OD-SSA Activity at NASA's Heliophysics Division

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ABSTRACT SUMMARY

Within the Heliophysics Division (HPD) of NASA's Science Mission Directorate (SMD) , Orbital Debris – Space Situational Awareness (OD-SSA) has been stood up as an "activity" in early 2021, with OD-SSA becoming an official part of HPD's Space Weather Program in FY24. OD (anthropogenic debris, micro meteorites and dust) are now included in HPD's definition of the Space Working Environment – defined as all parts of the space environment that affect human activities in space. Here we will present an overview of the OD-SSA activities in HPD, past and present, including:

- Addressing the measurement gap of <3cm OD (instrument development concepts and flight opportunities)
- Mission Design Lab activities on a dedicated small OD characterization mission
- New OD science – signatures of objects moving through a space plasma

1. US NATIONAL CONTEXT and HELIOPHYSCIS DIVISION ROLE

Over the past few years the Office of Science and Technology Policy at the US White House has been developing the US National Orbital Debris Strategy, which has been codified into the National Orbital Debris Implementation Plan, published in July 2022. This plan covers three areas:

1. Debris Mitigation
2. Tracking and Characterization of Debris
3. Remediation of Debris

While there are roles identified for NASA covering items in all three of these areas, several items under "Tracking and Characterization of Debris" now fall under the purview of the Heliophysics Division of NASA's Science Mission Directorate.

At a broad organizational level, NASA has identified the small orbital debris problem as an agency risk, which has been split into three individual risks:

- Space Sustainability: Orbital Debris Risk
- Space Sustainability: Interference to NASA Operations Risk
- Space Sustainability: Space Traffic Management Risk

To address and help mitigate these risks, NASA's Science Mission Directorate (SMD) directed the Heliophysics Division (HPD) to:

- Develop and deploy the space-based instruments and other investigations to better constrain the micro-debris environment in the 500 to 1000 km altitude range;
- Develop and deploy space-based instruments and other investigations to allow for better prediction of the natural processes that lead to the losses of orbital debris in the Earth atmosphere; and
- Work to integrate these measurements into the Orbital Debris activities conducted by NASA, and especially the Orbital Debris program office at NASA Johnson, as well as to improve Space Weather forecasts.

The HPD has partnered with NASA's Orbital Debris Program Office (ODPO) to help address the insufficient state of knowledge of the small (<3 cm) orbital debris population. ODPO is the steward of NASA's Orbital Debris Engineering **Model** (ORDEM 3.2) – and the small OD population is the least good characterized leading to the largest uncertainties in the model, representing a significant cost driver in spacecraft design. Our lack of knowledge of these Lethal Non-Trackable (LNT) objects currently represents the biggest threat to NASA's operation missions in Low-Earth Orbit (LEO) - and of course be extension to all active spacecraft in LEO.

> ***One cannot fully understand OD without understanding the environment (SSA), and you cannot fully understand the operational environment (SSA) without characterizing the debris population and its effects. All of this is best done by leveraging the relevant expertise of HPD.***
>
> ***Small natural and man-made space objects (Orbital Debris [OD}, micrometeorites, dust) are to be considered alongside traditional Space Weather in making up the Space Working Environment (SWE) and are part of HPD's Space Weather Program.***

2. SMALL SPACE RESIDENT OBJECT GROWTH

Fig. 1 shows the current number of tracked objects in space, the vast majority of which are in LEO. The tracked object growth was originally driven by step-wise increases of fragmentation debris in the wake of collisions or anti-satellite tests, but increasingly the growth is dominated by the increase of deployed satellites in large constellations (such as StarLink), which is forecast to continue on an exponential growth for the foreseeable future.

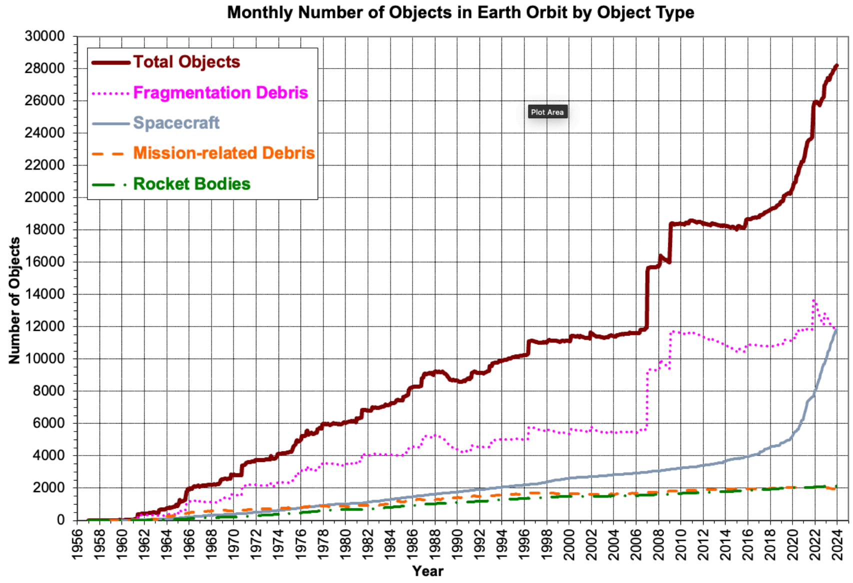


Figure 1: 2024 Space catalog for object greater than 10cm. Credit: NASA Orbital Debris Program Office (ODPO).

