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The NASA Orbital Debris Engineering Model 3.1: Development, Verification, and Validation

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ABSTRACT

The NASA Orbital Debris Program Office has developed the Orbital Debris Engineering Model (ORDEM) primarily as a tool for spacecraft designers and other users to understand the long-term risk of collisions with orbital debris. The newest version, ORDEM 3.1, incorporates the latest and highest fidelity datasets available to build and validate representative orbital debris populations encompassing low Earth orbit (LEO) to geosynchronous orbit (GEO) altitudes for the years 2016-2050.

ORDEM 3.1 models fluxes for object sizes > 10 µm within or transiting LEO and > 10 cm in GEO. The deterministic portion of the populations in ORDEM 3.1 is based on the U.S. Space Surveillance Network (SSN) catalog, which provides coverage down to approximately 10 cm in LEO and 1 m in GEO. Observational datasets from radar, *in situ*, and optical sources provide a foundation from which the model populations are statistically extrapolated to smaller sizes and orbit regions that are not well-covered by the SSN catalog, yet may pose the greatest threat to operational spacecraft. Objects in LEO ranging from approximately 5 mm to 10 cm are modeled using observational data from ground-based radar, namely the Haystack Ultrawideband Satellite Imaging Radar (HUSIR – formerly known as Haystack). The LEO population smaller than approximately 3 mm in size is characterized based on a reanalysis of *in situ* data from impacts to the windows and radiators of the U.S. Space Transportation System orbiter vehicle, i.e., the Space Shuttle. Data from impacts on the Hubble Space Telescope are also used to validate the sub-millimeter model populations in LEO. Debris in GEO with sizes ranging from 10 cm to 1 m is modeled using optical measurement data from the Michigan Orbital DEbris Survey Telescope (MODEST).

Specific, major debris-producing events, including the Fengyun-1C, Iridium 33, and Cosmos 2251 debris clouds, and unique populations, such as sodium-potassium droplets, have been re-examined and are modeled and added to the ORDEM environment separately. The debris environment greater than 1 mm is forecast using NASA's LEO-to-GEO ENvironment Debris model (LEGEND). Future explosions of intact objects and collisions involving objects greater than 10 cm are assessed statistically, and the NASA Standard Satellite Breakup Model is used to generate fragments from these events. Fragments smaller than 10 cm are further differentiated based on material density categories, i.e., high-, medium-, and low-density, to better characterize the potential debris risk posed to spacecraft. The future projection of the sub-millimeter environment is computed using a special small-particle degradation model where small particles are created from intact spacecraft and rocket bodies.

This work discusses the development, features, and capabilities of the ORDEM 3.1 model; the new data and new data analyses used to build the model populations; and sample verification and validation results.

1 INTRODUCTION

The NASA Orbital Debris Program Office (ODPO) began development of the Orbital Debris Engineering Model (ORDEM) in the mid-1980s in support of the Space Station Program Office [1]. The ORDEM software currently serves as the primary tool to provide a timely, validated model of the human-made orbital debris environment. It facilitates modeling assessments by spacecraft owner/operators, as well as for ground-based observation planning. Initial manifestations of the model included analytical solutions representing the debris environment [2]. The first computer-based version of ORDEM was released in 1996 as ORDEM96 [3] and pioneered the use of debris population ensembles characterized by altitude, eccentricity, inclination, and size. ORDEM2000 replaced the curve fitting approach with a finite element representation of the debris environment [4]. ORDEM 3.0 [5] represented a significant upgrade in terms of model features and capabilities. It extended the model to the geosynchronous orbit (GEO) region (up to 40,000 km), which enabled analysis of more varied orbits – such as geosynchronous transfer orbits (GTO) and other highly-elliptical spacecraft orbits – and sensor orientations. Additional upgrades included expansion of observation program datasets in underrepresented regions and the addition of uncertainties on the reported orbital debris flux. Most significantly, ORDEM 3.0 included a distribution in material density of orbital debris fluxes [6].

The orbital debris environment is dynamic and must be periodically updated. As newer datasets become available, they provide more information on the evolution of the orbital debris environment. In addition, newly developed data analysis techniques can be applied to both new and legacy data to improve the assessment of orbital debris populations. The newest version of the model, ORDEM 3.1, includes the same capabilities as ORDEM 3.0 and incorporates the newest and highest fidelity datasets available to NASA for both constructing and validating the modeled orbital debris populations. New approaches to analyzing the available data have also been implemented for the large breakup clouds (Fengyun-1C, Iridium 33, and Cosmos 2251), *in situ* impact data, and the GEO population. ORDEM 3.1 is in the final stages of review and represents NASA's best estimate of the current and near future orbital debris environment.

