In-situ Detection of Small Space Debris with the LArID concept: Breadboard verification and the path to a flight mission

Noah Ledford[a]*, Martin Schimmerohn[a], Robin Putzar[a], Clemens Horch[a], Stephan Busch[a], Mark Millinger[b], Frank Schäfer[a]

[a] *Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Ernst-Zermelo-Str. 4, 79104 Freiburg, Germany*, noah.ledford@emi.fraunhofer.de

[b] *European Space Agency, ESTEC, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands*

ABSTRACT

In-situ debris measurement has been a concern since the dawn of the space age. The difficulty of measuring the small high-velocity particles continues to today, and the need is only increasing as more debris and satellites occupy the high-demand orbits around Earth. The Large Area low Resource Impact Detector, LARID, developed at Fraunhofer EMI, under ESA contract, combines different sensor technologies to allow for reliable measurements of micro-meteoroid and space debris environment in the 0.2 to 10 mm range. This size is small enough to not be detectable from the ground, but large enough to still damage subsystems on spacecraft. Detection through multi-physics methods combining acoustic emission, resistive grid penetration, and impact flash measurement provided a reliable and modular detector design that was then verified through hyper-velocity impact testing. The successful completion of the breadboard technology demonstration phase allows for detailed Flight Model planning and mission profile comparisons.

In this work, the proposed changes from the breadboard to the flight model are discussed. Then, taking these assumptions, four different mission profiles are compared. Highlighting what the three different paths offer and comparing how best to add to the measurements of the orbital debris environment. These consist of: 1) a station-mounted module that can be recovered and the measurements verified; 2) a dedicated small satellite mission to fly into expected dirty orbits to measure the debris environment there, and 3) an expansive approach integrating the detector onto an upper stage or habitat module for maximum surface area and potential structural health options and 4) hosted payload options taking advantage of the modularity and low resource requirements of the detector to fit on to missions in interesting orbits. Each scenario is evaluated for its unique potential to contribute to orbital debris metrics, offering a roadmap for deploying a reliable, in-situ measurement system. The findings present a clear path toward operationalizing LARID as a critical tool for providing reliable quantitative data on the number and characteristics of MMSD in the 0.2 mm to 10 mm range for the growing debris risk in space, ultimately supporting safer and more sustainable orbital operations.

1 INTRODUCTION

Concern about the micro-meteoroid and space debris (MMSD) environment has been integral to space mission design from the industry's earliest days. In-situ measurements date back to earliest day of the space age. A good overview of the history of these measurements can be found in Schimmerohn 2021[1]. Determining the size and velocity of MMSD particles has consistently proven challenging. The recent increase in the number of satellites and man-made space debris has intensified the focus on these small but high-energy particles.

Measuring sub-centimeter particles moving at velocities exceeding 7 km/s presents significant difficulties. Past detection methods have utilized various physical effects, each with unique strengths and limitations. Some detectors could measure only one impact, others suffered from a large number of false positives, and the unforgiving space environment means even minor errors can compromise a mission.

Ground-based MMSD detection has progressed substantially, now capable of measuring particles down to 3-5 cm in size. However, physical constraints limit the detection of smaller debris from Earth. Space-exposed objects returned to Earth have been crucial in developing our understanding of the smaller debris environment. Yet, these measurements are limited in scope, providing only cumulative data on impacted surfaces rather than real-time, individual event information.

2 DEVELOPMENT SUMMARY

To address the observational gap in our understanding of the space environment, the ESA contracted Fraunhofer to design the Large Area low resource Integrated Impact Detector (LArID). While the goal of creating a modular, low-resource detector capable of measuring small impactors was ambitious, the breadboard successfully demonstrated the required performance. The LArID Breadboard specific mass and power consumption were <8 kg/m2 and <30 W/m2, respectively.

2.1 Detector description

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 detector consists of two layers separated by a predefined distance. When an MMSD particle impacts the first layer, an array of photodiodes directly behind it measures the impact flash. This first layer is a 6 µm thick PET foil, commonly used in Multi-Layer Insulation. The impact also generates vibrations detected by acoustic sensors adhered to the corners of the detector. The particle then proceeds to impact the second layer, which is composed of a flexible Printed Circuit Board (PCB) with traces arranged in a horizontal and vertical grid pattern. This layer has the maximum commercially available transverse dimensions of 412 x 412 mm and a thickness of 188 µm. The second impact again produces a flash and vibrations. Additionally, the resistive grid enables the determination of which traces were broken in the impact event, providing a location and size measurement of the impactor with a resolution of 0.2 mm, corresponding to the pitch of the resistive grid traces. The combination of measurements from different impact phenomena allows the detector to have self-correcting capabilities. For example, if a spacecraft-induced vibration triggered the acoustic sensors but no impact flash was detected, the measurement would be flagged as a possible false-positive signal.

