# THE MULTI-LAYER ACOUSTIC & CONDUCTIVE-GRID SENSOR (MACS) TECHNOLOGY DEMONSTRATION ON HTV-X3

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## ABSTRACT

Millimeter-sized orbital debris (OD) represents the highest penetration risk to spacecraft operating in low Earth orbit (LEO). However, there is a lack of direct measurement data on such small debris in the environment, leading to large uncertainties in the OD risk assessments for mission support. To address this critical data gap, the NASA Orbital Debris Program Office (ODPO) has explored various particle detection technologies for *in situ* measurements of small OD since the early 2000s. The effort has led to the development of the Multi-layer Acoustic & Conductive-grid Sensor (MACS), a collaboration with JAXA.

MACS combines several simple particle impact detection principles to maximize information that can be extracted from each debris detection for high quality data. Such measurement data is needed to support meaningful improvements to the modeling of the millimeter-sized OD populations and increase the fidelity of OD impact risk assessments, which will enable the development and implementation of cost-effective protective measures for the safe operations of future space missions. To fully advance the technology readiness level (TRL) of MACS, a technology demonstration of MACS on a JAXA H-II Transfer Vehicle (HTV) mission in early 2027 has been confirmed. A successful demonstration of MACS will pave the way for using MACS to address the critical data gaps on the millimeter-sized OD at 600-1000 km altitudes in the future. This paper provides a summary of the rationale, MACS technology development, and preparation for the upcoming HTV-X technology demonstration mission.


## 1 BACKGROUND

When a large, trackable object collides with an operational spacecraft, it can lead to the catastrophic destruction of the vehicle. When a small, millimeter-sized OD hits a spacecraft, the outcome may not be catastrophic, but the impact can be severe enough to penetrate the fuel tank, damage the battery, or disrupt other critical systems prompting an early termination of the mission. Since the OD population closely follows a power-law size distribution, there is far more small debris than large debris in the environment. For spacecraft operating in LEO, the likelihood of non-catastrophic but mission-ending damage caused by millimeter-sized OD is orders of magnitude greater than the likelihood of an accidental collision with a large, trackable object. The seriousness of risks from small OD has been confirmed by detailed impact risk assessments for human spaceflight and robotic missions. For example, the critical OD penetration risk to the International Space Station (ISS) is driven by debris in the 1-3 millimeter-size range [1] and the highest penetration risk to robotic spacecraft in LEO is dominated by debris in the millimeter-size range [2].

Fig. 1 shows sources of the LEO measurement data used by the ODPO for OD environment modeling and

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risk assessments. The largest objects are tracked by the Space Surveillance Network (SSN) operated by the Department of Defense (DOD). The ODPO collaborates with the DOD to collect additional measurement data on OD down to approximately 5 millimeters in size using the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) operated by the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL). The ODPO also tasks the Jet Propulsion Laboratory's Goldstone Radar to statistically sample OD as small as 2-3 millimeters in size. Data for sub-millimeter-sized OD come from inspection of a limited number of available returned vehicle and hardware surfaces.

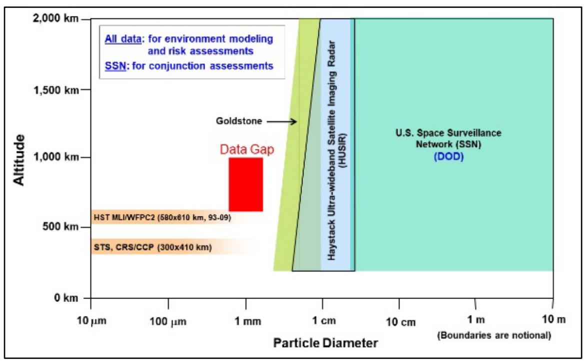


*Figure 1. NASA's OD measurement coverage in LEO. A critical data gap on the millimeter-sized OD exists between the altitudes of 600 and 1000 km.*