This paper discusses ORDEM 3.1 features in Section 2, datasets and models used for building the model in Section 3, and sample model validation results in Section 4. A summary is given in Section 5.

2 ORDEM 3.1 FEATURES

The fundamental capability of ORDEM is providing fluxes (number per m^2 per year) of debris for a given year. The software includes "spacecraft mode" as well as "telescope/radar mode" settings. The spacecraft mode is useful to spacecraft designers, owners, and operators for assessing the debris flux in a particular spacecraft orbit. The telescope/radar mode setting supports debris researchers and those planning observation campaigns or sensor programs given a particular sensor location and pointing direction. In spacecraft mode, fluxes are output in terms of local azimuth, elevation, and relative velocity in the frame of the spacecraft, whereas for telescope/radar mode, fluxes are output in terms of altitude in the field of view of a ground-based instrument. Fluxes are calculated as a function of cumulative size, meaning the fluxes are presented for a given size and larger. This is based on the risk assessment view that if an impact from a debris particle of a given size will critically damage a spacecraft component, so will all larger sizes of debris. Eleven half-decade size thresholds, or fiducial points, are considered in calculating and presenting the cumulative fluxes: 10 µm, 31.6 µm, 100 µm, 316 µm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, and 1 m.

Fluxes are modeled for objects greater than 10 µm in low Earth orbit (LEO, altitudes below 2000 km) and greater than 10 cm in GEO. Note that while GTO and GEO orbits physically overlap, the dynamics (including perturbation forces and impact velocities) as well as the physical size and structure of satellites within the GEO region are unique. Thus, ORDEM provides debris fluxes in GEO only for sizes of 10 cm and larger. Any fluxes below 10 cm at altitudes above LEO are due solely to high-eccentricity debris sources.

A major advancement in the development of ORDEM 3.0, and maintained for ORDEM 3.1, was the breakdown of debris into material density categories, which were incorporated to better assess the risk to spacecraft from different families of debris. Five populations are modeled, including intacts (spacecraft and rocket bodies); low-density (1.4 g/cc as used for risk assessments) fragments; medium-density (2.8 g/cc) fragments and microdebris; high-density (7.9 g/cc) fragments and microdebris; and sodium-potassium (NaK) coolant droplets (0.9 g/cc) from the Radar Ocean Reconnaissance Satellite (RORSAT) class of spacecraft.

3 ORDEM 3.1 MODEL POPULATIONS

The ORDEM models are data-driven, and reliable data are required to build a realistic and valid model. Table 1 gives a summary of the ground-based and *in situ* datasets used for building and validating the ORDEM 3.1 model, including calendar year (CY) range of measurements and limiting sizes.

Table 1. Datasets used for building and validating the ORDEM 3.1 model populations.

Data Source	Source Type	Orbit Region	Detection Size Range (approximate)	Calendar Year(s): Model Build	Calendar Year(s): Model Validation
STS windows, excluding cargo bay windows	*in situ*	LEO	10 – 300 µm	1995-2011	N/A
STS radiators	*in situ*	LEO	300 µm – 1 mm	1995-2011	N/A
HST Bay 5 MLI cover	*in situ*	LEO	10 – 300 µm	N/A	1990-2009
HST WFPC-2 radiator	*in situ*	LEO	50 – 300 µm	N/A	1993-2009
HUSIR, 75˚E	Radar	LEO	>5.5 mm	2007*, 2009*, 2013-2015	2016-2017
HUSIR, 20˚ S	Radar	LEO	>2 cm	2015	N/A
Goldstone	Radar	LEO	2 – 8 mm	N/A	2016-2017
SSN	Radar, Optical	LEO, GEO	>10 cm (LEO), >1 m (GEO)	1957-2015	2016
MODEST (UCTs and CT debris)	Optical	GEO	>30 cm	2004-2009	2013-2014

* Datasets used for characterization of large breakups (Fengyun-1C [FY-1C], Iridium 33, and Cosmos 2251). Data from special Haystack observation campaigns around the time of the event were used.

The fundamental dataset for ODPO modeling efforts is the ODPO-maintained space traffic database, which characterizes satellites launched – including known and/or estimated orbital elements and physical characteristics – as well as details of known historical breakups and maneuvers. The space traffic database is largely predicated upon the Space Surveillance Network (SSN) catalog, which is considered nearly complete for objects larger than approximately 10 cm in LEO and 1 m in GEO. The yearly space traffic is propagated forward in time using the NASA LEO-to-GEO Environment Debris (LEGEND) Model [7]. The LEGEND model provides the baseline for most sub-populations in ORDEM, which consist of a large number of orbits with specified orbital elements, the number of objects on each orbit, as well as size (characteristic length), and material-type assignment for each object.