2.2 Testing Summary and Results

Verification of the LArID concept was conducted through a campaign of hyper-velocity impact tests on the breadboard model, as shown in Figure 2. These tests examined different-sized impactors at various angles and composed of different materials. Additionally, two configurations were compared: the initial configuration as described above, and a second configuration featuring a second resistive grid instead of the thin PET layer. Detailed results can be found in paper submitted for IAC 2025 [Ledford 25].

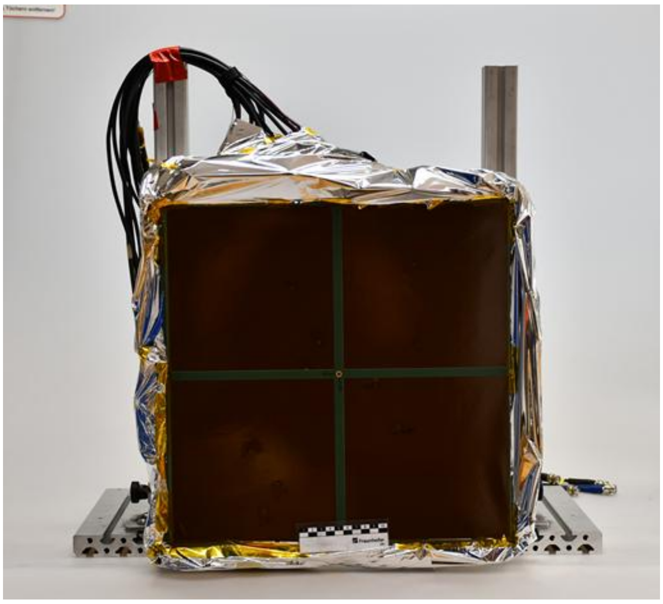


Figure 2. LArID Breadboard model.

The analysis of test results focused on three key measurements: the time of flight between the two layers, the distance traveled by the particle between the layers, and the size of the impactor as measured. The various sensor systems exhibited significantly different responses, with the acoustic sensor systems performing noticeably worse than the resistive grid. Both the photodiodes and the resistive grid effectively measured the time of flight. The resistive grid also accurately measured the size of the impactor. The most effective methods achieved median errors of 0.46 µs for the time of flight, 0.7 mm for the distance traveled, and 0.12 mm for the impactor size. While the breadboard successfully measured the impactors, several potential improvements were identified for implementation in a flight model.

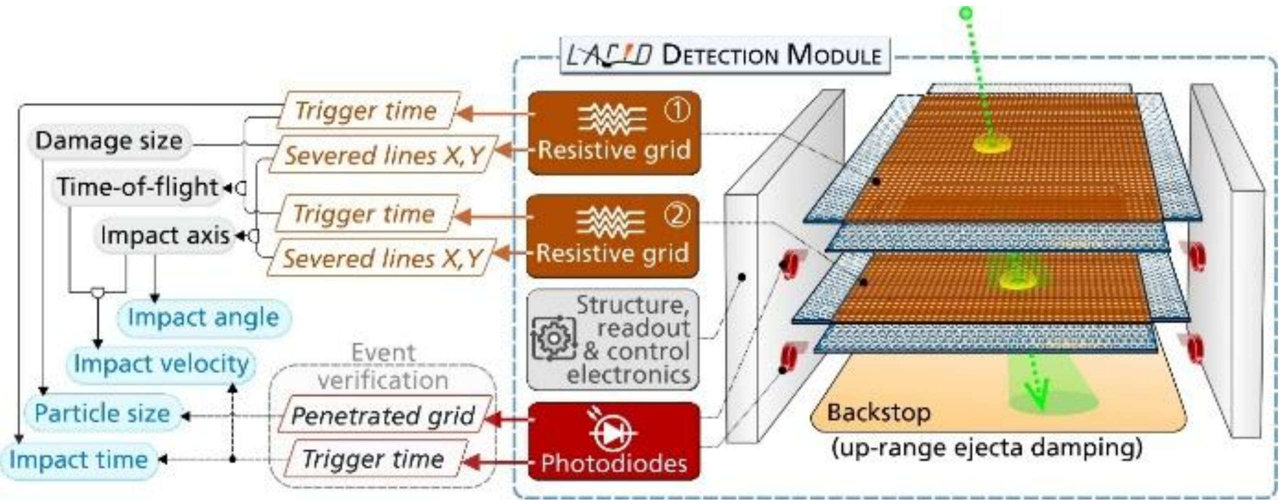


Figure 1 LArID Flight model Conceptual design.

