Orbital Debris and Space Situational Awareness Activities in NASA's Heliophysics Division

Alex Fletcher[1] and Reinhard Friedel[1]

[1] NASA Headquarters, 300 E St SW, Washington, DC 20546 USA, Email: alex.fletcher@nasa.gov

ABSTRACT

Orbital debris (OD) and space situational awareness (SSA) activities are part of the Space Weather program in Heliophysics Division (HPD) of the Science Mission Directorate at NASA. HPD supports many projects with the goal of characterizing and tracking the OD population – in particular the measurement gap for OD with size <1 cm. This paper discusses past and present OD/SSA activities in HPD, including technology development for instruments to characterize small OD in situ, new OD science: analysis of the interaction of OD with the space plasma environment, and support of space traffic management and the space weather program.

1 INTRODUCTION

Orbital debris (OD) comprises the population of material, both natural and anthropogenic, that is resident in the space environment, but which has no meaningful function and whose existence endangers the safety of operations in space. With the reduction of launch costs and the growth of mega-constellations, the number of spacecraft being launched into orbit has grown precipitously. Without mitigation, the amount of OD will soon follow the same trend.

Fig. 1 shows the techniques for measuring OD as a function of altitude and OD size [1]. Larger debris (~>10 cm) is directly tracked. OD between approximately 0.5 cm and 10 are statistically characterized by radar. There are in situ measurements of very small OD from Hubble and the shuttle, but these are out of date. Note that there is a "data gap" for sub-centimeter debris where there are no measurements, but the debris is large enough to pose a lethal threat to spacecraft. Impact of even millimeter scale debris could be mission ending.

The flux of small, non-trackable, hazardous OD is also much higher than the flux of large trackable objects. While there are an estimated 25,000 objects with a size >10 cm in orbit, there are ~500,000 >1 cm and ~100,000,000 >1 mm. Therefore, most of the OD that is hazardous to missions is untracked and uncharacterized. Furthermore, the typical models for OD (NASA's ORDEM [2] and ESA's MASTER [3]) disagree as to the flux of debris within the data gap.

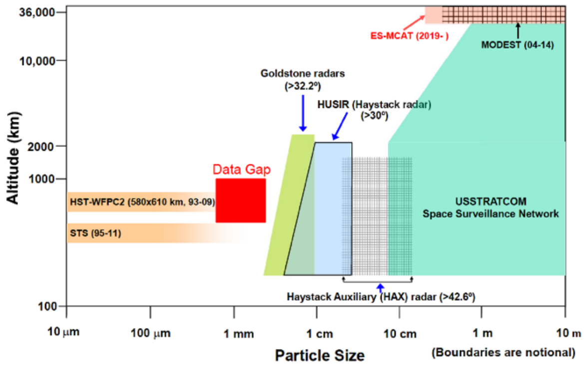

Figure 1. OD measurement methodologies [1] as a function of altitude and debris size. There is a data gap for hazardous debris on the scale of a few mm that is not currently tracked or measured. Courtesy: NASA ODPO

2 WHY HELIOPHYSICS?

NASA has identified the small OD problem as an agency risk, which includes OD risk, interference to operations risk, and Space Traffic Management (STM) risk. A NASA Office of Inspector General (OIG) report [4] provided a set of recommendations, including to "Prioritize obtaining direct measurements needed to fill the 3 mm and smaller sized debris gap at the 600 to 1,000 km altitude in LEO." The Heliophysics Division (HPD) at NASA has partnered with NASA's Orbital Debris Program Office (ODPO) to address the insufficient state of knowledge of the small OD population.

HPD, being part of the Science Mission Directorate, must pursue science goals. The OD-SSA program in HPD provides the basic science elements around the detection of small space objects and explores the scientific utility that might be derived from them. Scientific benefits include the study of basic plasma physics of objects moving through a magnetized plasma, which is difficult or inaccessible in the laboratory due to spatial scales. Another benefit would be the use of OD as a probe of global space weather processes. The operational benefit (which is not HPD's role) would be a better specification of small OD environment, the reduction of OD model uncertainties, and better NASA risk assessment, space survivability, and cost models.

Essentially, one cannot fully understand OD without

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)

understanding the operational environment, and one cannot fully understand the operational environment without characterizing the debris population. This is best done by leveraging the relevant expertise of HPD. HPD's objectives are to 1) develop and deploy space-based instruments to better constrain the small debris population in the 500 to 100 km altitude range; 2) develop and deploy space-based instruments to better predict natural processes that lead to OD loss in the atmosphere; and 3) integrate these measurements into the OD activities at NASA, especially ODPO, as well as improve space weather forecasts.

Orbital debris and space situational awareness (OD-SSA) activities are now part of the Space Weather program in HPD of the Science Mission Directorate at NASA. OD, including anthropogenic debris, meteoroids, and dust, are part HPD's definition of the space working environment - defined as all parts of the space environment that affect human activities in space - along with traditional space weather.

