HIGHLIGHTS OF RECENT RESEARCH ACTIVITIES AT THE NASA ORBITAL DEBRIS PROGRAM OFFICE

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ABSTRACT

The NASA Orbital Debris Program Office (ODPO) was established at the NASA Johnson Space Center in 1979. The ODPO has initiated and led major orbital debris research activities over the past 38 years, including developing the first set of the NASA orbital debris mitigation requirements in 1995 and supporting the establishment of the U.S. Government Orbital Debris Mitigation Standard Practices in 2001. This paper is an overview of the recent ODPO research activities, ranging from ground-based and in-situ measurements, to laboratory tests, and to engineering and long-term orbital debris environment modeling. These activities highlight the ODPO's commitment to continuously improve the orbital debris environment definition to better protect current and future space missions from the low Earth orbit to the geosynchronous Earth orbit regions.

1 HISTORY AND BACKGROUND OF THE NASA ODPO

The NASA Orbital Debris Program Office (ODPO) was officially established at the NASA Johnson Space Center in Houston, Texas, in 1979. The ODPO is the only organization in the United States that conducts a full range of research activities on orbital debris. The ODPO is funded by the Office of Safety and Mission Assurance (OSMA) at the NASA Headquarters (HQ). The roles and responsibilities of the ODPO are defined in the NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Requirements, NPR 8715.6.

In addition to conducting orbital debris research and supporting NASA mission compliance with the orbital debris requirements, the ODPO also provides technical and policy level support to NASA HQ and other U.S. government departments and agencies, and represents the U.S. government in international forums on orbital debris, including the Inter-Agency Space Debris coordination Committee (IADC) and the Committee on the Peaceful Uses of Outer Space (COPUOS) of the United Nations. The ODPO also publishes the NASA Orbital Debris Quarterly News (ODQN) to share the latest assessments of the environment and major research results with the international user community. Additional information about the ODPO and all past issues of the OQDN are available at: https://orbitaldebris.jsc.nasa.gov/.

To characterize the orbital debris populations, from low Earth orbit (LEO, the region below 2000 km altitude) to geosynchronous Earth orbit (GEO, the region near 35,786 km altitude), the ODPO relies on data from difference sources. Fig. 1 shows the current measurement data coverage on orbital debris of different sizes from LEO to GEO. The Joint Space Operations Center (JSpOC) uses the Space Surveillance Network (SSN) to track the biggest objects in space and maintains the orbits of most of the tracked objects in the U.S. Satellite Catalog. As of April 2017, the SSN can track objects approximately 10 cm and larger in LEO and objects approximately 1 m and larger in GEO. The planned Space Fence can improve the SSN coverage to objects significantly smaller than 10 cm in LEO, but its full operations are still a few years away.

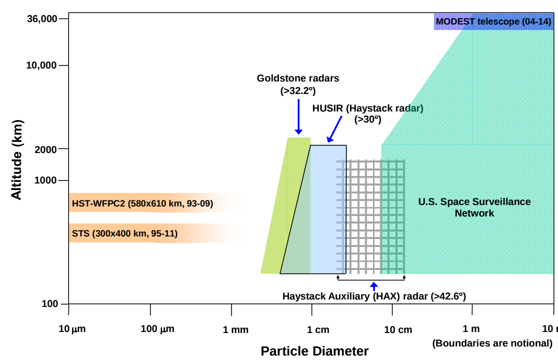

Figure 1. Measurement data used by the NASA ODPO to describe the orbital debris populations in the near-Earth space environment. There are gaps in altitude, debris size, and inclination.

The ODPO is responsible for characterizing objects too small to be tracked by the SSN, but large enough to threaten human spaceflight and robotic missions. To accomplish this objective, the ODPO utilizes ground-based radars, optical telescopes, and inspection of surfaces returned from space to collect data. The Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) and the Haystack Auxiliary Radar (HAX) are operated by the MIT Lincoln Laboratory. The ODPO acquires about 1000 hours of data per year from the two radars to sample debris as small as 5 mm in LEO [1]. The ODPO also has access to about 100 hours of data per year from the Goldstone radars for debris as small as about 2 mm in LEO. For sub-millimeter debris populations in LEO, the data come from the inspection of the window

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and radiator panels of the Space Shuttles as well as the inspection of the surface of the Hubble Space Telescope Wide Field Planetary Camera-2 radiator. To extend the GEO debris coverage, the ODPO has used the Michigan Orbital Debris Telescope (MODEST) to sample GEO debris as small as approximately 30 cm in size [2].