As illustrated by Fig. 1, there is a general lack of direct measurement data on the millimeter-sized OD in LEO, but the need is more critical between the altitudes of 600 and 1000 km, as indicated by the red zone. More than 400 spacecraft, including about 20 from NASA, currently operate in that altitude range and more are expected in the future. Direct measurement data of the millimeter-sized OD is needed for reliable OD impact risk assessments to support the development and implementation of cost-effective protective measures for the safe operation of missions in that altitude range. This critical OD data gap in LEO has been recognized by NASA [2]; the 2018 U.S. Space Policy Directive 3 - the National Space Traffic Management Policy [3]; the 2021 U.S. National Orbital Debris Research and Development Plan [4]; and the 2022 U.S. National Orbital Debris Implementation Plan [5].

## 2 MACS OVERVIEW

To address the critical data gap on the millimeter-sized OD above 600 km altitude, *in situ* measurement is the most effective solution [2]. For more than 20 years, the ODPO has investigated various small OD *in situ* measurement technologies and combinations of technologies, such as aerogel, acoustic sensors, resistive grids, and others [6, 7, 8]. The most recent concept is MACS, which includes a key component from JAXA as described below. The ODPO has collaborated with JAXA, under several agency agreements, to develop, test, and optimize the design of MACS at the component and system levels since 2017.

MACS is a four-layer sensing system as illustrated in Fig. 2. The first layer is JAXA's conductive-grid thin film Space Debris Monitor (SDM), which is a flight-demonstrated and patented technology specifically designed to measure the sizes of the impacting debris. The second and the third layers are identical Kapton® thin films, and the last layer is a low-density syntactic foam panel. Multiple Acoustic Orbital Debris Identification (AODI) sensors are attached to each layer to measure impact time and location. The AODI acoustic sensors on the backstop foam panel are also used to measure impact kinetic energy. The impact time and location data from different layers are combined to calculate impact speed and direction. Mass and material density of the impacting debris can be calculated from its size, speed, and impact kinetic energy.

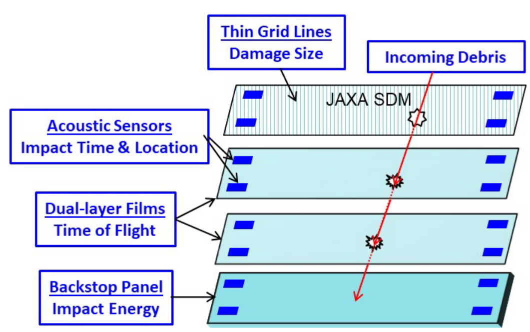


*Figure 2. MACS Detection Principles.*

To address the critical data gap on the millimeter-sized OD, specific measurement data is needed. A simple detection of "something" is insufficient for meaningful improvements to OD modeling and risk assessments. That is why the 2022 U.S. National Orbital Debris Implementation Plan calls for the following to improve characterization of small debris in LEO: "*Investigate technology development and mission opportunities for in-situ measurement sensors to identify, develop, and mature in-situ measurement technologies; leverage researched technologies; and encourage the development of novel concepts capable of collecting similar types of data, including size, mass, material density, speed, and direction, on the millimeter-sized orbital debris. Identify mission opportunities to deploy sensors to collect statistically meaningful data on the millimeter-sized orbital debris between 600 km and 1000 km altitudes* [5]." The innovative design of MACS with a unique combination of SDM, AODI, multi-layer thin films, and the backstop foam panel allows it to collect the necessary measurement data to meet this objective.

As the ODPO and the JAXA SDM team matured the MACS design, an opportunity for a technology demonstration of MACS on a future HTV-X3 flight was identified in 2022 and confirmed in 2023. The HTV-X3 launch is tentatively scheduled for early 2027. The MACS technology demonstration on HTV-X3 is sponsored by the NASA Office of Safety and Mission Assurance (OSMA) via its funding of the ODPO, the Heliophysics Division (HPD) of the NASA Science Mission Directorate (SMD), the ISS Program, and JAXA (SDM and HTV-X3). The mission profile, including altitude and duration, of HTV-X3's technology demonstration phase after it leaves the ISS has not been finalized, but the MACS demonstration provides a great opportunity to fully mature the MACS TRL and demonstrate its small debris detection capability. A successful MACS demonstration on HTV-X3 will pave the way for NASA to pursue a mission to address the critical millimeter-sized OD data gap above 600 km altitudes in the near future.