Fig. 2 shows the density distribution at LEO as a function of altitude with the Starlink and OneWeb mega-constellations. The Collisional cross-section in those shells is high -> high collision risk whenever debris is too small to be tracked or collision avoidance maneuvers are impossible for other reasons. By the time there are 65 000 satellites in orbit, "**one out of every 15 points of light you see in the night sky will be a moving satellite**" (Samantha Lawler, University of Regina).

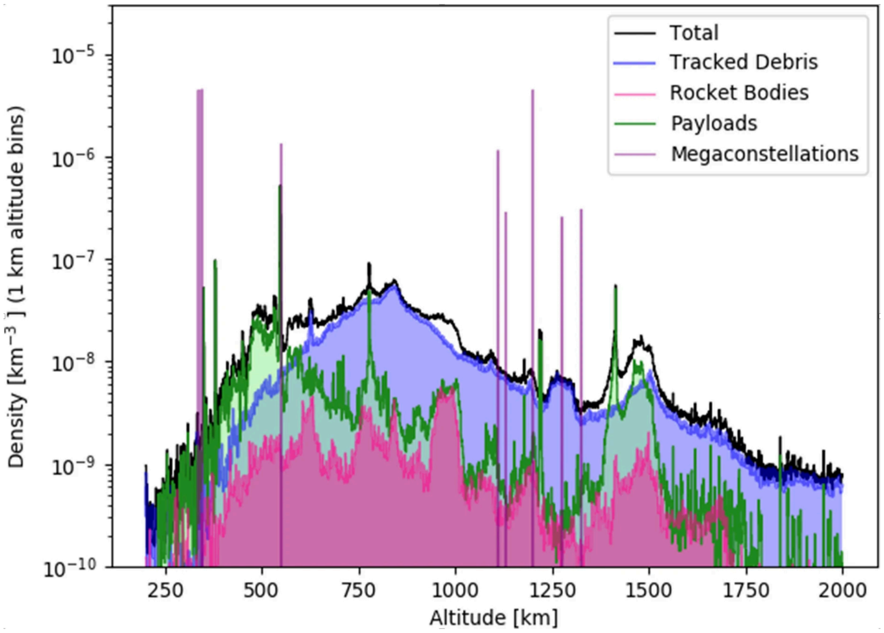


Figure 2: Density Distribution of tracked objects. Credit: [1]

All satellites in orbit shed small debris – from paint flakes to fragmentation objects from micro-meteorite hits or other collisions with small debris objects. With increasing number of satellites in LEO, the small debris population is expected to grow correspondingly, especially in the orbital shells of mega constellations. Fig. 3 shows an estimated cumulative cross-sectional area flux of objects in space, at International Space Station (ISS) altitudes, while Table 1 shows the estimated increase in object flux relative to 10cm objects. Based on these numbers one would except a population of several hundreds of thousands of LNT objects just in the 1-10cm size range to be present right now – and scaling up as LEO becomes more congested. Objects below 1cm in size can still be lethal, and the population of objects in the millimeter range is expected to be in the millions.

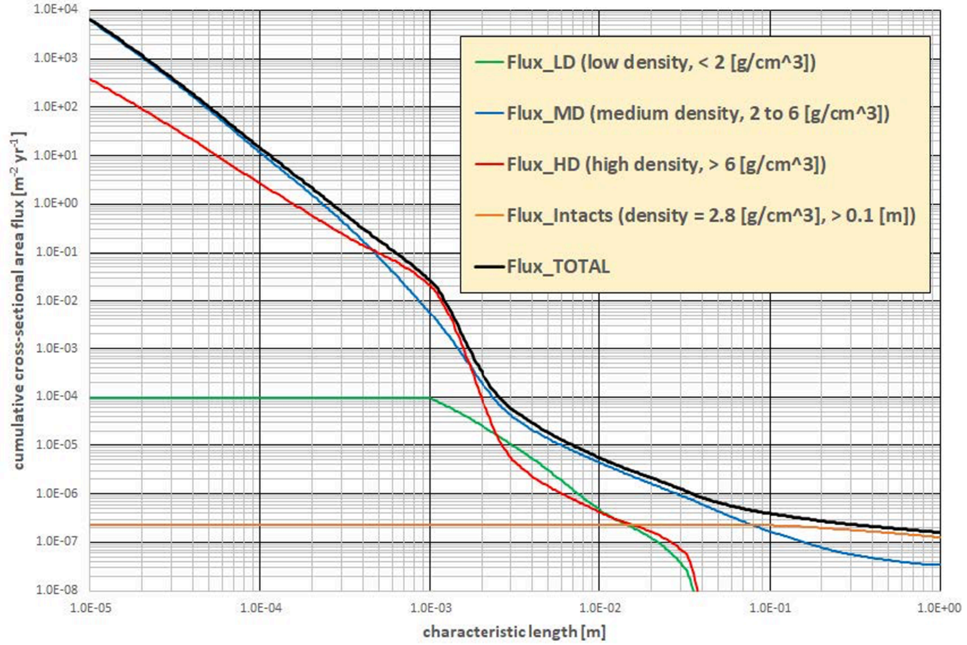
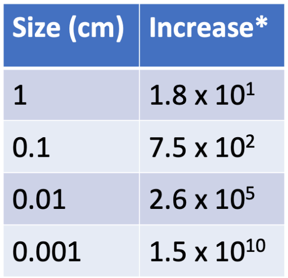


