A NEW LARGE AREA DETECTOR FOR IN-SITU OBSERVATION OF SMALL ANTHROPOGENIC DEBRIS IN LOW EARTH ORBIT - SAILOR

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ABSTRACT

Data on the flux of orbital debris in the critical size range of 0.1 – 50 mm is urgently needed. To obtain it, a large area detector (SAILOR) using thin deorbit sails (or drag sails) with acoustic sensors and a camera imaging system is proposed. The acoustic sensors will give impact time and a rough estimation of impact location and hole size on the sail. A pair of such sails, one behind the other, will provide impactor speed (to ± a few %) and trajectory (to ± a few degrees). The optical detector system will image the holes in the sails, providing hole shape and a separate measure of hole size (good to ± a few %). A 3-year mission, SAILOR, would be launched in 2029 to a sun-synchronous, near-polar orbit at 850 km, consisting of one spacecraft with a 25 m^2 exposed area. Given the expected flux, this should provide space debris measurements in the critical mm-sized regime.

1 THE DEBRIS FLUX PROBLEM IN LOW EARTH ORBIT

The dust flux in Low Earth Orbit (LEO) has long been of scientific and engineering interest. In the earliest days of spaceflight, it was feared that the risk of damage to satellites from impacts from natural cosmic dust would prevent effective safe access to space. It was therefore a priority in early missions to determine the flux, using electronic detectors to measure the flux in-situ via its impact on a sensitive detector. The early flux measurements were worryingly high, but it was soon realised that false triggers on the electronic detectors were responsible [1].

By the 1980s, the advent of the NASA Space Transportation System (STS), permitted both launch and retrieval/repair of quite large bodies. This encouraged new flux measurements based on the damage to the retrieved exposed surfaces. Several missions in the 1980s and 1990s (*e.g.*, Solar Max [2], LDEF [3], EuReCa [4]) provided surfaces for analysis, and this was then later supplemented by materials retrieved from service missions to the Hubble Space Telescope (HST) [5]. This opened up the prospect of longer time series data sets, permitting the study of the question of the growing flux of anthropogenic orbital debris.

However, the cessation of STS flights ended this type of activity, instead measurements began to be made on the exterior of the International Space Station (ISS), using a mixture of active (which return electronic data) and passive sensors (which need retrieval for analysis).

In parallel to this, dust flux measurements in LEO were also made using electronic in-situ detectors mounted on satellites, e.g. DEBIE [6, 7] and GORID [8]. One issue that arose, however, was the degree to which the data was contaminated with false triggers, which in the case of DEBIE contributed 1000 false triggers for each real impact event [9].

Since the start of the 2010s, the problem of orbital debris is thought to have become significantly worse. The rapid growth in the number of satellites has provided more potential sources of debris. At small sizes (up to cm scale and above), the debris arises from a variety of causes, including degradation of spacecraft surfaces by the environment, secondary ejecta from actual impacts and catastrophic disruption of satellites (from either internal or external causes). At larger scales, the satellites themselves are an impact hazard, causing more frequent collision avoidance manoeuvres in the more popular orbits (such as that of the ISS, or at 600 – 1000 km). Further, spent upper stages, discarded boosters or adaptor rings, and even, at their end of life (EOL), whole dead satellites are also impact hazards (and hence become orbital debris in their own right).

The increasing awareness of the issue has resulted in a multi-pronged approach to reducing the risk. Better spacecraft manufacturing reduces surface degradation effects, improved operation procedures to lessen the chance of an internal cause of a disruption event, more rapid EOL de-orbit strategies (with the de-orbit period reduced from 25 to 5 years after EOL), and active removal of defunct larger objects, are all part of the more pro-active approach to the issue.

Whilst catastrophic disruption may seem the most serious hazard (arising from impact by objects of 5 cm and above), as pointed out by many (e.g. [10]) impact by smaller (0.1 – 50 mm) sized debris can also generate secondary ejecta, severely damaging instruments and even causing an EOL anomaly for a satellite. Given that

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

the flux increases significantly as size decreases, the result is that the much more frequent impacts by this size of debris can represent a greater risk (in terms of spacecraft operations) than the more dramatic catastrophic disruption events [9].