Based on measurement data, the ODPO develops different models to support NASA missions and other space applications. The Orbital Debris Engineering Model (ORDEM) provides mathematical descriptions of the debris environment in terms of debris impact flux, debris size, mass, and other information needed for orbital debris impact risk assessments. Additional detail of the latest ORDEM is provided in Section 3.

The LEO-to-GEO environment debris (LEGEND) model is the ODPO's debris evolutionary model. It is a numerical simulation tool for long-term orbital debris environment projection studies. Based on different user-specified scenarios, LEGEND can be used to quantify the effects from different future launches, including large deployments of CubeSats and mega-constellations [3], and assess the effectiveness of different mitigation (*e.g.*, the 25-year decay rule) and remediation (*e.g.*, active debris removal) measures to support policy and requirement development [4, 5].

The NASA Standard Satellite Breakup Model describes the outcome of an explosion or collision in terms of the fragment size, area-to-mass ratio (A/M), and delta velocity distributions [6]. This model is a key component to support LEGEND because it describes the severity, longevity, and the spread of the fragment cloud after a breakup event. Since the key laboratory-based experiment that supported the development of the current breakup model was conducted in the early 1990s, based on a target that was designed and fabricated in the 1960s, the ODPO has led an effort for new experiments and plans to use the data to update the model in the coming years (see Section 2).

The Object Reentry Survival Analysis Tool (ORSAT) is a high fidelity model maintained by the ODPO to assess the survivability of components from upper stages or spacecraft during the reentry process. One of the orbital debris requirements for NASA and U.S. missions, which has been adopted by many international agencies, is to limit the human casualty risk from surviving reentry debris (with impact kinetic energy greater than 15 J) to less than 1 in 10,000. The ODPO has used ORSAT to support many NASA missions in the past and will continue to seek ways to upgrade the model to improve its fidelity.

The Debris Assessment Software (DAS) integrates the tools that are needed to assess mission compliance with most NASA orbital debris mitigation requirements into a single package [7]. DAS includes ORDEM, the NASA meteoroid model, orbit propagators, and a reentry survivability module based on ORSAT. Once the user enters the mission profile, including orbit, timeline, and other details, DAS automatically assesses if the mission will meet the applicable requirements. DAS has been used by all NASA missions in preparation for the Orbital Debris Assessment Reports (ODARs) and End of Mission Plans (EOMPs). A minor update to improve the interface of DAS is planned for late 2017.

2 DEBRISAT

The DebriSat project is a collaboration of the ODPO, the Air Force Space and Missile Systems Center (SMC), The Aerospace Corporation, the University of Florida, and the Air Force Arnold Engineering Development Complex (AEDC). The project's goals are to design and fabricate a 56-kg class spacecraft ("DebriSat") representative of modern payloads in the LEO environment, conduct a hypervelocity impact test to catastrophically break it up, collect fragments as small as 2 millimeters in size, measure and characterize the physical properties of the fragments, and then use the data to improve the satellite breakup models and other space situational awareness applications [8, 9].

Fig. 2 shows the fully assembled DebriSat, including the multi-layer insulation covering the main body and the three solar panels attaching to one side of the body, before the hypervelocity impact at AEDC. To increase the project's benefits further, Aerospace designed and built a target resembling a launch vehicle upper stage ("DebrisLV") for the pre-test shot. DebrisLV had a mass of 17.1 kg with body dimensions of 35 cm (diameter) × 88 cm (length).

