# UPDATE OF THE ESA SPACE DEBRIS MITIGATION HANDBOOK

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## ABSTRACT

The ESA Space Debris Mitigation Handbook was first released in April 1999 with the aim to inform planners, designers, and operators of space systems on possible risks due to the man-made debris and natural meteoroid environment at altitudes ranging from low Earth orbits (LEO) to the geostationary ring (GEO). In this paper, we present an outline of the contents of the ESA Space Debris Mitigation Handbook second edition, highlighting the major new and significantly updated elements. Then, we describe the extensive analyses being conducted with the models in order to provide state-of-the-art predictions for supporting the Handbook update process. Some examples of these predictions are given to illustrate the diversity and relevance of the new Handbook contents. Finally, we describe the innovative, internet-based methods that are being employed to develop, review and distribute version 2.0 of the Handbook.

## 1. INTRODUCTION

The ESA Space Debris Mitigation Handbook represents Europe's definitive technical document on space debris. It conveys current knowledge of the space debris environment, mitigation & shielding techniques concisely to the expert and non-expert reader alike. It is intended to serve as the technical reference and justification for the European Space Debris Mitigation Standard and has a wide distribution amongst national space agencies, the space industry, academia, and the media.

The first edition of the Handbook [1,2] (developed jointly by ESA and the Technical University of Braunschweig) addressed the historic evolution of the debris environment, and the current and future collision risk for certain target orbits and certain size thresholds. The future evolution, and the global stability of the debris environment were analysed for different mitigation scenarios (e.g. launcher and spacecraft passivation, de-orbiting, or retrieval), and for different deployment scenarios (e.g. constellations). Recommended debris mitigation practices were outlined for the operational and for the post-operational mission phase, including passive and active concepts (e.g. shielding, and avoidance manoeuvres).

Since the construction of version 1.0, our knowledge of the space debris problem has increased markedly. New environment measurement campaigns using ground-based radar and optical sensors have discovered new sources of debris, improved the understanding of other sources and better defined the overall environment characteristics. In turn, this measurement data has helped to improve the accuracy of debris environment models which, in parallel, have gone through another generation of development and reached a new level of sophistication. The enhanced debris models have then been heavily exploited in exhaustive simulation campaigns to produce high fidelity predictions of debris environment evolution for a number of important policy-forming studies. In particular, these models have played an important role in finding the most efficient and safe measures that will ultimately bring future debris population growth under control.

In recent years, research into the effects of debris impacts on spacecraft has advanced our knowledge of spacecraft system vulnerability and the potential strategies that can be taken to improve the protection levels of spacecraft designs [3]. New technologies have been developed to achieve cost-effective debris shielding both from the external shielding and internal configuration of critical components/sub-systems. The performance of these new protection technologies have been evaluated and the opportunity has now arisen for the Handbook to provide clear and constructive guidelines to spacecraft designers on the methodologies for integrating the best debris protection solutions. Similarly, improved knowledge and simulation of the survivability of space vehicle components during re-entry and the subsequent on-ground casualty risk [4] will also help designers ensure safe disposal of systems after end-of-mission.

At the same time, the world's national space agencies have been developing their own independent debris mitigation standards and procedures for their missions

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to follow. It is important that the readers of the ESA Space Debris Mitigation Handbook are made aware of the mitigation practices and technologies being used world-wide in order that they can appreciate the wider picture.

## 2. DESCRIPTION OF CONTENTS

A new project is now underway to update the contents and extend the scope of the first release of the Handbook. While following the basic outline from the first release, the new Handbook (version 2.0) places a stronger emphasis on predictions of the future debris environment evolution between LEO and GEO altitudes.

The environment evolution and stability at heavily used altitude regions is being studied parametrically for different traffic model and mitigation measure assumptions, using the Debris Environment Long Term Analysis (DELTA) model [5]. DELTA is being exploited heavily to assess the effectiveness and consequences of different mitigation measures, including their ability to ensure that long-term mission collision risks are kept within tolerable limits. Such measures include the post-mission disposal options of de-orbiting to various residual lifetime orbits and re-orbiting to various graveyard orbit regions (applicable to LEO, MEO and GEO regimes). Post-mission disposal manoeuvre and fuel requirement analyses and cost-benefit analyses are also being performed in order to find the package of mitigation methods that provide the optimum balance between benefit, cost, and risk.