Figure 3: Size Distribution of orbital objects at ISS altitudes. Credit: NASA Orbital Debris Program Office (ODPO).

Table 1: Expected increase of object flux relative to 10cm object flux at ISS altitudes



Size (cm)	Increase*
1	1.8 x 10^{1}
0.1	7.5 x 10^{2}
0.01	2.6 x 10^{5}
0.001	1.5 x 10^{10}

Objects below 10cm are currently not routinely tracked, and objects much smaller than 3cm are basically unobservable from the ground at present. Fig. 4 shows current capabilities and highlights the data gap that is addressed by the OD-SSA program in HPD. The Space Surveillance Network routinely tracks down to around 10cm object size, augmented by intermittent observations from the Goldstone and Haystack Radars in a non-tracing counting mode only. At the smallest size range past samples returned from orbit (Space Shuttle window impacts, and impact plates returned from the Hubble servicing mission) give a temporally limited snapshot of the sub-1mm population for a few select orbital heights, leaving a data gap from sub mm to several cm where we have insufficient data to characterize the population. HPD's approach to filling this gap has been to develop new OD measurement instruments and to capitalize on ride share opportunities to test these new concepts on orbit.

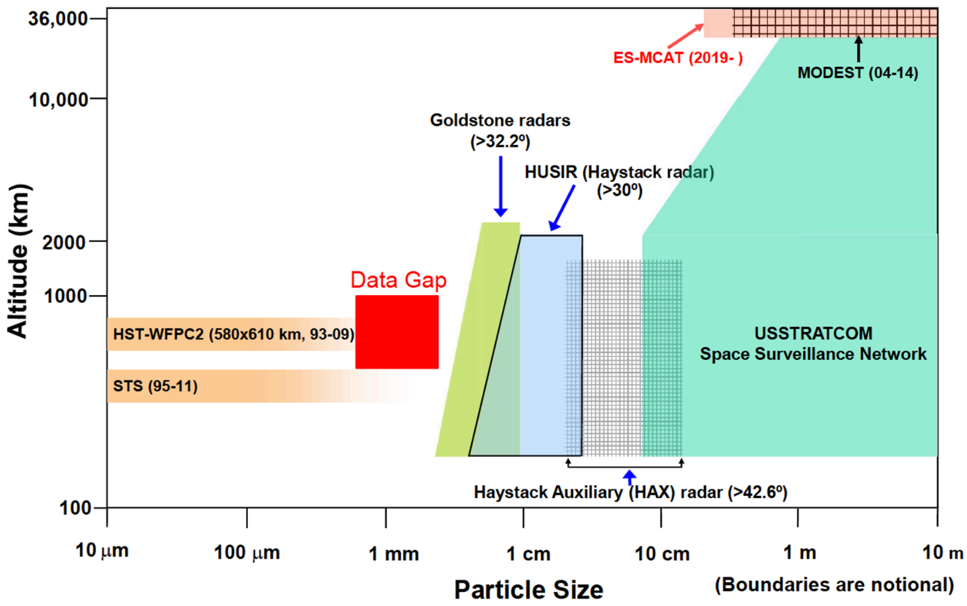


Figure 4: Tracking capabilities for space objects as a function of orbit altitude and size. Credit: NASA Orbital Debris Program Office (ODPO)

3. ORBITAL DEBRIS DRIVING NEW SCIENCE

HPD has traditionally been dedicated to understanding the varying natural space environment – from neutral density to low energy eV plasma to high energy MeV radiation belt particles, and the accompanying plasma electric and magnetic field environment from DC to hundreds of kHz. Recently, a new class of phenomena has received increasing attention – signals or disturbances created by orbital objects. Objects moving through space plasmas at orbital speed create their own set of plasma interactions, leading to the generation of waves or disturbances in the background plasma density.