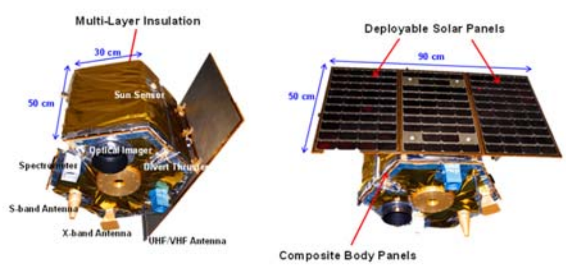

Figure 2. Fully assembled DebriSat before the hypervelocity impact at AEDC.

To maximize the impact kinetic energy delivered by the projectile at the 7 km/sec impact speed, the AEDC team developed a special projectile design featuring a hollow aluminum cylinder embedded in a nylon cap that does not require a sabot. The nylon cap served as a bore rider for the aluminum cylinder to prevent hydrogen leakage and also to protect the barrel. The mass of the projectile was 0.57 kg, with a diameter of 8.6 cm and a length of 9 cm. To limit secondary damage to the fragments, the interior of the target chamber was fully populated with "sot catch" polyurethane foam stacks, consisting of panels with different densities (0.048, 0.096, and 0.192 g/cm^3)

and with a total thickness of up to 61 cm.

The hypervelocity impacts on DebrisLV and DebriSat were successfully carried out at AEDC in April 2014 [10]. The impact speeds of the projectiles for the two tests were 6.9 and 6.8 km/sec, respectively. Fig. 3 and Fig. 4 show the impact sequences of DebrisLV and DebriSat. Portions of the rear nylon cap fragmented and trailed the aluminum cylinder during flight, but this did not affect the planned catastrophic outcome of the impact tests.

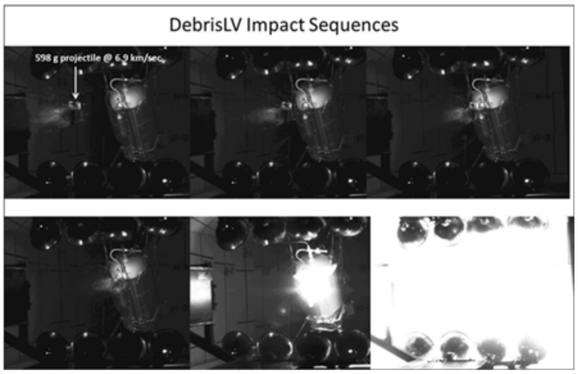

Figure 3. Impact sequences of DebrisLV (from left to right, from top to bottom)

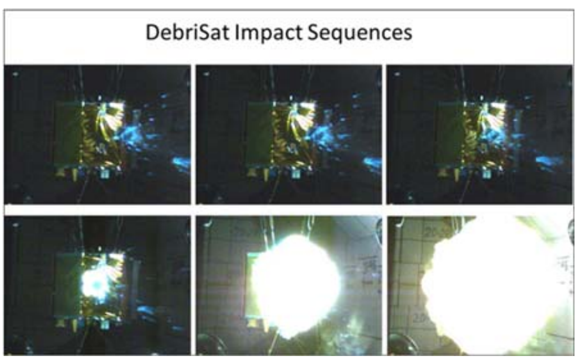

Figure 4. Impact sequences of DebriSat (from left to right, from top to bottom).

After completion of the impact tests at AEDC, all foam panels, loose foam pieces, and loose fragments from each test were collected for post-impact processing. Foam panels were scanned with X-ray and the images were processed to identify the locations of all 2 mm and larger fragments before extraction. Based on the foam panels and fragments collected so far, the number of DebriSat fragments 2 mm and larger is expected to reach approximately 250,000, about a factor of 4 more than the pre-test prediction based on the current NASA Standard Satellite Breakup Model.

Once the physical characterization (mass, dimensions, shape, volume, material density, digital images, etc.) of the collected fragments is completed, the data will be used to improve the breakup model to better describe fragments generated from the breakups of modern spacecraft, such as Iridium 33. The data will also be used to develop fragment shape and bulk density distributions for future ORDEMs to improve the orbital debris impact damage assessments [11]. Representative fragments also will be selected for additional laboratory radar and optical measurements to acquire data to improve the NASA radar debris size estimation model and to develop an optical debris size estimation model to help interpret optical measurement data from telescopes. Selected fragments will be subjected to laboratory space environment effects chamber testing, followed by the same optical measurements to characterize potential space environment effects on the optical properties of debris over time.