The historical population (i.e., initial reference population) for ORDEM 3.1 covered launches from 1957 to 2015. Fragments from confirmed historical fragmentation events were created using a special version of the NASA Standard Satellite Breakup Model (SSBM), which extends the standard model to incorporate material density assignments for fragments less than 10 cm based on percentages derived from analysis of fragments generated by the Satellite Orbital Debris Characterization Impact Test (SOCIT) series [8] as well as known satellite material breakdowns [9]. For the future projection, covering 2016 through 2050, objects were added to the population assuming a repeat of the previous 8-year launch traffic cycle and a post-mission disposal success rate of 90% for rocket bodies and spacecraft. Future collisions and explosions were modeled statistically. Objects greater than 10 cm were allowed to collide according to the “cube” collision assessment algorithm in LEGEND [10]. Probabilities of explosion for intact objects were assessed using an object-class-dependent explosion rate model [11].

In LEO, LEGEND models fragments down to 1 mm in diameter, and assigns material densities according to fragment size and area-to-mass ratio. In GEO, LEGEND models fragments down to 10 cm. To build a statistically complete representation of debris populations, the initial reference population was adjusted based on data from instruments optimized to observe debris with sizes smaller than the SSN cataloging threshold, including ground-based and *in situ* sensors.

3.1 Radar-based populations

The Haystack Ultrawideband Satellite Imaging Radar (HUSIR) is a 37 meter dish, X-band radar operated by the Massachusetts Institute of Technology Lincoln Laboratory, which provides data for LEO debris larger than approximately 5.5 mm. The sensor is located at a latitude of 42.6° N and operates in a staring mode for debris observations. The radar, with its 0.058° 3-dB two-sided beamwidth at 10 GHz, is pointed at a fixed point in space with respect to the local topocentric coordinate system, and objects pass through the radar beam. Data used for building the ORDEM 3.1 model populations were collected during CY 2013-2015 with staring directions of 75° elevation, due East (referred to as "75E") and 20° elevation, due South (referred to as "20S"). Composite data from HUSIR CY 2013-2015 were used to scale the initial LEO populations modeled by LEGEND. Special populations in LEO, including specific debris generation events, anomalous non-explosive events, and the NaK population, were modeled and scaled independently, as discussed in Section 3.1.1. Final scalings were applied to the modeled populations based on size, eccentricity, and inclination to better match the HUSIR data.

3.1.1 Special populations

ORDEM 3.1 includes several "special populations" of objects, so designated based on certain criteria, including unique cloud attributes, a notable release mechanism, anomalous or significant production of fragments, or lack of a readily-identifiable source or production mechanism. These special populations are summarized in Table 2 and include 10 custom breakup events; the major breakup clouds from the FY-1C antisatellite test and the Iridium 33/Cosmos 2251 accidental collision; debris from shedding events by the SNAPSHOT vehicle and Transit series of spacecraft; and the NaK droplets that were released from RORSATs. With the exception of the 10 custom breakup events, these specific populations were not included in the LEGEND baseline model, but were modeled, propagated, and added to the ORDEM populations independently. Since collisions in LEGEND are limited to objects greater than 10 cm, fragments from these special populations generally do not affect the modeled future collision rate.

Table 2. Special debris populations modeled in ORDEM 3.1.

Description	Estimated Parent Altitude and Inclination at Event Date	Debris Event Date
Ten custom breakup events	Event-specific	Event-specific
Chinese Anti-satellite Test (i.e., ASAT, FY-1C)	~850 km, 98.8°	11 Jan 2007
Iridium 33 / Cosmos 2251 collision	~790 km, 86.4° / ~790 km, 74.0°	10 Feb 2009
SNAPSHOT (1965-027A) satellite debris event	~1300 km, 90.3°	Multiple events and a single large event in 1984
Transit constellation satellite debris events (33 events)	~1100 km, 90°	Deposited at end-of-mission + 20 years, per vehicle
NaK	900-1000 km (one at 700-760 km), ~65°	Assumed steady-state per CY 2013-2015 HUSIR data

These special populations were scaled statistically based on comparisons to the HUSIR data. Ten specific historical breakup events were identified as requiring custom adjustments. To better match the radar data, these 10 breakups were assigned size-dependent scale factors to adjust the overall number and the slope of the cumulative size distribution of fragments smaller than 10 cm. The major breakups of FY-1C, Iridium 33, and Cosmos 2251 were reanalyzed for ORDEM 3.1 and the model results were compared to Haystack data from special observation campaigns around the time of each event. These comparisons indicated the need for an overall scaling of the number of fragments as well as incorporating momentum transfer effects in the modeling of these major clouds. In addition, comparisons were made to the HUSIR CY 2013-2015 data, which represent the state of the clouds after nearly a full solar cycle. This analysis showed that the fragments for these clouds, in particular Iridium 33, appeared to be decaying at a faster rate than predicted by the models, and enhancements were made to the area-to-mass ratios of debris in these clouds to capture this behavior. The SNAPSHOT/Transit events are anomalous in that they appear to be slowly shedding off mass over time. These events were initially modeled using the NASA SSBM with a maximum separation velocity of 5 m/s, and final modeled clouds were developed using a Bayesian approach [5, 12].