## 3 SPACE DEBRIS MONITER

JAXA's SDM is the first layer of the MACS sensing surface. It is a patented technology funded by JAXA during its development. The SDM consists of multiple thin film sensor sections that are integrated to provide measurement data on OD ranging from approximately 100 μm to several millimeters in size. The sensor sheet for detecting debris is manufactured from a single-sided copper foil polyimide film, with 50 μm wide sensor lines etched into the copper foil surface at 100 μm intervals as shown in Fig. 3. When the SDM is powered on, current flows through the sensor lines. Therefore, the SDM can measure the size of the debris and position of the linecuts by detecting the number and locations of sensor lines that are severed and no longer energized due to debris perforation [9].

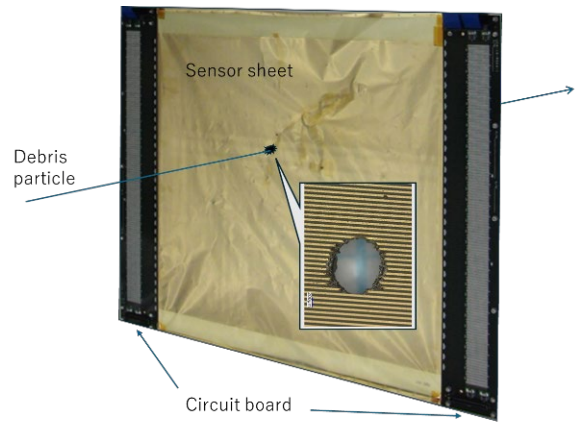


*Figure 3. SDM overview.*

The SDM design is unique in that the detection is based on a simple linecut mechanism and requires little calibration. The SDM layer is a thin film with a thickness of 12.5 μm. Thin film perforation by large objects at hypervelocity has been well studied before. When OD in the 100 μm to millimeter size range impacts and perforates SDM, the size of the damage hole is approximately 10-30% larger than the size of the impacting debris. The correlation can easily be established by laboratory hypervelocity impact testing [10].

*Table 1. Specifications of SDM for MACS.*

| | |
|---|---|
| Thickness of film | 12.5 μm |
| Detection area size per sheet | 410 x 430 (mm) |
| Conductive line thickness | 50 μm |
| Conductive line spacing | 50 μm |
| Number of lines per sheet | 4096 |

The SDM was successfully demonstrated in orbit on HTV5, which was launched on 19 August 2015 (Fig. 4). The HTV5 SDM detected one impact during its one-month operational period before the reentry of HTV5. Since that time, the fabrication method of the sensor has been changed, and its dimensions were also increased to allow for a larger detection area. The SDM consists of two sensor sheets and Data Measurement Equipment (DME). The MACS SDM being developed for the HTV-X3 demonstration has a detection area of 430 × 410 mm each and two sheets are attached on a main frame as shown in Fig. 5 and Tab. 1 [11]. The total effective detection area is approximately 0.35 $m^2$.

