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TeSeR – Technology for Self-Removal – Status of a Horizon 2020 project to ensure the Post-Mission-Disposal of any future spacecraft

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Abstract

One major source of new space debris are spacecraft (S/C) that are not removed from orbit after the end of their operational lifetime. Many regulations (e.g. ISO 24113) require the removal of S/C at the end of operation - known as Post-Mission-Disposal (PMD) - with a compliance rate of 90% to ensure that S/C do not become a new source of space debris. An analysis performed by ESA shows that the success rate of PMD in 2013 was in the range of about 50%-60%.

The goal of TeSeR (Technology for Self-Removal) is to take the first step towards the development of a cost-efficient, but highly reliable PMD module. This PMD module is to be attached to the S/C on ground and it shall ensure the PMD of the S/C at the end of the operational lifetime. This PMD module shall be scalable and flexible, thus, enabling the PMD of any future S/C in an Earth orbit. Ultimately, the gap between the required 90% PMD success rate and the current success rate can be closed.

The technological enhancements and developments required for successful PMD are addressed and analysed in TeSeR. The project's primary aims are

- to develop, manufacture and test an on-ground prototype of the PMD module,
- to develop three different removal subsystems (solid propulsion, electro-dynamical systems and deployable structures) for easy plug-in/plug-out implementation to the PMD module.

This is the first step to demonstrate the main aspects of such a PMD module and the required main technologies. The technical activities are supported by non-technical tasks, e.g. investigation of legal issues relating to a PMD module, execution of a market study and consideration of this technology as a leverage to advance ISO norms. This double tracked approach ensures that the technological developments are embedded into the needs of the space community right from the start.

Up to now the prototypes of the three removal subsystems have been developed, manufactured and tested with a common interface for implementation into the PMD module prototype. The PMD module prototype will be manufactured until summer 2018. Afterwards the removal subsystems will be integrated via the same interface.

Airbus is the coordinator (and potential launch customer) of TeSeR. The project is conducted together with 10 notable institutes and companies from all across Europe with experts who have been working in the space debris issue for many years.

Keywords: space debris, post-mission-disposal, autonomous, standardized, modular, prototype

Acronyms/Abbreviations

ADCS	Attitude Determination and Control System
ADR	Active Debris Removal
AHEP	Activation at Host EoL Phase
AIV	Assembly, Integration, Verification
C&DH	Command and Data Handling
CONOPS	Concept of Operations
DECP	Decommissioning Phase
EES	Electro-Explosive Subsystem
EMF	Electro-motive force
EOM	End of Mission
EOL	End of Life
FEA	Finite Element Analysis
GEO	Geostationary Orbit
GG	Gravity gradient
GS	Ground Station
HOLP	Host operational life phase
IADC	Inter-Agency Space Debris Coordination Committee
ICE	Ignition Control Electronics
IF	Interface
ISO	International Organization for Standardization
LEO	Low Earth Orbit
LEOP	Launch and early operation phase
LTS	Long-Term Sustainability of outer space operations
MPC	Multi-Purpose Concept
PMD	Post-Mission-Disposal
RBEDDS	Rigid Boom Electro-Dynamic Drag Sail
RS	Removal Subsystem
SAD	Safe-and-Arm Device
SDSS	Self-Deployable Deorbiting Space Structure
SRM	Solid Rocket Motor
STM	Space traffic management
S/C	Spacecraft
TC	Telecommand
TeSeR	Technology for Self-Removal
TM	Telemetry
TT&C	Telemetry, Tracking, and Command

1. Introduction

One solution to prevent the generation of new space debris is to ensure that future S/C are removed from orbit after end of operation However analysis show a huge gap between the required PMD success rate of 90% to an actual rate of 60%.

One possibility to close the gap is a PMD module. This module shall be autonomous, scalable and flexible thus it can be easily mounted on different S/C on ground (see also Fig. 1). At the end of operations of a S/C (be it intended or unintended) the PMD module is activated from ground and removes the S/C from its orbit so it does not become space debris. Due to its autonomy from the S/C and high reliability the PMD module improves the overall PMD reliability of the S/C.

The TeSeR objective is to develop, manufacture and test an on-ground prototype of an autonomous PMD module to remove S/C after end of operation. That includes the development of three different removal subsystems (solid propulsion, electro-dynamical systems and deployable structures) for easy plug-in/plug-out implementation to the PMD module. This enables the removal of different sizes of S/C in different orbits.

Those objectives are supported by mission analysis to identify further efficient removal subsystems and multi-purpose concepts to increase the benefit of technologies. Furthermore legal aspects of a PMD module and the assessment from an insurance point of view provide major non-technical information to ensure that a PMD module is embedded into the needs of the space community right from the start.

Autonomous de-orbit systems are also under development by D-Orbit (partner of the TeSeR project) with the focus on solid propulsion system. The additional benefit of TeSeR is that different removal subsystems can be implemented, thus increasing flexibility.

TeSeR started in February 2016 and runs until January 2019. Until summer 2018 the removal subsystem prototypes have been finished and the PMD module prototype is in the final integration phase. Afterwards the prototypes undergo different functional and environmental tests.

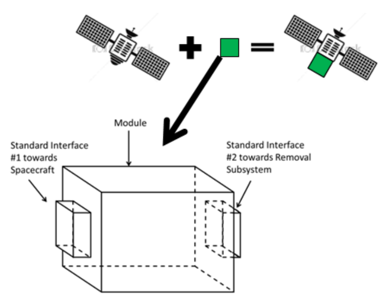

Fig. 1. Principle of the PMD module to be attached to the S/C (green box) and two standard interfaces

2. Mission Analysis

A comprehensive survey of de- and re-orbit techniques and concepts was completed and a taxonomy of approximately forty concepts was built. Twelve of the concepts from the taxonomy do not appear in previous literature. A qualitative analysis was carried out on all forty concepts, and a comparison matrix was built using twelve metrics for comparison. These metrics included, but were not limited to, technology readiness level, advancement degree of difficulty, mass and volume efficiency, and sensitivity to orbit eccentricity and inclination. Based on the project brief, using the comparison matrix the five most promising concepts for the PMD module were down-selected for further study. These concepts were: drag augmentation, solar sailing, electrodynamic tether, low thrust propulsion and high thrust propulsion. A further three additional concepts were also defined by considering combinations of the down-selected concepts. A quantitative analysis of the down-selected concepts was performed using a purpose built analytical analysis tool. This tool was designed to rapidly predict re-entry epochs of space objects, given specific mission parameters. The analytical nature of this tool allowed for a Monte Carlo analysis, resulting in trade-off analyses within and between the different concepts for various mission parameters.