However, whilst larger debris can be observed and tracked from the ground, the critical 0.1 – 50 mm size range cannot be tracked, thus in-orbit measurements are needed. Still, the retirement of the STS means no new data can be obtained in this size range from retrieved surfaces. Worse, due to the complicated compositional nature of the retrieved surfaces, analysis of the HST data is plagued by issues relating to determining the origin of the impactors (natural dust or orbital debris?) [4,11]. Indeed, the 0.1 – 50 mm size range has long been identified as a critical data gap in flux measurements *(e.g.*, see Figure 4 in [12]).

Several missions using small area detectors have been flown or proposed in recent years, often mounted on CubeSats *e.g.*, see Table 2 in [10] for a list. The often stated or implicit intention is to operate a fleet of such detectors for a number of years, to build up exposed surface area and hence detect the mm-sized debris.

Alternatively, one can orbit a single large-area detector. Accordingly, the Space Debris Sensor (SDS) [13] was flown by NASA on the outside of the ISS (launched late 2017, and operational in early 2018). The SDS had a 1m^2 area, and with an intended 2-year minimum mission, given the expected flux, should have sampled the 0.1 mm size range of impactors [13]. It was a three-layer device, with the first two layers being thin sheets of Kapton equipped with polyvinylidene (PVDF) acoustic sensors to detect impacts as incident particles passed through them. This arrangement was to provide time of flight information (and hence impact speed), impact location on each layer (and hence trajectory) and also a measure of hole size (which would be similar to particle size for penetration in a thin film) – as described in [14]. The front layer also had a resistive grid deposited on it to detect hole size by changes in resistance, and hence again measure particle size [15]. The third, thick, rear layer was to capture particles and was also equipped with PVDF sensors. The SDS took data for 26 days before operations errors unfortunately prevented further data acquisition [16].

The vital need for data in the 0.1 – 50 mm size range thus necessitates new missions, either a large fleet of small area detectors simultaneously providing data which, when combined, provides the flux [10], or a small number of large area detectors. ESA has therefore been studying a possible large-area detector based on using drag sails equipped with acoustic sensors and cameras to measure the dust flux in the requisite size range. This proposal, called SAILOR (Sail Array for Impact Logging in Orbit), is described in more detail below.

2 SAILOR – OVERVIEW

2.1 Pre-Phase A Study (2022)

A pre-phase A study commissioned by ESA and completed by OHB, Germany, in Nov 2022 (ESA contract Number: 4000137548/22/NL/GLC/my), suggested that a large area detector could be based on deorbit sails equipped with acoustic sensors. Such a mission would involve a spacecraft with two sails, each 100 m^2 in area, separated by a 50-100 cm distance. A camera system was considered essential to observe the holes in the sails after each impact. The acoustic sensors would provide the time of impact on each sail as well as the impact location and hole size. The near-simultaneous coincidence of such an impact on both sails would indicate the passage of an impactor. The camera system would then image the holes in the sails, confirming the event as arising due to an impact and providing an independent measurement of hole size.

The orbit for SAILOR was given in the pre-phase A study as sun-synchronous with 6:00 LTAN or LTDN ($i = 98.7°$) at an altitude between 800 and 1000 km. This was chosen as it is deemed an altitude at risk from space debris. Given this orbit, estimates from MASTER (ESA's flux modelling software) suggested that in the critical size range of 1 - 50 mm the debris flux was in the order of 10^{-2} m^2 year^{-1}, with 5 impacts on a 100 m^2 sail in a 3-year mission and 9 in a 5-year mission.

The deemed urgency of this mission was reflected in a desire for a quick launch, within the next few years.

2.2 Phase A Study (2024 – 2025)

The pre-phase A study was then followed by a Phase A deeper design study. This started in the summer of 2024 and is to be completed in 2025 Q2. That study's detailed findings will be reported directly to ESA and briefly summarised here.

In summary, the mission appears feasible however, balancing the need for timely data acquisition with the use of high-TRL components has presented challenges. To ensure a successful flux data collection while maintaining mission reliability, the detector area has been set at 25 m², leveraging flight-proven technology.

