Reliability analysis of space debris mitigation strategies using the Monte Carlo method

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Abstract. In light of growing space exploration, the risk of collisions involving satellites, rockets and the International Space Station has increased significantly due to the growing number of space debris (objects in orbit that are no longer useful). In this scenario, several public and private organizations have developed strategies to mitigate this problem. The CBERS-1 satellite, launched in 1999 in a Brazil-China collaboration, is still in orbit, despite being decommissioned in 2003. This study aims to evaluate the effectiveness and reliability of various mitigation strategies that could have been implemented during the decommissioning of CBERS-1, using the DRAMA (Debris Risk Assessment and Mitigation Analysis) program and the OSCAR (Orbital Spacecraft Active Removal) application, which uses the Monte Carlo method. The objective is to ensure that CBERS-1 re-enters the Earth's atmosphere within a period of 25 years, meeting the ESA (European Space Agency) space debris mitigation requirements. This analysis contributes to understanding and improving space debris mitigation practices in the context of increasing activity in space.

Keywords: Space debris, mitigation strategies, CBERS-1, DRAMA, reliability.

1 Introduction

The intensification of space endeavors has led to a substantial accumulation of space debris, mainly composed of defunct satellites, rocket fragments, and other discarded parts, posing a threat to ongoing missions and future endeavors. Although there were early concerns about space regulation, formal guidelines for reducing space debris only came out in the late 2000s. In particular, the 2010 Committee on the Peaceful Uses of Outer Space (COPUOS [1]) aimed to limit released debris, prevent ruptures during operations, reduce in-orbit collisions, avoid intentional destructions, minimize post-mission ruptures, and limit prolonged presence in low Earth orbit. and geosynchronous after the end of the mission.

Satellite collisions, anti-satellite weapon tests, micrometeoroids impacts and human-related activities are some of the sources of space debris. The accumulation of debris not only jeopardizes present space operations but also exacerbates the possibility of the Kessler Syndrome, cited by Kessler and Cour-Palais [2], in which cascading collisions generate additional debris, rendering certain orbital regions unsuitable for future missions.

Space agencies advocate for proactive measures to deorbit satellites at the end of their operational life in order to mitigate the proliferation of space debris. However, older satellites like the CBERS-1, which lack deorbiting technology, remain in orbit indefinitely. The CBERS-1 satellite (shown on Fig. 1) provided crucial data for various applications, including deforestation control and strategic national projects, when it was active. It covered the whole Earth in 26 days, with a sophisticated system ensuring high-quality data acquisition. By utilizing tools such as Debris Risk Assessment and Mitigation Analysis (DRAMA) to evaluate active removal strategies, the objective is to identify a strategy that could have been implemented to ensure that the satellite does not become space debris, thereby adhering to space debris mitigation standards and minimizing any additional clutter in Earth's orbit.

2 DRAMA applied to CBERS-1

The Debris Risk Assessment and Mitigation Analysis (DRAMA) program of the European Space Agency (ESA) offers a comprehensive approach to the analysis and compliance of space missions with space debris mitigation standards. Developed according to European Cooperation for Space Standardization software engineering

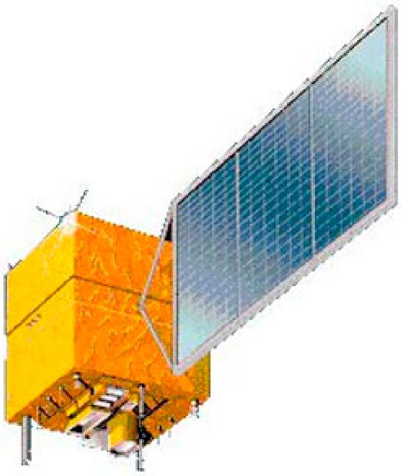

Figure 1. Image from the Sino-Brazilian CBERS-1 satellite.

standards, DRAMA covers various phases of a space mission, including management, design, and operation. It consists of five distinct tools, namely ARES, MIDAS, CROC, OSCAR, and SARA, each of which is specifically designed to evaluate distinct aspects of space debris risk and mitigation. This project focuses on the CROC and OSCAR tools.

2.1 Cross Section of Complex Bodies (CROC)

The CROC tool calculates the cross-sectional area of a complex body, aiding in establishing relevant parameters for the study of the CBERS-1 satellite. We utilized the "Randomly tumbling satellite" option to calculate the average cross-sectional area of CBERS-1, taking into account the fact that the satellite has been deactivated and is likely to tumble randomly. The average cross-sectional area calculated was 13.77 m^2.