Four different scenarios were considered in the quantitative analysis, de-orbit from Low Earth Orbit (LEO) in a short (1-year) or long (25-year) period, and re-orbit from Geosynchronous Earth Orbit (GEO) in a short or long period. The output of the quantitative analysis provided preliminary mission parameters, systems sizing and trade-off data on each of the down-selected concepts and combination concepts. The applicability of the concepts can be summarised briefly for comparisons sake by combining the parametric results and initial qualitative analysis, as can be seen in Table 1 and Table 2. In these tables each concept is denoted by its initial; D(rag), S(olar Sailing), E(lectrodynamic Tether), L(ow Thrust Propulsion), H(igh Thrust Propulsion), C(ombination Sail), LD(Low Thrust Propulsion and Drag) and HD(High Thrust Propulsion and Drag). Each concept is then colour coded for applicability, green being (H)igh, yellow (M)oderate and red (L)ow. Not NR denotes a concept which is not recommended and I denotes a concept which is inapplicable.

It can be seen that none of the down-selected concepts have been recommended for the 25-year re-orbit manoeuvre from GEO, as all of the systems considered are active systems, and the failure risk increases to an unacceptable level over the longer duration. From this analysis it was concluded that each system had its advantages, and challenges, no concept was universally useful. Therefore, recommendations were made on how each system could be used to its maximum potential and which systems were more effective than others in specific situations. The most prominent of these results was the need for the PMD to de-tumble the spacecraft prior to deployment of the removal system.

Table 1. Concept Applicability Comparison for de-orbit from Low Earth Orbit

	1 year							
	D	S	E	L	H	C	LD	HD
<1kg	H	*I*	H	L	M	H	L	M
1-10kg	H	*I*	H	L	M	H	L	M
10-100kg	M	*I*	H	M	M	H	M	M
100-500kg	L	*I*	H	M	H	H	M	H
500-1000kg	L	*I*	H	H	H	H	H	H
1000-2000kg	L	*I*	M	H	H	H	H	H
>2000kg	L	*I*	M	H	H	M	H	H
	25 years							
	D	S	E	L	H	C	LD	HD
<1kg	H	*I*	H	L	M	H	L	M
1-10kg	H	*I*	H	L	M	H	L	M
10-100kg	M	*I*	H	M	M	H	M	M
100-500kg	L	*I*	H	M	H	H	M	H
500-1000kg	L	*I*	H	H	H	H	H	H
1000-2000kg	L	*I*	M	H	H	H	H	H
>2000kg	L	*I*	M	H	H	M	H	H

Table 2. Concept Applicability Comparison for re-orbit from Geosynchronous Earth Orbit

	1 year							
	D	S	E	L	H	C	LD	HD
<1kg	*I*	M	*I*	L	M	*I*	*I*	*I*
1-10kg	*I*	M	*I*	L	M	*I*	*I*	*I*
10-100kg	*I*	M	*I*	M	M	*I*	*I*	*I*
100-500kg	*I*	M	*I*	M	H	*I*	*I*	*I*
500-1000kg	*I*	H	*I*	H	H	*I*	*I*	*I*
1000-2000kg	*I*	H	*I*	H	H	*I*	*I*	*I*
>2000kg	*I*	H	*I*	H	H	*I*	*I*	*I*
	25 years							
	D	S	E	L	H	C	LD	HD
<1kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
1-10kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
10-100kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
100-500kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
500-1000kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
1000-2000kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*
>2000kg	*I*	NR	*I*	NR	NR	*I*	*I*	*I*

3. Concepts of a PMD-Module

The definition of different concepts for a PMD module comprised the following steps:

- derivation of a comprehensive set of system, subsystem and functional requirements
- definition of a consistent operational and autonomy concept for four different scenarios
- definition of common interfaces towards both, the RS and the S/C
- definition of a system architecture to satisfy the requirements.

Design Variables

To facilitate the design of the PMD module at this early stage, we define several host-S/C classes taking into account three host-S/C size classes (500, 1000, and 4000 kg) and two orbit classes (700 and 1200 km altitude).

In addition to these design classes, another design variable is the Removal Subsystem (RS) used. The strategy for removal from orbit (de-orbit or re-orbit), and thus which RS can be used for each case is defined by the original orbit of the host-S/C. We assume that a host-S/C on the LEO orbit will be de-orbited, while a host-S/C on the high LEO orbit can be either de-orbited or re-orbited to a higher circular graveyard orbit.

Furthermore, on a functional level, a basic and three advanced design cases were defined to account for the novelty of the development:

- a basic case for short-term development completely controlled by a ground operator;
- advanced #1 that offers additional benefits for the operators like collecting health information about the S/C and sending it to ground;
- advanced #2 that offers health checks of the S/C and status detection by implementing own sensors and the most
- advanced # 3 including autonomous status detection of the S/C, implementation of an independent removal triggering process and subsequent autonomous performance of the PMD operations.

For details of the autonomy concept including the status detection process, refer to [1].

The basic operational and autonomy concept is aimed at “triggering” the removal from orbit and the passivation of the host spacecraft (i.e. safely disabling) at the end of its operational lifetime. It was found that future spacecraft using the PMD module technology will be required to be designed to be self-passivated. The PMD module itself will also have to be passivated having performed the removal operations unless in case of a direct, controlled atmospheric re-entry. The operational autonomy concept foresees – for the foreseeable future – a human operator “in the loop”. However, in the case of e.g. satellite mega-constellations, autonomous removal presents a viable business case as it can significantly reduce removal operations cost.

Concept of Operations

The top-level CONOPS for the PMD module shown in Fig. 2, and it can be broken down to the following phases:

During **PMD module dormant mode** the host-SC is performing its nominal operations. The PMD platform as well as the RS are dormant. Weekly the PMD platform turns on by timer in order to be ready to transit to removal mode if commanded by ground.

PMD module wake up mode is similar to dormant mode operations, with the difference that the host-SC has gone into fault resolution mode. We have to assume therefore that any resources used by the host-SC (e.g. power for heaters) are no longer available and must be provided by the PMD platform itself.