3 PROPOSED CHANGES FOR THE FLIGHT MODEL

Four main areas stand out as offering potential improvement to the LArID system, each discussed in detail below and a conceptual design is shown in Figure 1. The primary modification involves adopting a configuration with two resistive grids and eliminating the acoustic sensors. This decision was made because the acoustic sensors' accuracy did not meet the project's stringent requirements for combining precise velocity measurement with low resource utilization. The combination of photodiodes and resistive grids provides a robust detection concept that can achieve the mission objectives while offering mutual verification.

3.1 Resistive grid optimization

The resistive grid is a key element in the detector operation. It delivers the location and time of impact measurements. Testing on the breadboard demonstrated that the precision offered by the resistive grid is crucial for determining the velocity of MMSD particles. The challenges seen in the testing were twofold: first, the smallest particles of interest did not consistently penetrate the 188 µm thick layer; secondly, the debris cloud from penetrating this layer damaged the impactor to such an extent that the measurement on the second layer was complicated. Both issues could be addressed by significantly reducing the layer thickness. Current state-of-the-art flexible PCB technology suggests this is feasible. Research from Fraunhofer ENAS [3] indicates that a thickness of 20 µm may be achievable. Additionally, reducing the trace width could increase the precision of size and location measurements, albeit with a trade-off in increased signal measurement resources.

A thinner resistive grid would improve distance traveled measurements by reducing particle fragmentation, resulting in cleaner measurements on the second layer. This is crucial for maintaining a low detector volume and high measurable angle-of-impact. Both design parameters require minimizing the distance between layers. Conversely, time of flight and distance traveled measurements benefit from a longer inter-layer distance to minimize individual measurement errors. These system-level trade-offs would be thoroughly investigated during flight development testing to determine the optimal configuration.

Additional considerations include the robustness of the second grid, as proximity to the first layer may lead to tearing from impact debris pressure. Challenges also arise when the debris cloud impacts the second layer before the projectile in angled impacts. While this requires special software evaluation, testing showed that angled impacts produced distinctly different signals compared to direct impacts. Overall, reducing the resistive grid thickness is expected to enhance system performance.

3.2 Impact flash detection

Photodiode-based time of flight measurements demonstrated superior performance during breadboard testing. While the current components are vacuum-sealed, space-rated detectors with heritage would be preferred for flight models. The sensitivity of the photodiode array could be optimized to accommodate a wider range of measurements, particularly for higher energy impacts anticipated in the space environment.

An optically opaque layer added to the resistive grids would prevent light from the first layer's flash from reaching photodiodes behind the second layer, resulting in cleaner signals and improved timing information. This could be implemented by applying a sputtering coating onto the resistive girds.

The possible addition of baffles on the photodiodes could improve stray light-inducing false signals. However, this risk is limited by the dual-physics nature of the detector with the resistive grid needing to register an impact at the same time. The impact flash was also notably brighter than the high-speed flashes used during testing by the high-speed cameras showing the robustness of the light measurement.

3.3 Backstop development

The breadboard testing performed did not include a backstop behind the second layer. This was chosen as it simplified the testing and is a possible configuration, see section 4.1 for details on the vertical-mounted configuration.

With a backstop, the full energy of the impacting MMSD would be captured. This transfer of momentum could be measured by the change in attitude as seen in Sentinel impact study [4]. Combining spacecraft mass distribution and stiffness data with these measurements would allow the estimation of energy input to the spacecraft. When coupled with particle velocity and size data from the detector, this would enable the determination of particle mass and density, further enhancing our understanding of the MMSD environment.

Aerogel would be the leading candidate for the first component of the backstop. Being used in missions such as Stardust and Cassini-Huygens [5]. Behind this, a Kevlar, Dyneema, or aluminum layer could be incorporated into the spacecraft outer wall providing actual shielding as well as a mounting for the LArID measurement device.