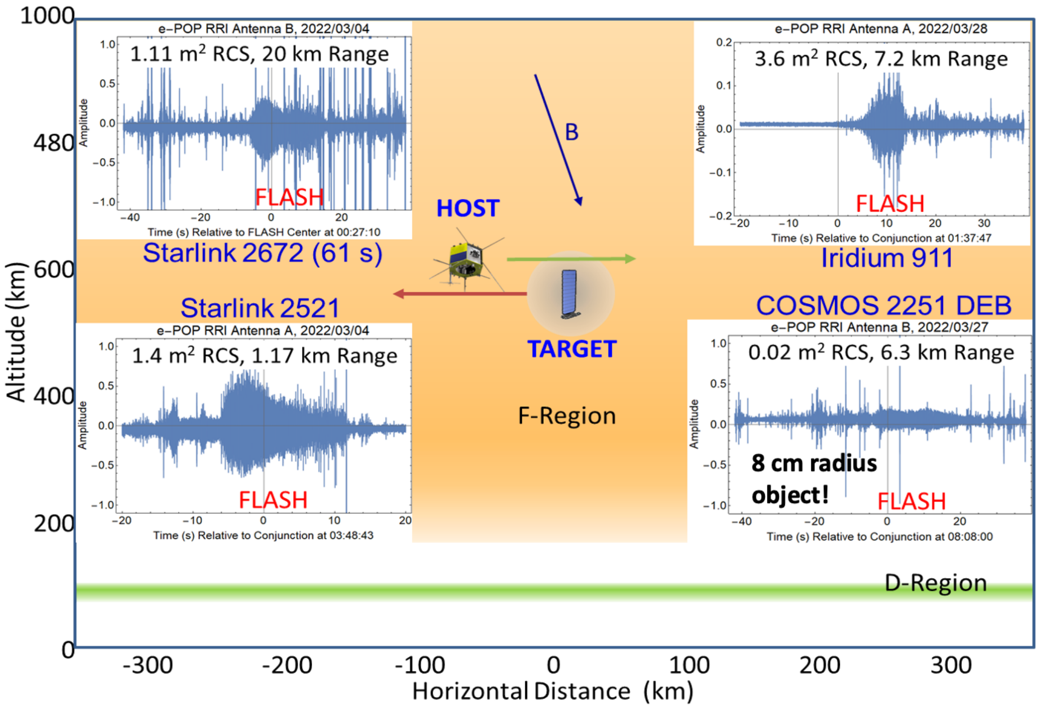


Figure 5: Measurements of electric fields during in situ experiments by the Swarm-E satellite using the Radio Receiver Instrument (RRI). The artificially enhanced plasma waves are labeled as a FLASH [2].

Fig. 5 shows a set of measurements from the Canadian Swarm-E satellite (host) when passing in the vicinity of another known space object (target). For a range of objects (0.02 to 3.6m2 in size) at a range of altitudes (400-800 km) and a range of separations (1.17 to 20km) the RRI instrument observes a "flash" of electric field activity. The basic science of the plasma object interaction is unexplored and is currently the object on an active research program - NASA's "Research Opportunities in Space and Earth Science" (ROSES) 2024 solicited proposals on "the signatures of objects moving through a space plasma".

HPD thus finds itself at the center of an opportunity to explore new science, develop new measurement techniques, help to define an under sampled small OD population environment, and to exploit OD themselves as a sensor of the environment. Fig. 6 explores this opportunity and the interconnected pieces in more detail.

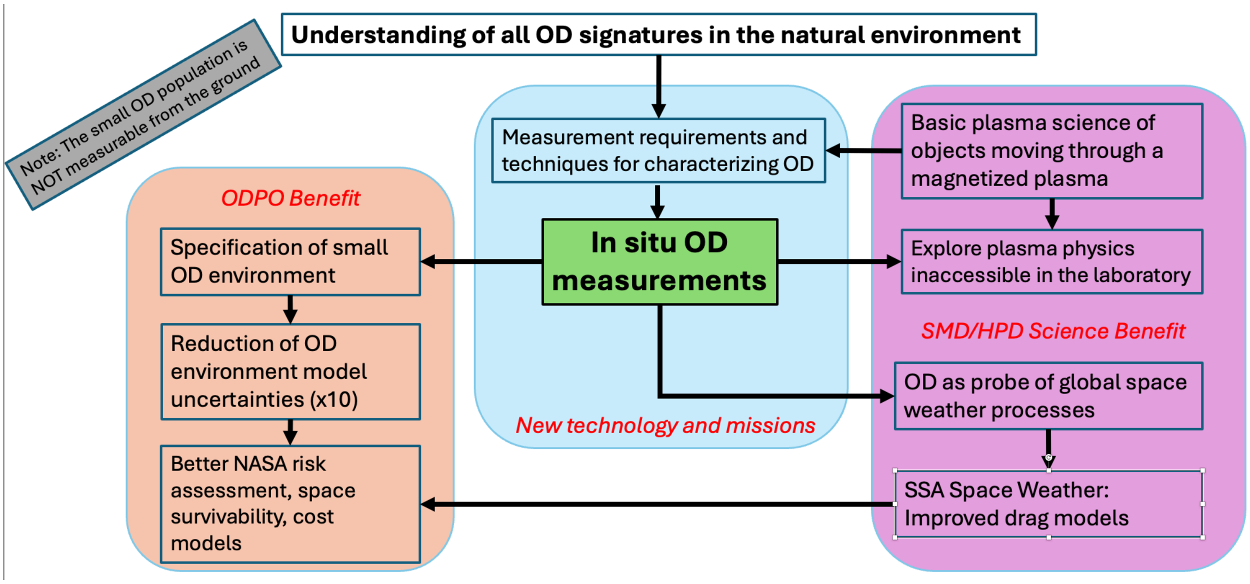


Figure 6: Orbital Debris driving new Science, Technology and Operational improvements

Central to the OD-SSA program in HPD is the need for new in-situ small OD measurements of objects that cannot be measured from the ground.