The **Removal preparation operations** phase comes once end-of-mission or end-of-life of the host-SC has been confirmed by the ground operators, and the host-SC has passivated itself. The PMD platform then detumbles the host-SC and brings it to the right attitude for RS deployment. The RS prepares itself for deployment in the next phase.

In **Removal operations** the RS is deployed and imparts the ΔV for removal from orbit. The PMD platform supports the RS operation and maintains the correct host-SC attitude for removal. It is currently under investigation whether and how any of the RSs can be used for attitude control during removal. After removal (either successful or unsuccessful), and in case the host-SC will remain in orbit after removal, the PMD module itself will be passivated.

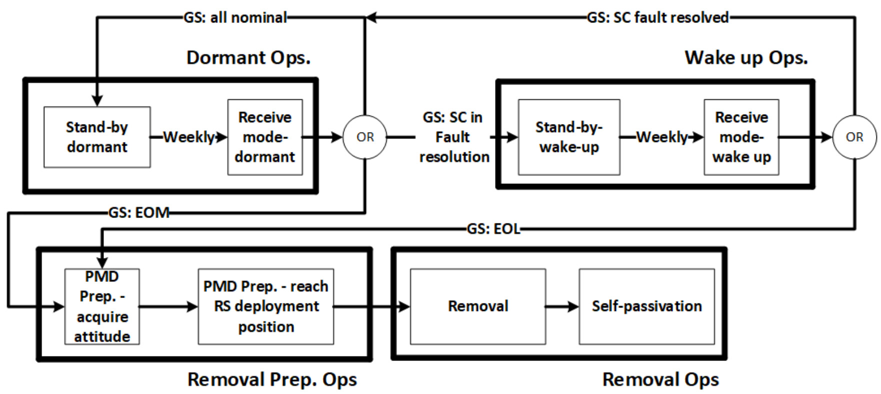

Fig. 2 Top-level Concept of Operations (CONOPS) for the PMD module operations. See text for detailed description.

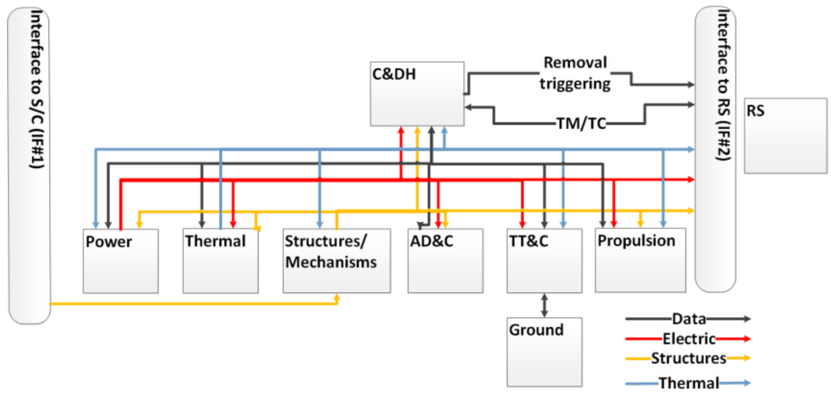

Fig. 3 A functional block diagram of a version of the PMD module, its subsystems, the connections between them, and the two interfaces to the host spacecraft and the removal subsystem (RS) respectively.

Functional Architecture

A diagram of the basic subsystems for the PMD platform, as well as the interfaces to the host-S/C and the RS can be seen in Fig. 3.

A particularity of the TeSeR project is that the PMD module will have to be attached to S/C of different sizes and flying in different orbits, and must be able to support the operation of each of the three different RSs. These multitudes of design cases was noticeable during the requirements analysis for the PMD platform, resulting in a "core set" of functional requirements common to all design cases, sets of additional functional requirements particular to different design cases, as well as modified performance requirements for some design cases. This resulted in different versions of the PMD module subsystems, or "modules". By combining these modules we can then create a PMD module for each of the variant removal cases. We also investigated the possibility for sharing specific functionalities with the host-SC but concluded that for the initial iterations of a future TeSeR PMD module emphasis should be given in independence, simplicity, and robustness.

4. PMD module prototype

The PMD module prototype consists of an autonomous nanosatellite platform based on current standard subsystems, where the different removal subsystems can be integrated and tested. Its main design criteria are:

- The PMD module shall provide the needed architecture to support the different removal subsystems, such power bus, data bus and on-board data processing.
- The PMD module shall control the activation of the deorbiting mechanism based on the removal subsystems requirements.
- The PMD module shall be able to accommodate any of the three removal subsystems ensuring compatible mechanical, electrical and data interfaces.
- The PMD module prototype shall be designed as a CubeSat following the standard nanosatellites specifications and products as much as possible.
- The PMD module prototype shall minimize the number of non-fully qualified products to leave the removal subsystem as the main driver for the qualification test campaign.

No special considerations regarding the orbit or the launcher shall be mentioned, like the launch interface or the parameters depending on the orbit since no flight opportunity is included in the present project.

The selected hardware for the PMD module prototype is the GomSpace 6U platform which, together with a customized interface board, shall be able to provide power, communication and software architecture for the success of the removal modules functionalities.

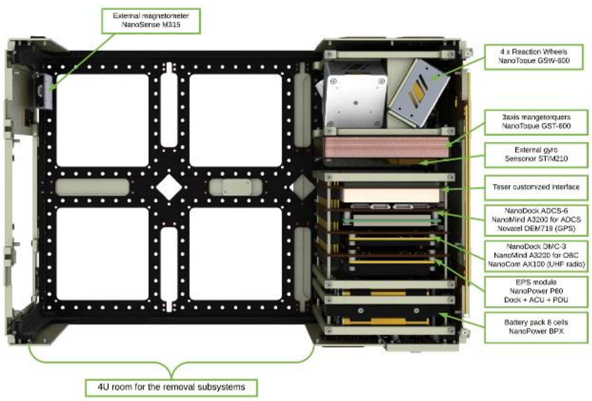

Fig. 4 Render of the Teser PMD module prototype with the main platform avionics.

The same PMD module prototype is accommodating sequentially each of the removal subsystems, and the complete system shall be functionally tested in all three cases. This flexibility in the platform interface has been reached thanks to the multiple configurable output power lines provided by the GomSpace NanoPower P60 and the numerous communication buses available in the main on-board computer, the GomSpace NanoMind A3200. The 6U structure has also been customized ensuring the proper deployment of all the elements and avoiding mechanical interferences.