The detector with integrated backstop would be tested on a ballistic pendulum, where the moment transferred would be measured with a laser interferometer. This reference data provides the database needed to give confidence in the measurements made in orbit by the spacecraft attitude determination system.

3.4 Electronic design

The electronic design performed well but would require modification to adjust to the proposed changes in the previous sections. A few highlights of the electrical design that are planned to be continued in the flight model are:

1) direct connection of individual traces without soldering harness to the grid, 2) using high-performance FPGA to continuously monitor the traces at high frequency, providing a time of impact signal from the resistive grid, 3) using multiple comparators to realize a discrete version of parallel analog-to-digital converters with high speed and low power demand, and 4) integrating the electronics within the side structure of the detector unit, keeping the system compact.

Tightly connected with the electrical design is the development of the LArID software. The LArID software needs to 1) control the detector operation, 2) handle the trigger time stamps of continuity changes, 3) compare signals from different sensor systems to eliminate false-positive measurements and 4) read out the position of the impact damages. In addition to adapting to the new grid and potential new EEE parts, the flight-ready design must implement a communication bus (e.g., RS422, CAN, or SpaceWire) to connect all LArID modules to the hosting space system.

4 FLIGHT MISSION PROFILES

4.1 Modular design and flexibility

One of the key advantages of LArID is its modularity, which enables flexible adaptation to different mission environments. This modularity allows for the mounting of base units in different orientations, as shown in Figure 3. Both horizontal and vertical mounting options are feasible, each offering distinct advantages:

Horizontal mounting: This configuration requires a backstop but allows for the assessment of momentum transferred to a spacecraft through sensitive attitude determination systems. If the detector is retrieved post-mission, the backstop design enables further analysis of fragments caught during impact events. This can significantly enhance the understanding of impact characteristics by scanning the resistive grid for perforation damages, investigating track characteristics in the backstop, and recovering impactor fragments for chemical composition analysis.

Vertical mounting: This option increases the flexibility to position detector base units in various orientations relative to the spacecraft's flight direction. With two identical resistive grids as detection layers, vertical mounting provides an increased detection surface area, allowing impacts from both hemispheres on the detector's front and rear sides to be detected.

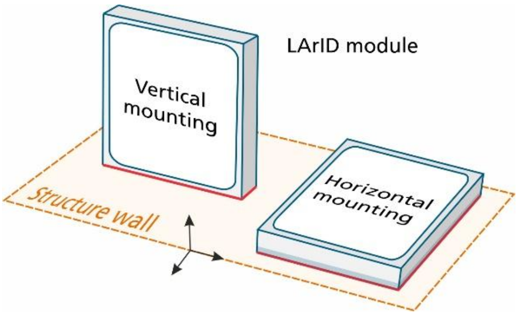


Figure 3. Mounting options for LArID.

4.2 Mission Scenarios for LArID

Given its modularity and flexibility, LArID offers a wide range of potential mission scenarios. Four main scenarios are proposed for a LArID flight model:

4.2.1 Installation on existing ISS payload platforms

The International Space Station (ISS) provides several external research accommodations that are ideal for hosting LArID detectors. Platforms like Airbus' Bartolomeo offer large volume, high power, and high data rates, offering options of running a higher-powered data acquisition system in parallel to see how the very high impact velocities compare to those that are testable in the lab. And verifying the low-power measurement methods at these speeds. The Bartolomeo platform, installed on the European Columbus module see Figure 4, provides single payload slots with dimensions of 800 × 800 × 1000 mm³ [6].

Utilizing existing commercial payload platforms on the ISS offers the fastest path to a LArID flight mission. Payloads are transported to orbit via regular supply launches and installed by the on-orbit crew using robotic arms.

The ISS provides the option to retrieve the LArID flight model post-mission, allowing for detailed post-mortem analysis. This includes scanning the resistive grid for damage, analyzing tracks in the backstop, and recovering impactor fragments for chemical analysis. Combining in-situ detection with post-mortem analysis enhances understanding of impact events and detector characterization, particularly for larger micrometeoroids with high impact velocities.

Figure 4. ISS Bartolomeo platform.

4.2.2 Dedicated small satellite missions

Small satellite technologies have evolved significantly, offering agile and low-cost development processes ideal for demonstrating new sensor technologies. A dedicated LArID small satellite mission can measure different and MMSD-specific orbital environments, potentially targeting spacecraft breakup clouds, and leveraging the flexibility of a standalone mission.