3 ORDEM

The ODPO's ORDEM is designed to provide mathematical descriptions of the orbital debris environment, in terms of time, the debris flux, size, spatial density, impact speed, impact direction, and other debris characteristics that can be used by spacecraft designers and owners to assess the orbital debris impact risks to their vehicles during mission operations. Since the orbital debris environment is very dynamic, influenced by on-going launch activities, major breakup events in the environment, and solar activity, the model needs to be updated on a regular basis to better reflect the reality. The first generation of the model, ORDEM96, followed an analytical approach that simplified the debris populations in LEO into six inclination bands and two eccentricity families. The next model, ORDEM2000, took a numerical approach. After debris populations were derived from the measurement data, a finite element model was developed to describe the environment in LEO without simplified assumptions on the orbital distributions of the debris populations [12].

The release of ORDEM 3.0 in 2013 included several major updates [13, 14, 15]. The region covered by the model was extended to GEO. While debris material in ORDEM2000 was assumed to be all aluminium, a simple material density breakdown representing the key material components expected in fragmentation and degradation debris was incorporated into the model. The data for the material distribution for small debris came from composition analyses of residual materials extracted from impact features identified on the window and radiator panels of the Space Shuttles for missions between 1995 and 2011. Uncertainties in the debris flux predictions are also included in ORDEM 3.0 output. Fig. 5 is a sample flux prediction for the International Space Station for the year 2013. Components from the three material density groups, high density (HD, stainless steel, titanium, *etc.*), medium density (MD, aluminium, *etc.*), and low density (LD, plastics, *etc.*) are also shown. The ORDEM2000 prediction is also included for comparison. Although the ORDEM2000 predicted flux at the millimeter-to-centimeter size range is higher than the ORDEM 3.0 predicted flux, the actual impact damage from the ORDEM 3.0 prediction is more severe because of the existence of the high density component.

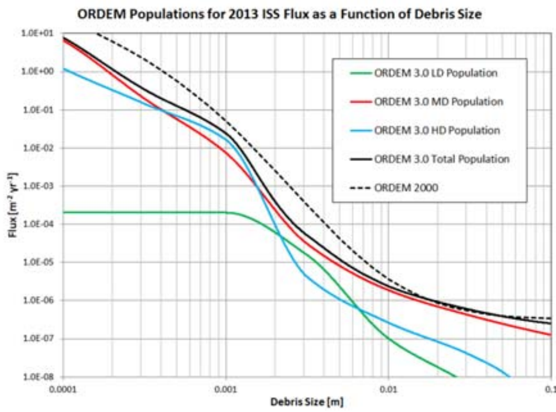

Figure 5. Predicted orbital debris fluxes for the ISS in 2013 from ORDEM2000 and ORDEM 3.0. The high, medium, and low material density debris components of the ORDEM 3.0 prediction are also shown for comparison.

The ODPO is currently working on ORDEM 3.1, which will update the ORDEM 3.0 debris populations with more recent measurement data, as listed in Tab. 1. The plan is to complete the update and release the model in late 2017.

Table 1. Data sources for debris populations, including their altitude and time coverages, for ORDEM 3.0 and the planned ORDEM 3.1.

Data Source	Region/Debris Size	Time Coverage (ORDEM 3.0)	Time Coverage (ORDEM 3.1)
JSpOC Catalog	LEO (>10 cm) GEO (>1 m)	Through 2008	Through 2015
HAX	LEO (>3 cm)	1999-2003	2007-2014
HUSIR (Haystack)	LEO (>5 mm)	1999-2003	2003, 2006-2010, 2014
Goldstone	LEO (>3 mm)	1996-1998, 2001, 2005-2006	2007-2014
STS Windows and Radiators	LEO (<1 mm)	1995-2011	1995-2011
MODEST	GEO (>30 cm)	2004-2006	2004-2009 2013-2014
HST WFPC-2 Radiator	LEO (<1 mm)	Not available	1993-2009

