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NASA's new orbital debris engineering model, ORDEM2010

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This paper describes the functionality and use of ORDEM2010, which replaces ORDEM2000, as the NASA Orbital Debris Program Office (ODPO) debris engineering model. Like its predecessor, ORDEM2010 serves the ODPO mission of providing spacecraft designers/operators and debris observers with a publicly available model to calculate orbital debris flux by current-state-of-knowledge methods. One key advance in ORDEM2010 is the file structure of the yearly debris populations from 1995 - 2035 of sizes 10 μm - 1 m. These files include debris from low-Earth orbits (LEO) through geosynchronous orbits (GEO). Stable orbital elements (i.e., those that do not randomize on a sub-year timescale) are included in the files as are debris size, debris number, and material density. The material density is implemented from ground-test data into the NASA breakup model and assigned to debris fragments accordingly.

These high-fidelity population files call for a much higher-level model analysis than what was possible with the populations of ORDEM2000. Population analysis in the ORDEM2010 model consists of mapping matrices that convert the debris population elements to debris fluxes. The spacecraft mode results in a spacecraft-encompassing 3-D igloo of debris flux, compartmentalized by debris size, velocity, local elevation, and local azimuth with respect to spacecraft ram direction. The telescope/radar mode provides debris flux through an Earth-based detector beam from LEO through GEO. This paper compares the new ORDEM2010 with ORDEM2000 in terms of processes and results with general output examples for LEO. The utility of ORDEM2010 is illustrated by sample results from the model and Graphical User Interface (GUI) for two cases in 2010, the International Space Station (ISS) and the EOS-AURA robotic spacecraft.

Introduction

The release of the NASA ODOP Orbital Debris Engineering Model 2010 (ORDEM2010) represents a significant improvement in the NASA's empirically-based debris assessment modeling program. Like its predecessors in the ORDEM series of engineering models, ORDEM2010 will be a publically available, data-driven model which includes assessments of the orbital debris environment as a function of altitude, latitude, and debris size. It provides NASA's state-of-the-art description of that environment in terms of debris flux onto spacecraft surfaces or the debris detection rate observed by ground-based sensors. Top level advances over the most recent predecessor, ORDEM2000, are summarized in Table 1.[1]

Table 1. Feature Comparison of ORDEM2000 and ORDEM2010

Parameter	ORDEM2000	ORDEM2010
Spacecraft and Telescope/Radar analysis modes	YES	YES
Time range	1991 to 2030	1995 to 2035
Altitude range with minimum debris size	200 to 2000 km (>10 μm)	200 to 34,000 km (>10 μm)* 34,000 to 38,000 km (>10 cm)
Model population breakdown	NO	Intacts Low-density fragments Medium-density fragments and degradation/ejecta High-density fragments and degradation/ejecta RORSAT NaK coolant droplets
Population material density breakdown	NO	Low-density (<2 g/cc) Medium-density (2-6 g/cc) High-density (>6 g/cc) RORSAT NaK coolant (0.9 g/cc)
Population cumulative size thresholds	10 μm, 100 μm, 1 mm, 1 cm , 10 cm, 1 m	10 μm, 31.6 μm, 100 μm, 316 μm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m
Population storage	LEO Bins – Alt, Lat, Inc, Vel	LEO-to-GTO bins - Hp, Ecc, Inc GEO bins - MM, Ecc, Inc, RAAN
Population extension	Max Likelihood Estimation	Bayesian statistics with ODPO models
Model S/C flux analysis method	S/C orbit segments	Igloo surrounding S/C
Model T/R flux analysis method	Segments along line-of-sight	Segments along line-of-sight

*sub-millimeter population has been validated for LEO only

Debris data detections that form the empirical basis of the model have been extended by ten years through statistical data collection as well as observation of specific breakup events (e.g., the FY-1C anti-satellite test and the Iridium 33/Cosmos 2251 accidental collision). This provides much better statistics than have been available to previous ORDEM model developments. A new approach to the analysis of the data below GEO utilizes Bayesian statistics in which the a priori condition of populations from several ODPO high-fidelity debris environment models (Table 2) is compared to the remote and in-situ datasets (Table 3). These datasets include debris object detections, estimated sizes, and ephemeris. Sizes throughout these datasets range from 10 μm to 1 m. Through the Bayesian process the model results are reweighted in number to be compatible with the data in orbital regions where the data is collected.[2-5] By extension, model results are reweighted in regions where no data is available (e.g., all sizes in low latitudes, sub-millimeter sizes at altitudes above ISS). The resulting debris and intact populations throughout LEO-to-GTO in the 10 μm through the >1 m size range serve as input to the ORDEM2010 model.

The GEO debris and intact populations, included in an ORDEM model for the first time, are also derived from NASA debris environment models, SSN data, MODEST data, and by slight extrapolation of GEO measurement data to smaller sizes with the NASA Standard Breakup Model.[6,7] The minimum size of debris in GEO is currently set as 10 cm in ORDEM2010.

Table 2. Contributing models (with corroborative data)

Model	Usage	Corroborative Data
LEGEND	LEO Fragments > 1mm GEO Fragments > 10cm	Haystack, SSN MODEST
NaKModule	NaK droplets > 1 mm	Haystack
Degradation/ejecta model	1mm > Degradation/ejecta > 10μm	STS windows & radiators

Table 3. Contributing data sets

Observational Data	Role	Region/Size
SSN catalog (radars, telescopes)	Intacts & large fragments	LEO > 10 cm, GEO > 70 cm
Cobra Dane (radar)	Compare with SSN	LEO > 4 cm
Haystack (radar)	Statistical populations	LEO > 5.5 mm
Goldstone (radar)	Compare with Haystack	LEO > 2 mm
STS windows & radiators (returned surfaces)	Statistical populations	LEO < 1 mm
HST solar panels (returned surfaces)	Compare with STS	LEO < 1 mm
MODEST (telescope)	Only GEO data set	GEO > 30 cm

ORDEM2010's resulting input population files contain material density for debris smaller than 10 cm for the first time in an ORDEM model.[8-10] These objects include non-breakup debris for which the compounds are known (e.g., sodium potassium coolant droplets from RORSAT nuclear core ejections), and breakup fragments, for which low-, medium-, or high-material density (i.e., plastics, aluminum, steel) are assigned based on the SOCIT4 ground collision test results.

ORDEM2000 binned populations in size, time, altitude, latitude, inclination and velocity. Spacecraft flux calculations were accomplished by a segmentation of the spacecraft orbit over the ORDEM2000 population bins and a summing over all populations encountered. Telescope/radar beam fluxes simply used sensor position on the Earth surface and line-of-sight as the debris flux encounter segments. ORDEM2000 ignored the debris population radial velocity, to conserve code storage space and because of the small magnitude of that quantity in LEO. ORDEM2010 includes realistically derived eccentric orbits in its flux calculations. The ORDEM2010 population bins for LEO-to-GTO in size, time, perigee altitude, eccentricity, inclination, and material density intersect a telescope/radar beam in the same manner as ORDEM2000. However, the ORDEM2010 spacecraft encounters debris flux by a completely different method, that of a spacecraft-encompassing 3-D 'igloo' (Figure 1). Population flux is tested for each igloo element in an igloo coordinate system of debris size, velocity, pitch, and yaw with respect to spacecraft ram direction. Flux is summed within that element. All element fluxes are summed together for the total yearly spacecraft encounter. This new directional debris flux calculation is supported by an updated graphical user interface (GUI) package designed for ORDEM2010 that includes a 2-D flux chart (i.e., Mollweide projection) that is displayed in the following sections of this paper.