The purple box on the left of Fig. 6 shows the science drivers and benefit that are central to HPD's focus in the Science Mission Directorate – understanding basic plasma interactions in the near-Earth space environment. While the focus here is in anthropogenic causes of plasma signatures, these signals are quite similar to the signals in the natural environment. As these signals are expected to become more widespread as LEO becomes more congested, it is paramount to understand them and to be able to differentiate them from the natural environment. In Fig. 5 we would not have been able to identify the anthropogenic signals if we didn't know that another object actually passed nearby. Near Earth space is an ideal laboratory to study these interactions that are inaccessible to experiments in the laboratory.

Conversely, once we have established the types of signals and their propagation, they become a diagnostic for detecting and characterizing these objects: this then drives the measurement requirements for new instrumentation in the central blue box in Fig 6. We anticipate here sensitivity and sampling requirements for plasma density and waves that go well beyond the current state of the art. Once new OD detection modalities are established this then also addresses the goal of "Develop and deploy the space-based instruments and other investigations to better constrain the micro-debris environment in the 500 to 1000 km altitude range" from Section 1. These new measurements can then support two goals:

1. Flowing to the left to the beige box, these measurements support the Orbital Debris Program Office in retiring the uncertainties in to OD models such as ORDEM. This supports both NASA and all other space missions in two ways – either by saving cost from no longer needing to over-engineer OD protection due to the better specification of the risk, or by highlighting additional requirements for spacecraft OD protection

that ultimately reduce mission risk.

2. Once we can measure small OD and deploy such measurements on many platforms, and can characterize the dynamical changes in the small to very small OD population, these small OD can be turned into a sensitive tracer – similar to ink in a fluid revealing fluid dynamics here the OD is the “ink” that reveals the dynamics of the neutral density environment – thus flowing back to the basic science in the purple box in Fig. 6. As a stretch goal this could eventually lead to better orbital drag models which in turn support NASA risk assessment for collisions (and also the wider Space Traffic Management tasks of both the civilian and military communities).

Central to this concept is the green box in the middle of Fig. 6: our ability to measure and characterize small OD. Using “Signals of objects passing through a space plasma” and a basic Research and Development loop within HPD as outlined above is a long-term effort which is unlikely to yield new in-situ OD characterization in the short term – but may have large scientific pay-off in the long term.

In the next sections we will thus focus on HPD’s activities to explore other, more direct OD measurement modalities and mission concepts.

4. UPCOMING IN-SITU OD MEASUREMENT OPPORTUNITIES

ODPO has defined as their main need the characterization of the small OD population in the 800-1000km region, which is the most under-sampled and where compared to lower orbits space resident objects have very long lifetimes of ~100s of years. Based on our current knowledge, it would take 3 m^2-years of data to collect sufficient statistics for this measurement – that is a one m^2 aperture collecting data for three years or a 3 m^2 aperture collecting data for one year. The ideal solution here would be a dedicated mission; a concept for that is introduced in Section 5. Here we concentrate on opportunities to increase the TRL of new measurement concepts and to exploit ride-along opportunities wherever they may go.

HPD’s OD-SSA program is currently the sponsor for two more mature instrument concepts that have established upcoming flight opportunities:

- Laser-sheet Anomaly Resolution and Debris Observation (LARADO) – STP-Sat7 launch late 2025
- Multi-layer Acoustics & Conductive-grid Sensor (MACS) – JAXA HTV-X3 launch ~2027
- Multi-Needle fast Langmuir Probe - ESA Verification of In-Situ Debris Optical Monitoring from Space (VISDOMS) mission launch ~2028

LARADO is an optical light sheet concept developed by the Naval Research Lab (NRL) with a flight opportunity through the Space Test Program’s flight 7 which is at no-cost to NASA.

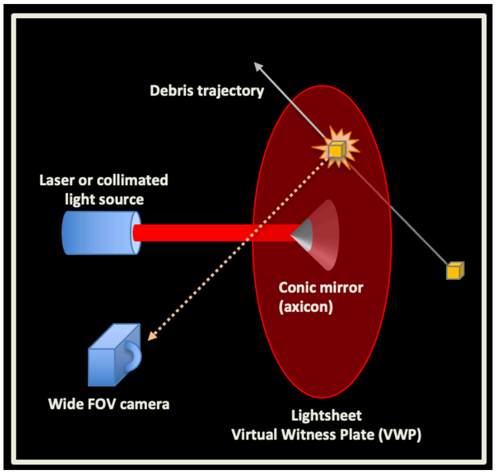


Figure 7: NRL’s LARADO concept. Courtesy Naval Research Laboratory, Andrew Nicholas