The further key constraints include the acoustic and optical detection system design and development. Regarding the acoustic development, there is a need to deploy a large area of detector surfaces which was originally designed to be an EOL deorbiting sail and not for high-precision flux measurements. This subsystem aims for impact time and rough location. This is combined with the optical detection system which has to take images of the millimetre and submillimetre impact holes on the sail, which raises technical difficulties. The optical system's goal is to further refine the location and give size and shape information about the impactor. These challenges led to a mission concept known as SAILOR, which is the design described in the rest of this document.

2.3 SAILOR

The baseline SAILOR mission was proposed as a constellation of four satellites. However, due to its complex and innovative nature, ESA requested an initial launch of just one spacecraft, with the possibility of manufacturing further copies. The first would be launched in late 2029 into a sun-synchronous orbit with an altitude of around 850 km, which yields the best flux data in the critical size range according to the MASTER database. In case of a successful mission, further flight models (FMs) would be launched to increase the combined detector surface area in the required region.

3 THE SAILOR SPACECRAFT

A render of a SAILOR spacecraft is shown in Fig. 1, and a side view is shown in Fig. 2. The spacecraft comprises two large detector surfaces, separated by 100 cm. The sails are approximately 10 µm thick and held in place by deployable cross-booms. The booms are stowed (along with the sail) during launch and deployed once in orbit.

The spacecraft's front (ram), rear, left and right sides can be defined based on its orientation: the hard-pointing vector is normal to the plane of the sails and aligned with the velocity vector, while the soft-pointing vector is normal to the plane of the solar arrays and directed toward the Sun.

The main structure on which the booms and sails are mounted is a carbon fibre cylinder that serves as the primary structure with an outer diameter of 160 mm and approximately 1.4 m in length (see Fig. 2). A separate system the "Rotor", (the innovative mechanics of the optical detection system) is also attached to the primary structure, mid-way between the two sails. A camera system will be mounted onto it to image the interior surface of both sails, looking for holes made by

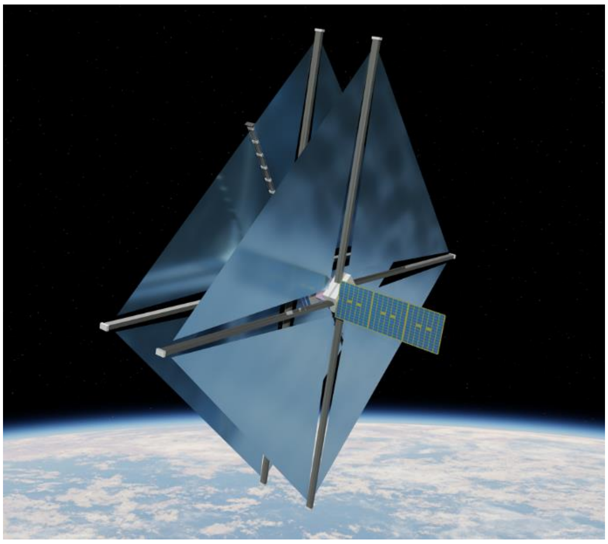

Figure 1. Design render of SAILOR, a two-layer, large-area detector surface spacecraft. Each sail (the blueish areas) has a 25 m2 exposed surface area. A solar panel (for power) can be seen deployed in front of one sail. The left side of the spacecraft is rendered with wireframes.

the impacts. The Rotor will revolve around the primary structure to enable the cameras to take pictures of the whole sail.

The booms and sails are based on the ADEO-L system [17,18]. ADEO is a scalable, boom-deployed, drag sail,

