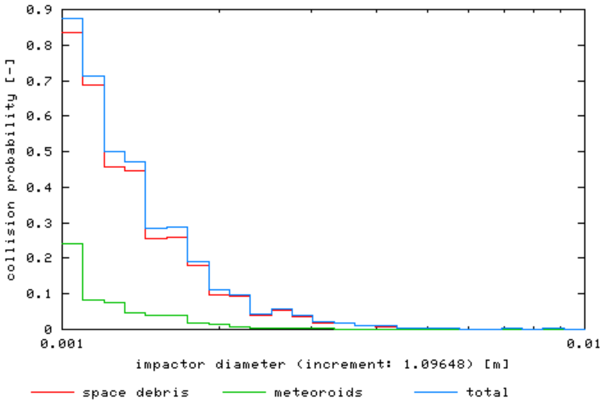


Figure 7. The annual collision probability with 1 mm – 1 cm objects for the LEO mission (provided by MIDAS).

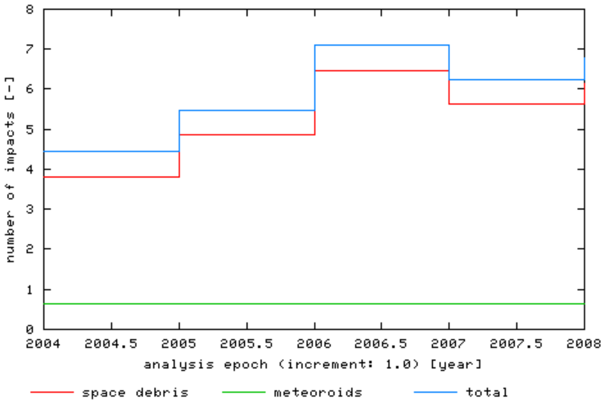


Figure 8. The total number of impacts from objects in the size range 1 mm – 10 cm in each year of the LEO mission (provided by MIDAS).

particles dominate the meteoroid population. The number of impacts on the satellite reaches a peak of ~ 7 in the third year of the analysis.

The natural orbital evolution of the LEO mission is depicted in Fig. 9 in terms of perigee altitude in the 100 years following the orbit epoch. This clearly shows that some form of manoeuvre is required if the satellite is to be removed from the crowded LEO region at the end of its useful life. This assessment is provided by the OSCAR tool within DRAMA. For the disposal manoeuvre analysis, the LEO mission is assumed to have a chemical propulsion system on-board with a specific impulse of 450 s. Using this system the satellite can perform one of three disposal manoeuvres: a direct re-entry, a delayed re-entry or a re-orbit to an altitude above the LEO region. The different perigee heights, delta-velocities and propellant masses for these options are detailed in Tab. 4. The altitude of the LEO mission means that a re-orbit manoeuvre is the most expensive option. A direct re-entry, defined as lowering the orbit perigee to 60 km, requires ~ 2.65 times more delta-velocity (and hence fuel mass) than a delayed de-orbit manoeuvre. The latter option ensures that natural orbital evolution will re-enter the satellite within 25 years.

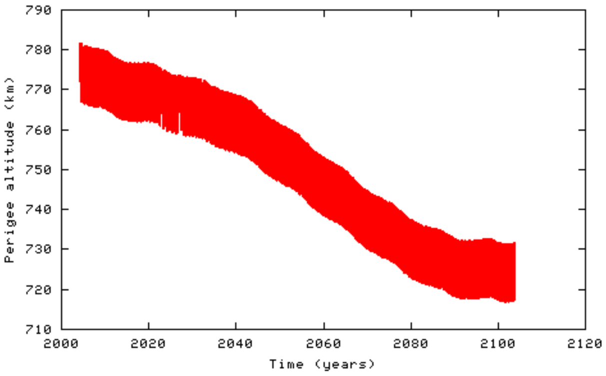


Figure 9. The natural perigee altitude evolution of the LEO mission over 100 years (provided by OSCAR).

Table 4. The required perigee height, delta-velocity and propellant mass for the disposal manoeuvre options for the LEO mission (provided by OSCAR).

Disposal Manoeuvre	**Perigee Height (km)**	**Delta-Velocity (ms^{-1})**	**Propellant Mass (kg)**
Direct De-orbit	6438.0	200.78	376.92
Delayed De-orbit (25 years)	6875.14	75.92	140.51
Re-orbit (2,000 km)	8378.0	562.78	1101.34

In the context of debris mitigation guidelines such as those provided by the European Code of Conduct for Space Debris Mitigation, the following comments can be made for the LEO mission profile. To avoid the loss of the system due to a collision-induced break-up or failure, the mission planners need to select an avoidance strategy that balances an acceptable level of risk with the operational and propellant costs of the manoeuvres. ARES shows that an accepted collision probability of 1 in 10,000, which reduces the risk from the catalogued population by ~ 58%, will require approximately two avoidance manoeuvres per year. A long-term strategy for those manoeuvres, performed a number of orbital revolutions before any predicted encounter, will help reduce the delta-velocity and fuel mass requirements. For small particle impacts, which cannot be avoided by manoeuvring the satellite, the MIDAS analysis shows that the design will need to be able to survive ~ 23 impacts in just four years. These impacts will be predominantly from millimetre-sized particles; spacecraft shielding and consideration of the placement of critical systems within the bus are recommended.