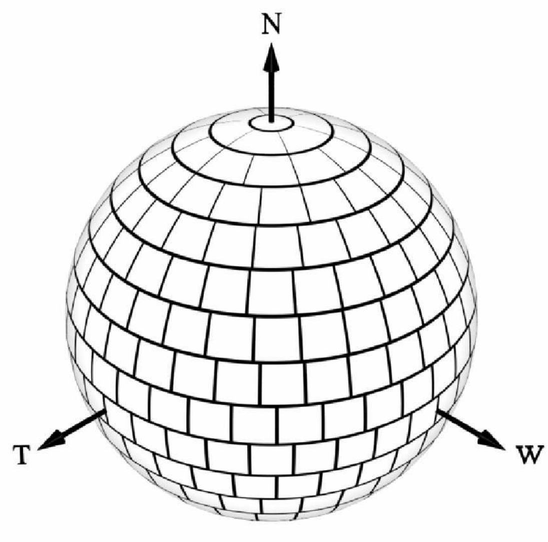

Figure 1. Sketch of an ORDEM2010 equal-area spacecraft-encompassing igloo

ORDEM2000 vs. ORDEM2010 Comparisons for 2010

There are two independent grounds for variations in the model results in the following 2010 comparisons. The most obvious is the difference in the two model population and analysis structures (noted partially in Table 1). These lead to predictable discrepancies, in particular, in the small debris environment where model studies are based on the same sparse dataset. LEO spatial density comparison charts for the year 2010 are displayed in Figures 2a-f by cumulative size. Figures 2a and 2b illustrate differences stemming from the techniques and assumptions in the extensions of debris to higher altitudes. The dataset used by both models here is in-situ STS window and radiator impact data, thus both curves cross at the ~400 km STS altitude. The general maximum likelihood estimation (MLE) is used in ORDEM2000 to extend sub-millimeter debris to higher (and lower) LEO altitudes. ORDEM2010's degradation/ejecta model generates sub-millimeter debris by assuming some rate of generation from all > 10 cm objects in the environment during a given year and propagating that debris. The rate of generation is honed by comparing the degradation/ejecta model populations with the in-situ STS data at the time and altitude of that data collection.[5] Since ORDEM2010 specifically ties the degradation/ejecta process to source objects, there is a higher spatial density in LEO regions that are populated by large intacts and debris (i.e., 700 km to 1000 km, and 1200 km to 1600 km). The >1 mm curves in Figure 2c transition between the >100 μm chart and the Haystack radar data and environmental model derived chart of Figure 2d.

The other major cause of variations between ORDEM2000 and ORDEM2010 environments in 2010 is simply the passage of time from each model's inception. The ORDEM2000 last historical population was 1999. Beyond that populations are based on growth factors derived from environmental models such as the discontinued EVOLVE series (i.e., ORDEM2000's 2010 population is 10 years into its projection period.). ORDEM2010 was locked in 2009 and explicitly includes the historical events FY-1C anti-satellite test breakup as well as the Iridium 33/Cosmos 2251 accidental collision. Figure 2d with Figures 2e and 2f for the larger heavily-observed debris environment are derived using copious Haystack, HAX and SSN radar data coupled with environmental models. The ORDEM2010 curves in these figures give a good representation of the environment today. The companion ORDEM2000 curves, however, show a general overestimation of spatial density in the LEO high traffic regions due to changes in space traffic since the year 2000. Interestingly, ORDEM2000 greatly underestimates the 10 cm spatial density in the range 700 km to 900 km, the regions where the FY-1C and Iridium 33/ Cosmos 2251 fragments are presently located.

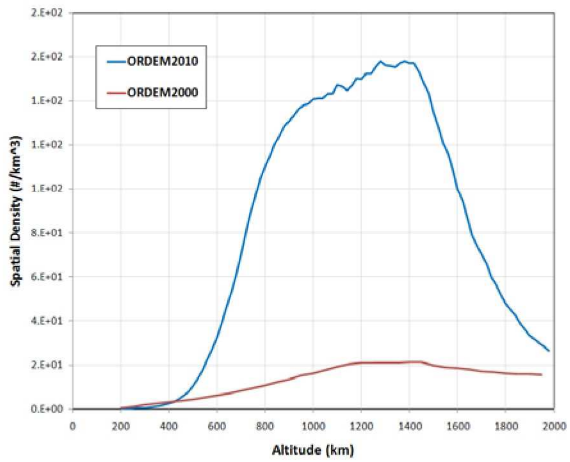

Figure 2a. 10 um and greater spatial density comparison

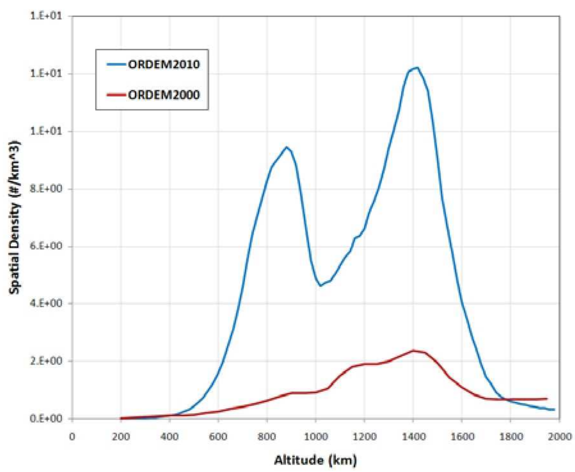

Figure 2b. 100um and greater spatial density comparison

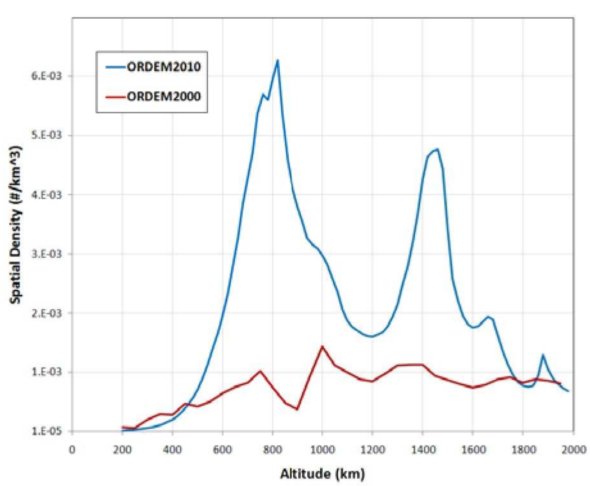

Figure 2c. 1 mm and greater spatial density comparison

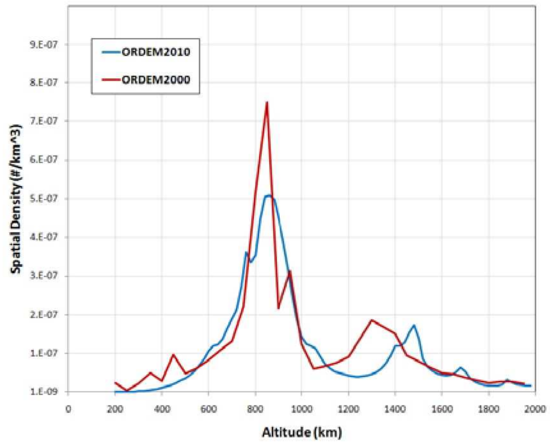

Figure 2d. 1cm and greater spatial density comparison

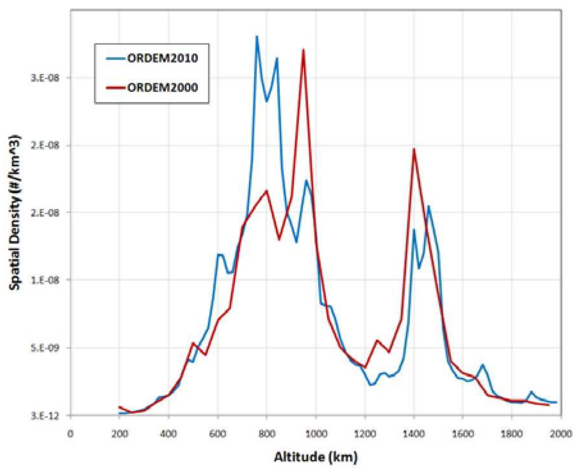

Figure2e. 10 cm and greater spatial density comparison

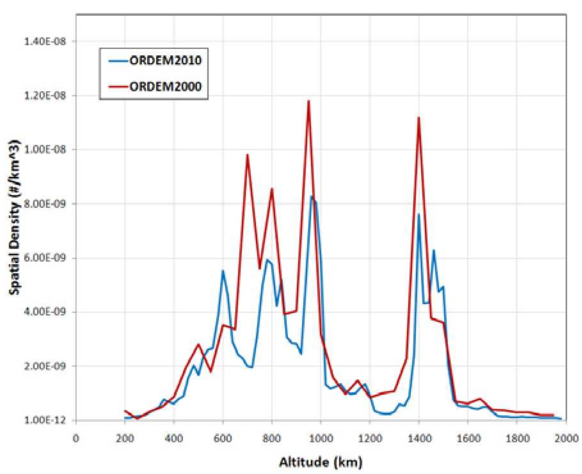

Figure 2f. 1 m and greater spatial density comparison

ORDEM2010 Study of Crewed Spacecraft (International Space Station)