HPD is sponsoring the development of the flight instrument, which has been delivered for integration in July 2024. Fig. 7 shows the LARADO concept. A light sheet is formed using a collimated light source, and a wide field camera is used to detect scattered light from objects penetrating the laser sheet. Implementation of this in STP-Sat7 achieves a ~0.6 m^2 detection area and will fly at 550km for at least one year and will represent the first new data on small OD in 15 years. While this new data is not in the ideal location, not collected for long enough and represents a simple measurement (we can detect rough size and number of objects only) it should serve as a useful starting point to adjust our models – by simply scaling from what would currently be expected in terms of measurement to what is actually observed. Of course, the main objective of a demonstration-validation mission is to prove the concept of measurement and raise the TRL. HPD is further supporting the development of a dual laser sheet dual frequency extension of the LARADO concept that should also be able to characterize speed and type of object.

MACS is developed by ODPO at Johnson Space Center and is a mature concept with some flight heritage from an earlier version deployment on the ISS in January 2018. This mission only collected three weeks of data and then failed due to an instrument lockup. The current MACS is a further enhancement of the original concept and shown in Fig. 8.

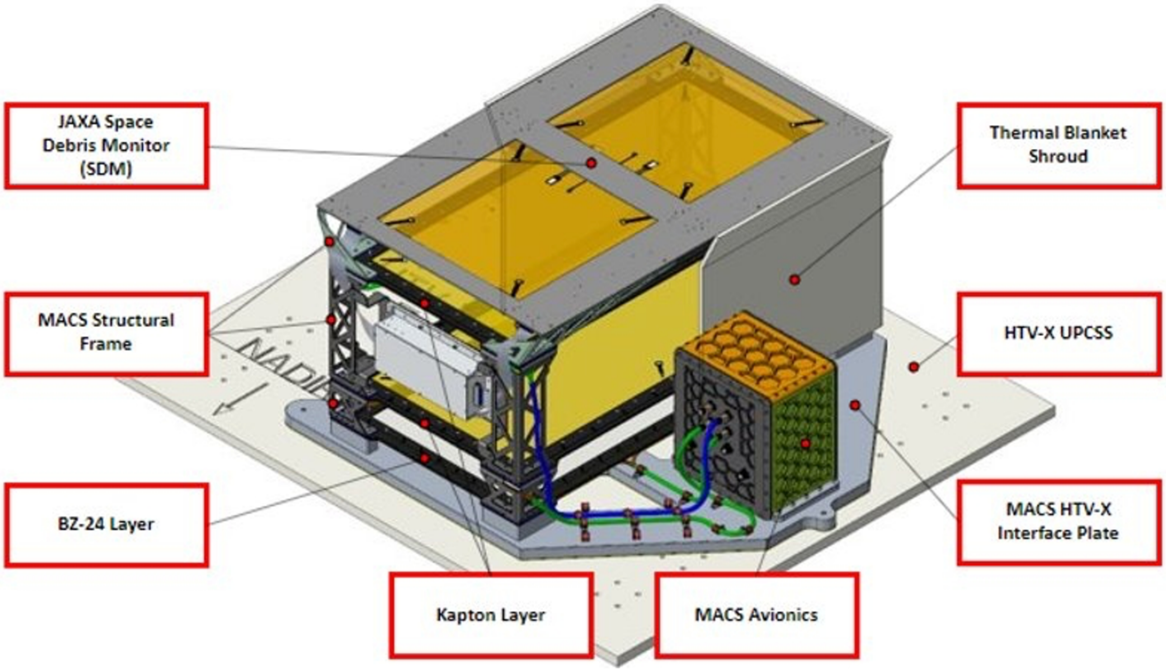


Figure 8: Single Wing MACS for deployment on JAXA HTV-X3. Courtesy NASA Orbital Debris Program Office, Johnson Space Flight Center.

The detection concept is simple – a front grid detector (provided by partners at JAXA) has embedded 50 micron separated lines where detecting the number of lines broken gives an estimate of object size. Two Kapton layers with acoustic sensors can define object trajectory and speed. A back BZ-24 layer measures total momentum deposited. This concept can be exploited for a full characterization of incoming OD: velocity, energy/density, size and some limited information on OD material properties.

To achieve the 3 m^2-year of data the full MACS would consist of three "wings", one of which is shown in Fig. 8. The HPD sample mission design presented in Section 5 would fly three of these wings for a total of 1 m2 in aperture. For the upcoming deployment MACS was invited to fly on JAXA's HTV-X3 resupply mission to the ISS, which has a number of tech-demo instruments for a secondary mission after it detaches from ISS. JAXA's interest here is to demonstrate its own technology that is part of MACS – the JAXA Space Debris Monitor (SDM). One MACS wing will be flown with an aperture of 0.34 m^2, and a nominal mission life of one year at around 500km altitude. As for LARADO, the main objective of a demonstration-validation mission is to prove the concept of measurement and raise the TRL, while whatever data that is collected will still be able to contribute to an update of the ODPO ORDEM model.