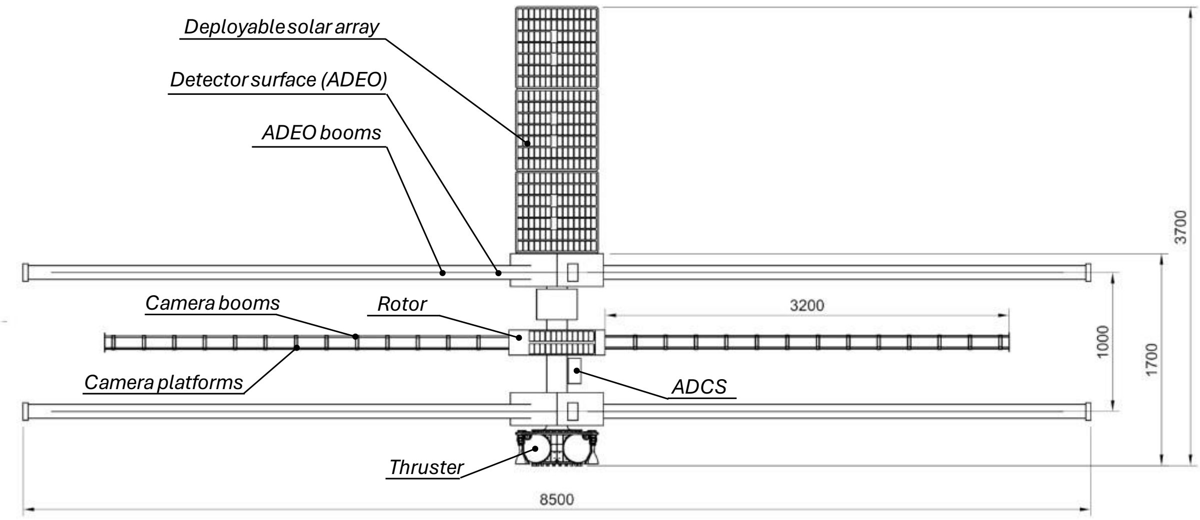

Figure 2. Side view of SAILOR spacecraft, with main parts labelled. The sails would be deployed on booms extending some 3.8 m from the spacecraft's main structure. The rotor would be of similar length and carry the cameras and illumination system.

which is designed to be used to de-orbit spacecraft from LEO at their EOL. A small version (ADEO-N, 3.6 m^2) has been demonstrated in orbit [19], indicating a high TRL for the generic system. The ADEO-L version has already been developed and can deploy a 25 m^2 sail as required here. Acoustic sensors will be fixed to the sails to detect impacts in real-time.

The sails, various sensors and spacecraft systems are briefly described in the next sub-sections.

3.1 Sail and booms

The sails are approximately 10 µm thick polyimide films with thin coatings. Each of the two layers of sail are divided into four, equal-sized quadrants. The sails are stowed folded during launch and drawn out on booms when deployed early in the mission. As a result of this method of deployment, the sails will be under tension when deployed. Although originally designed as sails for EOL de-orbiting purposes, the lack of significant aerodrag at the planned operational altitude (850 km) means this is not an issue during normal operation. To be noted regarding dark sky compliance (for the benefit of ground-based optical astronomy), in nominal operations, the sail surfaces stay parallel to the ground-to-space observers' point of view due to the constant velocity vector pointing on 6:00 SSO, thus the light pollution would be minimized even with this area of light-reflecting surfaces. Thermal analysis shows that during operations these thin films will have little thermal inertia and in cases, quickly heating and cooling can happen.

The booms are monostable. They are also stowed during launch, and spring out when deployed into a stable, long rod shape. They will connect to the sails via spring-like connectors, providing tension to the sails. Once deployed, they will remain in this configuration (Fig. 1).

3.2 Acoustic sensors

The acoustic sensors to be used on the sail are PVDF thin film sensors. These are unpowered piezoelectric sensors, which operate in an in-line bending mode. They are glued to the sail and respond to the acoustic waves passing through the sail arising from an impact. The waves spread out symmetrically from the impact point, generating electrical signals on the sensors. The use of PVDF sensors as hypervelocity impact detectors was demonstrated in [14] and they have flight heritage, having been used on the NASA SDS mission [13,16].

The PVDF sensors are thin (typically 35 µm including coatings) and have active areas of 12 mm × 15 mm, depending on the type used. They would be glued to the sail in a grid-like pattern. The four sensors nearest to an impact (a “unit cell”) would provide signals that can be used to triangulate the data, yielding estimates of impact time, location and hole size (for penetrating impacts). The use of four sensors in each cell permits redundancy in the triangulation (and allows a measure in each event of acoustic wave propagation speed). Due to the shape of the sail quadrants, at the sail edges, there would be triangular unit cells with only three sensors per cell. However, this still provides sufficient data for analysis of an impact [20].

