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THE ENVIRONMENTAL CUBESAT MISSION E.CUBE FOR LOW EARTH ORBIT DATA ACQUISITION

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ABSTRACT

The scientific objectives of the e.Cube missions are the development of the technologies and methodologies to increase spacecraft autonomy during collision avoidance manoeuvre, to characterise untraceable space debris objects to update and improve the debris environmental model, and finally, to model the upper atmosphere and the thermomechanical loads for more accurate re-entry prediction. These objectives address distinct but interlinked aspects of space sustainability, spanning the entire lifetime of any space mission.

The e.Cube satellite consists of a 12-unit CubeSat, flying in Low Earth Orbit to carry out three payloads to address the scientific objectives of the mission. In particular, the collection and analysis of the debris environment are based on a particle detection device in the frontal part of the CubeSat, while the characterisation of the upper atmosphere is based on a re-entry data collection device. Finally, the collision avoidance manoeuvre will rely on artificial intelligence.

Keywords: Space sustainability, space debris mitigation, collision avoidance manoeuvres, re-entry

1 INTRODUCTION

In the context of the Italian and European Space Situational Awareness and Space Traffic Management, the environmental CubeSat mission concept e.Cube wants to provide a significant contribution to the development of key areas to ensure safer and more sustainable access to Space [9][3]. The e.Cube mission concept is being developed at Politecnico di Milano, in collaboration with D-Orbit SpA, Temis, Università di Padova and Intelligentia. It aims at contributing to the advancement of technologies and methodologies for space debris mitigation and remediation [2]. In fact, the space surrounding our planet is densely populated by an increasing number of space debris, which poses a threat to the current and future access to space [1]. While debris objects larger than 5-10 cm can be tracked from Earth and avoided via Collision Avoidance Manoeuvres, smaller debris are not currently catalogued. Instead, statistical distributions are used to quantify the collision risk in different orbital regions and to define mitigation guidelines through long-term evolution models. Another aspect that the e.Cube spacecraft wants to tackle is the mitigation of satellites at the end-of-life via disposal manoeuvres. The uncertainties related to our limited knowledge of solar activity and its interaction with the atmosphere could make accurate re-entry predictions a challenging task.
From these premises, the scientific objectives of the e.Cube missions are the development of the technologies and methodologies to increase spacecraft autonomy during collision avoidance manoeuvre, to characterise untraceable space debris objects to update and improve the debris environmental model, and finally, to model the upper atmosphere and the thermomechanical loads for

more accurate re-entry prediction. These objectives address distinct but interlinked aspects of space sustainability, spanning the entire lifetime of any space mission.
The e.Cube satellite consists of a 12-unit CubeSat, flying in Low Earth Orbit to carry out three payloads to address the scientific objectives of the mission. In particular, the collection and analysis of the debris environment are based on a particle detection device in the frontal part of the CubeSat, while the characterisation of the upper atmosphere is based on a re-entry data collection device. Finally, the collision avoidance manoeuvre will rely on artificial intelligence.
The data and results of the e.Cube mission will be used to validate tools and techniques currently used within the space debris community: long-term evolution models for space debris, re-entry prediction, and to improve autonomous CAM for future space traffic management. In line with the idea of the e.Cube mission to contribute to the international discussion and cooperation on space debris mitigation, all the data and results of the on-board experiments will be freely shared with the whole debris community to be used for advancing the definition of space debris mitigation guidelines.

2 MISSION OBJECTIVES

The scientific objectives of the e.Cube mission address distinct but interlinked aspects of space sustainability, spanning the entire lifetime of any space mission. The first two objectives investigate the two sides of the same spectrum: the collision avoidance of traceable debris on one side and the improvement of the damage assessment from untraceable debris on the other.