4 SPACE DEBRIS SENSOR

To address the millimeter-sized debris data gap in LEO as shown in Fig. 1, the ODPO has been leading the development of various *in situ* particle impact detection technologies since 2002 [16, 17]. The Debris Resistive/Acoustic Grid Orbital NASA-Navy Sensor (DRAGONS) is intended to be a large area impact sensor for *in situ* measurements of micrometeoroids and orbital debris (MMOD) in the millimeter or smaller size regime. The nominal detection area of a DRAGONS unit is 1 m^2, consisting of several independently operating panels. The approach of the DRAGONS design is to combine different particle impact detection principles to maximize information that can be extracted from detected events. For reliable orbital debris impact risk assessments, direct measurement data on impact time, debris flux, debris size or mass, impact speed, impact direction, and material density of the impacting debris are needed. The combination of dual-layer thin films, resistive grids, acoustic sensors, and a back plate allows DRAGONS to meet this tough data measurement requirement.

After more than 10 years of concept studies, technology development, and hypervelocity impact testing, a matured DRAGONS unit with a detection area of 1 m^2 has been selected for a technology demonstration mission on the International Space Station (ISS) in late 2017. To avoid confusion with the SpaceX Dragon spacecraft, the experiment was renamed Space Debris Sensor (SDS). The objectives of the 2-3-year SDS ISS deployment are to advance the DRAGONS Technology Readiness Level (TRL) to 9 and to demonstrate its capabilities of detecting and characterizing the sub-millimeter orbital debris populations at the ISS altitude. [18]. The ODPO completed the fabrication and testing of the flight unit, delivered the unit to NASA/KSC, and completed all required preflight integration and testing in December 2016 (Fig. 6).

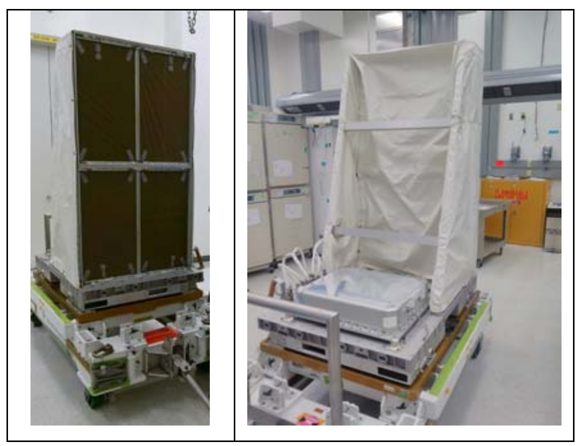

Figure 6. SDS in the ISS processing center at the NASA Kennedy Space Center. Left: Front view of the SDS. Dimensions of the frame are approximately 172 cm (height) x 122 cm (width). Right: Rear view of the SDS, including its electronic box.

Additional hypervelocity impact and other tests will be carried out on a SDS ground unit in 2017-2018, in preparation for calibration and interpretation of data from the SDS after its deployment on the ISS. The ODPO will continue to explore options to improve the DRAGONS design and performance and will seek opportunities to deploy DRAGONS to higher LEO altitudes. A recent NASA Engineering and Safety Center (NESC) study on the MMOD assessment for the Joint Polar Satellite System has concluded that (1) orbital debris smaller than 3 mm poses the highest penetration risk to most spacecraft and (2) for the flux of particles smaller than 3 mm, orbital debris model validation for altitudes above 600 km is most effective using *in situ* data [19]. The study also recommends increasing efforts to directly characterize the debris environment, especially at altitudes above 600 km for which there is currently no *in situ* data. Since NASA currently operates close to 20 missions between 600 and 1000 km altitudes, a high priority for the ODPO is to identify mission opportunities to deploy DRAGONS above 600 km to collect data critical to improving orbital debris impact risk assessments for current and future missions in the region.

