

CleanCube: A Zero Debris CubeSat Platform

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ABSTRACT

Following a successful pre-phase A study to assess the feasibility of CubeSats being compliant to various space debris mitigation requirements, ISISPACE is engaging into the Phase A work for a proposed a 12U IOD/IOV CubeSat mission “CleanCube”. The project is part of ESA’s Zero Debris initiatives to demonstrate the technologies that can provide compliance to stricter space debris mitigation requirements. The mission will host a set of primary payloads for space debris mitigation purposes as well as secondary payloads which will be funded through other paths. To ensure a wide applicability of the solutions found, a consolidated set of requirements was created by incorporating the currently applicable ESA Space Debris Mitigation Requirements, the French Law, FCC and ISO Standard as well as a foreseen future evolution of requirements. The emphasis of this study is placed on addressing the gaps in current CubeSat designs in terms of space debris management. This concept actively addresses them, challenging the common approach of a passive compliance enforcement. This will ensure the long-term sustainability of the CubeSats niche outside of the low range of LEO, ensuring the survivability of downscaled technologies. The study addresses the feasibility for early identification after launch, refined space situational awareness, improved system reliance & health monitoring and high reliability in active collision avoidance manoeuvres, passivation as well as end-of-life concerns. Additionally, the mitigations towards dark and quiet skies will be addressed.

1 INTRODUCTION

With the exponential increase of the population in high demand orbits, the risk of Kessler syndrome prevails. This drives the need for stricter regulations related to space debris mitigation. ISISPACE has a wide variety of customers spread all over the world, and for each customer, a slightly different set of debris mitigation requirements is applicable. There are requirements depending on the desires of the customer itself, the country of satellite registration and the launch authority. To navigate this landscape, a study has been executed to find several suitable satellite architectures that would comply with an overarching set of debris mitigation requirements.

The mission under study is an IOD/IOV CubeSat mission focusing on design gaps that can provide compliance to these requirements. The baselined concept consists of a 12U CubeSat operating in LEO at ~550 km altitude and a ground segment with high emphasis on space surveillance. While most CubeSats currently rely on passive compliance to space debris mitigation requirements (e.g. passive re-entry within the required time by limiting the launch altitude), the mission under study will rather demonstrate reliable deorbiting with a de-orbit device as well as hard passivation. Additionally, the mission will include measures such as collision avoidance capabilities, LEOP identification and more. Several technological challenges from the Zero Debris Charter [1] and the Zero Debris Technical Booklet [2] are addressed during the study.

One of the main objectives of the Phase-A project is to assess improvements related to space traffic management. Multiple trade-offs have been performed to find a solid system baseline that ensures compliance to the requirements. As main highlight, firstly, different methods for collision avoidance have been assessed based on their reliability and effectivity. The methods under study were chemical propulsion, electrical propulsion and use of differential drag. Secondly, a trade-off has been performed towards improving spacecraft identification shortly after a rideshare launch. Methods that are under study are the use of a retroreflector, GNSS beacons, Doppler measurements through a satellite communications link and others.

Another important aspect is an assessment on how to quantify and improve reliability figures on the relevant debris

mitigation technologies. The current ESA requirements [1] only request a certain reliability for end-of-life disposal and passivation, but it could be anticipated that in the future this is also required for collision avoidance. It is currently a challenge for CubeSats to associate functionalities with reliability figures due to the use of COTS components. Therefore, several methods are addressed on how to quantify the reliability (see Chapter 3).

This work is funded through the ESA Phase A CleanCube project. As the project is still ongoing, not all trade-offs and design considerations have been concluded, so therefore this paper presents an in-between status. This paper is an update of the previously published paper during the pre-Phase-A study of this mission [11]. The work described in the paper is performed by a consortium led by ISISPACE, with the following partners: Neuraspace, Aurora Propulsion Technologies, Foundational Space and Gama.

This paper starts with a lay-out of the requirements that are used as input to the study. Next, in Section 3, the topic of reliability is discussed, since this serves as input to most of the topics outlined thereafter. In the next sections, the following items are addressed: end-of-life disposal, collision avoidance, space traffic management and passivation. In Section 9 a conclusion as well as recommendations for future work can be found.