The NaK model was revised for ORDEM 3.1 to be in steady state. This was based on analysis of the newest HUSIR data, along with a new screening method for NaK droplets, which suggested there is still a significant contribution of small (< 1 cm) droplets at the highest altitudes, where atmospheric drag should have removed them by now [13]. The NaK population is the only special population explicitly identified in the ORDEM population types due to its unique characteristics (e.g., spherical shape and unique material density). Debris from all other events/sources are included within the other material density families (low-, medium-, or high-density). Note that ORDEM 3.0 included a special population from an unknown source at approximately 56° inclination; this population is no longer evident in recent HUSIR data, so it is not included in ORDEM 3.1.

3.2 *In situ*-based populations

Data for debris in the sub-millimeter size range in LEO are provided by the database of impacts to the U.S. Space Transportation System (STS) orbiter vehicle (i.e., the Space Shuttle), as archived by NASA's Hypervelocity Impact Technology (HVIT) group. The database contains information on impacts to the shuttle, categorized by mission and surface. Data on impacts to the shuttle windows (excluding the cargo bay windows) and radiators from STS missions 71 through 133 (1995-2011) were used for building the ORDEM 3.1 small particle population. The window and radiator data approximately cover size ranges of 10 μm – 300 μm and 300 μm – 1 mm, respectively.

The small particle population less than 3 mm was modeled separately from the radar-based population using a special small-particle degradation model [14]. This model simulates how large intact objects (i.e., spacecraft and rocket bodies in historical and future environments as simulated by the LEGEND model) create micron-sized particles. The number of micro-debris objects, created by a surface degradation process, was assumed proportional to the surface area of a source body (i.e., intact object). The average production rate was calculated using an arbitrary initial production rate based on particle size, time interval, and the surface area of the source object. The initial size distribution was sampled randomly from a uniform log scale between 10 μm and 3 mm. The number of objects produced in a time interval was sampled from a Poisson distribution using the average production rate. The newly created particles were simulated with zero delta-velocity, so they shared the same orbit with the source body at the creation time, and their orbits were evolved over time under standard orbit perturbations. The predicted impact rate of these modeled particles on the STS for each mission (including year, epoch, and spacecraft orientation) was computed, and the number of predicted damage features of various sizes was calculated using empirical damage equations [15]. In general, these equations are of the form:

$$Y = c \cdot d_p^{\alpha} \cdot \rho^{\beta} \cdot v^{\gamma} \cdot (\cos\theta)^{\delta}\,, \tag{1}$$

where d_p is the particle diameter, ρ is the mass density, v is the impact/relative velocity, θ is the impact angle, and the ensemble (c, α, β, γ, δ) are fit coefficients for the specific dependent feature characteristic Y, which represents the crater depth, diameter, etc. The adjustable size-dependent production distribution for this initial reference population was modeled as a log-log cubic polynomial. The parameters of this production curve were adjusted to match the observed feature distribution from the STS impact database, with the goodness-of-fit being measured by a maximum-likelihood-estimation technique. A similar analysis was used for ORDEM 3.0 where the missions and surfaces were merged for fitting. For ORDEM 3.1, the analysis was expanded so that each STS mission and each window and radiator element was fitted independently in order to better preserve altitude and directionality effects.

3.3 Optical-based populations

For the GEO region, the SSN catalog provides coverage down to a limit of approximately 1 m. The population of smaller objects in the GEO population was characterized using composite data from Michigan Orbital DEbris Survey Telescope (MODEST) observation campaigns in 2004-2006 [16] and 2007-2009 [17]. MODEST detections include objects correlated to those in the SSN catalog, termed correlated targets (CTs), as well as uncorrelated targets (UCTs), which may be either debris or intacts. The MODEST data is considered complete down to approximately 30 cm (converting absolute magnitude to size [18]). The focus for ORDEM development is on the smaller (fainter) UCTs, which are most likely to be debris, so MODEST UCTs with sizes greater than 1.25 m (magnitude less than 17.1) were excluded.