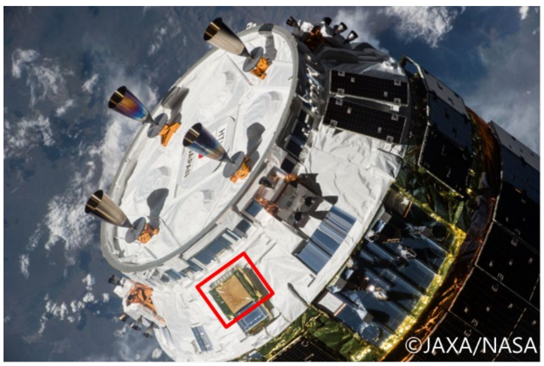


*Figure 4. SDM (the gold surface indicated by the red square) on HTV5.*

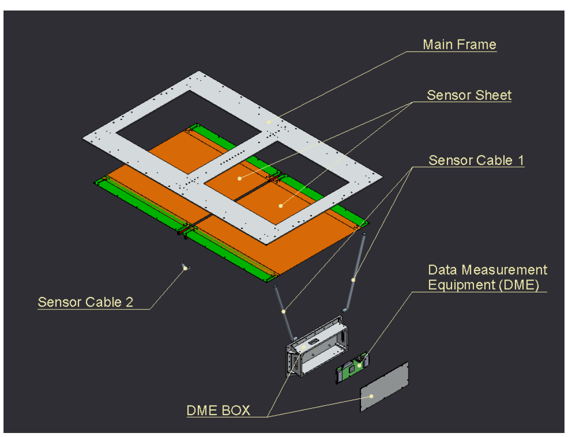


*Figure 5. Illustration of the MACS SDM.*

## 4 AODI ACOUSTIC SYSTEM

The MACS AODI sensor detects strain waves produced by particle impacts at multiple acoustic sensor locations on each layer [12]. The difference in signal arrival times is used to identify the location and time of an impact using the same multilateration approach as that used by GPS and seismometers. This process is done on each of the four layers of MACS - SDM, two Kapton® thin films, and the backstop syntactic foam panel (Fig. 6). Since the separation distance between layers is known, the direction and speed of the particle are readily determined [13]. The orbit of the particle can also be calculated based on the location and orientation of the MACS and the telemetry of HTV-X3 at the time of impact detection.

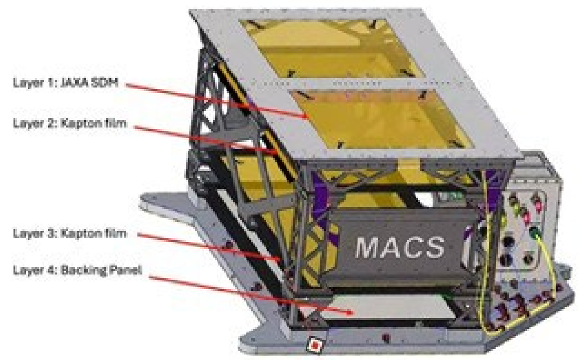


*Figure 6. AODI Overview.*

The AODI sensors used are highly sensitive polyvinylidene (PVDF) strain sensors (12 mV per micro-strain). These sensors are special designs, fabricated and demonstrated to withstand the harsh space environment at temperatures from cryogenic to 105°C. Their flexibility and relatively small thickness (28 µm) minimize the mechanical load on the underlying polymer film layers. Their active sensing area (5 × 10 mm) was selected to provide consistent sensitivity over the primary frequency bandwidth of interest (5 to 200 kHz) for small debris detections.

The AODI sensors collect data from at least four sensors on each of the four layers. Note that those on the first layer are independent of the operation of the SDM. The four primary sensors are located near the corners of each layer, while a fifth sensor is near the middle-bottom. Since each determination of impact location requires only three sensors, using five sensors improves the overall accuracy of the determination while also providing a redundancy factor against potential sensor damage or malfunction.

On each layer the signal arrival times at each sensor are converted to a set of time differences using the wave speed on the layer material. While wave speed is relatively constant, any small changes in temperature or time are monitored by including a sound source (*i.e.*, pinger) on each layer to provide a known reference location for calibration. Additionally, while sensor data from all layers are used for particle speed and direction calculations, the preference is given to those on the second and third layers, which are identical Kapton® thin films with identical wave characteristics.