Additionally, we modeled CBERS-1 with a 100 m^2 Drag Sail system for deorbiting simulations. In this case, the satellite would have a deorbiting system, so it would be expected to go in the direction of maximum drag. Therefore, the free-fall functionality was chosen to select the highest drag value, which represents the cross-sectional area in the mission's chosen direction, as shown on Fig 2.

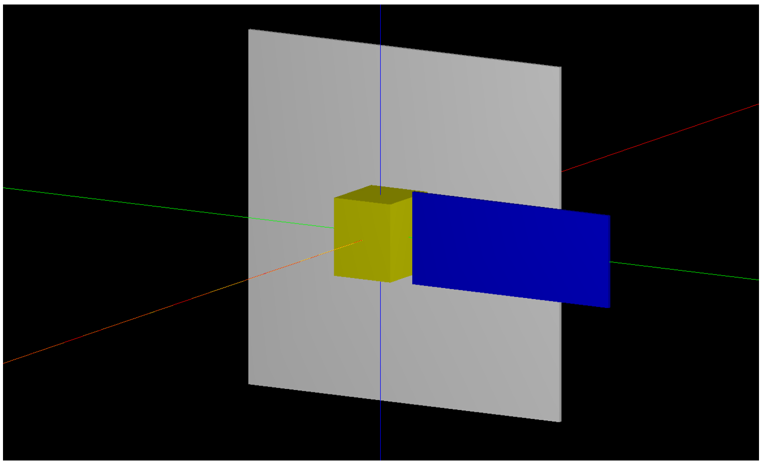

Figure 2. 3D model of the Drag Sail system, with 100 m^2 area, integrated into CBERS-1, with a cross-sectional area of 105.87 m^2.

2.2 Orbital SpaceCraft Active Removal (OSCAR)

The OSCAR tool, a component of the DRAMA program of the European Space Agency, is specifically designed to calculate the orbital life of a spacecraft and assess post-mission disposal strategies. It analyzes various disposal strategies after the spacecraft's nominal end of life, considering different orbits. For CBERS-1's location in low Earth orbit (LEO), the options available to the spacecraft include either direct deorbiting, which results in atmospheric reentry within a single revolution, or delayed deorbiting, which transfers the spacecraft to an orbit with a 25-year residual life as recommended by ESA's Space Debris Mitigation Requirements. For geostationary orbit (GEO), it is recommended to elevate the spacecraft's orbit post-mission to avoid interference with active objects.

The OSCAR tool simulates solar and geomagnetic activity during satellite disposal using the Monte Carlo Process, incorporating ISO 27852:2011 and ECSS-E-ST-10-04C standards. The tool requires certain satellite-specific parameters, such as the semi-major axis, eccentricity, inclination, RAAN (Right Ascension of the Ascending Node), argument of perigee, and mean anomaly.

The orbital elements of CBERS-1 were defined using TLE (Two-Line Element Set) values verified on January 5, 2024, as shown on Fig. 3, along with physical parameter data from INPE [3].

1 25940U 99057A 24005.46092816 .00000283 00000-0 11324-3 0 9994

2 25940 98.7854 341.5891 0005960 109.0038 251.1794 14.36073159269202

Figure 3. From left to right: Satellite catalog number; Inclination (degrees); RAAN (degrees); Eccentricity (decimal); Argument of perigee (degrees); Mean anomaly (degrees).

3 Mitigation Strategies for Space Debris

Space debris removal can be classified as active or passive. Active mitigation typically targets large debris by utilizing technologies such as dedicated propulsion systems for deorbit maneuvers, drag sails to enhance atmospheric drag, and even satellites equipped with harpoons, nets, or other specialized tools designed for the removal of space debris. Passive mitigation entails conceiving satellites to minimize the generation of debris in the event of a collision and implementing deorbit strategies throughout the operational lifespan of the object.

We examined four active deorbiting strategies employing the DRAMA program, namely chemical propulsion, electric propulsion, an electrodynamic tether system, and a drag augmentation device. Additionally, we evaluated three out of the four deorbit scenarios, except the reorbit option. Reorbiting is only feasible for geosynchronous orbit (GEO) satellites due to the significant velocity change required, which would significantly reduce the satellite's mission lifespan.