New knowledge gained from the recent MASTER-99 model release [6] and the associated PROOF-99 tool is being used to update the chapters of the Handbook describing the current debris/meteoroid environment. The DISCOS database is being evaluated to provide information on historical launch & fragmentation events. New assessments of on-ground risks and survivability of large objects during re-entry events are being included. Finally, new shielding and protection techniques/methodologies are being described and practical advice given on how to incorporate debris protection into the satellite design process. The planned table of contents for the updated Handbook is given in below.

1) Introduction
1.1 The space debris problem & the need for mitigation
1.2 Scope and purpose of the handbook

2) The current orbital debris & meteoroid environments
2.1 Launch history
2.2 Historic fragmentation events
2.3 Non-fragmentation sources
2.4 The orbital debris environment
2.5 Validation of current debris environment models
2.6 Meteoroid environment

3) Impact flux analysis for space vehicle design
3.1 LEO missions
3.2 GTO and HEO missions
3.3 MEO missions
3.4 GEO missions
3.5 Meteoroid flux
3.6 Impact flux on oriented surfaces

4) The future space debris environment
4.1 The Business As Usual scenario
4.2 Future launch traffic
4.3 Satellite constellations
4.4 Nano-satellite swarms
4.5 On-orbit explosions
4.6 On-orbit collisions
4.7 Comparison of long-term debris environment predictions

5) Long-term effectiveness of mitigation measures
5.1 Prevention of explosions and operational debris release
5.2 Reduction of solid rocket motor debris
5.3 De-orbit of upper stages & spacecraft in LEO
5.4 Use of disposal regions for LEO, MEO & GEO
5.5 Satellite constellation mitigation

6) Long-term forecasting of debris impact risk
6.1 LEO missions
6.2 GTO missions
6.3 MEO missions
6.4 GEO missions
6.5 Collision probability over mission lifetime
6.6 Limitation of satellite constellation system collision probability
6.7 Cost versus benefit of mitigation measures

7) Debris mitigation guidelines & techniques
7.1 Reducing mission-related objects
7.2 Reducing debris generated from on-orbit explosions
7.3 Reducing debris generated from on-orbit collisions
7.4 Disposing of space systems at end-of-life

8) Post-mission disposal assessment
8.1 Orbital lifetime assessment for de-orbiting
8.2 Propulsive manoeuvre estimates for a controlled de-orbit
8.3 Propulsive manoeuvre estimates for an uncontrolled de-orbit

9) Re-entry survivability & casualty risk assessment
9.1 Survivability of space vehicle components
9.2 On-ground casualty risks during re-entry
9.3 Re-entry of hazardous materials

10) On-orbit collision avoidance assessment
10.1 Definition of collision avoidance criteria
10.2 Avoidance manoeuvre frequency
10.3 Collision avoidance strategies
10.4 Co-ordinated station keeping in GEO

11) Spacecraft protection
11.1 Effects of hypervelocity impacts on spacecraft
11.2 Spacecraft shielding design options
11.3 Damage equations
11.4 Methods for Assessing Damage Risk & Implementing Protection

## 3. POST-MISSION DISPOSAL ASSESSMENT

To allow a comparison of the capabilities of chemical and electric propulsion systems to de-orbit spacecraft on near-circular orbits in the LEO region, a basic software tool 'Deorbiter' has been developed by the DERA Space Debris Group to calculate the respective disposal orbit, ΔV, transfer time and fuel mass requirements. This tool has been used extensively to obtain de-orbit propellant mass estimates over a wide range of spacecraft area-to-mass ratios and post-mission lifetime limitations handbook.

Fig. 1 and 2 show the fuel mass fraction distributions over post-mission lifetime for four reference missions using a chemical and electric propulsion system respectively. These reference missions were chosen to reflect de-orbit manoeuvre requirements for moderate and high altitude LEO circular orbits (800 km and 1400 km respectively), and low and high area-to-mass ratios (0.005 $m^2$/kg and 0.05 $m^2$/kg respectively). A specific impulse of 260 seconds was assumed for the chemical propulsion system. A thrust of 25 mN and an effective exhaust velocity of 34 km/s were assumed for the electric propulsion system.