As the LEO mission reaches the end of its useful life, the Code of Conduct recommends that it is removed from the protected low Earth orbit region (the region of space < 2,000 km altitude) within 25 years. A manoeuvre to lower the perigee of the orbit to just below 500 km altitude is shown by OSCAR to be the most efficient in terms of delta-velocity and propellant mass. The actual mass of fuel required for the manoeuvre is calculated to be on the order of 140 kg. The operators of the LEO mission may want to allow a certain tolerance on this value to account for errors in estimating the remaining fuel on-board.

3.2. GEO Mission

It is recognised that the debris environment in GEO presents a lower collision risk to a satellite compared to the LEO environment. This is reflected in the ARES analysis for the GEO mission profile (Tab. 1), which gives annual collision probabilities less than 1 in 1,000,000, as shown in Tab. 5. For debris sizes between 1 mm and 10 cm, MIDAS shows that the meteoroid population, rather than man-made debris, determines the level of risk. (Note that meteoroid streams are not included in the MIDAS tool.) Fig. 10 displays an almost constant collision probability of ~ 28% throughout the 10 year analysis interval considered for the mission (1-Jun-2010 to 1-Jun-2020).

MIDAS also provides the DRAMA user with the ability to examine the impact flux and damage statistics for different surfaces of the satellite. By considering the GEO satellite to be composed of two 14 m^2 solar arrays and a 2.5 m × 5.6 m bus, the results listed in Tab. 6 can be derived. In this analysis aluminium honeycomb sandwich panels are assumed for the bus surfaces, with 1 mm thick walls spaced 35 mm apart. As expected it is the front panel of a solar array and the leading face of the satellite body (the ram direction) that have the greatest probability of suffering an impact. The probability of penetration on the front of a solar array is approximately twice that of the leading face given the lack of shielding on the array.

Table 5. Annual collision probability and flux, due to the whole and catalogued populations ≥ 10 cm, for the GEO mission (provided by ARES).

Annual collision probability with the catalogued population	3.240×10^{-7}
Annual collision probability with the whole population	5.670×10^{-7}
Flux due to the catalogued population	1.247×10^{-3}
Flux due to the whole population	6.527×10^{-3}

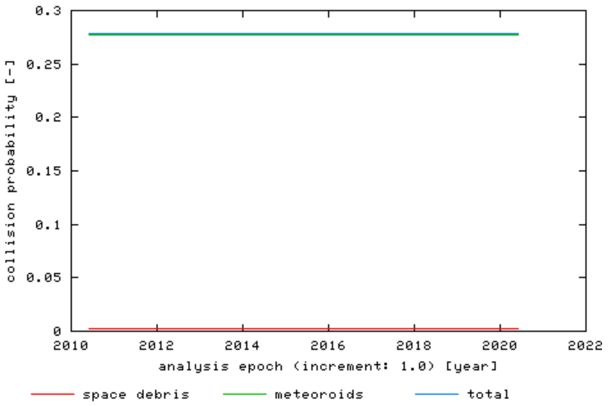


Figure 10. The collision probability with objects in the size range 1 mm – 10 cm in each year of the GEO mission (provided by MIDAS).

Table 6. The total number of impacts and penetrations over the 10 year analysis interval, and the failure flux at the mid-point of the analysis for each surface of the GEO satellite (provided by MIDAS).

Surface	**Total No. Impacts**	**Failure Flux ($m^{-2}yr^{-1}$)**	**Total No. Penetrations**
Leading Face	0.399	1.176×10^{-3}	0.181
Space Facing	0.238	5.734×10^{-4}	0.088
Trailing Face	0.095	2.133×10^{-4}	0.033
Earth Facing	0.173	4.435×10^{-4}	0.068
North Facing	0.192	1.786×10^{-3}	0.123
South Facing	0.196	1.885×10^{-3}	0.130
Solar Array (×1) Front	0.348	2.255×10^{-3}	0.347
Solar Array (×1) Back	0.251	1.272×10^{-3}	0.196

To manoeuvre the satellite above the protected GEO region at end-of-life, debris mitigation guidelines recommend increasing the orbit perigee to 36,032 km (assuming a solar reflectivity coefficient of 1.2). Tab. 7 gives the requirements for this manoeuvre, provided by OSCAR, for one electric and one chemical system. The chemical propulsion manoeuvre is assumed to consist of four Hohmann transfers. It should be noted that the two types of propulsion system vary significantly in both their hardware attributes and the technique they need to employ to dispose of a spacecraft. Thus the results in Tab. 7 do not necessarily imply that the electric system is the more effective system to use. Factors other than just fuel mass-efficiency must be taken into account, due to the different limiting factors of the two systems.

Table 7. The requirements for the GEO re-orbit manoeuvre for an electric and chemical propulsion system (Isp = Specific Impulse) (provided by OSCAR).