2 REQUIREMENTS

The strictest requirements currently present are the ESA Space Debris Mitigation Requirements [3], tightening the restrictions imposed already by the ISO Standard [4]. Then, in the frame of the Phase-A project, several sustainability requirements have been added to further tighten the existing standard, keeping in mind a possible future evolution of the requirements. These requirements have all been consolidated, and as a conclusion, the most driving requirements for CubeSat missions are stated below:

- The reduction of the LEO disposal phase to 5 years with a probability of successful disposal above 90%.
- Unambiguous identification within 1 day after launch
- Collision avoidance capability available 2 days after launch.
- Reliability higher than 0.9 to maintain recurrent manoeuvre capabilities for collision avoidance purposes
- Need for quick responsiveness to Conjunction Data Messages (CDM), < 12 h between reception of CDM and execution of manoeuvre
- Probability of successful passivation of at least 90%
- Need of failure prognostics, wear out data and Failure In Time (FIT) data

Besides ESA, two other main sources of requirements are accounted for: FCC [8] and the French law [5]. Especially the French law contains several requirements that are stricter than ESA. For example, if the mission lifetime is only one year, the satellite shall de-orbit within three years.

3 RELIABILITY

Reliability computations have been shown to be a key issue when using commercial COTS electronic, electrical, electromechanical (EEE) components which is typically done for CubeSats. The use of COTS components provides great advantages of short lead times, low Size, Weight and Power (SWaP) and extensive functionality at a competitive price point. But a widely acknowledged disadvantage of the COTS approach is lower reliability. Broadly speaking, there are two reasons for this. Firstly, the random failure rate may be higher due to lower design margins and reduced quality control for commercial-grade components. Secondly, the in-orbit environment is more challenging compared to the terrestrial environment that COTS EEE components are typically exposed to. These COTS components most often do not come with any reliability figures from the manufacturers, which is the source for the difficulty of performing a reliability analysis. Other methods exist, such as using FIDES analysis, but since this is a time-consuming exercise, it is often not compatible with CubeSat timelines and costs. Nevertheless, the applicable requirements still request the provision of a quantified reliability. Therefore, as part of the study, an assessment has been performed on the use of FIDES or alternative methods for critical items. A balance was found using statistical data from past missions for equipment that has flown before, as well as FIDES for any new developments [10]. Limiting FIDES solely to new developments saves a significant amount of time compared to executing it for all equipment.

Additionally, within ISISPACE exercises are continuously being performed to increase reliability without quantifying it. A high-level assessment of reliability figures (e.g. through parts count) can be made with the goal of comparing certain spacecraft architectures with each other, which can feed into conclusions on how to increase the reliability. This activity, together with Failure Mode Effect & Criticality Analysis (FMECA) studies, shows that the most efficient method to increase reliability is to implement a one fault tolerant architecture through redundancy, which is typically not implemented in CubeSats. Based on this assessment, a first conclusion is made to make this mission one-fault tolerant for space debris mitigation technologies requiring a reliability assessment: passivation, de-orbit and collision avoidance

manoeuvres (CAMs). To execute CAMs successfully, nearly the entire platform is required: the AOCS, propulsion system, OBDH, power system and TTC. Therefore, the CleanCube platform will be fault tolerant on all critical platform avionics.

To enhance the reliability of satellite disposal and passivation, it is concluded that systems that are as stand-alone as possible can achieve the highest reliability. The downside of this approach, however, is that it brings the additional risk of those stand-alone systems accidentally triggering and that it may lower the overall mission reliability. Therefore, careful considerations need to be made to balance mission reliability vs. disposal reliability. For de-orbit devices, the best approach is considered to have a watchdog timer set at multiple months, and if the watchdog has not been kicked throughout that time, the device will deploy. This allows for a high reliability approach in a fully stand-alone set-up from the platform. For passivation, it is more complicated as battery passivation is tightly linked to the satellite power system, and any malfunctioning there would directly impact the full mission. The mechanisms for de-orbit and passivation and their reliability are discussed in Chapter 4 and 7 respectively.

A last consideration related to this topic is the need for improved methods to assess the health status throughout the mission of critical functions related to debris mitigation. The approach that will be taken for this is that first, a review is performed regarding what additional telemetry of each critical equipment could be meaningful as an indication of the health status, using internal sensors on the boards. To handle this information, more detailed on-board data analysis and FDIR implementation can be implemented, providing early detection of off-nominal behaviour. This increased autonomy will enhance the reaction time, in contrast to the traditional implementation based on threshold values triggering a change in satellite modes, subsystem resets and on ground data analysis.

4 END-OF-LIFE DISPOSAL

The requirement related to end-of-life disposal is to de-orbit after the end-of-life within 5 years with a probability of success higher than 90%, and it can be anticipated that the required probability of success may increase even more in the future. Using propulsion for a de-orbit manoeuvre is often considered the solution to this, but, it is seen that propulsion is particularly difficult for CubeSats, due to the following reasons:

- CubeSat propulsion systems are a challenging technology, so the reliability of the unit itself is likely not compatible with the requirement (i.e. propulsion system stand-alone after a 3-year mission lifetime is expected to have a reliability < 90%).
- Nearly the entire platform needs to be operational at the end-of-life to perform a deorbit manoeuvre. Working ADCS is required, as well as high power for the propulsion unit and a functioning communication system to plan and schedule a manoeuvre. Ensuring this scenario at the end-of-life with a 90% probability of success is currently deemed unrealistic.