On a longer mission horizon is the opportunity to obtain a ride share for a low swap OD instrument on ESA's VISDOMS mission. VISDOMS in in formulation at ESA but not yet with a manifested flight opportunity (which would be in 2028 or later). NASA has an MOU with ESA to support each other with shared ride opportunities for OD instruments, and the optical camera that is used for passive glint detection from OD objects on VISDOMS is the same camera that is part of the strawman payload for our mission concept in Section 5.

The low SWAP availability on VISDOMS dictated a simple instrument, preferably with high TRL. The Multi-Needle Fast Langmuir Probe concept developed at Embry Riddle University has flight heritage on rockets and is also part of the upcoming NASA's Escape and Plasma Acceleration and Dynamics Exploreres (ESCAPDE) mission to Mars. We are in early discussions with ESA to fly an updated version of this instrument on VISDOMS, which will be capable of sampling the background plasma at ~80kHz, fast enough to detect density perturbations caused by passing OD object, one of the proposed "signatures of objects moving through a space plasma" discussed in Section 3.

5. MISSION DESIGN STUDY FOR A DEDICATED OD MISSION

One of the activities with the HPD OD-SSA program was to consider an integrated mission concept for a HPD-led satellite mission that addresses the outstanding NASA Agency risk on the small OD environment, while also providing a home/platform for a range of interconnected activities and research needs related to OD, SSA, and associated impacts on spacecraft. This also directly addresses the directive given to HPD by SMD leadership (Section 1).

The aim was to bring together four distinct but related communities that cover the following topical areas (TAs):

- **Orbital Debris Measurements** - Addressing a measurement gap in the OD size range (0.1–10 mm) that has been identified as an Agency risk.
- **Space Situational Awareness Science** - Addressing scientific questions related to the spacecraft drag environment and how it impacts SSA capabilities and OD dynamics.
- **Space Situational Awareness Research to Operations (R2O) Development** Addressing the basic research needed to combine simple low-latency data with models to provide up-to-date estimates of the relevant environments.
- **Dust / Impact Science / Satellite Effects** - Addressing spacecraft effects from natural and small anthropogenic particles (<0.1 mm).

Tiger Teams were conducted in each topical area to identify measurement priorities. Table 2 shows a a top-level summary of the relationship of the proposed measurements to the Topical Areas, SMD Science, and other key areas.

Table 2:Top Level OD Mission Summary.

Measurement	**TA-1 OD**	**TA-2 SSA Science**	**TA-3 SSA R2O**	**TA-4 Dust-Impact**	**Space Traffic Management**	**Science Area**	**SC Risk reduction**
Optical laser based OD	🟩				🟩	HPD, AD, ESD	All SMD
Large Impact OD	🟩					HPD	All SMD
Dust Impact OD	🟩			🟩		HPD, PSD	
ESA passive Optical	🟩				🟩	HPD, AD, ESD	All SMD
Imaging Spectrograph		🟩	🟩			HPD	
EUV		🟩	🟩			HPD	
Energetic Particle		🟩	🟩			HPD	
Dust Impacts with Electric Field Signals	🟩			🟩		HPD, PSD	

The mission concept would fly at the altitude of interest (800km) in a dawn-dusk orbit on the day-night separator, allowing virtually all sides of the spacecraft to be used – one side always facing the sun, one always looking anti-sunward, one pointing zenith and one nadir. For science area we looked at contribution of this mission concept to other SMD divisions. Astrophysics Division and Earth Science Division concern is on "Space Sustainability: Interference to NASA Operations Risk" and focusses on field of view obstructions and impact on science observation from OD objects while Planetary Science Division has an interest in better characterizing Heliophysics dust environment (See TA-4 below).

Orbital Debris Measurements (TA-1) where covered with four instruments covering size ranges from large spacecraft bodies to micrometer dust. The ESA passive optical is the same as planned for VISDOMS (Section 4) and capable of detecting glint from small objects near the spacecraft to larger objects as far away as GEO for more of an SSA mission, and point away from the sun. The optical laser based OD consists of the LARADO concept (Section 4) and is capable of measuring cm size to millimeter size objects. The large Impact OD is represented by MACS (Section 4) and covers the same size range as LARADO but in more detail – flying both concepts together allows for inter-calibration by positioning the light sheet on a boom in front of MACS. Both point in the ram direction. Dust impact OD measures the sub millimeter OD dust in the ram direction and the micrometeorite environment in the zenith direction.

Space Situational Awareness Science (TA-2) is designed to provide science measurements that help in understanding the neutral density environment. Pointing nadir is a imaging spectrograph here modeled on the remaining un-flown DMSP instrument. Pointing upwards is an energetic particle detector to characterize precipitating particles that become the dominant driver of neutral density dynamic during mainly active times, modeled on instruments flown on NOAA POES. Pointing Sunward is a simple EUV instrument to characterize the dominant solar emission lines that heat the neutral atmosphere.