The remainder of the paper discusses HPD-supported OD-SSA projects that will close the small debris data gap and mitigate of this debris to human activities in space. Section 3 covers instrument development to measure and characterize OD in situ. Section 4 discusses new OD science of measuring the signatures of objects moving in a magnetized space plasma. Section 5 discusses using the spacecraft as a sensor.

3 IN SITU DEBRIS DETECTION

HPD supports development of several instruments to characterize the small OD population. The main objective is demonstration-validation missions to prove the concept of measurement and raise the TRL. Additionally, whatever data is collected can still contribute to enhance the ODPO ORDEM model. HPD also supports technology development for this purpose through a special topic in the NASA ROSES HTIDeS program element.

MACS (Multi-layer Acoustics & Conductive-grid Sensor) is an instrument to measure OD in the millimeter size regime being developed by the ODPO at Johnson Space Center. It is a mature concept with some flight heritage from an earlier deployment on the ISS in 2018. MACS combines several impact technologies to maximize information from impact events (size, impact location, velocity vector, impact energy). MACS combines conductive grids, acoustic sensors, dual-layer films, and a backstop. A front grid detector (provided by JAXA partners) has embedded lines separated by 50 microns. The number of lines broken provides the impactor size. Kapton layers with acoustic sensors provide the impactor trajectory and speed. The backstop measures total momentum deposited. MACS is a successor to the SDS (Space Debris Sensor), which unfortunately experienced anomalies once deployed to the ISS [5] and collected only 3 weeks of data. MACS is currently planned to fly on the JAXA HTV-X3 vehicle in 2028. HTV-X3 is an ISS resupply mission that has a number of technology demonstrations after it detaches. Fig 2. shows a single wing MACS.

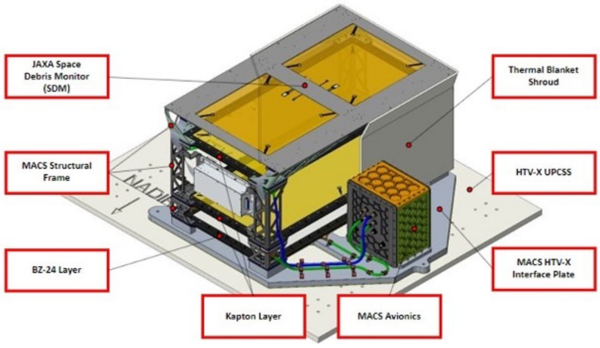

Figure 2. Single wing MACS for deployment on JAXA HTV-X3. Courtesy: ODPO/JSC

LARADO (Lightsheet Anomaly Resolution And Debris Observation) is an instrument to detect nearby objects being developed at the Naval Research Laboratory (NRL) [6]. LARADO use a collimated light source (i.e., laser) and conical mirror to create a sheet of lite in the volume around the spacecraft. Fig. 3 shows the LARADO concept. A wide field-of-view camera detects scattered light from objects passing through the sheet. The primary benefit of this technique is that it reached beyond the physical volume of the spacecraft. Any instrument that relies on a physical impact target will be strictly limited by the size of what can be realistically launched into orbit. The more power available to the laser, the larger the volume of the light sheet. LARADO will require significantly less time to characterize the population in a certain orbit. LARADO is planned to fly on STPSat 7 in late 2025. This implementation achieves ~0.6 square meters of detection area and will fly at 550 km altitude for at least one year. This would represent the first new data on small OD in 15 years.

An extension of LARADO is LARADO-N, where N is "neuromorphic". A neuromorphic camera provides high speed output, large dynamic range, and reduced data bandwidth. LARADO-N adds a second lightsheet, which enables the determination of the velocity vector of objects passing through both. The second sheet is also a at different wavelength, which can be used to broadly classify the material of the OD via albedo.

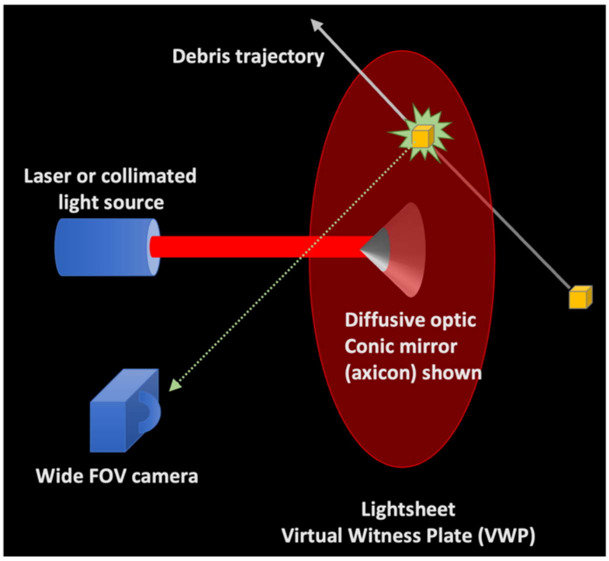

Figure 3. NRL's LARADO concept. OD passes through a lightsheet created by a collimated light source and conical mirror. A camera detects the scattered light. Courtesy: Andrew Nicholas/NRL

Another instrument that reaches beyond the volume of the spacecraft is an in situ LIDAR sensor being developed at the Aerospace Corporation [7]. A pulsed LIDAR-based sensor system generates a short-range optical fan-shaped beam and uses the time-resolved return reflection signal to identify nearby objects. This system has low enough requirements to be on a CubeSat or as a hosted payload on a larger mission. Multiple scatterings can provide velocity vector information of the passing object.