The original purpose for the development and upkeep of the ORDEM series is for the safety analysis of crewed spacecraft. The ORDEM2000 artificial debris environment coupled with the NASA natural meteoroid environment are currently embedded into the NASA BUMPER finite element risk assessment code.[11] BUMPER applies these debris and meteoroid fluxes to over 150,000 elements describing the surface geometry and shielding of the ISS (See Figure 3).

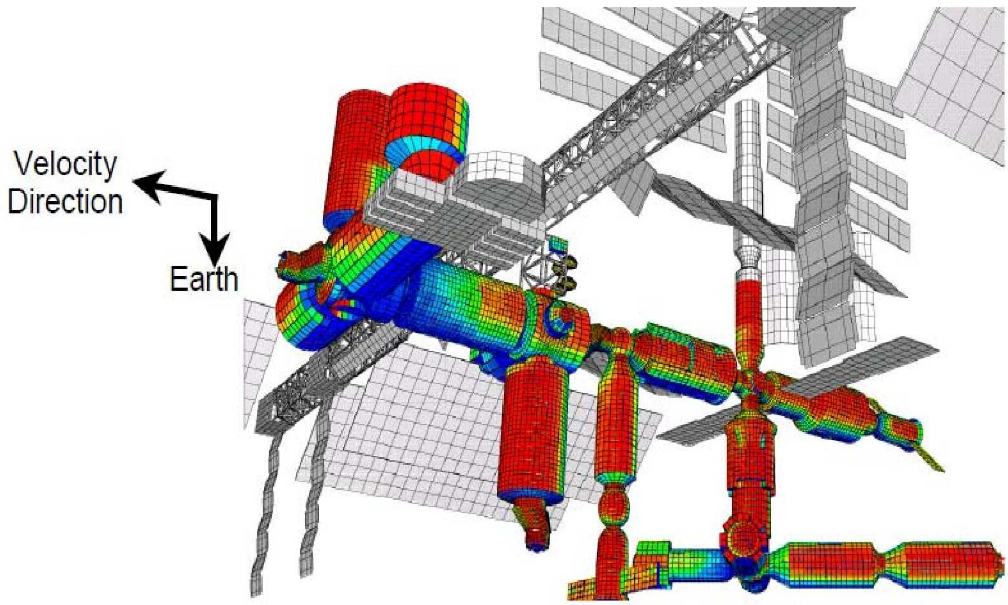

Figure 3. ISS with BUMPER finite elements, high probability of impact is in red, low probability of impact is in blue, ORDEM2000 is implemented in BUMPER currently (reprinted Ref 11).

Debris flux from ORDEM is compared to sets of empirical ballistic limit equations also stored in BUMPER, which describe failure thresholds of specific ISS components. From these, probability of penetration is derived per element. Over the last decade studies through BUMPER have led to better understanding of penetration risk and enhancements of shielding for the ISS. Currently most critical components in the velocity ram and port/starboard sides are shielded to 1 cm debris at typical impact velocities of 9 km/s and impact angles of 45 deg. This shielding threshold makes the artificial debris environment the most important source of catastrophic impact threat to the ISS, as the natural meteoroid environment has a much lower flux by this size.

The horizontal plane of a LEO spacecraft carries the main source of orbital debris. As noted above, the ORDEM2000 population bins which ignored debris radial velocity made use of this fact. The ORDEM2000 debris flux in BUMPER is therefore restricted to that plane. With the spacecraft-encompassing igloo structure, ORDEM2010 will lend itself to use in BUMPER for in plane and out of plane debris fluxes. Figures 4-6 illustrate the ORDEM2010 GUI output for a single spacecraft mode run with the ISS orbit (Inc = 51.63°, Hp = Ha = 400 km, year = 2010).

Figures 5a-c display GUI generated charts for debris larger than 10 μm. Figure 5a is a 2-D flux chart also known as a Mollweide map, a pseudo-cylindrical equal-area map projection used for global or sky maps. In ORDEM2010 usage of the Mollweide projection is through a flattening of the spacecraft-encompassing igloo defined in the spacecraft mode. The spacecraft velocity vector (ram direction) is defined by the azimuth, elevation coordinates (0°,0 °). Anti-ram is defined where (180°,0°) and (-180°,0°) meet. Zenith is defined at (0°,90°), and nadir at (0°,-90°). In the GUI charts in this paper the analysis igloo 'blocks' are 10°x10°, with debris velocity increments of 1 km/s. The most high-fidelity igloo available in ORDEM2010 is this '10 x10 x1' representation. In Figure 5a the highest fluxes (in red) are close to the horizontal plane and off-ram toward the port/starboard sides, as noted above. The lowest fluxes (in blue) are at higher elevations and at zenith and nadir. The dominance of flux in the off-ram direction toward the port/starboard sides is also illustrated in Figure 5b, a 'skyline' view of the flux collapsed to the horizontal plane. Finally Figure 5c, a velocity distribution of flux, indicates high flux regions are also high velocity regions. Figures 6a-c depicting larger debris (over 10 cm) shows that same behavior. The off-ram peaks in ISS flux are characteristic of debris in highly elliptical orbits near their perigees. Historical breakups of high eccentricity intacts do account for nearly half of all such events.