5 EUGENE STANSBERY METER-CLASS AUTONOMOUS TELESCOPE

The Meter Class Autonomous Telescope (MCAT) is a joint project of the ODPO, the U.S. Air Force, and the Air Force Research Laboratory (AFRL). The goal of the project is to replace MODEST and extend measurement coverage for faint objects in GEO with an autonomous and fully dedicated telescope (Fig. 1). The ideal location for the telescope is as close to the equator as practically possible. The original site for the telescope was on Legan Island in the Kwajalein Atoll [20]. However, to provide a unique longitude coverage for GEO debris, a decision to install the telescope on Ascension Island (7° 58′ S, 14° 24′ W) was made in 2012 (Fig. 7) [21].

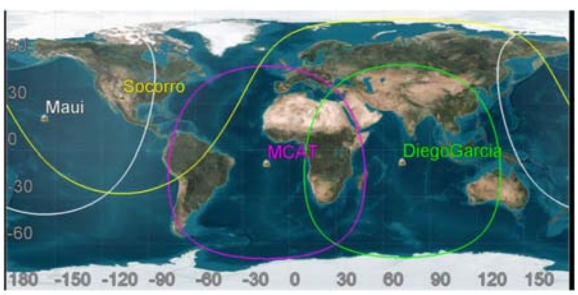

Figure 7. Ascension Island provides a close-to-the-equator and unique longitude coverage for GEO debris.

MCAT is a fast f/4, 1.3-meter telescope with a double-horseshoe modified equatorial mount designed by DFM Engineering. Its field of view is 41′ × 41′. MCAT is equipped with a 4k x 4k Spectral Instrument imaging camera and utilizes both the Sloan Digital Sky Survey griz filters and Johnson/Kron-Cousins BVRI filters. A second, smaller 0.4-meter Officina Stellare telescope, with a similar field of view, will be installed next to MCAT in late 2017 (Fig. 8). The ODPO's optical facility on Ascension Island, MCAT, and the small telescope have been named the John Africano NASA/AFRL Orbital Debris Observatory, the Eugene Stansbery MCAT (ES-MCAT), and the James Benbrook telescope, respectively, to recognize the long-term contributions from three outstanding individuals to the ODPO's orbital debris optical and radar projects.

Figure 8. The ES-MCAT (right) and Benbrook (left) domes at the J. Africano Observatory on Ascension Island.

The ES-MCAT achieved the first light in 2015. The ODPO conducted a User Readiness Review (URR) on the telescope in August 2016. The team will continue to test the operations of the facility and develop various observation modes with a goal to reach full autonomous operations for routine GEO debris survey in 2018-2019. In addition to statistically sampling untracked small GEO debris, ES-MCAT will also collect data on objects with low orbital inclinations in LEO, provide rapid response to observe fragments generated from a new breakup event near GEO, and support other space situational awareness applications on an as-needed basis [22]. Although the Benbrook telescope cannot compete with ES-MCAT for faint object detections, with a similar suite of filters, it can allow simultaneous observations with ES-MCAT in 2 wavelengths for GEO survey mode or for object characterization. Both the ES-MCAT and Benbrook data will be used to derive GEO debris populations for future ORDEM updates.

6 NASA PROCEDURAL REQUIREMENTS FOR LIMITING ORBITAL DEBRIS

An update to the NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environment (NPR 8715.6B) became official on 15 February 2017. NPR 8715.6B replaces the previous version, NPR 8715.6A with Change 1, which was released on 25 May 2012. The ODPO supported the OSMA on this recent revision and will lead the efforts to update the NASA Technical Standard, NASA-STD-8719.14A, "*Process for Limiting Orbital Debris*."

The purpose of NPR 8715.6B is to define the roles, responsibilities, and requirements to ensure NASA, including its mission partners, providers, and contractors, take steps to preserve the near-Earth space environment, in accordance with the U.S. National Space Policy and the U.S. Government Orbital Debris Mitigation Standard Practices to mitigate the risk to space missions and human life due to orbital debris and meteoroids.

Key changes from NPR 8715.6A with Change 1 to NPR 8715.6B include the following.