This AODI sensor system was tested at NASA White Sands Test Facility (WSTF) using hypervelocity impact speeds from 5.27 to 7.19 km/s. Particles ranged in size from 0.2 to 1.76 mm diameter, and 7 materials were used over 168 test shots (Fig. 7). Test results showed that SDM and the Kapton® films were easily penetrated by projectiles in the size range of interest. All projectiles reaching the backstop foam panel showed no measurable changes in speed or direction. Projectile impact speeds were typically measured within 1.5 ms and directions within 1.5° of true, meeting or exceeding the pre-established MACS system requirements.

*Figure 7. AODI test instrument being installed outside a target chamber at WSTF.*

In addition to signal timing, signal amplitude on each layer was also collected from the tests and used to assign the projectile to a material type. Of particular interest was the level produced on the backstop foam panel. Initial tests using a Lexan panel suggested that the signal level was approximately proportional to the kinetic energy of the impacting particle. However, the impacts on the Lexan panel produced considerable secondary ejecta and caused significant damage to the thin films of the other layers. To resolve this problem, the team conducted research to identify a better backstop panel material, which resulted in selecting type BZ-24 syntactic foam (Engineered Syntactic Systems). This low density (0.39 g/cm$^3$), high stiffness material produced good projectile capture mechanics, strong acoustic signals, and little impact ejecta. Hypervelocity impact tests at WSTF confirmed that the signal levels produced were approximately proportional to the projectile impact kinetic energy. Since there is a concurrent measurement of particle speed, this can be used to calculate the particle mass. With mass and size, one can obtain a value for the particle material density sufficient to assign the detected debris to a material density category (high, medium, low), consistent with the material density category used by the NASA Orbital Debris Engineering Model (ORDEM) [14].

For projectiles not able to perforate the first three layers to reach the backstop foam panel, there is other information available to contribute to the material density determination. One is the number of layers penetrated. Based on the WSTF testing, it is found that steel projectiles will go through the first 3 layers and produce impact signals on the backstop BZ-24 panel even at sizes as small as 0.2 mm, while aluminum projectiles must be larger than 0.5 mm, and plastic projectiles larger than 1 mm to reach the final backstop BZ-24 panel. Another important indicator of projectile material is found by comparing signal levels on the various layers. A particle passing through the first layer will produce some ejecta consisting of the removed first-layer material and any spalling from the particle. This additional material travels slower and is detected as a delayed signal on the next layer. The intensity of this delayed signal gives a useful discriminator of particle composition. It is found to be very small for steel projectiles, but many times larger for aluminum projectiles, and even larger for plastic projectiles. This information provides an additional indicator of particle material density and possibly morphology.

The specifications of the AODI system and the accuracies of its impact speed, direction, and location determinations are summarized in Tab. 2. Combining the AODI acoustic sensor data and the SDM data also provides a cross check on each of their results. The impact location on the SDM is independently identified by the positions of the severed lines and can be used to compare with the location determination from AODI. Additionally, studies have found that the acoustic sensor signal levels on the SDM are dependent only on the perforation hole size, hence proportional only to projectile size for all materials and velocities studied. Although somewhat approximate, this latter feature can give an indication of the projectile size to support the validity of the more accurate SDM values.

*Table 2. Specifications of the MACS AODI.*

| | |
|---|---|
| Nominal detection area | 430 × 910 mm |
| Layer separations (mm) | 100, 300, 100 |
| Layers 2 and 3 thickness | 12.5 µm |
| Backstop panel thickness | 10 mm |
| Nominal particle impact speed | 15 km/s |
| Speed accuracy (at nominal) | +4/-3 km/s |
| Impact location accuracy (X,Y) | +/- 12 mm |
| Direction accuracy (re: X,Y axis) | +/- 2.5° |

## 5 MACS DEVELOPMENT

MACS component level development and testing started in 2018. The initial efforts focused on the evaluation of the SDM breadboard unit gridline breakage and its acoustic responses to millimeter-sized projectiles at hypervelocity impact speeds. Fig. 8 shows the test configuration of a SDM breadboard unit with 4 acoustic sensors attached to its corners (left) and the perforation hole from the impact of a 1 mm-diameter stainless steel projectile at 7.06 km/s vertical impact speed (right).