CubeSat Mission Scenario

A 27U CubeSat format is envisioned, with deployable panels connected by hinges and actuators, similar to solar array deployment. The detector panels are stowed at the sides of the spacecraft bus, which is based on standard CubeSat components. This design achieves a detection surface area of approximately 0.5 m², unconstrained by the spacecraft body, see Figure 5

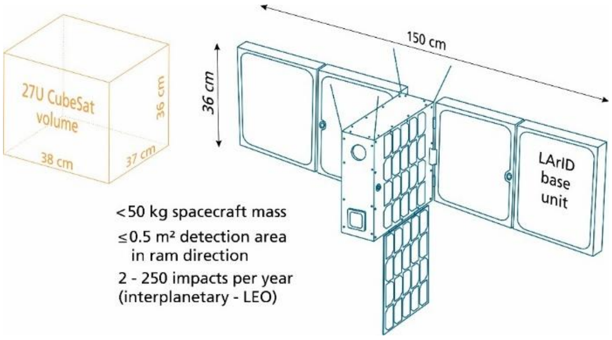


Figure 5. CubeSat Mission concept.

The expected impact detection rate varies with the orbit environment. Considering fluxes from the LArID environmental analysis, this translates to a minimum of 2 to 250 detectable impacts per year from interplanetary environments to highly congested low Earth orbits.

The wing design allows for the detection of satellite attitude changes induced by impact momentum transfer. A large wing provides a greater lever arm for outside panels, enhancing the analysis of impact-induced attitude disturbances by larger MMSD objects. This would require a backstop as discussed above.

Microsatellite Mission Scenario

Increasing the size to a microsatellite format enables the deployment of more detector units. An example configuration involves a <200 kg microsatellite with two three-parted wings, achieving a detection surface area of approximately 3.4 m² in the ram direction. This significantly increases the annual rate of detectable impacts to between 15 and 1800, depending on the orbit environment, see Figure 6.

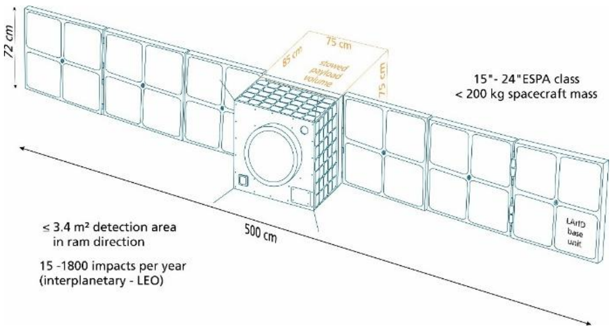


Figure 6. Microsatellite mission concept.

4.2.3 Integration on large structures

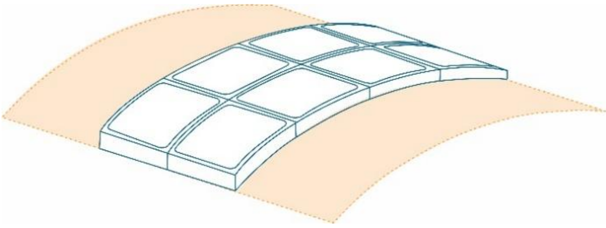
Integrating LArID modules into the outer structures of future space stations is a viable option. This would involve adding detection modules to Whipple shield surfaces or integrating them as part of these shields. While this scenario is more applicable for later development stages, it provides a promising path for expanding detection capabilities in space. Additionally, it could be incorporated into a structural health monitoring system.

Habitat Integration

Integrating LArID modules into the outer structures of future space stations could be a viable option. This would involve adding detection modules to Whipple shield surfaces or integrating them as part of these shields. While this scenario is more applicable for later development stages, it provides a promising path for expanding detection capabilities in space. It could also be incorporated into a structural health monitoring system.

Upper Stages and Payload Adapters

Integrating LArID detectors onto upper stages or payload adapters requires equipping these systems with separate power supply, command and data handling, and communication subsystems. This can be achieved with moderate effort by adapting commercial off-the-shelf (COTS) components commonly used in CubeSats. However, this method would require significant collaboration with the launch provider and extensive environmental testing. Furthermore, operational times for modern upper stages are limited due to stringent de-orbit requirements, which may reduce the number of expected impacts.