- Clarify the applicability of the NPR. It is limited to missions that do not fall under the regulatory authority of other U.S. federal department or agency.
- Clarify the process for requests for relief from requirements, including the roles and responsibilities of the Chief of Safety and Mission Assurance and the evaluation elements to be considered.
- Establish a process to notify the Secretary of State for any non-compliance with the U.S. Government Orbital Debris Mitigation Standard Practices, as required by the 2010 U.S. National Space Policy.
- Clarify the roles and responsibilities of the Conjunction Assessment Risk Analysis (CARA) team and the Human Space Flight Operations team for conjunction assessments with robotic and human spaceflight missions, respectively, and their interactions with the Joint Space Operations Center (JSpOC) and other NASA organizations.
- Identify the responsible person for ensuring mission compliance for secondary payloads.
- Add the roles and responsibilities of the Meteoroid Environment Office (MEO).

The roles and responsibilities of the NASA Orbital Debris program Office are also clearly defined in Section 2.1.3:

2.1.3 The NASA Orbital Debris Program Office (NASA ODPO):

a. Develops, maintains, and updates the orbital debris environment models and associated uncertainties to support the Chief, SMA, and programs and projects with the mitigation of orbital debris risk, and compliance with this NPR.

b. Conducts measurements of the orbital debris environment and conducts other research as needed to support the development of the orbital debris environment models.

c. Assists NASA mission project managers in technical orbital debris assessments by providing information and completing evaluations of the Orbital Debris Assessment Reports (ODARs) and End of Mission Plans (EOMPs) on behalf of the SMA Technical Authority.

d. Assists the Department of Defense and other U.S. Government departments and organizations on matters related to the characterization of the orbital debris environment and the application of orbital debris mitigation measures and policies.

e. Contributes to the determination, adoption, and use of international orbital debris mitigation guidelines through international forums such as the United Nations Committee on the Peaceful Uses of Outer Space, the IADC, and ISO.

In addition to limiting the generation of orbital debris in all Earth orbits, NPR 8715.6B also states the intent to limit the generation of debris in other orbits where debris might pose a hazard to future spacecraft, including the Moon, Mars, or in the vicinity of Sun-Earth or Earth-Moon Lagrange Points. Appropriate requirements are under development and will be included in the upcoming update to the NASA Technical Standard, NASA-STD-8719.14A.

NPR 8715.6B is available at https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=6A and the NASA Orbital Debris program Office's website: https://orbitaldebris.jsc.nasa.gov/reference-documents.html

7 SUMMARY

The examples provided in Sections 2-6 highlight the NASA ODPO's commitment to continue the 38-year tradition of characterizing the orbital debris populations with measurement data and modelling efforts to support NASA missions and environment management policy development. They also demonstrate the ODPO's willingness to break new ground to seek new and innovative ways to improve the understanding of the orbital debris environment. Many of the projects are collaborative efforts with other U.S. and international organizations, a model that the ODPO will seek to expand in the future.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

1. Hamilton, J., Blackwell, C., McSheehy, Juarez, Q., Anz-Meador, P. (2017). Radar Measurements of

Small Debris from HUSIR and HAX, this conference.