Several new analysis techniques were employed in building the GEO component of ORDEM 3.1 [19]. In an effort to exclude non-GEO objects which may masquerade as GEO objects due to the short arc of GEO observations and the resulting circular orbit assumption, a so-called "debris ring filter" was applied in inclination (INC), right ascension of the ascending node (RAAN) space. Over a period of decades, uncontrolled objects in near-GEO orbits naturally precess in INC-RAAN space due to effects from the Earth's oblateness and the gravity of the Sun and the Moon [16]. This natural precession traces a loop in the Cartesian coordinates of (INC·cos(RAAN), INC·sin(RAAN)), which represents the projection of the orbit's angular momentum vector on the equatorial plane. To exclude those objects whose orbits lie outside of the natural precession loop, the debris filter developed for ORDEM 3.1 takes into account the angle between an object's angular momentum vector and a unit vector orthogonal to the stable Laplace plane, assumed to have an inclination of 7.2° [20]. Fig. 1 shows the MODEST 2004-2009 UCTs and CT debris in (INC·cos(RAAN), INC·sin(RAAN)) space. Four GEO breakups that occurred prior to the MODEST observations and during the historical period covered by LEGEND are also shown for reference. These are the Titan 3C Transtage (1968-081E, SSN #3432), Ekran 2 (1977-092A, SSN #10365), Ekran 4 (1979-087A, SSN #11561), and Ekran 9 (1982-093A, SSN #13554). These fragmentations are not explicitly included in the ORDEM 3.1 populations, but are implicitly included via the MODEST data; this approach prevents any potential overestimation of these fragments that are resident in the set of MODEST UCTs. By extension, fragments from any unconfirmed or unknown GEO breakups that have not been modeled are also implicitly included.

New methods were also utilized for assigning non-circular orbits to the MODEST UCTs. Since MODEST detections use a circular orbit assumption for UCTs, non-circular orbits were assigned to the UCTs based on correlations determined from the modeled GEO breakups between mean motion, eccentricity, and the angle between an object's orbit plane and the stable Laplace plane. The GEO model population was extended to 10 cm based on the slope of the cumulative size curve of the objects in the filtered composite dataset, and orbital parameters were statistically sampled based on the non-circular orbital elements of objects in the filtered composite dataset.

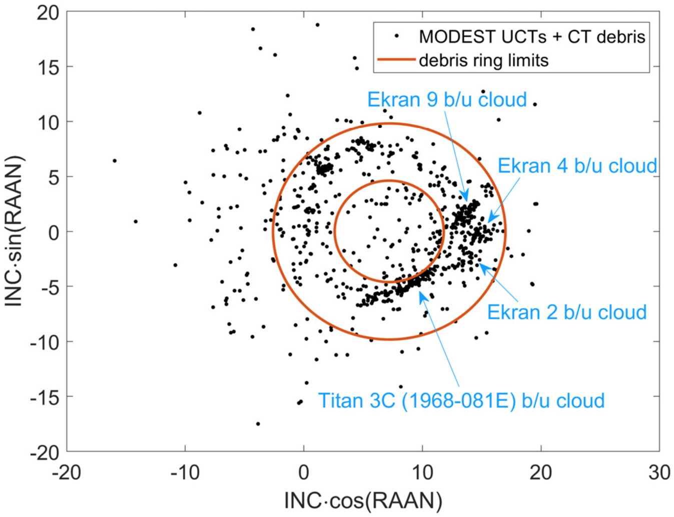

Fig. 1. MODEST 2004-2009 UCTs and CT debris with size 30 cm – 1.25 m, projected in (INC·cos(RAAN), INC·sin(RAAN)) Cartesian space and overlaid with the debris ring filter limits. General regions of fragments from the four GEO breakups that occurred prior to the MODEST campaigns are indicated for reference. Objects seen outside the ring were excluded from the model as probable non-GEO objects imitating GEO behavior over the short-time arc of observations.

4 MODEL VALIDATION

An independent set of data sources was used to validate ORDEM 3.1 to ensure the model provides a valid representation of the orbital debris environment. Typically, these observations come from the same sensor that provided data used for building the model, but for later years, to ensure that model predictions remain applicable in an evolving and dynamic orbital debris environment. In other cases, additional data sources provide a unique perspective on the environment that may extend the size of the orbital debris observation or contain more information about a particular orbital regime than was available from the source(s) used for building the model. The data used for validating the ORDEM 3.1 model populations are shown in Table 1.