Therefore, the probability of success points us in the direction of a deorbit device that is stand-alone from the platform. If needed, the deorbit functionality can be one-fault tolerant to increase the reliability. Since this mission is an IOD for such technologies, and to increase the reliability, the satellite includes two stand-alone de-orbit devices, where both systems are able to work upon command as well as autonomously, i.e. if a ping has not been received by the de-orbit device within a to be defined amount of time, it will be automatically deployed. This trigger would also work in the case of a dead-on-arrival. For the purpose of the in-orbit demonstration mission, two different de-orbit devices are proposed, each able to be deployed upon command as well as autonomously.

The first system proposed is a drag device from GAMA, named the AstroBrake. In order to ensure a high reliability, the electronics of the device are carefully selected, tested, and placed in a redundant configuration, designed both against the risk of early-deployment and deployment failure. The behavior is completely hardware-defined, removing any software risk from the equation. Power is ensured autonomously through Lithium-Thionyl Chloride primary cells that allow up to 5 years of power independence, which actuate a gearbox motor system at end-of-life. The structural members (booms) are stored coiled. When deployment is triggered, the gearbox unlatches the door and unwind the booms, pulling the 2m² polyimide sail open. The deployment trigger can be timer-only (up to 5 years), through health-sensing via redundant heartbeat signals from the spacecraft systems as a timer reset mechanism, or through redundant on-demand trigger signals. This whole system, designed by GAMA under the name Astrobrake-S, is packaged in less than a unit configuration and is compliant with today's dominant CubeSat structures on the market, thus making it a great option for CubeSats with sizes 3U and up.

The second system that will be deployed is a tether that interacts with the plasma environment in LEO; a Plasma Brake from AURORA. Similarly to the drag sail, it is aimed to have a high reliability and independence from the platform through an autonomous trigger. However, unlike the drag sail it still requires some power during its operation. The solution would be stand-alone as the required power cells can be included on the device itself. The main advantage of this

solution is that it also works at higher orbital altitudes where atmospheric drag becomes inefficient. The Plasma Brake uses Coulomb drag to interact with the upper atmosphere plasma, slowing down the spacecraft. This is done by charging a thinner-than-a-hair metallic microtether to -1000 V, resulting in an electric field that deflects the environmental plasma, causing the deorbiting force. For the deployment of the tether, the satellite is spun up by the device.

Having a stand-alone de-orbit device with a high reliability comes at a higher cost, but the main advantage is that it allows to by-pass high reliability needs on the platform, allowing faster mission development timelines.

5 SPACE SITUATIONAL AWARENESS

One of the main goals of space debris mitigation is to better understand the space environment, and a solution needs to be provided to enhance information on the whereabouts of the spacecraft. For this purpose, the mission needs to include a space surveillance segment, for which Neuraspace has been selected as service provider [6]. Supporting Neuraspace, Foundational Space will provide space surveillance data from their laser ranging stations.

The current ESA requirements ask for unambiguous identification 1 day after orbit injection, which is particularly difficult for spacecraft on rideshare launches (referred to as the so-called 'CubeSat confusion' [7]). Currently it may take several weeks until all CubeSats on a rideshare launch have been matched with a Two Line Element (TLE). Even when powering on the on-board GNSS receiver within 1 day after launch, it stays difficult to match a TLE with the GNSS data [12]. Therefore, it is expected that the orbit will be determined by combining several different sources of data. During the study, a trade-off has been performed to identify several suitable methods for the LEOP identification issue. All of the selected methods will be tested as part of the IOD to allow for a performance comparison. The selected methods are summarized below, it is important to note that all methods will also make use of GNSS data downlinked from the satellite:

- The satellite will include a uniquely identifiable laser retroreflector provided by Foundational Space. This solution would be of low impact to the satellite design while providing very high accuracy orbit determination. A main consideration of this method is that a suitable ground segment needs to be in place.
- The Neuraspace optical telescopes [13] will be used to provide orbit determination of the objects on the rideshare launch, and in combination with Doppler shift assessments made during the first communications ground station pass, it can lead to an accurate orbit determination.
- LEDs on the satellite will be used to enhance on-ground visibility. The LEDs can be tracked by the Neuraspace optical ground stations.

While each of the above options comes with its pros and cons, all of them are considered sufficiently suitable to include them as part of the IOD. This will allow to demonstrate their performance as well as resolve any technical implications. It is expected that after the IOD, the most suitable solution out of the three can be selected on a mission-by-mission basis. It is important to note that the same solutions can be used throughout the entire mission to improve satellite surveillance.