2. Seitzer, P., Smith, R., Africano, J., Jorgensen, K., Stansbery, E., Monet, D. (2004). MODEST Observations of Space Debris at Geosynchronous Orbit, *Adv. Space Res.* 34, 1139-1142.
3. Matney, M., Vavrin, A., Manis, A. (2017). Effects of CubeSat Deployment in Low Earth Orbit, this conference.
4. Liou, J.-C., Johnson, N. (2006). Risks in Space from Orbiting Debris, *Science* 311, 340-341.
5. Liou, J.-C. (2011). An Active Debris Removal Parametric Study for LEO Environment Remediation, *Adv. Space Res.* 47, 1865-1876.
6. Johnson, N., Krisko, P., Liou, J.-C., Anz-Meador, P. (2001). NASA's New Breakup Model of EVOLVE 4.0, *Adv. Space Res*. 28, 1377-1384.
7. Opiela, J., Vavrin, A. (2017). New Version of DAS Now Available, *Orbital Debris Quarterly News* 21-1, 4-7.
8. Werremeyer, M. (2013). Design of Sub-systems for a representative Modern LEO Satellite. Dissertation, University of Florida.
9. Clark, S. (2013). Design of a Representative LEO Satellite and Hypervelocity Impact Test to Improve the NASA Standard Breakup Model. Dissertation, University of Florida.
10. Liou, J.-C., Opiela, J., Cowardin, H., Huynh, T., Sorge, M., Griffice, C., Sheaffer, P., Fitz-Coy, N., Wilson, M., Rushing, R., Hoff, B., Nolen, M., Polk, M., Roebuck, B., Woods, D. (2014). Successful Hypervelocity Impacts on DebrisLV and DebriSat, *Orbital Debris Quarterly News 18-3*, 3-5.
11. Cowardin, H., Liou, J.-C., Krisko, P., Opiela, J., Fitz-Coy, N., Sorge, M., Huynh, T. (2017). Characterization of Orbital Debris via Hyper-velocity Laboratory-based Tests, this conference.
12. Liou, J.-C., Matney, M., Anz-Meador, P., Kessler, D., Jansen, M., Theall, J. (2002). *The New NASA Orbital Debris Engineering Model ORDEM2000*, NASA/TP-2002-210780.
13. Stansbery, E., Matney, M., Krisko, P., Anz-Meador, P., Horstman, M., Opiela, J., Hillary, E., Hill, N., Kelley, R., Vavrin, A., Jarkey, D. (2014). *NASA Orbital Debris Engineering Model ORDEM 3.0 – User Guide*, NASA/TP-2014-217370.
14. Stansbery, E., Matney, M., Krisko, P., Anz-Meador, P., Horstman, Vavrin, A., Jarkey, D., Xu, Y.-L. (2015). *NASA Orbital Debris Engineering Model ORDEM 3.0 – Verification and Validation*, NASA/TP-2015-218592.
15. Matney, M., Krisko, P., Vavrin, A., Anz-Meador, P. (2016). ORDEM 3.0 Verification and Validation Findings, *Orbital Debris Quarterly News 20-1&2*, 7-10.
16. Liou, J.-C., Burchell, M., Corsaro, R., Drolshagen, G., Giovane, F., Pisacane, V., Stansbery, E. (2009). In situ measurement activities at the NASA Orbital Debris Program Office, Proceedings of the 5th European Conference on Space Debris, ESA SP-672.
17. Corsaro, R., Giovane, F., Liou, J.-C., Burchell, M., Cole, M., Williams, E., Lagakos, N., Sadilek, A., Anderson, C. (2016). Characterization of Space Dust Using Acoustic Impact Detection, J. *Acoust. Soc. Am.* 140 (2), 1429-1438.
18. Hamilton, J., Liou, J.-C., Anz-Meador, P., Corsaro, R., Giovane, F., Matney, M., Christiansen, E. (2017). Development of the Space Debris Sensor (SDS), this conference.
19. Squire, M., Cooke, W., Williamsen, J., Kessler, D., Vesely, W., Hall, S., Schonberg, W., Peterson, G., Jenkins, A., Cornford, S. (2015). *Joint Polar Satellite System (JPSS) Micrometeoroid and Orbital Debris (MMOD) Assessment*. NASA/TM-2015-218780.
20. Stansbery, E., O'Cconnell, D., Talent, D., Walker, E., Africano, J., Nishimoto, D., Kervin, P. (2003). Meter-Class Autonomous Telescope for Space Debris Research, Proceedings of the 2003 AMOS conference.
21. Lederer, S., Stansbery, E., Cowardin, H., Hickson, P., Pace, L., Abercromby, K., Kervin, P., Alliss, R. (2013). The NASA Meter Class Autonomous Telescope: Ascension Island, Proceedings of the 2013 AMOS conference.
22. Lederer, S., Cowardin, H., Buckalew, B., Frith, J., Hickson, P., Pace, L., Matney, M., Anz-Meador, P., Seitzer, P., Stansbery, E., Glesne, T. (2016). NASA's Orbital Debris Optical and IR Ground-based Observing Program: Utilizing the MCAT, UKIRT, and Magellan Telescopes, Proceedings of the 2016 AMOS conference.