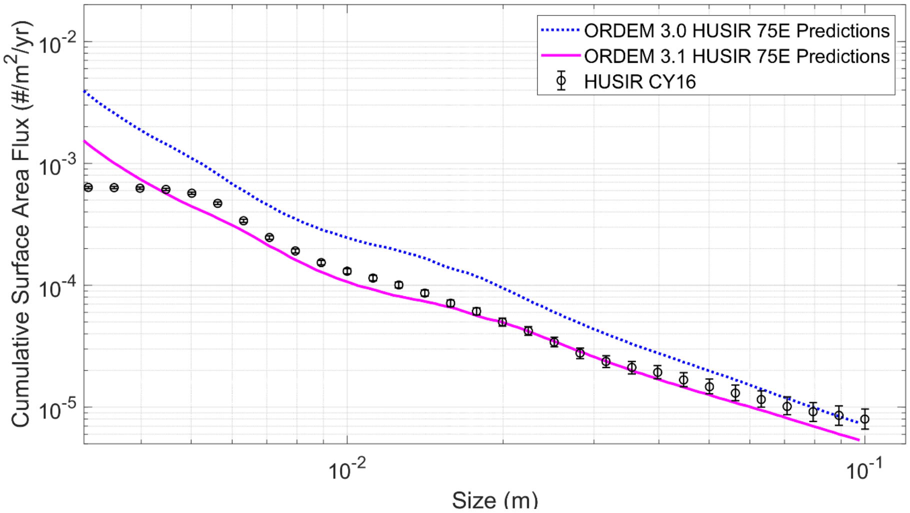

Fig. 2. Comparison of the surface area flux vs SEM size between ORDEM 3.0, ORDEM 3.1, and measurements from HUSIR 75E in 2016. The altitude is restricted to 400 – 1000 km.

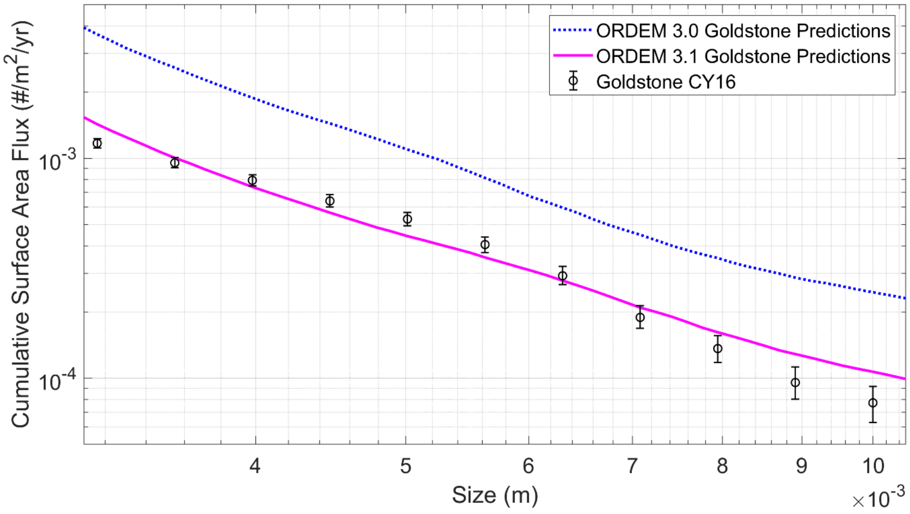

Fig. 3. Comparison of the surface area flux vs SEM size between ORDEM 3.0, ORDEM 3.1, and measurements from Goldstone in 2016. The altitude is restricted to 400 – 1000 km.

For LEO, HUSIR 75E data from 2016-2017 were used for validation of the > 5.5 mm populations. In addition, Goldstone radar data from 2016-2017 were used to validate the model populations at sizes smaller than the HUSIR threshold (down to approximately 2 mm). Sample validation results for cumulative surface area flux as a function of size for the altitude range 400 km to 1000 km in 2016 is shown in Fig. 2 for HUSIR 75E. The surface area flux is defined as the number of debris objects that pass through the radar beam, divided by the surface area of the radar beam (assuming the 3-dB beamwidth of the radar) per unit time – in this case on a yearly basis. The roll-off in sensitivity for HUSIR at approximately 5.5 mm at 1000 km is seen in the level-off of the data curve at small sizes in Fig. 2. The uncertainties on the HUSIR data are the one-σ uncertainties for counts from a Poisson distribution (see Ref. 21 for details). The ORDEM 3.0 prediction is also shown for reference. The ORDEM 3.0 results represent a prediction of over a decade into the "future" relative to the years covered by the radar data used for building ORDEM 3.0. Thus, ORDEM 3.1, which was built from datasets that are more recent, is expected to better agree with the newer data. Fig. 3 shows a similar comparison of the cumulative surface area flux as a function of size for ORDEM 3.0, ORDEM 3.1, and Goldstone data in 2016. Goldstone is more sensitive to the smaller debris particles than HUSIR, and the data is well-matched to the model prediction down to approximately 3 mm. Fig. 4 shows a comparison of surface area flux vs. altitude between ORDEM 3.0, ORDEM 3.1, and HUSIR 75E data for a limiting size of 1 cm and larger in 2016 . Overall, ORDEM 3.1 is considered a very good match to the radar data and a significant improvement over ORDEM 3.0.