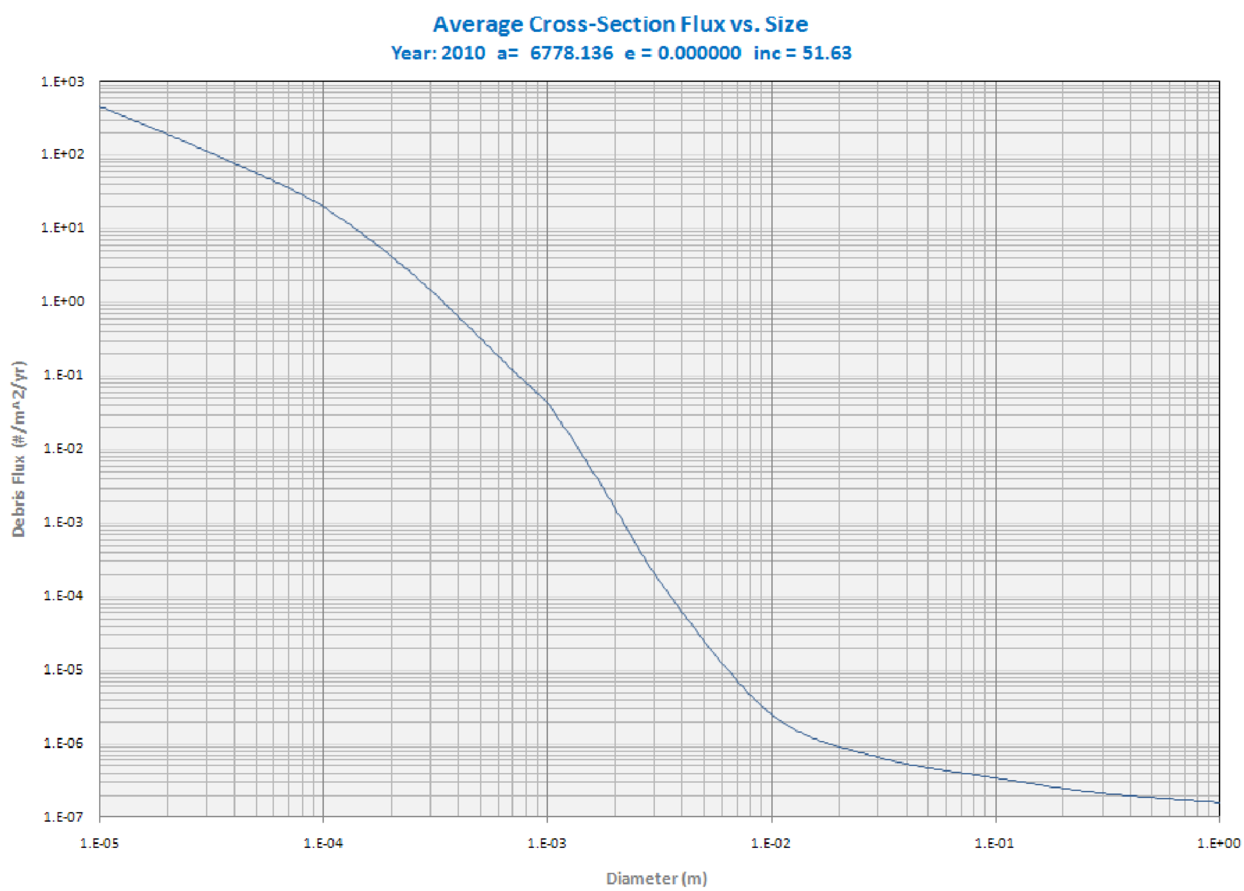

Figure 4. GUI output of flux vs. size for ISS in 2010

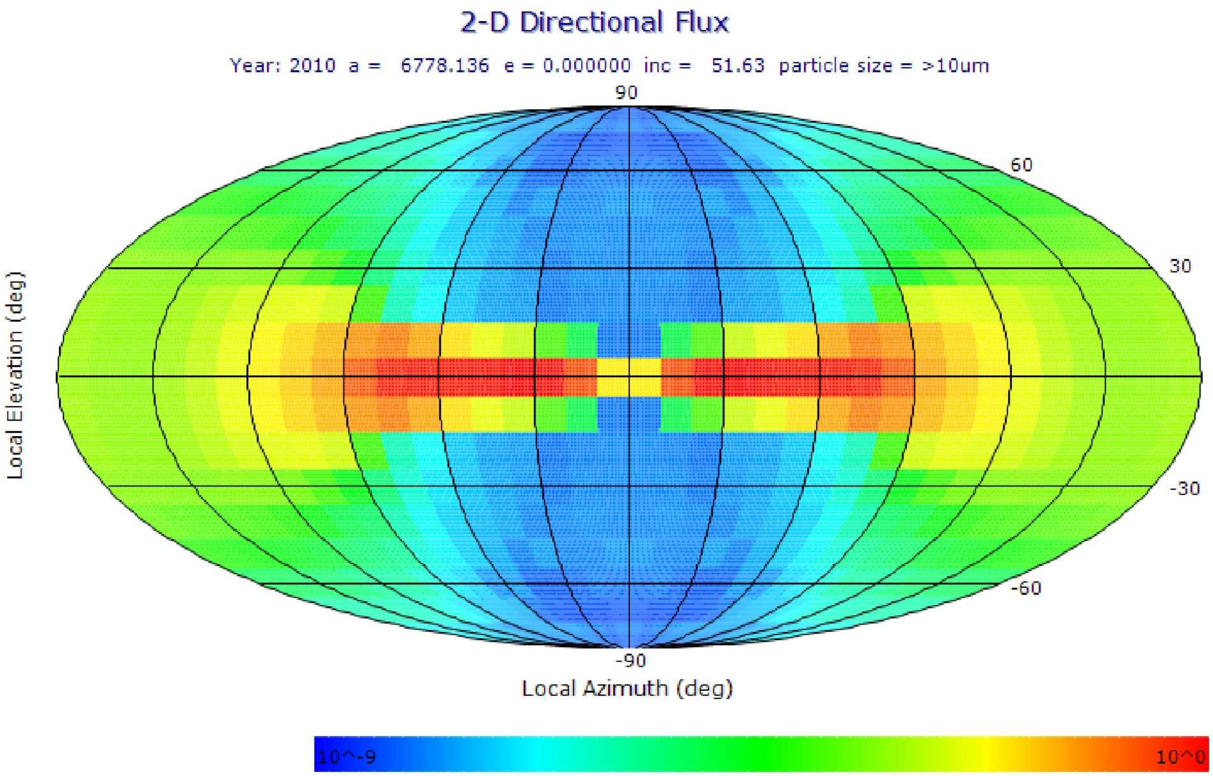

Figure 5a. GUI output of 2-D flux larger than 10 μm for ISS in 2010

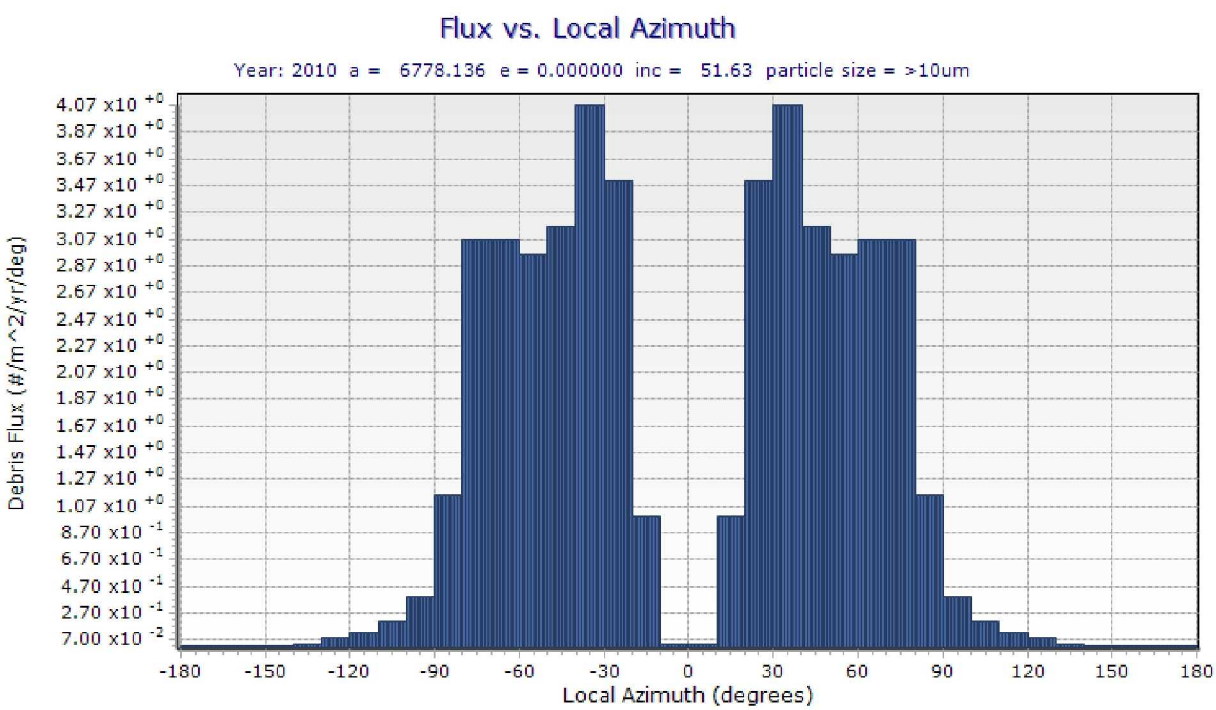

Figure 5b. GUI output of flux collapsed to horizontal plane larger than 10 μm for ISS in 2010