- **None:** The "None" scenario evaluation reveals whether the satellite complies with space agency guidelines. The standard recommends deorbiting or reorbiting within 25 years post-mission, but the Federal Communications Commission [4] has revised this to 5 years for LEO satellites licensed in the United States by September 2022. The duration of Sino-Brazilian space debris in Earth's orbit is determined by this assessment, which serves as a baseline for evaluating the impact of an unplanned deorbit mission.
- **Direct De-Orbit:** In this scenario, the satellite would enter Earth's atmosphere on its next perigee pass immediately following the maneuver. As a result, only a chemical-powered system could be employed, as other disposal mechanisms are assumed to lack sufficient thrust to sufficiently lower the perigee, allowing the satellite to burn up in the Earth's atmosphere within a single orbit.
- **Delayed De-Orbit:** In this scenario, there is a remaining lifespan after the deorbit maneuver is completed. It is generally the most commonly used strategy, as it requires less propellant for the maneuver and allows for analysis with an electrodynamic tether or drag sail. If it is properly planned, it will comply with the 25-year rule recommended by space agencies.

4 Deorbiting Technologies and Results

Common to all simulations, the Monte Carlo Process allowed observing the dynamics of solar and geomagnetic activity over time, which greatly influenced the deorbiting of CBERS-1, directly affecting atmospheric drag force and, consequently, the satellite's trajectory and return time.

According to simulations, the lifetime that CBERS-1 will remain in orbit is approximately 153 years, that is, the prediction of the satellite's deorbitation without human interference ("None" scenario) exceeds the 25-year rule in a frightening way, and the variation of its perigee and apogee over the years can be seen in Fig. 4

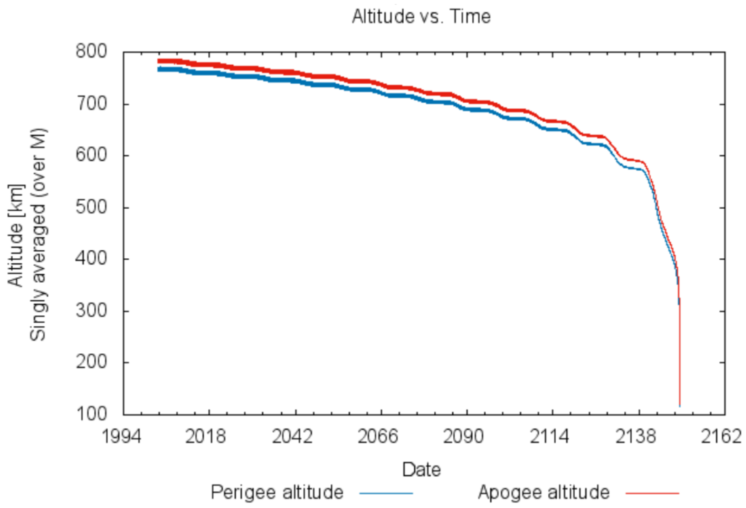

Figure 4. Deorbiting the CBERS-1 satellite without using deorbiting technologies.

4.1 Propulsion

The deorbiting system changes how a body moves relative to a reference system. It uses different types of energy, like chemicals in the propellant and electricity from batteries or solar panels.

The chemical propulsion method uses the engine at apogee to lower the satellite's perigee. The OSCAR program calculates the propellant mass needed to achieve the desired perigee altitude within the orbit's lifetime limit, typically 25 years. Studies, such as Janovsky et al. [5], have evaluated propulsion techniques for deorbiting LEO spacecraft. The research indicated that solid propellant is most suitable for medium-weight satellites like CBERS-1, aligning with findings from Okninski et al. [6]. OSCAR's standard recommendation of Specific Impulse was effective for these maneuvers.

The electric propulsion process closely resembles the chemical propulsion described previously. The study conducted by Rydén et al. [7] highlights electric propulsion systems such as Arcjets and Ion Thrusters as formidable contenders for deorbit maneuvers due to their enhanced suitability for the implementation of mitigation technology. For medium-weight satellites, Arcjets offer greater efficiency per unit mass, cost-effectiveness, and simpler implementation compared to Ion Thrusters.

Based on this, we referenced the article by Wollenhaupt et al. [8], which provides a historical review of Arcjet project developments, and utilized OSCAR's database to aid in choosing system properties.

By using solid propellant chemical engines and electric motors (Arcjet 1.8W) with Hydrazine, we compared various metrics necessary to achieve deorbiting in 25 years and in 5 years, as shown on Table 1.

Table 1. Propulsion System Performance

	25 years			5 years		
	Mass	Velocity	Altitude	Mass	Velocity	Altitude
Chemical Propulsion	33 kg	64 ms^{-1}	529 km	61 kg	118 ms^{-1}	333 km
Electric Propulsion	19 kg	76 ms^{-1}	630 km	41 kg	167 ms^{-1}	464 km

4.2 Electrodynamic Tether

The deorbiting of a satellite using an Electrodynamic Tether involves using electromagnetic principles to alter the satellite's orbit without the need for fuel. Typically, this system possesses a plasma-tipped end. In the presence of the Earth's magnetic field, a current is generated along the cable, generating electromagnetic forces that decelerate the system, ultimately leading to atmospheric reentry. It is worth noting that this architecture also offers the advantage of generating power for the satellite during its mission, as described by Andringa and Hastings [9].