Space Situational Awareness Research to Operations (R2O) Development (TA-3) couples the data from TA-2) with a reduced real-time data downlink to feed specialized ground-based models to showcase new now casting capabilities for the neutral density (drag) environment.

Dust / Impact Science / Satellite Effects (TA-4) consists of a simple large plate consisting of several typical spacecraft materials and simple dipole antennae at each corner. NASA has been utilizing secondary data from electric field instruments for decades to characterize dust in the Heliosphere – on missions such as CASINI and Parker Solar Probe. Dust impacting a spacecraft can crate little plasma discharge clouds that produce electric field signals that are picket up by science grade electric field instruments on those missions. All one can do here is to count the corresponding signal spikes – it is a completely uncalibrated indirect measurement of the dust / small OD particle hitting the spacecraft. The idea here is to fly a matrix of typical spacecraft materials exposed to small OD / dust impacts and to use the electric field measurements to locate which part of the plate was hit (knowledge of materiel) and to characterize the signal. The plate can also be positioned so that a simultaneous detection by the optical laser-based OD instrument may be possible. By properly "calibrating" the electric field signal it may be possible to obtain a better characterization of the dust measurements made by past missions.

Our Mission Design Study considered several combinations of instruments (subsets), number of spacecraft and orbits, based on ESPA rideshare deployments. A minimal implementation of one ESPA deployed spacecraft covering only TA-1 and a subset of TA-3 only yielded a 25% cost savings compare to our recommended ESPA Tug option (See Fig. 9) that can provide all the measurements identified in Table 2. The ESPA TUG is an ESPA based spacecraft with propulsion.

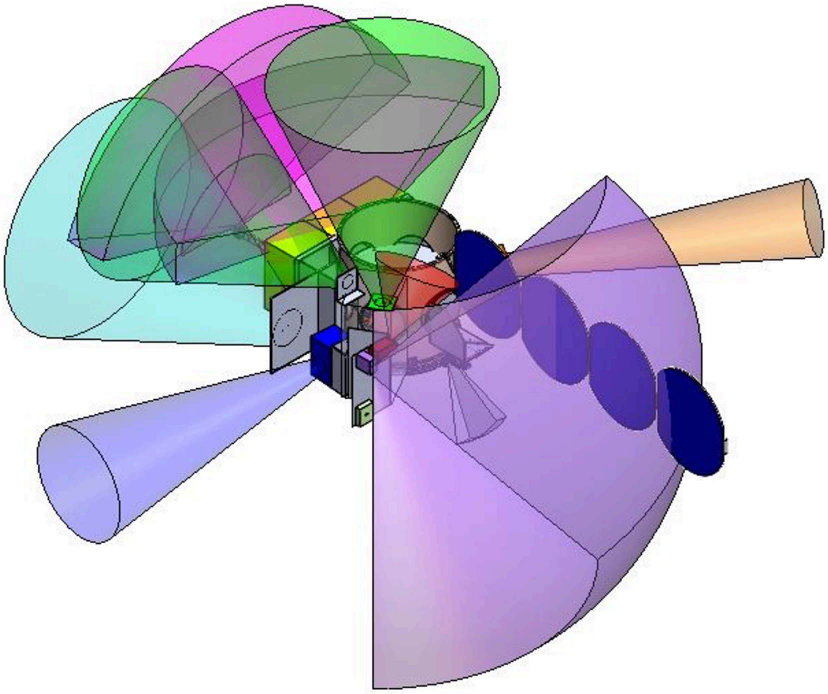


Figure 9: ESPA Tug concept.

A full report containing the Tiger Team outputs, mission design lab study results and overall HPD OD-SSA program philosophy ("Report on the NASA SMD HPD study to conceptualize a research and analysis program and mission concept to address the measurement need of small (<3 mm) orbital debris") is available on request.

It should be noted here that an OD-SSA mission is not a funded part of HPD's current future mission plans, our efforts here are strictly limited to conceptual planning.

6. OTHER OD-SSA RELATED HPD ACTIVITIES

HPD's OD-SSA program leverages other NASA Research Opportunities in Space and Earth Science (ROSES) existing or anticipated Programs:

- Heliophysics Instrument Development for Science (HTIDS) program - Instrument development call for characterizing small OD (HTIDs-SWE). Solicited in ROSES 22 and 23. 4 projects currently supported.
- Heliophysics Supporting Research (HSR) - Special Topic in HSR on "Signatures of objects moving through a space plasma". Solicited in ROSES 24.
- Solicited Proposal on identifying indications of minor debris strikes in spacecraft telemetry (reaction wheels). I proposal currently supported.
- Anticipated pipeline instrument development program for OD-SSA mission instruments in ROSES 25.

Concepts in development / consideration:

- Langmuir multi needle probe for 80kHz measurements of density variations (with ESA VISDOMS) looking for space environment signatures of small orbital debris (as noted in Section 4).

- Solar panel as a sensor – acoustic sensor equipped panels to detect impacts – potentially huge aperture (with Goddard Space Flight Center).

- Passive glint observations in star-trackers. Their noise, our data!

7. REFERENCES

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