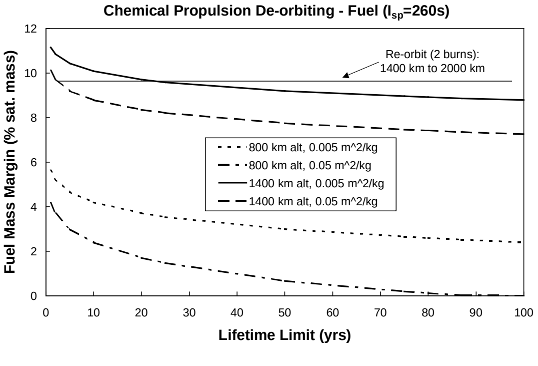

Fig.1 Fuel estimates for the post-mission disposal of LEO spacecraft using chemical propulsion to lower perigee

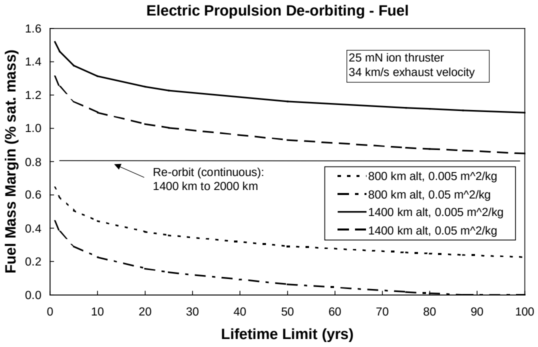

Fig.2 Fuel estimates for the post-mission disposal of LEO spacecraft using electric propulsion to lower the orbit

In general, the above results show that electric propulsion systems consume nearly an order of magnitude less fuel (in terms of mass) than chemical propulsion systems to de-orbit the spacecraft to the required post-mission lifetime orbit. In addition, electric propulsion system hardware is often lighter than chemical systems. For a 25-year lifetime de-orbit, the chemical propulsion system uses a fuel mass which is about 10% of the end-of-life mass for a low area-to-mass ratio spacecraft at 1400 km altitude. In practice, this would mean at least doubling the chemical fuel tank capacity over and above that required for orbit raising and maintenance. Re-orbiting to 2000 km altitude appears to be just as expensive as 25-year de-orbiting.

For the ion thruster system considered, this number drops to only 1.3% of the spacecraft mass. However, the transfer time to the final disposal orbit at 550 km is calculated to be about 200 days (for a 1000kg spacecraft). Attitude control must be maintained and ground station operations must continue over this period, thus incurring extra costs due to component redundancy and operations team manpower. The net effect of fuel mass savings plus extra costs to achieve a reliable de-orbit manoeuvre will be one of the main determining factors for the selection of electric propulsion over chemical propulsion for the de-orbit of different spacecraft configurations and mission profiles.

## 4. COST-BENEFIT ANALYSIS

Using the de-orbit propellant mass estimates shown above and the long-term debris impact flux prediction capabilities of the DELTA model, it has been possible to perform a simple cost-benefit analysis for end-of-life de-orbiting for different LEO missions. The simple parametric cost model used for this analysis uses a cost metric (rather than actual cost) to consider the evolution of relative mission cost figures for an unmitigated debris environment and for one that is effectively mitigated by de-orbiting (combined with passivation measures). In the later case, the step increase in the mission cost metric due to the increase in launch mass associated with the extra propellant for de-orbiting has to be considered. The cost model is defined as follows:

Cost Metric =
mission failure probability X replacement cost
(+ end-of-life manoeuvre cost)

Mission failure probability =
total collision probability (size) X impact failure probability (size)

Table 1. Impact failure probability model

| Debris size range | Impact failure probability |
|---|---|
| 1 mm - 2.2 mm | 10% |
| 2.2 mm - 4.7 mm | 30% |
| 4.7 mm - 1 cm | 60% |
| >1 cm | 100% |

Replacement cost = manufacture cost + launch cost

Launch cost = vehicle mass X launch cost per unit mass

End-of-life manoeuvre cost = fuel mass X launch cost per unit mass

Fig.3 shows the DELTA long-term predictions of mission failure probability due to debris impact for a mission lasting 10 years with a spacecraft mass and area of 1000 kg and 5 $m^2$ respectively. In an unmitigated debris environment, the mission failure probability is predicted to more than double over the next 100 years for both the 800 km and 1400 km altitude operational orbits. When passivation and 25-year lifetime de-orbiting is introduced, exposure to this effectively mitigated environment produces a constant mission failure probability over time.

In order to illustrate the impact of de-orbiting on missions of different cost scales, we have chosen an ‘expensive’ mission with a replacement cost of $175m, and a ‘low cost’ mission with a replacement cost of just $50m. For each of these, we consider evolution of the cost metric for the unmitigated future debris environment, and for the mitigated environment achieved by de-orbit using chemical or electric propulsion systems (leading to different step increases in each case). The post-mission lifetime considered for the de-orbit manoeuvre was 25 years, and the average launch cost per unit mass was assumed to be $30,000 per kg.