Two sources served as the basis for the parameters: the first was the article by Kawamoto et al. [10], which conducted a numerical simulation under conditions similar to those of the current CBERS-1 satellite, providing relevant data for analysis in this project; the second, by Andringa [9], described the upcoming ProSEDS mission, where a deorbiting system using the Electrodynamic Tether principle would be tested.

After simulations, it was confirmed that the electrodynamic system would be capable of deorbiting CBERS-1, with the achieved perigee height and the activation time of the cable needed for deorbiting in both 25 years and 5 years scenarios, as shown on Table 2.

Table 2. Electrodynamic Tether Performance

	25 years		5 years	
	Perigee Altitude	Time	Perigee Altitude	Time
Electrodynamic Tether	630 km	83 days	464 km	168 days

4.3 Drag Sail

Drag sails are devices that increase a satellite's surface area, thereby enhancing the atmospheric resistance it experiences, leading to accelerated deorbiting. The dimensions of the sail determine the drag and reflectivity coefficients. Data from the article by Colombo et al. [11] provided standard values for both coefficients. Additionally, both the ADEO mission and the article by Underwood et al. [12] indicate the use of non-reflective materials for the sails to comply with the requirement of not disturbing astronomers. Therefore, the values for both coefficients across all sails are determined accordingly.

According to the OSCAR tool, licensed by ESA, for drag augmentation devices known as Drag Sails, a cross-sectional area of 99 m^2 is required to ensure compliance with ESA's space debris mitigation requirements, i.e., deorbiting the satellite within 25 years.

Based on this, simulations were conducted for the four sail sizes studied, considering the maximum cross-sectional area, assuming the satellite will have an Attitude and Orbit Control System (AOCS), optimizing the Drag Sail system to achieve this maximum area, as shown on Table 3.

Table 3. Results for each Drag Sail

Sail Area	25 m^2	100 m^2	225 m^2	450 m^2
Maximum Cross Section (m^2)	37.82	105.87	223.53	446.80
Remaining Time in Orbit (years)	112.10	22.25	10.21	7.92

5 Reliability of Satellite Deorbiting Strategies

The reliability of satellite deorbiting strategies is crucial for managing space debris, directly impacting the safety and efficiency of operations. Certain points may serve as a basis for analyzing this reliability:

The probability of success varies among the different technologies. Electrodynamic tethers and drag sails are irreparable if damaged by space debris, posing significant mission risks, especially in high debris density environments. On the other hand, chemical and electric propulsion methods show higher resistance to minor impacts. However, electric propulsion, while more robust, is slower and less powerful, increasing orbital exposure time and risks.

In terms of mass requirements, chemical propulsion requires substantial propellant mass, presenting challenges in design and launch costs and potentially limiting payload capacity. Electric propulsion, although more fuel-efficient, takes longer to perform deorbiting maneuvers, which can pose operational disadvantages.

Regarding complexity and cost, chemical propulsion provides a direct and quick deorbiting approach but incurs high costs due to intensive fuel consumption and the need for a powerful propulsion system. Electric propulsion and passive devices like electrodynamic tethers and drag sails offer lower long-term operational costs but increase initial project complexity and development requirements.

According to Colombo et al. [11], shorter orbital times reduce collision risks with space debris, making the reliability of deorbiting strategies dependent on balancing costs, deorbiting time, and vulnerability to debris damage. Chemical propulsion emerges as the most reliable and effective strategy for rapid and controlled deorbiting, suitable for critical or high-payload missions despite high costs and complexity. Combining electric propulsion with passive devices like electrodynamic tethers or drag sails can provide a balanced solution in terms of cost, efficiency, and sustainability, albeit with time and vulnerability challenges.

6 Conclusions

This project's analysis based on space debris mitigation studies, particularly on the Sino-Brazilian satellite CBERS-1, verified the necessity for implementing effective deorbiting technologies and validated their performance across diverse simulated scenarios. The study concludes that conventional propulsion systems commonly used for satellite maneuvers and deorbiting are viable. Furthermore, innovative systems like Electrodynamic Tether and Drag Sail, despite being in the experimental phase, exhibit notable advantages in terms of cost-effectiveness and ease of implementation. In theory, both systems are capable of achieving satellite deorbiting as effectively as traditional propulsion systems, or potentially even more effectively depending on mission requirements.

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