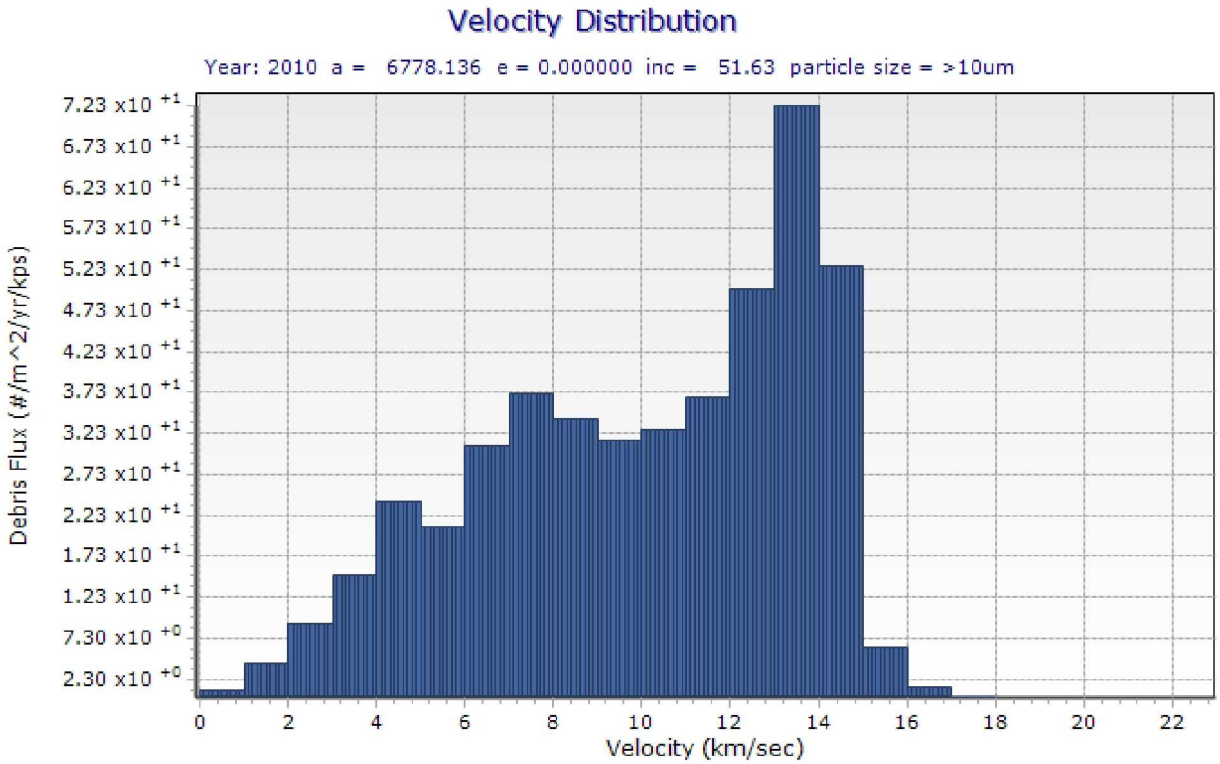

Figure 5c. GUI output of flux velocity distribution for debris larger than 10µm for ISS in 2010