The basic unit would involve 4 sensors per cell, one at each corner of a square by 50 × 50 cm. Laboratory testing of such PVDF sensors of thin Kapton films has shown that with a sail spacing as planned here, the reconstructed speed should be accurate to about 1% [20], and the impact direction should be reconstructed within a few degrees of the pre-impact direction. There is no published data on the accuracy of the hole size determined by the PVDF sensors, but this is not likely to be better than ±10% when estimating projectile diameter.

An in-situ method of monitoring the performance of the acoustic sensors will be provided by use of acoustic “pingers”. These will also be glued to the sails, and when stimulated with an AC voltage, these piezo-electric devices vibrate, exciting the sail, thus providing a known signal which can be used to calibrate the acoustic sensors’ response.

3.3 Camera system

To image the holes in the sails made by the passage of impactors, a camera system is planned. This would consist of a rotating device (the Rotor) positioned along the main chassis of the spacecraft, mid-way between the two sails (Fig. 2), a pair of booms, and the cameras fixed onto camera platforms on the booms. The booms would be stowed during launch. Once deployed symmetrical and operational, they would act as a single subsystem, completing one full revolution at least every 15 minutes. A series of cameras positioned along the length of the booms would create images of the front and rear sails in their field of view, and after one full rotation of the Rotor, both sails would be imaged with sufficient resolution to see the shape of holes with 0.1 mm diameter and above. Illumination will be provided from the camera booms. The sails will have DataMatrix codes printed at regular spacings across their surface, so all holes in an image can be accurately located.

That the hole size from an impact on a thin film is a good estimator of the cross-sectional area of the impactor has been shown in hypervelocity tests in the laboratory [20], in line with the expectations from the parametrization of [21].

The resolution of the camera system is thus the critical limit in the ability to optically measure hole size. Given the design specification, the resolution should be 50 µm, this means that a 1 mm hole size will be good to ±5%.

3.4 Power

The spacecraft will carry three deployable solar panels, and four body-mounted ones on the rotor to provide power for normal operations. The panel will be placed at the front end of the main structure, perpendicularly to the sail to minimize the obscuration on the sail. Placing the solar panels elsewhere was considered, but the constraint of a good view of the sun reduces the options.

The solar panels will be used both to power the systems, or to charge the onboard batteries as required. The batteries will be lithium-ion and will be connected to the 28V bus of the spacecraft.

3.5 Propulsion

Onboard propulsion will be needed for a variety of reasons. The mission should be designed as flexibly as possible to facilitate a choice of launchers and orbits, e.g. if an initial altitude is chosen which is lower than the operational selected, there will be a need to raise the orbit. Then, once on the correct orbit, there will be a need for manoeuvres such as collisional avoidance (by accelerating/ decelerating the spacecraft to arrive at a slightly different time in an orbit and hence avoid a collision), and at EOL de-orbiting. The Δv required over a mission lifetime is calculated as part of the Phase A study, and suitable-sized engine and propellant tanks are been identified. This would be attached at the rear end of the main spacecraft structure. Discussions with potential suppliers of a suitable main propulsion system are underway and the appropriate design features are incorporated into the Phase A study.

3.6 ADCS

Separate from the main propulsion there will be an attitude determination and control system (ADCS). This will ensure the spacecraft is oriented correctly for all operations. During normal data acquisition, the ram direction will be aligned along the main spacecraft structure, with the main propulsion system at the rear. Thus, when deployed, the two sails will be orthogonal to the ram direction.

Potential suppliers of the ADCS have been identified, and the necessary design features they require are being included in the Phase A study.

3.7 Onboard computer and Intelligent Payload Controller

An onboard computer (OBC) will handle all normal spacecraft operations. A separate Intelligent Payload Controller (IPC) will monitor, process and store the data from the camera and acoustic sensors, acting as an interface between the payloads and the main computer/comms/power etc. It will be capable of deciding the data acquisition and processing mode of operations and sending data directly to the COM system (bypassing the OBC) to avoid bottlenecks. Data processing of the camera images will include hole identification (including location, size and shape). Similarly, for the acoustic data it will determine if triggers have been obtained, and the impact time, location and hole size. Based upon this information from both sails will determine the speed and trajectory of an impactor. Both processed and raw data will be available for downloading depending on the mode of operation.