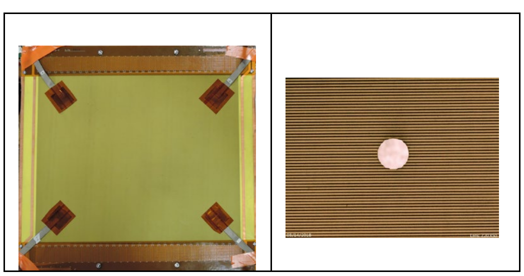

*Figure 8. SDM test article (left) and a 1 mm diameter damage hole (HITF18172, 2018).*

Two layers of Kapton® films and a backstop BZ-24 foam panel were added to the system after the initial SDM testing for the MACS prototype unit (Fig. 9). Fourteen week-long hypervelocity impact test series with a total of 168 shots on the MACS prototype unit were carried out at WSTF between 2021 and 2023. Projectiles made of low, medium, and high density materials were used for the tests. They included polymethyl methacrylate (1.2 g/cm$^3$), glass (2.45 g/cm$^3$), aluminum (2.80 g/cm$^3$), aluminum oxide (3.95 g/cm$^3$), titanium (4.45 g/cm$^3$), stainless steel (7.67 g/cm$^3$), and copper (8.96 g/cm$^3$). Sizes of the projectile ranged from 0.2 to 1.76 mm in diameter. The impact speeds ranged from 5.27 to 7.19 km/s. Most of the impacts were vertical but some were 15° off the normal.

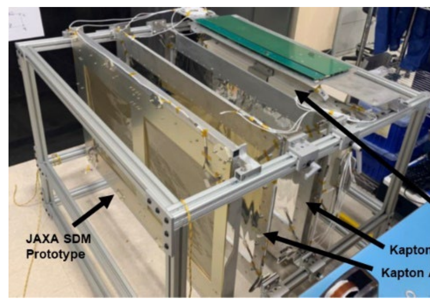


*Figure 9. MACS prototype unit with 4 layers.*

SDM and AODI data were recorded for all test shots. Visual inspection of each layer was conducted inside the target chamber after each shot. At the conclusion of each test series, the MACS prototype unit was shipped back to the ODPO at Johnson Space Center for detailed photo documentation of impact features. Fig. 10 shows the damage holes on the four layers from the impact of a 0.3 mm-diameter stainless steel projectile at 7 km/s.

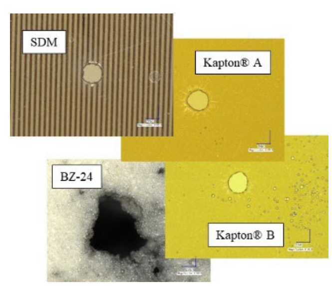


*Figure 10. Impact features on the 4 layers of the MACS prototype unit (HITF23124, MACS148, 2023).*

The 14 impact test series aimed to achieve several objectives. The first was to characterize the acoustic responses from projectiles made of different materials and with different sizes at different layers. The second objective was to optimize the separations between layers for good impact speed measurements with minimal secondary ejecta damage. The third objective was to probe the acoustic responses from different impact locations on each layer surface. The fourth objective was to document the degree of layer penetration by projectiles made of different materials and with different sizes. The fifth objective was to combine data from SDM, AODI, and the backstop BZ-24 panel to characterize the overall MACS detection capability.

The 14 hypervelocity impact test series and the lessons learned significantly improve the TRL of the MACS prototype unit. Additional component-level environmental tests were also conducted to further increase the TRL of MACS. The tests included random vibration, thermal vacuum, atomic oxygen, and shock tests on the MACS components (Fig. 11). The environmental testing effort was partially funded by SMD/HPD.