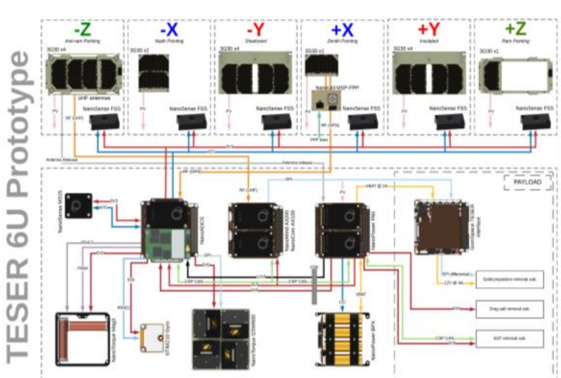

Fig. 5 System diagram of the Teser PMD prototype including the three difference interfaces for the removal subsystems.

Fig. 6 Render of the Teser PMD module prototype accommodating the three removal subsystems: The Solid propulsion (to the left), the EDT (in the centre) and the drag sail (to the right).

The completed PMD module prototype, together with the removal subsystem based on drag sail technology, shall be flight validated under a full environmental test campaign covering the levels of most of the available launch opportunities and LEO (Low-Earth Orbit) space environment. In this way, the system is completely qualified and verified for the flight in a possible next phase of the project.

The following tasks present the remaining activities for the prototype of the TeSeR project:

- Finalizing the manufacturing of the PMD standard subsystems provided by GomSpace;
- AIV campaign – Assembly, Integration and Verification of the PMD prototype, integrating each of the Removal Subsystems;
- Environmental Test Campaign, including Structural, Mechanical and Thermal Tests;
- Preparation of Hardware delivery to European Commission;
- Post-test Reports, presenting the results of the AVI and Environmental Test campaigns.

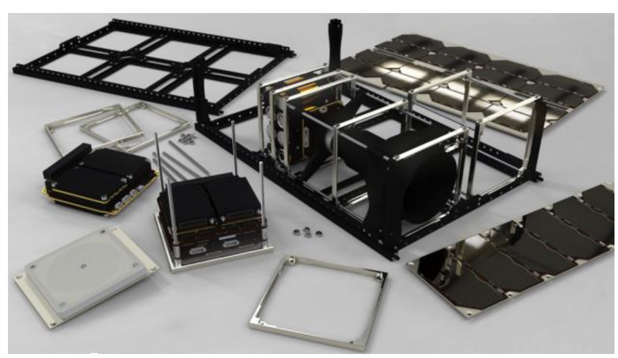

Fig. 7 GomSpace 6U platform used for Teser project with, the structure, some of the advanced avionics systems and modular structure.

This project will conclude showing the feasibility and technology capacities to develop a modular removal module with different technologies. The technology shall be delivered ready for flight with the competition of the AIV phase.

5. Removal technology: Solid propulsion

The Controlled Removal Subsystem is a smart device which is able to provide a predetermined Delta-V for orbit change. The RS is characterized by a modular architecture: each function is allocated in discrete units to be fitted on the main structural bus, to allow rapid reconfiguration and customization according to the required degree of self-reliance requested by the customer. According to the specific mission requirements, the Controlled RS may be characterized by different architectures. In the frame of this project, the addressed configuration includes the following subsystems: the Electro-Explosive Subsystem (EES), and the Solid Rocket Motor (SRM).

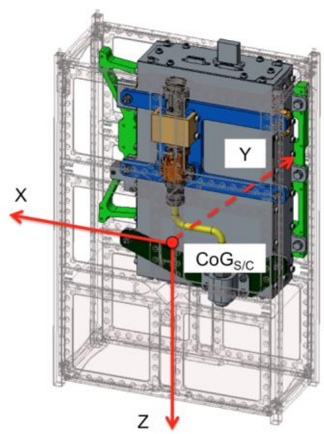

Fig. 8 D-Orbit Controlled RS integrated into 6U Structure

The **Electro-Explosive Subsystem (EES)** comprises a Safe and Arm Device to prevent inadvertent ignition of the solid rocket motor, and the relative commanding electronics. The EES is a subsystem dedicated to the ignition of the SRM. One EES unit per SRM is needed (or for each pulse of the SRM, in case of multi-pulse SRM) and features the following subsystems:

The **Safe-and-Arm Device (SAD)**: an electromechanical assembly featuring a mechanical barrier between the igniter (Electro-Explosive Device, EED) and the pyrotechnic chain of the SRM. The SAD has a mono-stable mechanical lock/unlock mechanism to avoid unwanted movements of the arming mechanism, as well as external manually operated safety provisions (remove-before-flight) to assure a disarmed condition during handling. Overall, two mechanical barriers are present, plus the manual provision.

The **Ignition Control Electronics (ICE)**: the ICE in an electronic board featuring a space-grade FPGA to control the overall EES actuation. On the same board resides the Firing Circuit, with four electrical barriers plus manually-operated provisions (both remove-before-flight and plug-before-flight) assure extremely high safety levels.

The EES is designed according to MIL-STD-1576 (USAF) standard and with reference to ECSS-E-ST-33-11C (i.e., Explosive Systems and Devices).

The **Solid Rocket Motor (SRM)** provides the necessary propulsive impulse. This module also includes thrust vector control (TVC) capabilities, when required by the specific mission.

Fig. 9 Close-up of the SRM (D-Orbit's RS prototype)

Operationally speaking, the RS is completely subject to the commands issued by the PMD Platform. The nominal mission is divided into the following phases: Launch-and-Early-Operations Phase (LEOP); Host Operational Life Phase (HOLP); Activation at Host EoL Phase (AHEP); Decommissioning Phase (DECP). The system may operate in the following modes:

- Housekeeping Mode: for housekeeping and testing purposes. Motor fire is disabled. This housekeeping acts as safe-mode as well.
- Fire Mode: for the actual motor fire. In this mode, the TVC, if present, is active for thrust direction control and the solid motor fire sequence is enabled (the actual execution of the sequence requires a series of specific commands, though).

The D3 is turned on by powering the power lines of the EESs and TVC. The nominal mission operations sequence is briefly described hereafter. Deviations from these phases may be possible depending on the host S/C mission and operations.