3.8 Comms

The comms will be via a UHF antenna, at approx.. 402 MHz. This will permit commands to be sent to the spacecraft, permitting a degree of ground control (although most operations will be autonomous) and allowing daily transmission of data to the ground (raw or processed). There will be a full duplex S and X band system for the up- and downlinks respectively.

3.9 Expected camera image data rates

Although in some modes a whole camera scan of the sail will be made and downloaded (e.g., to check successful deployment and routine health monitoring), in normal operation only two images per impact are required.(one per sail). During normal operations, onboard processing will compare and contrast each new image with the previous image of that part of the sail, and only where there is a difference will the new image be retained for further processing. Equally, if the acoustic system triggers and suggests an impact location, the associated image of that part of the sail would be retained. Given the expected flux in the chosen orbit, we can expect some 53 impacts per day from the submillimetre debris and hence 106 images relevant images. A single full image of a suitable camera system would be some 5.1 Mbyte of data, but this would be reduced to approximately 0.6 Mbyte by onboard processing. With two images per impact this suggests a data rate for downlinking of some 63 Mbyte per day. This compares to approximately 540 Mbyte per day if all images were downloaded from the entire sail.

4 ORBIT, PREDICTED FLUX AND IMPACT SPEED.

The preferred orbit for SAILOR is a sun-synchronous dawn-dusk (LTAN 06:00) orbit at 850 km altitude. The flux is estimated from MASTER to be some 7.68×10^{2} m^{-2} yr^{-1} for objects > 0.1 mm objects and 1.44×10^{-2} m^{-2} yr^{-1} for objects > 1 mm objects in the epoch 2027-2030. This corresponds to 57,606 impacts by > 0.1 mm objects and 1 by a 1 mm+ impactor on a 25 m^2 surface during the nominal 3-year mission.

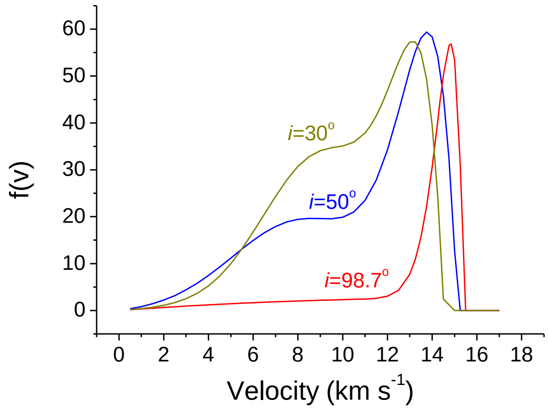

Figure 3. Variation of debris impact speed with inclination of the orbit of the impacted spacecraft. Details of the parameters used are in [22].

The expected debris impact speed in a given orbit is significantly influenced by the inclination of the orbit. This is illustrated in Fig. 3, which was created from the parametrization in [22] and for a given inclination averages over all altitudes. As can be seen at a high inclination expected for SAILOR, the debris impact speed is heavily biased toward 15 km s^{-1}. A full simulation using ESA's MASTER code is being performed for the preferred orbit for SAILOR.

5 DISCRIMINATION BETWEEN TRUE IMPACT EVENTS AND FALSE TRIGGERS

The data rate will be a combination of true impact events and false triggers arising from spacecraft dynamics and external influences (e.g., see [7,9,16] for a typical discussion). In the worst case, these false triggers can outnumber the real impact events almost 1000:1 [5]. However, here, the combination of impacts nearly coincident in time on two layers of sails, plus confirmation by the optical camera system that holes have appeared in the right places on the sails, will solve the problem of distinguishing between the true and false triggers. Based on assumptions about sampling rate of the acoustic sensors, the amount of data generated by true impacts per day (given the anticipated flux), will be some 5 Mbyte. However, there will be periods when it is anticipated that all triggers will be stored and downloaded for data quality control reasons.

6 END OF LIFE DISPOSAL

A full EOL and debris mitigation strategy is being prepared as part of the phase A study. This strategy has several strands. As well as the obvious need to arrange de-orbiting of the spacecraft to be compliant with ESA policy (*i.e.*, within 5 years of the end of the planned operational life), there is also the need to consider a means of de-orbiting in case of various failures.