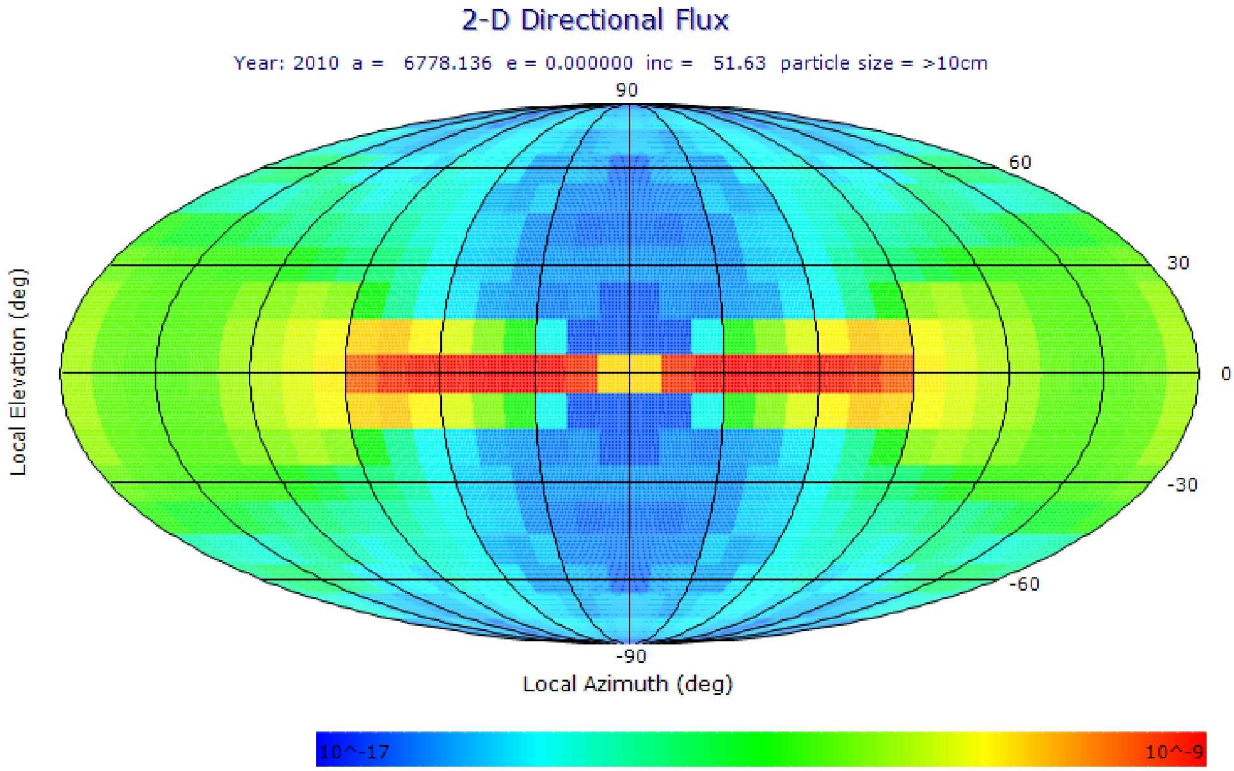

Figure 6a. GUI output of 2-D flux larger than 10 cm for ISS in 2010

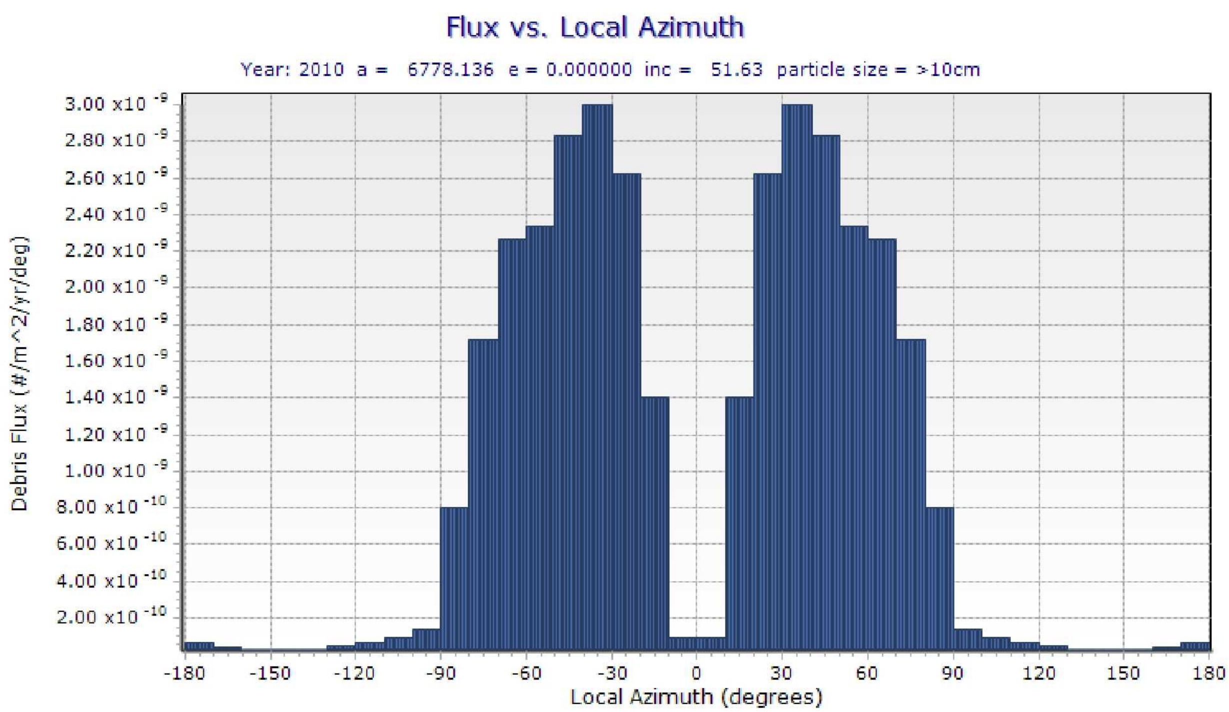

Figure 6b. GUI output of flux collapsed to horizontal plane larger than 10 cm for ISS in 2010

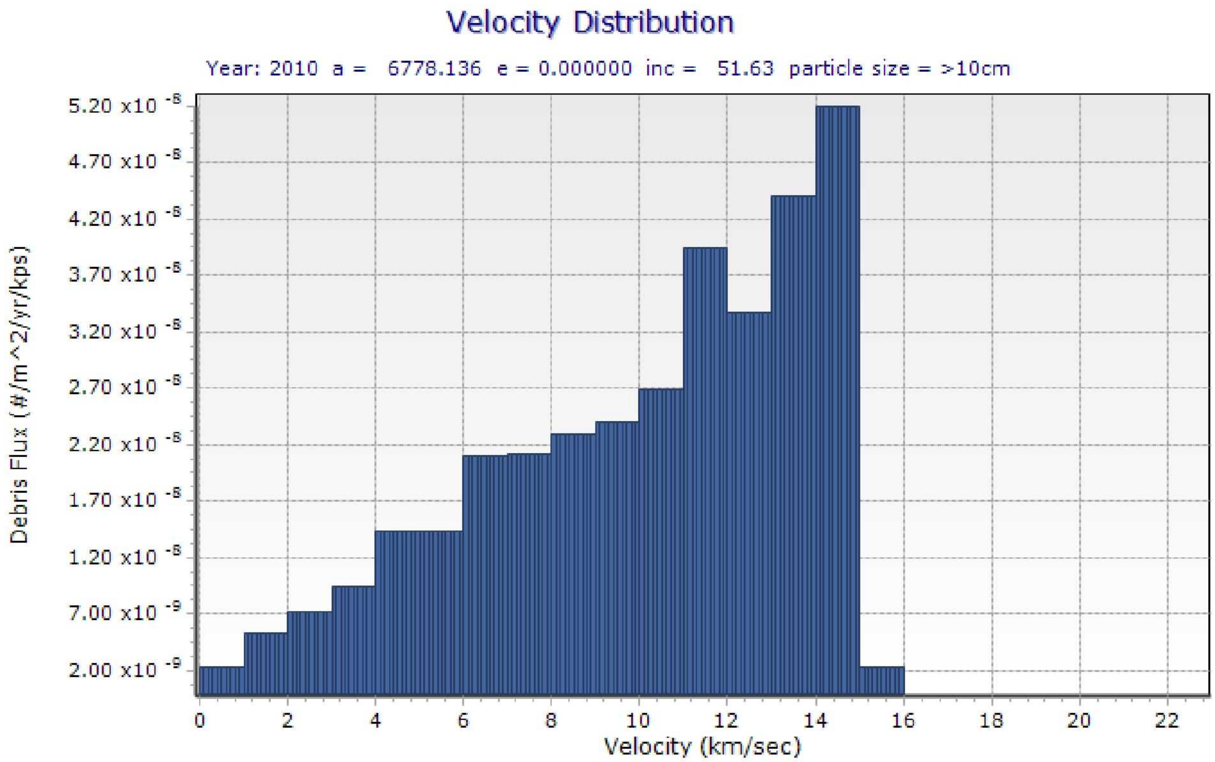

Figure 6c. GUI output of flux velocity distribution for debris larger than 10 cm for ISS in 2010

ORDEM2010 Study of Robotic Spacecraft (EOS-Aura)

Since 1995 all NASA programs have been required to perform orbital debris assessments per the NASA Safety Standard 1740.14 and its successor NASA Standard 8719.14, at several stages of development (PDR, CDR). The ODPO developed the Debris Assessment Software (DAS) package to assist in this task.[12] DAS, now on version 2.0.1, is downloadable from the NASA website, http://orbitaldebris.jsc.nasa.gov/mitigate/das.html. DAS is updated quarterly with up-to-date solar flux tables. The package includes NASA orbital propagators for long-term mission analysis, the ORDEM model with its artificial debris flux calculations, penetration probability codes, and a reentry survivability prediction code, and resulting ground casualty calculations.
Currently, DAS 2.0.1 incorporates ORDEM2000. However, it will be replaced by ORDEM2010 this year. The high-fidelity and detailed flux directionality of this model will be of use to orbital spacecraft designers. An example is shown in this section for the NASA/GSFC Earth Observing System (EOS) satellite, Aura.[13] The spacecraft was launched in July 2004 joining two other members of the EOS project, Terra and Aqua, all three in sun synchronous orbits.