2.1 Obj. 1 – CAM. Development, validation and testing of on-board algorithms for autonomous collision avoidance

To demonstrate autonomous collision avoidance capabilities during at least three relevant in-flight scenarios. This will be achieved by implementing the semi-analytical collision avoidance algorithms developed at PoliMi within the Manoeuvre Intelligence for Space Safety (MISS) software tool which couple the uncertainties in the environment model and orbit determination measurements [4][10]. Supervised artificial intelligence techniques will be employed for the planning and decision making in the operations for autonomous Collision Avoidance Manoeuvres (CAM). During the CAM in-flight experiment, synthetic conjunction data messages, simulating the possible collision threat with a debris, will be transmitted to the spacecraft and the CAM command module will autonomously decide, compute, and command the required manoeuvre to be performed [5]. An expected output of this objective is to advance the proposed CAM algorithms to autonomy level E4 E4 (goal commanding) according to "ECSS-E-ST-70-11C – Space segment operability".

2.2 Obj. 2 – DEBRIS. Characterisation of untraceable space debris objects to update and improve space debris environmental models (BRIS).

Obj. 2 will be fulfilled through the design of a particle detection device, which will characterise in-situ sub-millimetre level particles in Low Earth Orbit by sensing the frequency, mass, energy, and direction of debris particles. The Particle Detection Device (PDD) will be pointed in the velocity direction with 1-degree accuracy, to maximise the particle collection. To properly characterise the sub-millimetre debris (less than 1 mm) and meteoroids environment, the PDD shall collect at least 200 particles during the spacecraft operating life.

2.3 Obj. 3 – RE-ENTRY. Characterisation of the upper atmosphere for more accurate re-entry prediction and of the thermomechanical loads experienced by the spacecraft during re-entry.

Obj. 3 aims at reducing the model uncertainties on the post-mission disposal, and specifically on the re-entry phase, which arise due to the atmospheric modelling (especially the solar activity) and to the satellite demise and break-up process, a process for which little to no mission-related data is currently available. This objective will be achieved by arranging a distributed network of sensors inside the spacecraft that will measure the evolution of the acceleration, pressure, and temperature during the re-entry phase to record the mechanical and thermal loads suffered by the spacecraft. The experiment shall collect data in the region between 200 km and 100 km of altitude with a resolution of at least 10 km. The CubeSat shall transmit at least 125 kbit/s data to the ground until an altitude of 100 km.

3 MISSION ANALYSIS

The selection of the mission and spacecraft architecture, the operational orbit, and the disposal strategy are fundamental aspects for the e.Cube mission. The selected configuration is a 12U CubeSat, which can best accommodate the three payloads required for the fulfilment of the objectives.

Given the distribution of space debris in the LEO region, the selection of the operational orbit directly influences Obj. 2. In fact, different orbital regions are characterised by different debris fluxes, which have a direct impact on the number of particles that can be analysed by the payload. The debris fluxes as a function of semimajor axis and inclination were computed with ESA MASTER 8. The regions with the highest fluxes correspond to Sun-Synchronous Orbits (SSO).

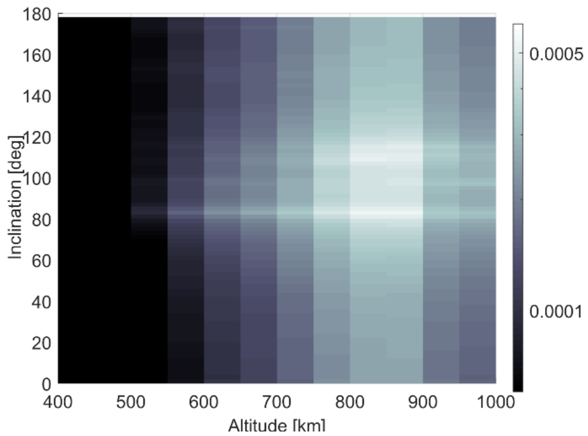

Figure 1. Debris fluxes for orbits between 400 km and 1000 km.