- Launch-and-Early-Operations Phase (LEOP)
  At launch, the RS is completely powered OFF. At Platform commissioning, the RS is powered on and boots the first time, transitioning to HK. The Platform performs an overall check of RS functionalities by performing a diagnostics on all

subsystems. At the end of these checks, the RS is turned OFF.

- Host S/C Operational Life Phase (HOLP)
  During HOLP, the RS is nominally turned OFF. The system is turned on every defined time set, set into HK, and checked for functionality.
- Activation at Host S/C EoL Phase (AHEP)
  At AHEP, the Platform turns on the RS. The RS is transitioned to HK, and functional tests are performed
- Decommissioning Phase (DECP)
  When the host S/C is finally set for decommissioning, the DECP begins with the acquisition of the attitude for the decommissioning maneuver by means of host S/C ADCS. The Platform transitions the RS to FR mode. The maneuver is performed, with RS in FR mode. After maneuver, eventual passivation is performed in FR mode (if needed by configuration, mission and decommissioning host policy).

The RS Power interface is DC 28 V: connections for two (nominal and redundant) power buses. The RS has no autonomous data handling system since it is subject to the PDM platform. It interfaces to the platform with a TTC-B01 serial data interface (one per EES).

The Controlled RS prototype is mainly focused on the EES, which is the most safety critical component of the assembly. The EES is the electro-mechanism that includes multiple barriers to prevent inadvertent ignition of the SRM. As included into the prototype, in the inert configuration, the pyrotechnical component (i.e., the EED) is substituted with a mechanical equivalent inert component. Hence, the prototype is configured as follows: one EES, in the inert configuration; one SRM mock-up (i.e., inert configuration).

6. Removal technology: Drag sail

Drag augmented PMD has been considered as presented in [2, 3, 4] and its benefit has been analysed in TeSeR in the re-entry analysis in section 9. In 2014 a proof of concept prototype developed by AAU using the Self-Deployable Deorbiting Space Structure (SDSS) [5, 6] concept was implemented in a GomSpace NanoRacks-GOMX-2 launched [7]. Although the launch failed catastrophically the satellite was recovered and the SDSS modules was activated successfully. Based on the experience and knowledge gained from this research emphasis in TeSeR has been to increase the number of foldings of the drag sail in order to increase the folded to unfolded area ratio thus increase the drag sail area and thereby decrease time to re-entry. As the SDSS principle is based on elastic strain energy stored in a highly flexible elastic frame during the folding process it has also been a focal point to be able understand and model the mechanical behaviour, i.e. stress levels throughout the folding process, see in Fig. 10.

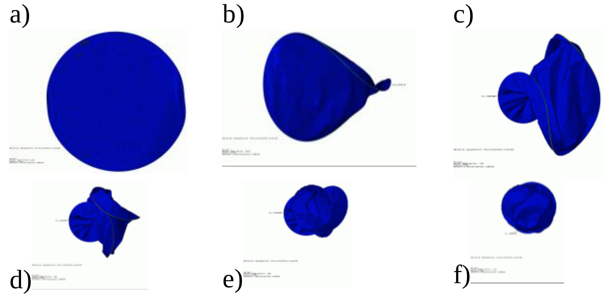

Fig. 10 a) - f) folding of the drag sail 3 times. The highly non-linear folding is achieved by activating bifurcations in the flexible frame. The flexible frame has a rectangular cross-section.

As the number of foldings increase the stress level increases momentarily in the highly elastic frame thus increasing the risk of a material rupture or permanent deformation thereby causing a failure to deploy the drag sail. The research performed AAU in this project have established numerical models of the folding of a highly flexible elastic frame without sail modelling 3 and 9 foldings with contact analysis enabled. Both nonlinear implicit and explicit transient dynamic Finite Element Analysis (FEA) has been obtained and validated with model tests [8]. The results obtained shows high peak stress levels, i.e. maximum principal stresses of 1600MPa at time 0,75s and at an angle of 270 degree during folding [8, 9]. For the foldable frame a stainless steel, austenitic, cold rolled strip, Sandvik SSS-11R51-0.5-19, Proof Strength (Yield Strength) Rp0.2=1824 MPa, Rm=1900MPa has been chosen for the TeSeR project as this material can withstand the high stress levels determined. Thus, 9 foldings have been achieved both in FEA and in tests as well as a successful deployment as an important achievement by the TeSeR project. Thus, by implementing 4 SDSS modules in the prototype module 6U CubeSat frame provided by GomSpace a drag area of 125663,71mm2 for each drag sail is achieved which is more than the recommended by research performed in TeSeR (see section 9). In order to further understand and model the deployment for the drag sail a full nonlinear FEA model including the drag sail and sail tunnel have been established. The FEA is performed using nonlinear transient dynamic FEA with contact included allowing the modelling of the self-contact during the folding process. The FEA are highly complex and seldom seen in research on space structures. Comparison between FEA results and tests shows good agreement on the dynamical behavior of the drag sail during unfolding. However, in tests aerodynamics have a huge damping impact on the unfolding/deployment of the drag sail as can be seen in the high speed footage of the test deployments.

Having obtained detailed knowledge on the mechanical behavior of the folding process a SDSS module have been designed for the TeSeR project as seen in Fig. 11.

Fig. 11 The SDSS module with an unfolded/deployed sail.

The chosen concept is hinged which reduce the number for contact points during deployment and thereby friction. The release assembly has the function to lock the folded sail in the stowed condition until removal is activated. There are 2 pre-tensioned wires attached to the cover which close the SDSS module and protects the folded and stowed sail. Each wire is guided to pass over a resistor. When removal is initiated a current is switch on and the resistor heats up and cuts each pre-tensioned wire thus releasing the folded sail thereby deploying the SDSS. The cover assembly has the function to store and interface/connect the removal system to the PMD module or the S/C directly. There is a cover and housing. The cover closes the SDSS module, i.e. locks the drag sail in the folded state, and protects the drag sail during mission. The cover is hinged to the housing in order to force the cover to open separately/independently in respect to the drag sail deploying to avoid collision/entanglement between the two systems. The cover is opened using a torsional spring in the hinge. All components are mounted to the housing/base. The drag sail is connected by a clamp hinged to the housing. The drag sail is hinged to the housing in order to force the drag sail to deploy away from the S/C. The TeSeR project has allowed AAU to further research the chosen drag augmented removal system and establish a foundation for further improvements and optimizations of the principle, i.e. self-deployable structures. The main findings obtained, i.e. parameters for elastic foldable structures (highly flexible elastic structures) are identified, an-isotropic materials such as Fiber Reinforced Polymers (uni-directional) exhibit delamination during unfolding due to shear stress effects, modelling of highly elastic structures with self-contact have been achieved, known stress levels allows for testing of relaxation in self-deployable space structures. Finally a prototype has been implemented into a GomSpace module 6U CubeSat frame.