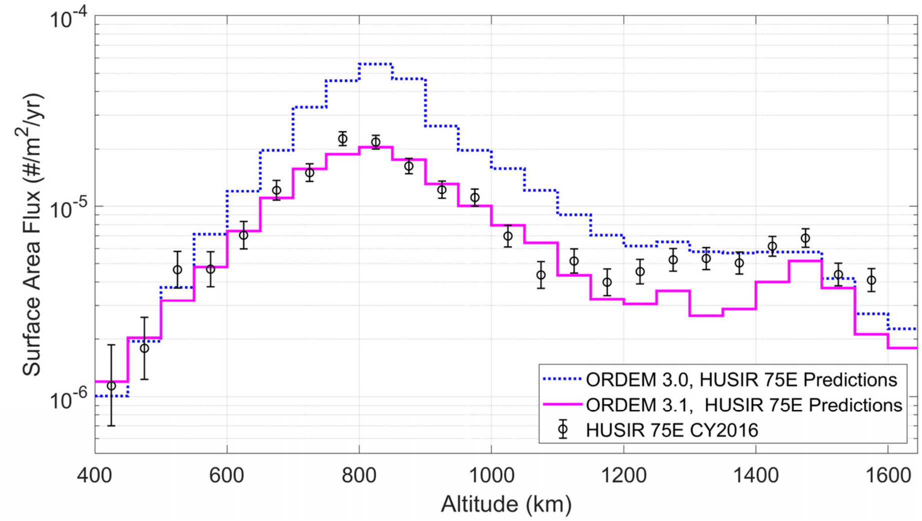

Fig. 4. Comparison of the surface area flux vs altitude for a limiting size of 1 cm and larger between ORDEM 3.0, ORDEM 3.1, and measurements from HUSIR 75E in 2016.

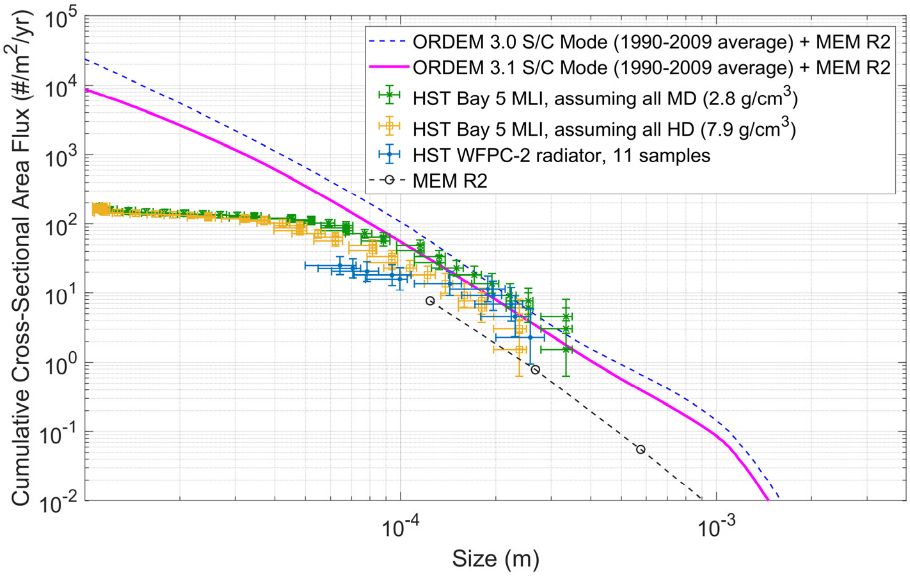

Fig. 5. Comparison of the cumulative cross-sectional area flux vs size between ORDEM 3.0, ORDEM 3.1, and impact data from the HST Bay 5 MLI and WFPC-2 radiator. The ORDEM curves include the meteoroid flux estimates from the MEM R2 model. Two sets of MLI data points are shown, assuming all points as either MD or HD. The MEM R2 model results are also shown for reference.