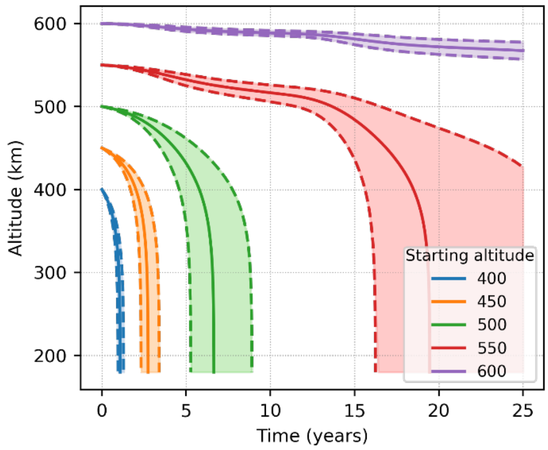

Figure 2. Natural decay time vs starting altitudes. Circular SSO orbits and solar flux uncertainties.

These orbits are the perfect candidates for a debris characterisation mission as they provide the possibility to collect a significant amount of data. Additionally, they have directional fluxes (concentrated in the front part of the spacecraft), which allow for a better detection of particles and design of the payload. Even if peak-flux can be experienced for orbits in the range 800-900 km, they would not be compliant, in case of failure of the on-board propulsion system, with the space debris mitigation regulations [6], that require a decay of the satellite within 25 years (see Figure 2). For this reason, the operational orbit will be a SSO below 550 km of altitude to be compliant with the space debris mitigation regulations even without disposal manoeuvre, which is a strong requirement, given the objectives and background of the mission.

The estimated number of particles impacts for a one-year mission for orbits between 400 km and 800 km with a 12U CubeSat (cross-section of 0.2 x 0.2 m^2) was analysed [9]. Particles with a diameter between 1 µm and 1 cm are considered as they are untraceable by current ground observation facilities [1]. Although a 500 km altitude orbit can detect less than half the total impacts with respect to an 800 km orbit, this amount is in line with the proposed target of 200 particles, while providing a safe EOL disposal considering a natural decay. Therefore, it is proposed an operational orbit of SSO type between 500 km and 550 km of altitude and a mission lifetime of at least 1 year, to reach the target of detected particles.

As Obj. 3 aims at characterising the re-entry of the spacecraft, it is important to design a proper disposal scenario. As the disposal phase is also part of the operational phase of the mission, it must be carried out within a timeframe that is compatible with the lifetime and reliability of CubeSat components. Therefore, a maximum disposal time of 6 months has been considered. The CubeSat will perform disposal manoeuvres to lower its perigee altitude and ensure the compliance with this requirement.

Another important aspect in view of the fulfilment of Obj 3 is the time spent in the lower parts of the atmosphere to maximise the acquisition of relevant data during the re-entry. The delta-V required for the disposal from the operational orbit with a single burn was computed [2]. The apogee altitude is the starting altitude of the operation orbit and the perigee is the target for the Re-entry Analysis Phase. It was observed that starting from a 550 km orbit, with about 100 m/s delta-v it is possible to reach a perigee of about 180 km. During Phase A, a more detailed disposal analysis will be performed that will also consider a multi-burn strategy, to better distribute the delta-V of each burn and reduce the effects of possible misalignments or failures.

4 PAYLOAD AND SYSTEM DESIGN

An overview of the payload technologies, their preliminary design, and their TRL is given in [9]. To increase the modularity and reliability of the payloads, each one of them will carry a dedicated on-board computer (OBC), which will process the acquired data.

4.1 CAM Command module

The payload for the CAM experiment is the CCM, a dedicated OBC implementing the algorithms for on-board CAM decision-making and design [9]. The CAM command will be handled by the OBC like a command sent from ground to perform a manoeuvre. The CCM will also log the key parameters related to the CAM decision-making and design process, and they will be transmitted to ground for analysis. The main objective of the CAM experiment is to advance the TRL and autonomy level of the on-board CAM algorithms and prove they can be used in future operational satellites. To this end, two criteria will be considered during the design of the CCM: 1) to make it as independent as possible from the platform, and 2) to clearly define the data interfaces with the OBC. The on-board CAM software is composed of 2 modules: the decision-making module and the CAM design module. The decision-making module determines whether a CAM is needed or not to keep the collision probability at close approach below a given threshold (typically 10-4) based on the sequence of CDMs and navigation information. It is based in machine learning algorithms, trained on ground with historical and synthetic CAM datasets. The CAM design module implements semi-analytical models for the efficient computation of maximum deviation or minimum collision probability impulsive CAMs2. The software implemented in the CCM will also include a supervision module.