	Electric Propulsion (Isp = 3248s, Thrust = 18mN)	**Chemical Propulsion (Isp = 320s)**
Delta-Velocity (ms^{-1})	8.85	8.85
Propellant Mass (kg)	1.30	13.21
Duration (days)	26.66	6.51

4. RE-ENTRY ANALYSIS

The re-entry analysis provided by DRAMA is demonstrated in this section by considering the uncontrolled entry into the Earth's atmosphere of a satellite. This satellite is described by a 1.7 m × 4.8 m parent object, of 1200 kg mass, composed of 65 child objects and 2 solar arrays. The Keplerian orbital elements at the re-entry interface are provided in Tab. 8.

Table 8. The initial orbit conditions for the re-entry analysis.

Orbit Epoch	1-Jul-2008
Semi-major Axis, a (km)	6,498
Eccentricity, e	0.0002
Inclination, i (°)	20
Right Ascension of Ascending Node, Ω (°)	130
Argument of Perigee, ω (°)	90
True Anomaly, θ (°)	300

The survival analysis, performed by SESAM, predicts that three types of object survive to impact on ground 33.7 – 37.6 minutes after the initial entry (Fig. 11). The majority of child objects demise at altitudes within 20 km of the break-up at 78 km altitude. The objects that survive are those representing reaction wheels (×4), a tank and a 160 kg payload box — a total of 6 objects. The impact corridor is shown in Fig. 12 to be in West Africa. Considering these items, the risk analysis of

SERAM generates the results summarised in Tab. 9. The low-resolution result for the total casualty probability, based on a combined casualty cross-section, is lower than the value recommended by the European Code of Conduct of 10^{-4}. However, the high-resolution result, which makes full use of the survival analysis, gives a value of more than twice the recommendation. Taking measures to control the location of the re-entry interface will enable satellite operators to reduce this risk.

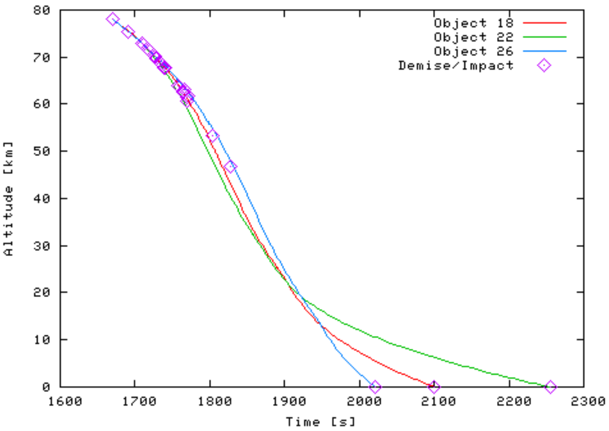


Figure 11. The demise and impact time of the child objects (provided by SESAM).

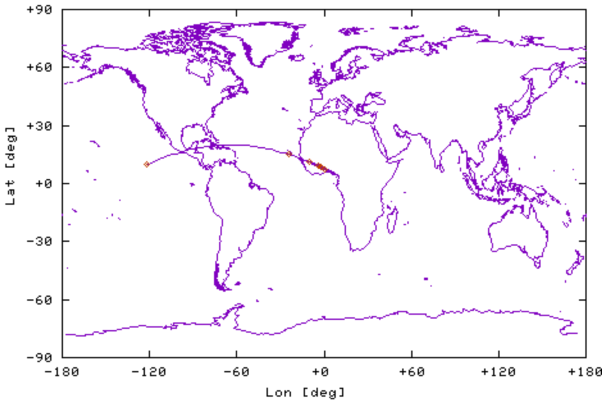


Figure 12. The ground track of the parent and child objects during re-entry (provided by SERAM).

Table 9. The results of the re-entry risk analysis for the child objects surviving to ground (provided by SERAM).

Probability of all 6 objects surviving re-entry and reaching ground	75.3%
Maximum total casualty cross-section (all fragments)	3.558 m^2
Total estimated mass at impact (all fragments)	31.217 kg
Maximum total casualty probability (high resolution)	2.173×10^{-4}
Maximum total casualty probability (low resolution)	3.763×10^{-5}

5. SUMMARY

The ESA DRAMA tool has been specifically designed to aid satellite programmes in the assessment and understanding of debris mitigation guidelines, such as those contained in the European Code of Conduct for Space Debris Mitigation. The tool encompasses five separate functions covering different aspects necessary for a successful space debris mitigation plan:

- ARES for collision avoidance manoeuvres
- MIDAS for impact flux and damage statistics
- OSCAR for disposal manoeuvres at end-of-life
- SESAM for re-entry survival analysis
- SERAM for re-entry risk analysis.

Combined, these tool provide the user with a large amount of numerical and graphical data. DRAMA represents an important step in the proactive implementation of debris mitigation measures in Europe.

6. ACKNOWLEDGEMENTS

The DRAMA tool was developed under the ESA/ESOC contracts 'Debris Risk Assessment and Mitigation Analysis (DRAMA) Tool' and 'Development of a Re-entry Risk Assessment Tool for the DRAMA Software'.

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