6 COLLISION AVOIDANCE

Related to collision avoidance capability, a fault tolerant system will be included to ensure an appropriate reliability. As mentioned in Chapter 3, to execute CAMs successfully, nearly the entire platform is required, and therefore also nearly the entire platform contributes to its reliability.

Firstly, since it is seen that propulsion can have a relatively low reliability on CubeSats, the differential drag method has been assessed. This method requires the spacecraft to be able to change its drag area. The satellite design has a 12U form factor with deployable solar panels. One concern is that differential drag may not allow to manoeuvre fast enough to ensure compliancy to the requirements (<12h until manoeuvre implementation). Based on analysis, this method is only sufficiently performing at low altitude regions (<500 km) and at medium/high solar activity. Therefore, this method is only seen as a back-up.

The main method for the mission is to use a propulsion system in a fault tolerant set-up. The following systems will be included:

- The ARM-C thruster from Aurora. This is a small coin-sized thruster. Due to its size, it only provides sufficient Delta-V to perform collision avoidance manoeuvres. There is a large benefit in this as a lot of CubeSat missions do not require any propulsion, except for collision avoidance.
 - The CubeDrive thruster from Dawn Aerospace. This is a larger thruster (~1U) that may also be used for other orbital manoeuvres besides CAMs. The thruster is included such that there is a fault tolerant design and to provide flexibility in selecting secondary payload providers for the CleanCube mission, which may require a more extended use of propulsion.
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The mission will implement the use of an external service that will be on call 24/7 for collision avoidance and reach out to ISISPACE in case urgent action is needed. The urgent action may be to implement a manoeuvre; hence, a high availability is also required on the operator side at ISISPACE. For many low-cost missions it is difficult to be on call during weekends and/or nighttime (e.g. for university projects), therefore, a statistical assessment has been performed to assess the risk of being unavailable during the weekend and in the nights. It has been found that for a mission lifetime of 2.5 years, up to 4 CDMs may be missed if satellite operators are unavailable during the weekend and at nighttime. Therefore, a high degree of automation is anticipated for collision avoidance activities. During the mission, the intention is to demonstrate collision avoidance manoeuvres with incremental automation. Two key activities that can and/or will not be automated are (1) a final go/no-go from an operator before uploading a manoeuvre, and (2) alignment with the secondary satellite operator.

A last stringent requirement is to be able to perform collision avoidance manoeuvres 2 days after orbit injection. On first thoughts, it is considered a high-risk activity to manoeuvre so shortly after a rideshare launch, when most of the objects have not been properly identified yet (see Chapter 5). This is in accordance with launch authority requirements, e.g. on Transporter missions it is not allowed to manoeuvre within 7 days after the launch [9]. If such requirements are present, this takes precedence over the ESA requirements. But even if the requirement is to be able to manoeuvre 7 days after launch, this remains a key challenge as it requires the full AOCS including propulsion system to be commissioned. For the CleanCube mission, automated LEOP sequences with check-points in between are being assessed to allow demonstrating a 2-day timeline for manoeuvring. During the mission itself, the goal is to perform a small manoeuvre as soon as allowed by the launch authority, even if no critical CDM has been received.

7 PASSIVATION

To minimize the internal break-up risk, the platform will implement passivation of its onboard energy sources. The following systems will be passivated: the propulsion system, reaction wheels and the electrical power system. The aim is to provide a reliability figure, but due to the use of COTS this may be challenging (see Section 3). Fault tolerance is currently under study on the passivation of the EPS (designed in-house) to increase the reliability of passivation. The propulsion system and reaction wheels are third party products on ISISPACE satellites, so the passivation implementation will be discussed with the providers.

8 OTHER CONSIDERATIONS

Several less critical but nonetheless important items are preparation for removal, dark and quiet skies, mitigation of effects of collisions with untraceable objects and on-ground casualty risk. None of them are addressed in detail in this paper as they are not driving for CubeSat designs. Nevertheless, it is noted that the satellite design does account for these items.

9 CONCLUSION AND FURTHER WORK

It can be concluded that space debris mitigation for CubeSats is becoming increasingly important and touches a wide range of subjects in mission and satellite design. Certain items that are required for debris mitigation purposes will also result in a performance increase for the mission itself, e.g. reliability assessments and health monitoring. A variety of mitigation technologies has been proposed, including a drag sail, a plasma tether and space traffic management solutions, each offering unique benefits and challenges. While progress has been made in identifying these options, significant trade-offs remain to be addressed. Factors such as cost and operational complexity must be carefully balanced to ensure that mitigation strategies are both effective and feasible for CubeSat missions.

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