7. Removal technology: EDT

An electrodynamic technique for on-orbit force generation was analysed which would lead to the uncontrolled removal of the host spacecraft from orbit. Because the re-entry is uncontrolled, the system is designed for spacecraft under 1 tonne in mass to reduce the risk of material surviving to impact the ground.

Electro-dynamic tethers (EDTs) have long been proposed as a potentially effective means of de-orbiting spacecraft – particularly from low Earth orbit (LEO) [10]. Such systems typically rely on the Lorentz force developed in a long conductive tether (either a wire or tape) cutting through the Earth's magnetic field due to the host spacecraft's orbital motion. The electro-motive force (EMF) thus generated drives a current through the tether, which is returned through the local ionosphere by some form of active or passive plasma-contacting electrode. The Lorentz force generated is related to the vector-product of the spacecraft's velocity $\underline{\boldsymbol{v}}$, relative to the local magnetic field, and to the strength of that field, $\underline{\boldsymbol{B}}$.

In self-powered mode, the current flow is such as to oppose the motion of the spacecraft, and thus an electro-dynamic drag is developed. This removes energy from the spacecraft's motion, causing it to lose altitude. As such, EDTs have the advantage of being both self-powered, and propellant-less. Additionally, if required, electrical power could be generated by the host spacecraft and a current forced through the tether by an opposing EMF such as to boost the orbital energy and thus take the host to a higher orbit.

However, to be effective, the EDTs, typically, have to be several km long, and be very thin to save mass. This makes them vulnerable to breaking due to micro-meteorite and debris impacts. As the force generated depends on the local magnetic field strength, they are best operated in the stronger magnetic field associated with lower altitude orbits. Also, being flexible, the tethers derive their stability through the gravity gradient (GG) effect, which also is most effective in LEO, and which causes the tether to take up a near-vertical orientation, depending on the relative strengths of the GG and Lorentz forces. Long thin EDTs have proven to be problematic to deploy, and in reality, are subject to complex dynamics, due to their flexible nature

In TeSeR, we propose an alternative form of EDT, where the "tether" element is replaced by much shorter (15m-150m) rigid electro-dynamic booms in a "bar" or "cross" formation, and where active solar-generated electrical power is used to pass a current through the booms. The main advantage of such a structure is that, for satellites in polar orbits, the stiff horizontal booms lead to a larger Lorentz force compared to a GG stabilised vertical boom (Fig. 12). Also, we believe the deployment should be more reliable and the attitude control should be greatly simplified (compared to the use of a flexible tether). SSC has experience in deploying metal tape booms (as used on its UoSAT spacecraft), rigidized inflatable booms and bi-stable rigid composite booms – as demonstrated most recently on the QB-50 InflateSail spacecraft [11].

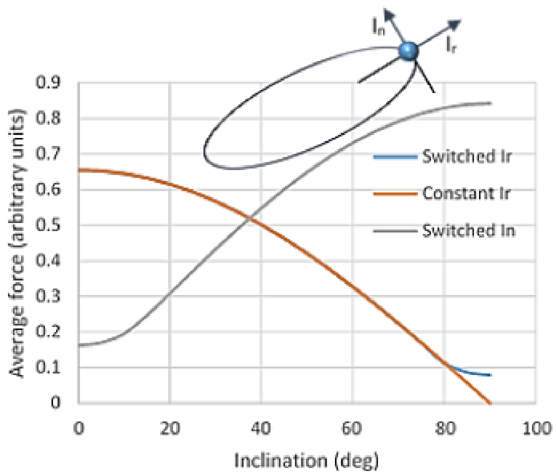

Fig. 12 Average drag force per orbit (arbitrary units) for horizontal (In) and vertical tethers (Ir) as a function of the orbit inclination (1000km altitude)

The TeSeR booms have thermionic dispenser cathode electron emitters mounted on their ends to act as the cathodes, and when positively biased (~200-300V) the bare conductive booms can act as electron collector anodes. The booms are switched from anode to cathode mode according to their orientation in the magnetic field to maximise the retarding force. In addition, by using an electrically conductive drag-sail to act as a large area electron collector, we also get the benefit of enhanced aerodynamic drag at lower altitudes. Thus, the system is in practice a hybrid - the Rigid Boom Electro-Dynamic Drag Sail (RBEDDS) [12].

To power the system, deployable solar arrays are incorporated into the sail deployment mechanism.

Fig. 13 shows the relative effectiveness of the different components of the hybrid system with altitude.

The system is highly scalable, according to the mass of spacecraft which it is intended to work with. Table 3 shows the sizing of the various elements for a maximum altitude of 1500km and a maximum orbital lifetime of 25 years assuming a twin boom system and equatorial orbit.

To test the electron emission scheme, an argon gas plasma source was designed and fabricated and mounted inside an ultra-high vacuum chamber to simulate the ambient ionosphere space plasma. A commercially available dispenser cathode thermionic emitter was set up with high voltage (240V) electric bias and with an isolated heater power supply (~6W). This was operated exposed to an argon plasma, which was monitored using a Langmuir probe. Using this set-up, we achieved electron emission, with a measured maximum emitted current of ~ 7mA. The lifetime of the cathode is quoted as 100,000 hours which is equivalent to ~11 years of continuous operation in space.