The sub-millimeter model populations were validated using new data from impacts to the Hubble Space Telescope (HST), specifically the multilayer insulation (MLI) cover on HST's Bay 5 (exposure time covering 1990-2009) and the Wide Field Planetary Camera 2 (WFPC-2) radiator (exposure time covering 1993-2009). Impacts to the Bay 5 MLI were analyzed to determine feature sizes and resulting projectile sizes based on newly-developed damage equations. New techniques to analyze craters on the WFPC-2 radiator using Scanning Electron Microscopy-Electron Dispersive X-ray (SEM-EDX) analysis were also developed, which contributed data on sub-millimeter impacts at HST altitudes. Validation of a total micrometeoroid and orbital debris environment (ORDEM 3.1 plus the meteoroid flux from the NASA Meteoroid Engineering Model Release 2.0 [MEM R2, see Ref. 22]) against these datasets is shown in Fig. 5. Uncertainties in the flux are the one σ Poisson uncertainties, as for the radar data. Sizes given for the HST impact data were calculated using empirical damage equations (of the form of Eq. (1)) relating feature size and estimated particle size for each surface. Distributions in impact angles and velocities were used to generate distributions in estimated particle size from the impact feature sizes, based on vehicle surface pointing directions, and the one-σ uncertainties from these distributions are shown by the horizontal uncertainties in Fig. 5. The model is considered in excellent agreement with these datasets.

The GEO component of ORDEM 3.1 was validated against a MODEST dataset covering 2013-2014. Initial validation indicated discrepancies between the model and the MODEST 2013-2014 data in terms of "clock angle," defined as an angle in the Cartesian coordinates of (INC·cos(RAAN), INC·sin(RAAN)) (see Fig. 1) where 0° is defined by a vector originating at (7.2°,0°) and pointing in the (0°,0°) direction, and the angle increases in a clockwise direction. Thus, two simulated breakups, potentially corresponding to unidentified breakups that occurred during the 2009-2013 break between the MODEST observation campaigns, were added to the model to better match the MODEST 2013-2014 dataset. Fig. 6 shows the distribution in clock angle for the initial (without the simulated breakups) and final (including the two simulated breakups) ORDEM 3.1 GEO population, as compared to the MODEST 2013-2014 data. Uncertainties shown for the MODEST data points are the one-σ confidence intervals from the standard Poisson counting error, incorporating the statistical weighting of the MODEST observations (see Ref. 19 for details). Clearly, the final ORDEM 3.1 model is improved by the addition of the simulated breakups and is a good match to the MODEST data.

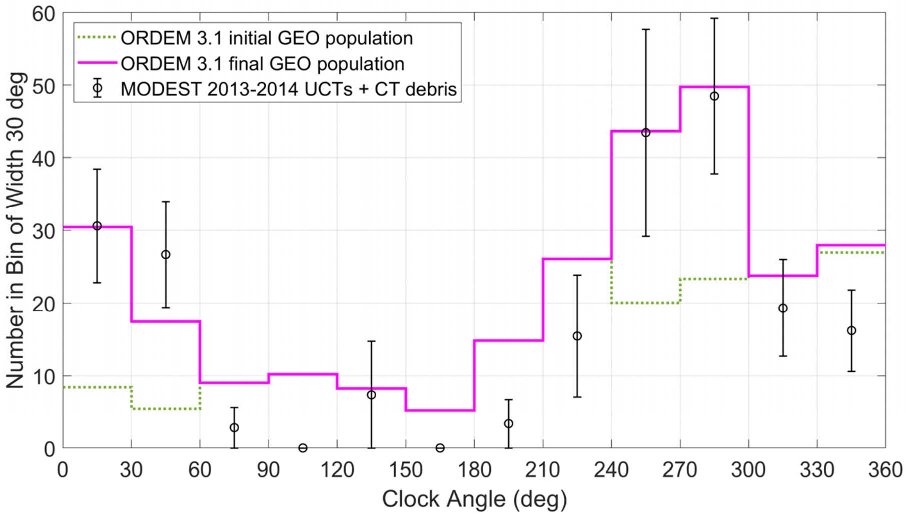

Fig. 6. Clock angle distribution of the ORDEM 3.1 initial GEO population, final GEO population including the addition of two simulated breakups, and MODEST 2013-2014 UCTs and CT debris, for sizes 30 cm – 1 m.

5 SUMMARY

The newest version of the NASA ODPO orbital debris engineering model, ORDEM 3.1, is in the final stages of review. Like ORDEM 3.0, version 3.1 provides fluxes of debris larger than 10 µm in LEO and 10 cm in GEO; fragments smaller than 10 cm are further differentiated based on material density categories (high, medium, and low) to better characterize the potential debris risk posed to spacecraft. Improved data analysis techniques applied during the population build phase of ORDEM 3.1 include new assessments of the major breakup events (FY-1C antisatellite test and Iridium 33/Cosmos 2251 accidental collision) to account for momentum transfer effects and higher-than-expected drag rates; incorporation of directional and altitude influences in the STS window and radiator impact dataset; and a refined analysis of GEO debris objects and orbit definitions. Validation efforts for the model populations indicate good agreement between the model and data from measurement sources/years independent of those used for building the model. As compared to ORDEM 3.0 predictions, ORDEM 3.1 provides significantly better fits to modern data and a more updated representation of a dynamic orbital debris environment.

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