The EOL disposal method after a successful mission for the high altitude (850 km) SAILOR, is an active strategy, required due to the low aero drag force at that altitude. The current plan is to use the main propulsion for a deliberate de-orbit manoeuvre at the EOL to move the spacecraft onto a planned disposal orbit that is compliant with the 5-year rule. In parallel, modelling is carried out to establish that all spacecraft sub-systems will effectively break apart and burn up on re-entry without presenting a serious impact hazard on the ground.

Scenarios are also modelled as to what to do in the event of various mission failures. The intervention strategies depend on the type of failure. For example, if the spacecraft is still under control (with operational ADCS, comms and propulsion) and thus capable of manoeuvre, but may have failed to deploy the deorbit sail for example, thus rendering the mission a failure? This would permit an intervention from the ground for an appropriate EOL disposal. However, if key spacecraft sub-systems fail, control may be lost at any stage of the mission. A dead-man switch is thus envisaged to deliberately deorbit the spacecraft in a fashion dependent on altitude and whether or not the sails have been deployed.

7 STATUS

The current status of SAILOR (March 2025) is that it is at the end of its Phase A study. If the associated ESA review is passed, it will then (April 2025) move into Phase B1, which will involve the construction of breadboard models of the spacecraft and its electronics, and associated test programmes.

In particular, Phase B1 will include:

- Manufacturing of test samples of the proposed sail,
- Testing of the sail folding for stowage (including when the PVDF sensors are mounted on the sail),
- Testing of the boom and sail deployment mechanisms,
- A 16-shot hypervelocity impact test programme to determine that the chosen sail and sensors operate as expected and generate data as expected for the flight electronics,
- Testing of a camera system to image holes in the sail with the requisite resolution,
- A full design of the spacecraft, with supplier involvement for all critical components and sub-systems.

The intention is to provide sufficient depth of design and analysis to permit ESA to agree to proceed further at the Nov. 2025 meeting of the member state ministers (CMP25).

If approved at CMP25, SAILOR would then proceed to Phases C and D, with a launch planned for end 2029. There would then be a 3-year nominal mission on orbit.

8 SUMMARY

The use of deorbit sails in space has a long history [17]. Here we discuss how an array of two, back-to-back, large-area deorbit sails separated by 100 cm, can be used as a real-time space debris sensor in orbit. This mission is called SAILOR. High-speed impacts on the sails (by cosmic dust or anthropogenic debris) will have two effects; they will generate an acoustic signal (which will propagate across the sail), and, if the impactor is more than a few times the sail thickness will create a hole in each sail (which will be imaged by a camera system). The acoustic signals will be detected by PVDF sensors, which will provide timing signals and impact locations on the sails, as well as hole size. The separate camera system will confirm that the impact event is real, and not a false trigger. The data from both sails will then be used to provide a time of flight and trajectory between the sails. This will provide a velocity vector for the impact.

Previous studies [18] have shown there is little deceleration of particles >0.1 mm in size when impacting thin films such as the sails, nor is there a significant deflection effect. Hence the recorded velocity vector will be a good representation of the original orbit of the impactor. Similarly, the size of the hole made by the passage of a sphere >0.1mm in size, has been shown [20] to be similar in size (to within 1 - 2%) to the diameter of the impactor, providing a second, independent measure of impactor size. With the orbit information, it will be possible to assign a likelihood that a given impactor has a cosmic dust or space debris origin.

Given the expected flux of space debris predicted by MASTER for the planned orbit, SAILOR will observe 4 or 5 impacts by mm-sized particles during its planned mission. Their impact speeds will be measured with a few % of the true value and their impact direction with a few degrees. Their size will be accurate at the 10% level for 1 mm-sized impactors. There will also be a significantly greater flux of smaller-sized impacts that will be reported by SAILOR based on the acoustic data alone. The results will be transformational for the knowledge of the true flux of orbital debris at the mm size scale.

9 ACKNOWLEDGEMENTS

Work on the SAILOR phase A study was financed by ESA Contract: 4000144690/24/D/BL.

AI tools were used to improve language.

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