Fig. 4 shows that for an expensive mission deployed at 800 km altitude, use of both chemical and electric propulsion for de-orbit lead to a very small, short cost region, followed by a long and large benefit region. The cost region is evident when the cost metric for the mitigated environment + the step increase due to the de-orbit manoeuvre cost is above the cost metric for the unmitigated environment. For an expensive mission at 1400 km altitude, the use of chemical propulsion to de-orbit leads to a significant and long cost region. However, the use of electric propulsion for this higher altitude appears to be very cost-effective.

Fig. 5 presents the equivalent projections for a low cost mission. Due to the larger cost for the de-orbit manoeuvre in relation to the replacement cost, implementation of de-orbiting has a much greater impact. For a low cost mission at 800 km, again both chemical and electric propulsion systems for de-orbit appear to be reasonably cost-effective. However, at 1400 km altitude, the use of chemical propulsion leads to a significant, long-term cost region and hence not a cost-effective option. Encouragingly, the use of electric propulsion to de-orbit a low cost mission from this higher altitude appears to be a cost-effective option, according to this simple, parametric cost metric model.

It is recognised that such a simple, parametric cost-benefit analysis does have limitations due to the assumptions made, especially concerning the use of launch cost per unit mass. In the real world, there is often some margin for spacecraft mass budget increase, which can be accommodated by the launch vehicle without the need for a more heavy lift configuration. In this case, no additional costs would be incurred to launch the spacecraft with extra fuel for de-orbit. However, in other cases, the margin might be exceeded, leading to the penalty of having to use a more expensive launch vehicle. Therefore, the parametric model used here can only be considered as an ‘average’ cost representation of a much wider statistical spread of real mission experience.

Additionally, the model does not consider ‘hidden’ costs associated with de-orbiting, such as additional hardware mass (e.g. larger fuel tanks, redundant hardware for reliability – particularly attitude control hardware). It is intended to further enhance the cost-benefit model in the future to account for these factors.

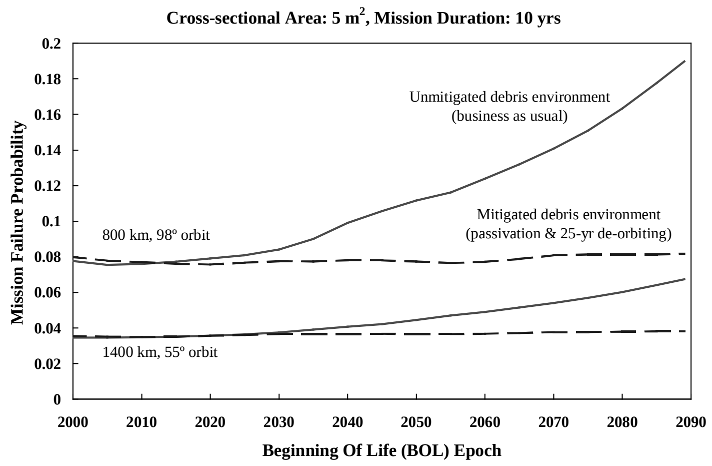

Fig.3 Mission failure probability forecasts for two different low Earth orbit missions, according to the DELTA model and assumed impact failure probability model

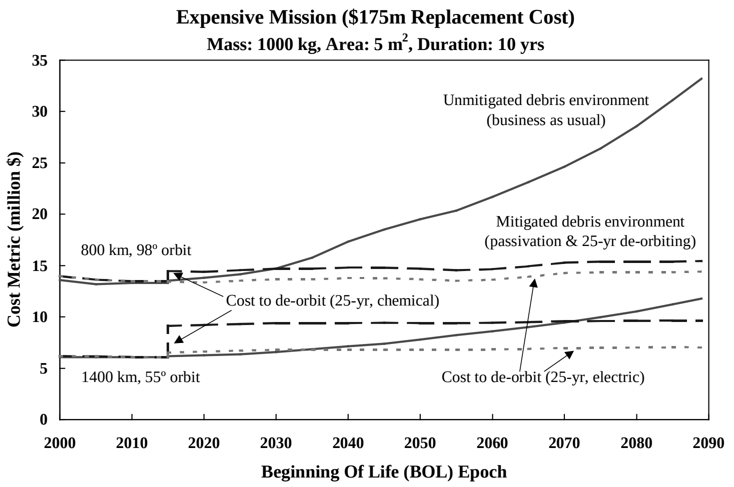

Fig.4 Cost-benefit projections for chemical and electric propulsion de-orbit of an 'expensive' mission in two different low Earth orbits