DENTS (Debris and meteoroid ENvironmenT Sensor) is an instrument being developed at the University of Colorado [8]. An impactor passes through PVDF (polyvinylidene fluoride) film and strikes an impact plate. A grid electrode detects ions from impact and electric field antennas detect the electric potential spike near the impact site. DENTS features a modular design that allows deployment on different platforms, and directional information of OD is provided by a fan of cells. The electric field antenna is a unique feature of DENTS, relative to other OD detection instruments. Hypervelocity impacts of OD, meteoroids, and dust on spacecraft surfaces vaporize and ionize the impactor and part of the surface, forming a plasma that rapidly expands into the surrounding background plasma. This causes a spike in the local electrostatic potential that is seen in electric field antennas. In fact, this phenomenon is seen on missions throughout the heliosphere for decades (e.g., Voyager, Cassini, Parker Solar Probe [9]). The electric field antenna on DENTS can help interpret data from all the other missions with these impacts.

A multi-needle Langmuir Probe is being developed at Embry-Riddle Aeronautical University. This probe measures plasma density, with the intention to measure the signatures that nearby OD makes in the background plasma (described further in the next section). This requires extremely high cadences (~80 kHz). The size, weight, and power requirements are low, allowing deployment on small satellites or as hosted payload. These probes could also be used to measure other kinetic-scale structures, instabilities, and turbulence for other scientific applications.

4 SIGNATURES OF OBJECTS IN PLASMA

Another avenue for characterizing OD is to infer OD properties from the disturbances that OD makes in the background space plasma. Any object immersed in plasma obtains an electric charge, which then enables the object to interact electromagnetically with that plasma. Charged OD produces plasma waves and potentially other nonlinear plasma structures that might be detected more easily than the OD itself. This is a new type of OD science, and investigations into this phenomenon and its use are primarily supported through a special topic within NASA ROSES Heliophysics Supporting Research (HSR) program element.

The linear response of OD moving through space plasma is to excite a wide variety of plasma waves. The wave mode depends on the ambient environment (plasma density, magnetic field, etc.) and certain modes might be quickly damped. Bernhardt et. al. [10] used the Radio Receiver Instrument on the Swarm-E satellite to examine conjunctions with other satellites and known debris objects. They claimed to detect compressional Alfvén waves associated with charged objects at a range of tens of kilometers.

Under certain conditions, charged OD could create nonlinear plasma structures such as shocks and solitons ahead and to the side of the OD, as well as vortices in the wake [11]. The focus of this work has largely been on ion acoustic solitons since typical orbital velocities lead to ion acoustic Mach numbers between 0.5 and 5, depending on plasma temperature. This is the range to create shock waves, and in certain Mach number ranges, solitons. The benefit of detecting nonlinear plasma structures is that their characteristic size is much larger than the small OD of interest and that these signatures may be more easily separable from the background of natural waves. However, further research is necessary to understand the exact conditions under which these structures might form in a realistic 3D magnetized plasma, and to understand the effect of Landau damping on formation and propagation.

5 SPACECRAFT AS A SENSOR

HPD is also supporting concepts that use the spacecraft itself, or it's standard components, as a sensor. If these techniques are refined and deployed to a large number of satellites, it would dramatically increase the effective area of measurement. For example, acoustic sensors embedded within solar panels can detect OD impacts. The solar panels typically make up most of the surface area of a satellite. Another concept is to extract streaks from star trackers caused by glints from OD passing nearby. The electrostatic potential spikes due to impacts discussed in relation to DENTS above also fall into the idea of using the spacecraft as a sensor.

A project at Northrop Grumman exploits the autonomous attitude reaction from OD impacts [12]. OD strikes impart rotational and linear momentum to spacecraft. The attitude control system (ACS) automatically corrects the attitude disturbance caused by the impact. Therefore, there are subtle signatures hiding within the ACS telemetry that can be extracted with specialized processing. This type of sensing would not require specialized hardware. Typical housekeeping telemetry would enable collecting data from existing assets, and software on the spacecraft could filter for OD impacts and relay only events of interest to the ground. The measurement correlates to momentum and mass of the impactor.

6 CONCLUDING REMARKS

The threat posed by OD to spacecraft operations is likely to grow significantly with the increased presence in space. Small OD that is not trackable but still large enough to cause damage to spacecraft is particularly important to characterize. NASA HPD has developed an OD-SSA program that is part of the space weather program to provide the basic scientific elements and instrumentation for the detection of small space objects, explore the scientific utility that can be derived, understand how the space environment affects small space objects, and improve space weather forecasting.

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