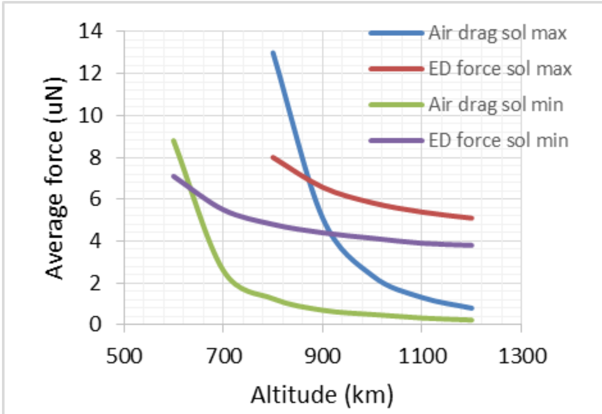

Fig. 13 Comparison of the average drag force (for a sail of 8m^2) with the ED force obtained with a 30m long vertical EDT system (2 booms 15m each) operating with 30 mA current flow (equatorial orbits)

Table 3. System Scaling

S/C Mass (kg)	Boom Length (m)	Sail Area (m^2)	Solar Array Orbit Average Power (W)
10	2 x 15	8	20
50	2 x 25	24	60
500	2 x 80	80	200
1000	2 x 115	100	270

A breadboard demonstrator of the complete system is currently in development based on the GOMSpace 6U CubeSat structure. The RBEDDS system occupies 4U, and is intended to demonstrate the deployment of the sail and EDT booms, as well as the electrical biasing schemes. Fig. 14 shows the configuration.

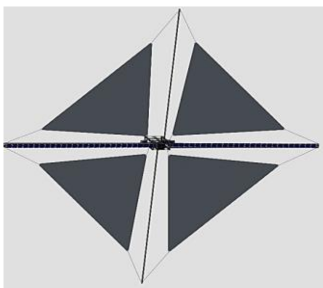

Fig. 14 6U CubeSat structure based ground demonstrator

8. Multi-purpose concepts & ISO

A feasibility assessment of a concept for a deployable multi-purpose space debris mitigation apparatus has been performed [13]. The idea behind the apparatus is to expand the potential benefit of a post-mission disposal technology by introducing other important features into the design. Specifically, such a device, when integrated with the TeSeR removal module on a host spacecraft, could be designed to provide at least the following capabilities:

- shielding against impacts from orbital debris and meteoroids during the mission life of the spacecraft;
- deorbiting from the low Earth orbit (LEO) region after the end of mission of the spacecraft;
- sensing of orbital debris and meteoroid impacts.

The design of the Multi-Purpose Concept (MPC) can be realised via a framework of deployable panels made from a debris shielding material. At the start of a mission the panels are deployed in a folded configuration with a large stand-off distance to protect the spacecraft against impactors up to several millimetres in size. Thus, the MPC acts as a highly effective multi-layered debris shield.

Once the spacecraft mission is completed, the MPC transforms into a large area drag-augmentation device with the potential to deorbit a spacecraft of up to 1,000 kg mass from 800 km altitude in less than 25 years. Thus, the area of the MPC is large enough to perform the spacecraft disposal in accordance with the IADC space debris mitigation guidelines [14] and ISO 24113 [15], without causing a significant increase to the area-time product.

During the mission phase, and possibly also the disposal phase, a network of sensors mounted on the panels collect data on impacts from space debris and meteoroids. This real-time information is useful both to operators and those endeavouring to improve models of the small debris population in LEO.

Other important MPC capabilities, besides those listed above, have also been investigated and show significant promise. The next step in this work is to trade-off design options for the MPC and start developing a prototype.

In another part of TeSeR, PHS Space will review all documented outputs of the project to identify possible new design rules for implementing the TeSeR post-mission disposal technology on spacecraft. The rules will be compared with existing ISO norms to see where changes or improvements might be made. For example, if the TeSeR removal module is considered to be an integral part of a host spacecraft then current passivation requirements in the ISO standards, especially ISO 24113, may need some adjustment. This could be necessary to allow the TeSeR module to remain operational after the spacecraft end-of-life. Alternatively, if the TeSeR module is regarded as an Active Debris Removal (ADR) device (i.e. functionally independent from the host spacecraft) then, since there are currently no ISO standards for ADR, any design rules from TeSeR could be an important input for the development of such norms.

9. Re-entry simulations

At present, there are two classical re-entry scenarios for spacecraft: controlled and uncontrolled re-entry. In a controlled re-entry scenario, also known as targeted re-entry, a final de-orbit thrust manoeuvre gets the spacecraft onto a well-selected re-entry trajectory directing any surviving fragments into an uninhabited target area. In contrast, if a spacecraft is entering the atmosphere just because of its natural decay without any deliberate actions, surviving fragments could impact anywhere within the latitude band defined by the orbit inclination. This is called uncontrolled re-entry.

The relatively new idea of semi-controlled re-entry is currently defined by ESA as phasing the location of the impact track on the ground. The probable debris fallout zone can extend for a length that can be smaller than one orbit ground-track, but that can also reach several orbit ground-tracks.

Semi-controlled re-entries might be of interest for satellites whose casualty risk would exceed the 10-4 in an uncontrolled re-entry, but which do not have the thrust capabilities for a controlled re-entry, e.g. by means of electric propulsion or by drag sail and tether assisted removal concepts. Therefore, the primary objective of semi-controlled re-entry is to minimize the on-ground casualty risk compared to an uncontrolled re-entry. In order to achieve this, two principle questions have to be answered: How long is the actual debris fallout zone? Where to direct this fallout zone?

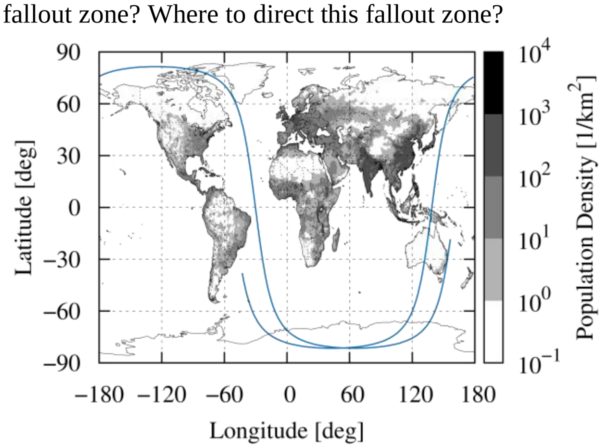

Fig. 15 Optimum arc of 7,000 s length with inclination 98.5 deg

The first question is actually an uncertainty quantification problem. The following examples assume an arc length of 7,000 s, currently considered conservative for a drag sail assisted semi-controlled re-entry. The second question addresses an optimization problem. Fig. 15 shows the optimum solution for an inclination of 98.5 deg and an arc length of 7,000 s. The mean population density within the affected impact zone is only 0.4% of the value for uncontrolled re-entry. This corresponds to a risk reduction of 99.6%, almost as effective as controlled re-entry.