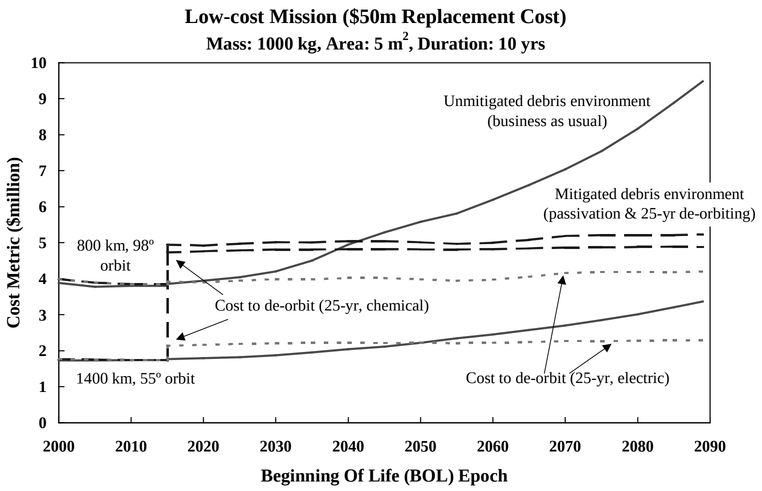

Fig.5 Cost-benefit projections for chemical and electric propulsion de-orbit of a 'low cost' mission in two different low Earth orbits

## 5. ON-LINE DEVELOPMENT & RELEASE

A new and novel web application called the Handbook Web Environment has been constructed for the handbook update project. This technology represents a new, efficient way of product development and distribution for a project team scattered across national boundaries. This web application has been specifically designed for:

- central storage and configuration control for multi-author, multi-stage development & review of the Handbook 2.0 document
- central project administration function
- central storage of project documentation
- reproducibility of most model/database output data extractions
- reproducibility of Handbook figures from the extracted data files
- conversion of the Handbook 2.0 document to PS, PDF, HTML formats for public web browsing & download
- access to wider scope of data through web browser ‘point-and-click’ operations on the figures
- controlled, multi-stage release of Handbook 2.0: internal ESA review, national agencies review, public access

The structure of the Handbook Web Environment is shown in Fig.6.

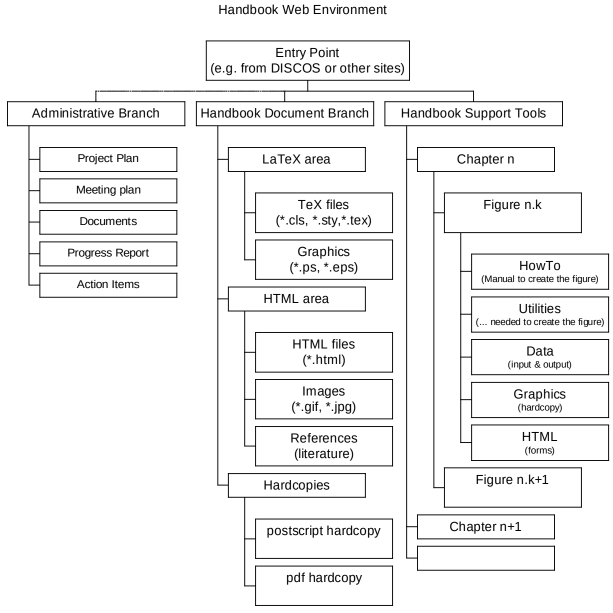

Fig.6 The structure of the Handbook Web Environment

## 6. CONCLUSIONS

The ESA Space Debris Mitigation Handbook is currently undergoing a significant update. This update includes new predictions of the current debris environment and collision risks from the ESA MASTER-99 model, model/measurement comparisons using the PROOF tool, new predictions of future orbital debris environment & collision risk evolution in LEO, MEO and GEO for many different spaceflight scenarios using the ESA DELTA model. Also, there are new guidance/advisory chapters for space system engineers on debris mitigation standards/techniques, post-mission disposal assessment, re-entry survivability and casualty risk assessment, and spacecraft protection. The second edition of the handbook is planned for release in the first quarter of 2002 in hardcopy and via browsing and/or downloading from a web site.

## 7. REFERENCES

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