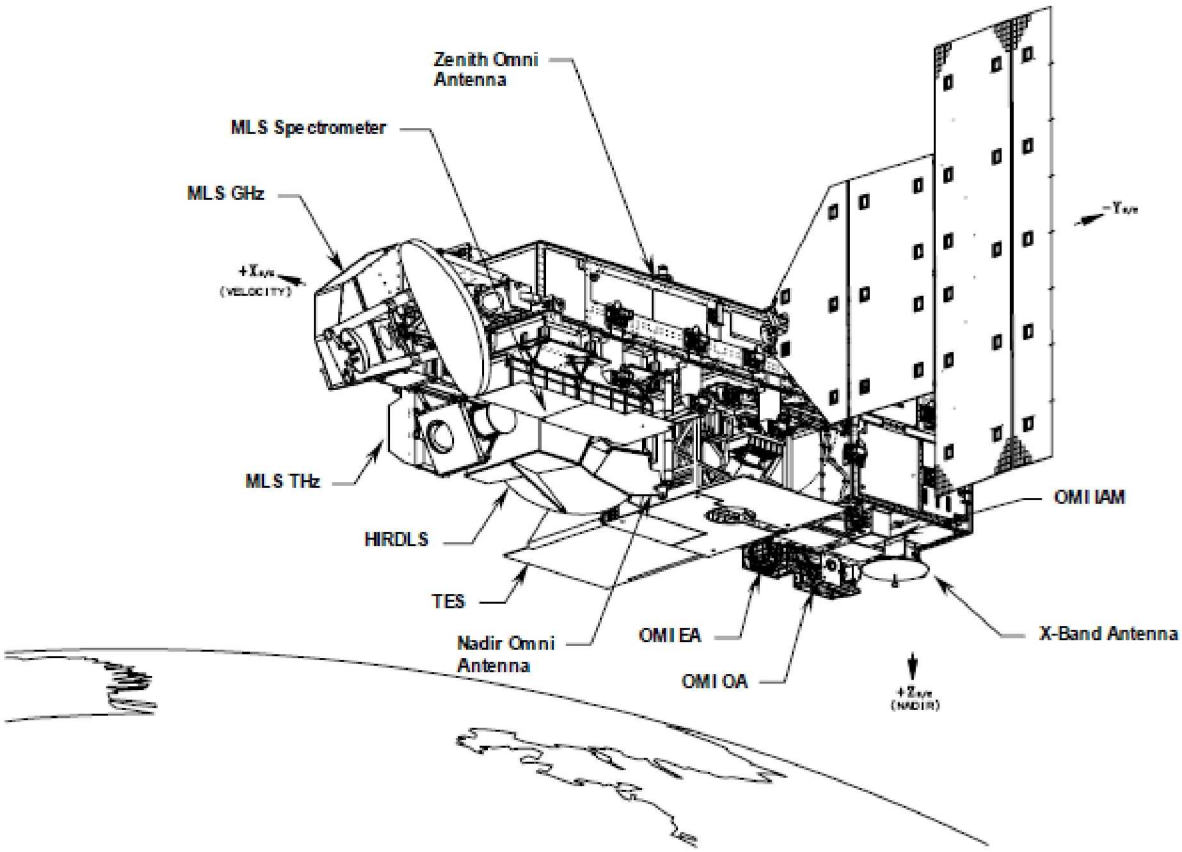

Figure 7. Aura spacecraft configuration (deployed), +X to the left in the figure is the spacecraft velocity (ram) direction[13]. The solar panel extends in +Y. Only 1 ½ panels are shown in the figure out of 12 panels.

In Figure 7 the deployed Advanced Microwave Scanning Radiometer (AMSR) dish is the ram direction (+X). The ORDEM2010 run GUI outputs for the Aura orbit (Inc = 98.2 °, Hp = Ha = 705 km) are illustrated in Figures 8-10.

In Figure 9a for fluxes of debris larger than 10µm the highest fluxes (in red) are close to the horizontal plane, but unlike the case of the ISS they peak in the ram direction. The lowest fluxes (in blue) are at higher elevations from the ram direction, at zenith, nadir, and in the anti-ram direction. The dominance of flux in the ram direction is also illustrated in Figure 9b, the skyline view of the flux collapsed to the horizontal plane. Figure 9c, the velocity distribution of flux indicates high flux regions are also high velocity regions. Figures 10a-c depicting larger debris (over 10 cm) shows that same behavior. The ram peaks in Aura debris flux and the symmetry of that flux indicate that the spacecraft is encountering debris close to its own (sun synchronous) orbit and supplementary posigrade orbits (i.e., ~82 deg). Historically over thirty breakups of sun synchronous intacts have occurred. Any exposed instrumentation in the Aura ram direction could be at risk of damage.