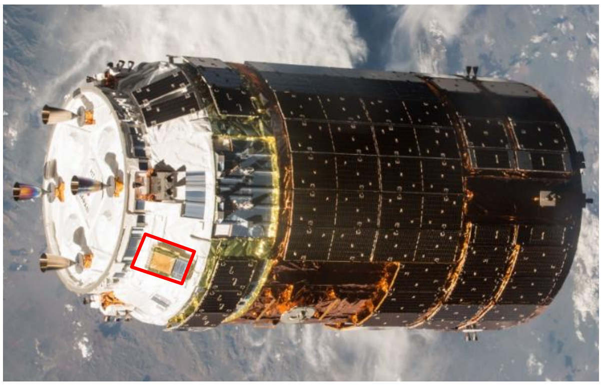


Figure 7. Top: Detector integrated on large external space structures. Bottom: Graphical representation of LArID modules attached to a habitat structure. Bottom: Example of JAXA's Space Debris Monitor attached to the HTV-5 for a 60-day mission (copyright JAXA/NASA).

4.2.4 Hosted payloads

Implementing LArID detection modules as an external payload on spacecraft offers another deployment option. The low resource demand of LArID facilitates integration, although the need for a large external surface in the flight direction could limit the number of optimal partners.

The modular nature of LArID allows for scaling the detection surface according to the available external surface area of the hosting spacecraft. This adaptability enables data acquisition in diverse orbital environments.

Modifications to a Flight Model are generally moderate, focusing on adapting the mechanical interface and communication bus to meet the payload requirements of the hosting spacecraft.

5 CONCLUSIONS

In conclusion, the detection of micrometeoroids and space debris (MMSD) remains a critical challenge for understanding and mitigating risks in space missions. The Large Area low Resource Impact Detector (LArID) offers a promising solution by providing essential in-situ data for developing accurate risk assessment models. This work has outlined the LArID concept and discussed potential improvements to enhance its performance.

LArID's versatility is demonstrated through four mission scenarios:

1. ISS Payload Platforms: Utilizing platforms like Bartolomeo for rapid deployment, high-resolution data collection, and potential payload return for post-mission analysis.
2. Dedicated Small Satellite Missions: Employing CubeSats and microsatellites for agile, low-cost deployment with scalable detection surfaces across targeted orbits.
3. Integration on Large Structures: Expanding coverage by incorporating LArID modules into habitat surfaces or upper stages/adapters.
4. Hosted Payloads: Integrating onto external spacecraft surfaces with minimal modifications, providing flexible ride-share options.

By addressing the observational gap in MMSD detection, LArID significantly contributes to enhancing spacecraft safety and orbital debris mitigation. The advancements in LArID's design and deployment strategies align with broader efforts to improve space situational awareness and assist in evaluating MMSD risks in Low Earth Orbit.

LArID's potential extends beyond LEO, with the capability to function in lunar or interplanetary trajectories, providing key measurements in previously unexplored regions. As space exploration evolves, technologies like LArID will play a crucial role in safeguarding future missions and expanding our understanding of the space environment.

6 REFERENCES

1. Schimmerohn, M., Ledford, N., Putzar, R., et. al., (2012). LArID: Concept of a large area low resource integrated impact detector. *International Astronautical Congress (IAC).* Dubai, United Arab Emirates.

2. Ledford, N., Schimmerohn, M., Putzar, R., et. al, (2025). Laboratory Testing of LArID: Paving the Way for In-Situ Quantification of Millimeter-Sized Space Debris, *International Astronautical Congress (IAC).* Sydney, Australia.

3. Selbmann, F., Roscher, F. , de Souza Tortato, et al., An ultra-thin and highly flexible multilayer Printed Circuit Board based on Parylene. *Proc. IEEE 2021 Smart Systems Integration (SSI),* Grenoble, France, 2021, pp. 1-4, https://doi.org/10.1109/SSI52265.2021.9466996 .

4. Krag, H., Serrano, M., Braun, V., et al. (2017) A 1 cm space debris impact onto the Sentinel-1A solar array. Acta Astronautica **137**, 434-443.

5. Kearsley, A.T., Burchell, M.J., Price, M.C. et al. (2012): Experimental impact features in Stardust aerogel: How track morphology reflects particle structure, composition, and density. *Meteoritics & Planetary Science* 6, (4), pp737-762. https://doi.org/10.1111/j.1945-5100.2012.01363.x

6. Bartolomeo User Guide, Issue 1, November 2018, Airbus DS. https://www.unoosa.org/documents/pdf/psa/hsti/Bartolomeo/BTL-UG.pdf

7 USE OF ARTIFICIAL INTELLIGENCE (AI) BY AUTHORS

AI was used to improve readability.