This shows that semi-controlled re-entry is an effective method to reduce on-ground casualty risk. Further details can be read in [16].

10. Legal aspects

Post-mission disposal (PMD) as mandatory requirement

The TeSeR project provides several key tools in answering some of today's challenges regarding debris. These would see the introduction of a new enforceable duty ensuring that PMD is incorporated within a broader, regulatory regime for S/C operations. This would include sanctions for failure. TeSeR can deliver core input about how best link technical standards with the existing body of legal rules and other instruments governing outer space activities. There is a need for re-formulation of applicable rules into a comprehensive technical and legal architecture that provides accessible solutions for long-term sustainable space operations.

Technology such as TeSeR should be included within its scope as a reference for after-life debris removal. Further initiatives are currently being pursued under the heading of space traffic management (STM). STM would bring together legal and technical rules into a regime, ensuring safe access into outer space, safe operations in outer space and safe return from outer space to Earth. Only once such a regime is in place can the community of stakeholders ensure long-term safety of space operations. PMD provides an opportunity to integrate such a model into PMD operations, and should form a core element.

The situation is compounded because the outer space environment has no legal status protecting it from the ongoing creation of debris. Although a part of the global commons, outer space has no formal legal personality. The only rules in force to protect this environment at international level are of technical nature. The existence of debris is not an unlawful state. The incentives to alter this status quo, including systems to assess fault for damage in outer space, are complex. They require clear policy commitments from all stakeholders to introduce and comply with binding legal and technical rules of the road. Through the requirement to adhere to the ISO 24113 norm at national licensing level, debris creation has, at least until now, been tackled at a primarily technical level of compliance. With some rare exceptions, there are no legal consequences for failure to adhere to the technical norms. In the absence of fault, these do these exist at international level. TeSeR, if integrated into a larger format of rules that link fault with failure to comply with technical standards, could see this change.

Long-Term Sustainability Guidelines

Over the past few years, there has been a discussion about rules relating to debris mitigation and remediation, also in the context of space traffic management (STM). All these activities fall within the broader goals of securing the Long-Term Sustainability of outer space operations (LTS). The COPUOS Working Group on the LTS Guidelines has developed a set of 21 voluntary mitigation guidelines, containing a set of optimum best-practice measures for the future. As instruments of soft-law, these guidelines call for voluntary self-adherence.

LTS Guideline B 22 addresses the importance of including debris management and remediation within the heading in the context of non-registered objects. The Guideline indicates that debris, or lack of functionality, is not seen as a reason for relinquishing title to such objects. This will be of assistance in developing rules for space traffic management STM.

Way forward

TeSeR opens the way for ensuring that mandatory debris-removal technology of the S/C can be integrated into a farther-reaching regime for space-traffic management. It will allow the regulators to link any failure to rely on core elements of space traffic regulation with fault, as well as deliver a standard or gauge for fault liability. Standard-setting and achieving a measure for imposing fault liability will serve the common interest in the short, medium and long term for ensuring sustainable space operations.

11. Insurance aspects

A comprehensive risks assessment and insurance aspects analysis has been performed in order to design a bespoke methodology to be used by the PMD module(s) manufacturers to manage the risk environment and to put the program stakeholders in the position to make the most educated decision with respect to the level of risks they will be targeting with corresponding implication in terms of risk retention, risk transfers and associated costs and benefits. More precisely, the study aimed to provide TeSeR technical teams a priori with the necessary information to make critical design choices on the spacecraft and its mission, assess the level of testing and qualification to be implemented and understand and quantify the trade-offs in terms of necessary margins and redundancy to match the PMD module(s) expected reliability. The objective being to assess and define the TeSer stakeholders risk appetite and their costs constraints in interaction with the market needs and demands.

Objectives

The risk and insurance analysis has contributed to the elaboration of a risk mapping methodology that is to identify and quantify the PMD technical risks, and possible mitigations / management approaches. The specific purpose of this methodology is to identify and define TeSeR performance criterias and confront them to potential technical solutions and scenarios in view to analyse all the potential impacts and thus advance towards the construction of an evaluation and selection process for the PMD mission that is the purpose of Beazley next assignment.

The objective the ongoing PMD evaluation and selection process consists in evaluating the resiliency of the different PMD solutions and to assess their advantages and constraints, investigating the possible combinations of solutions susceptible to improve the PMD mission performance and the spacecraft reliability, and providing guidelines and recommendations, including insurance perspectives for various mission scenario.

Outcomes

Technical and risks management choices will have a fundamental impact on the PMD mission risk profile and its resulting insurability and insurance costs.

Safe heritage design and proven operations are fundamental and have an impact on spacecraft overall cost. Risk retention for new designs / equipments is to be considered as a facilitating factor.

Prior identification and management of all possible failure scenarios and contingency plans is critical and as such should be implemented as early as possible in the design phase.

Insurability of the PMD missions will depend of space insurance market experience with TeSeR philosophy and solutions with demonstration of maximum level of heritage, qualification and risks mitigation. We consider that the integration of risks management and insurance aspects as early as possible in the project is key. In this view, the PMD manufacturers commitment to full transparency and their willingness to involve space insurance professionals in the Consortium and at early PMD design stages and throughout the project development will be certainly be well received and constitutes as a positive and prudent strategy when space insurance procurement for PMD modules will be necessary.

12. Conclusion

Within two and a half years the TeSeR team developed from scratch the concept and design of a PMD module which has the flexibility to accommodate and control three different removal subsystems (solid propulsion, drag sail, electrodynamic technology). The on-ground prototype of the module and the prototypes of the three removal subsystems are either finished or will be finished until the end of the year including different functional and environmental tests to be finalized until the beginning of 2019.

TeSeR shows that a flexible, modular PMD module is feasible and could cover the need to remove different S/C from different orbits with the same concept thus reducing the effort compared to tailor-made solutions which will in the end reduce the costs. As a next step the PMD module prototype including its removal subsystems could be tested in orbit to demonstrate its functionality in the relevant environment – and thus increasing trust in the space community that the PMD module actually works as required. Furthermore the concept should be refined so it is also suitable for larger S/C beyond the CubeSat standard. In addition an industrialisation roadmap has to be defined to enable a series production.

The results show that the PMD module is a very promising candidate to ensure that future S/C do not remain in orbit after end of operation and cause a threat for the space infrastructure.

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