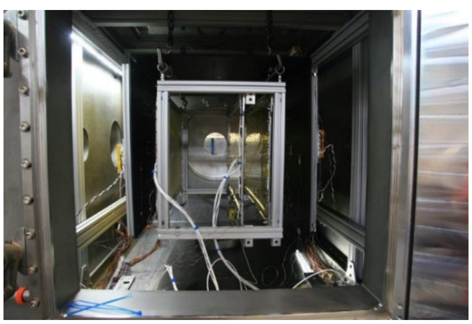

*Figure 11. Test setup of the MACS Kapton® layers and the BZ-24 foam panel inside a thermal vacuum chamber.*

## 6 MACS HTV-X3 TECHNOLOGY DEMONSTRATION MISSION

The MACS team started to explore potential mission opportunities in 2022. As recommended by the JAXA SDM team, a MACS technology demonstration on a future HTV-X3 mission was confirmed in early 2023. The concept of operations is to mount a MACS flight unit with a detection area of 0.35 m$^2$ to the unpressurized cargo base of HTV-X3 (Fig. 12). After HTV-X3 completes its supply delivery to the ISS, it will leave the ISS and start the technology demonstration phase of the mission. MACS will be activated at that point to complete specific tasks and collect data on small debris. At the end of the technology demonstration phase, HTV-X3 will follow a controlled reentry to target the footprints of any potential surviving fragments over a remote ocean area.

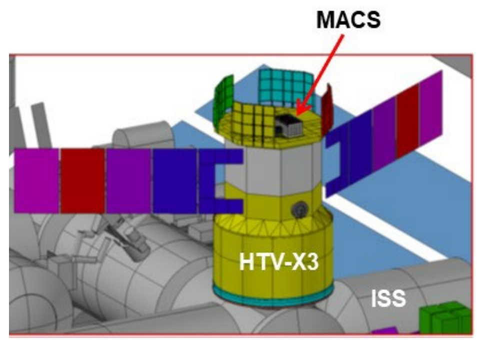


*Figure 12. Illustration of MACS on HTV-X3.*

Major MACS project development milestones are summarized in Tab. 3. A successful Systems Requirements Review (SRR) was completed in November 2023, followed by the Preliminary Design Review (PDR) in May 2024. The next milestones are Critical Design Review (CDR) in November 2025, MACS delivery in September 2026, and the System Acceptance Review (SAR) in November 2026. The launch of HTV-X3 is currently scheduled for March 2027.

The mission profile of HTV-X3's technology demonstration phase has not been finalized. Due to propellant limitations and the need to balance different mission objectives, it is likely that the altitude for demonstration will be lower than 500 km with a duration on the order of 6 months or less. Regardless, the mission success criteria for MACS are to fully demonstrate the system performance via an end-to-end data collection, processing, and downlink to ground station at the beginning and near the end of the technology demonstration phase. Any OD impact data collected, while insufficient to address the millimeter-debris data gap, will be used to improve the modeling of the debris environment.

*Table 3. MACS Project Schedule.*

| | |
|---|---|
| MACS Approval to Proceed | Feb 2023 |
| MACS SRR | Nov 2023 |
| MACS PDR | May 2024 |
| MACS CDR | Nov 2025 |
| MACS Delivery to JAXA HTV-X3 | Sep 2026 |
| MACS SAR | Nov 2026 |
| HTV-X3 Launch to the ISS | Mar 2027* |

**Tentative*

## 7 SUMMARY

Addressing the millimeter-sized OD data gap between 600 and 1000 km altitudes is a very challenging task. Specific data, including size, mass, speed, direction, and material density of the detected OD are needed for meaningful improvements to the modeling of the environment and risk assessments for mission support. Such data is beyond the reach of ground-based radars but can be obtained by specially designed *in situ* measurement instruments such as MACS. A successful technology demonstration of MACS on HTV-X3 will lay the foundation to pursue a mission to deploy MACS at high LEO altitudes to collect much-needed measurement data to better quantify risks from OD for the safe operations of future missions.

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