4.2 Particle Detection Device (PDD)

In-situ space debris and meteoroids detectors developed so far are based on several physical principles. Among those, the most common systems employ strip-film conductive and piezoelectric materials. Piezoelectric detectors employ patches of piezoelectric materials (e.g. PVDF [7]) and measure the electric spike due to charge separation following the material deformation during the impact transient. The detection capability of piezoelectric sensors is currently in the range of 1 µm to 1 mm at a velocity of up to 10 km/s ; its sensitivity can be set by the conditioning electronics. Other systems proposed for debris impact detection come from direct heritage of scientific instruments for dust collection used in several space missions (e.g. Cassini, Stardust, BepiColombo, a detailed list is reported in Bauer et al. [8]) and employ acoustic sensors or piezoelectric panels to measure the momentum transferred to the payload during impact events. Such systems were developed to detect mostly dust and micrometeoroids with impact velocities and fluxes larger than those typical of space debris and require complex conditioning electronics.

As baseline, we will evaluate the use of a piezoelectric detector sandwiched with two layers of conductive stripes. This combination will make possible to both cross-validate the two sensors and extend the working range of the detector through a proper adjustment of the sensitivity of the two elements.

4.3 Re-entry Data Collector (RDC)

The RDC has two main objectives:

- The measurement of the density, below 200 km altitude,
- The measurement of thermal and mechanical loads in the final mission phase before the re-entry.

First, the knowledge of the air density in the thermosphere is crucial for improving the accuracy of the SW models used to estimate the re-entry trajectory of debris. A first approach is identified in the direct measurement of the density in situ, which was typically performed with expensive payloads, not suitable for a CubeSat mission. Nevertheless, a second indirect approach can be considered: the density can be computed also as an indirect parameter after the measurement of other quantities, in particular temperature and pressure. The latter approach is suitable for CubeSat mission, being the temperature and pressure sensors for CubeSat already available on the market, and they do not need any development or customisations. The second objective of the RDC is the understanding of the thermal and mechanical loads acting on the CubeSat during the latest phase of its life. Inertial Measurement Units (IMUs) based on Micro Electro-Mechanical Systems (MEMS) technology are the state-of-the-art and several Commercial off-the-shelf (COTS) options are currently available on the market. The inclusion of temperature sensors and strain gauges to measure the internal heat loads and displacements, respectively, will be considered in Phase A, when a more consolidated internal design of the CubeSat will be available.

4.4 System design

The preliminary mission design of the CubeSat for the main subsystems, considering the requirements arising from the payloads and the operational phases was presented [9]. When applicable, possible options for the equipment selection have been given, alongside the TRL of the components. Given the large availability of COTS with low prices and space heritage, the approach here is to select systems and components from Italian and European manufacturers. This reduces risks and allows to focus on the scientific and technological nature of the mission.

Structure and configuration

The structure of the spacecraft is a standard 12U CubeSat, which is compatible with the integration of COTS components. The preliminary configuration of the e.Cube spacecraft is shown in [9]. Some highlights are the presence of the PDD on the front face, and two deployable solar panels to guarantee the power production. On the back, the two main engines used for CAM and disposal manoeuvre are visible.

5 CONCLUDING REMARKS

Please email us if you do not understand these instructions or if you require any further information or assistance. We look forward to receiving your contributions for this conference.

The preliminary mission design for the e.Cube mission is presented. The e.Cube mission aims at contributing to the advancement of technologies and methodologies dedicated to space debris mitigation and remediation (1) to increase spacecraft autonomy in performing CAMs, (2) to support space debris modelling with in-orbit collected data about non-trackable fragment objects, (3) to characterise the atmosphere for more accurate re-entry predictions and the thermomechanical loads experienced by the spacecraft during re-entry.

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