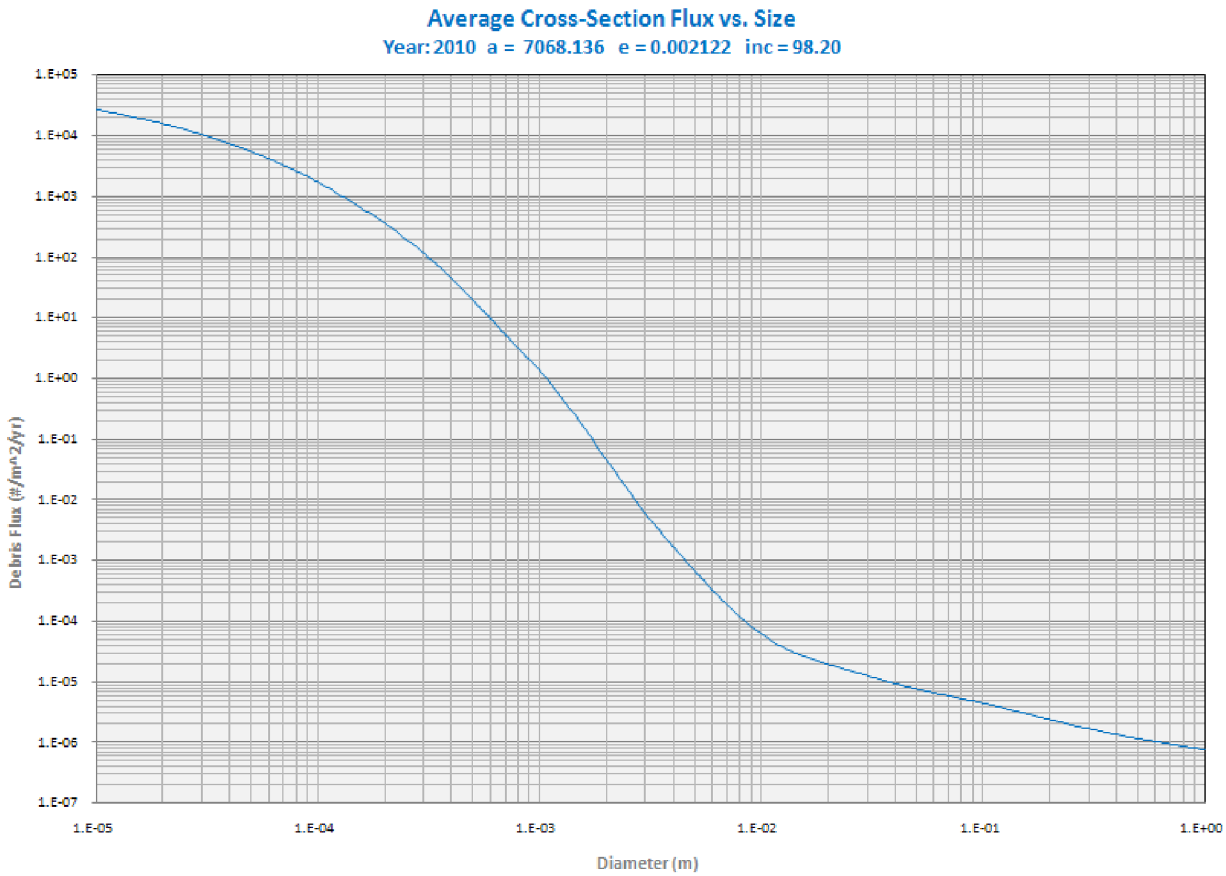

Figure 8. GUI output of flux vs. size for Aura in 2010

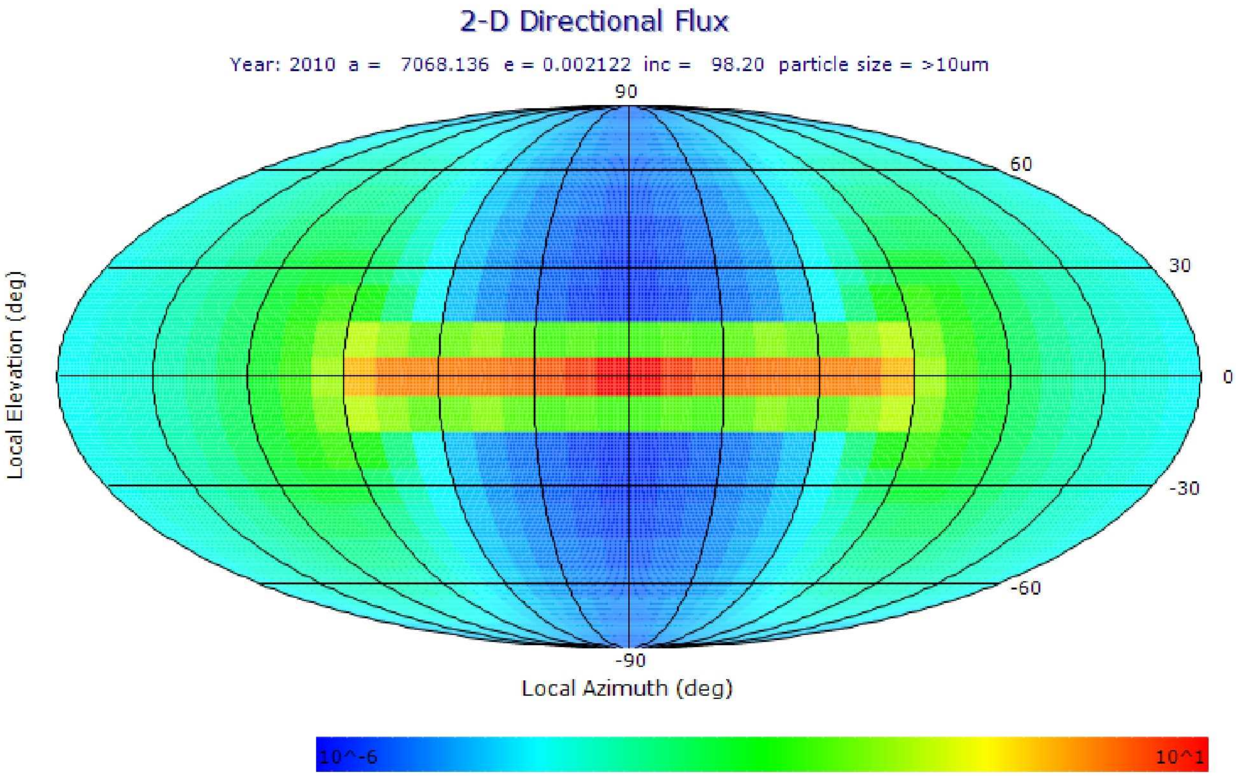

Figure 9a. GUI output of 2-D flux larger than 10 μm for Aura in 2010

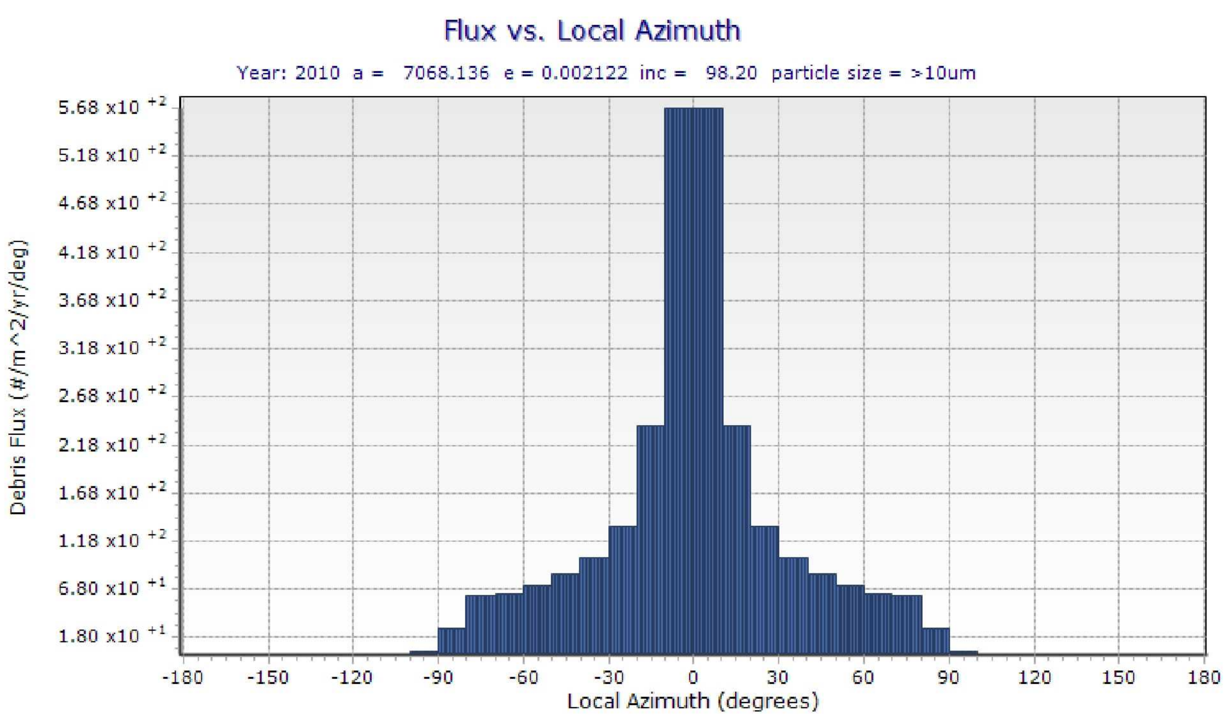

Figure 9b. GUI output of flux collapsed to horizontal plane larger than 10 μm for Aura in 2010

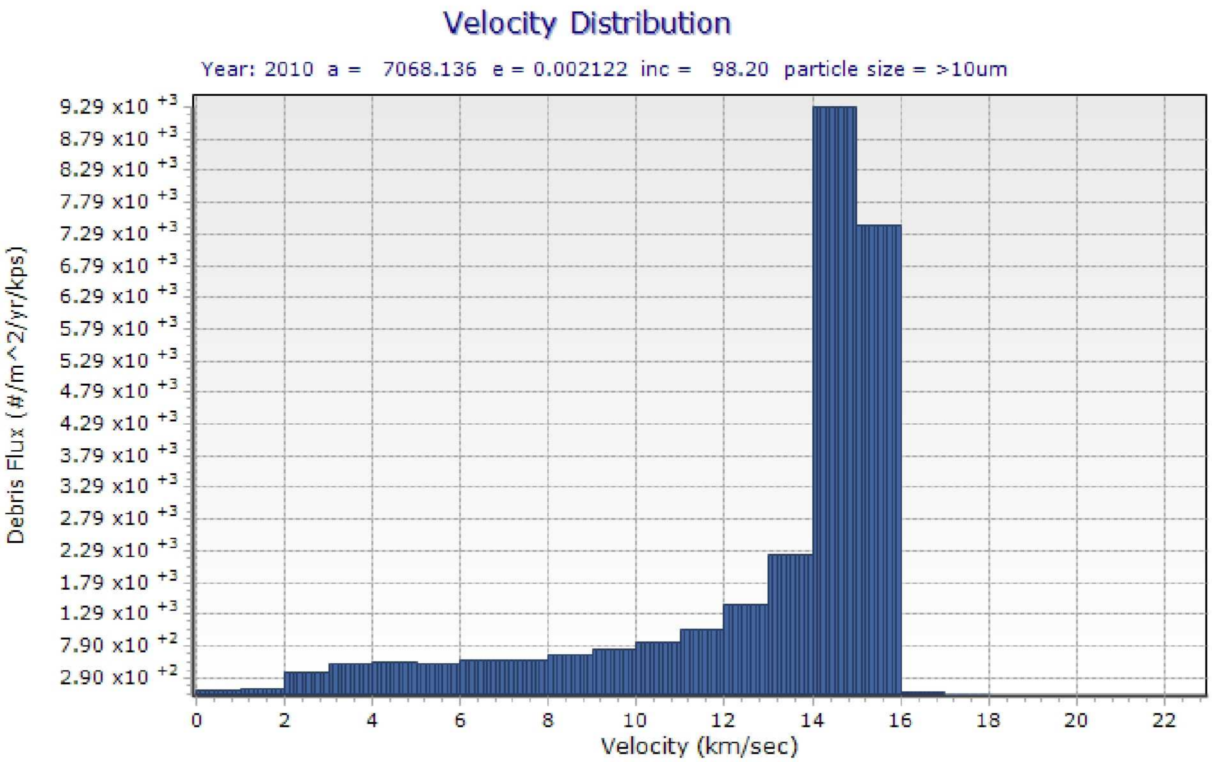

Figure 9c. GUI output of flux velocity distribution for debris larger than 10μm for Aura in 2010

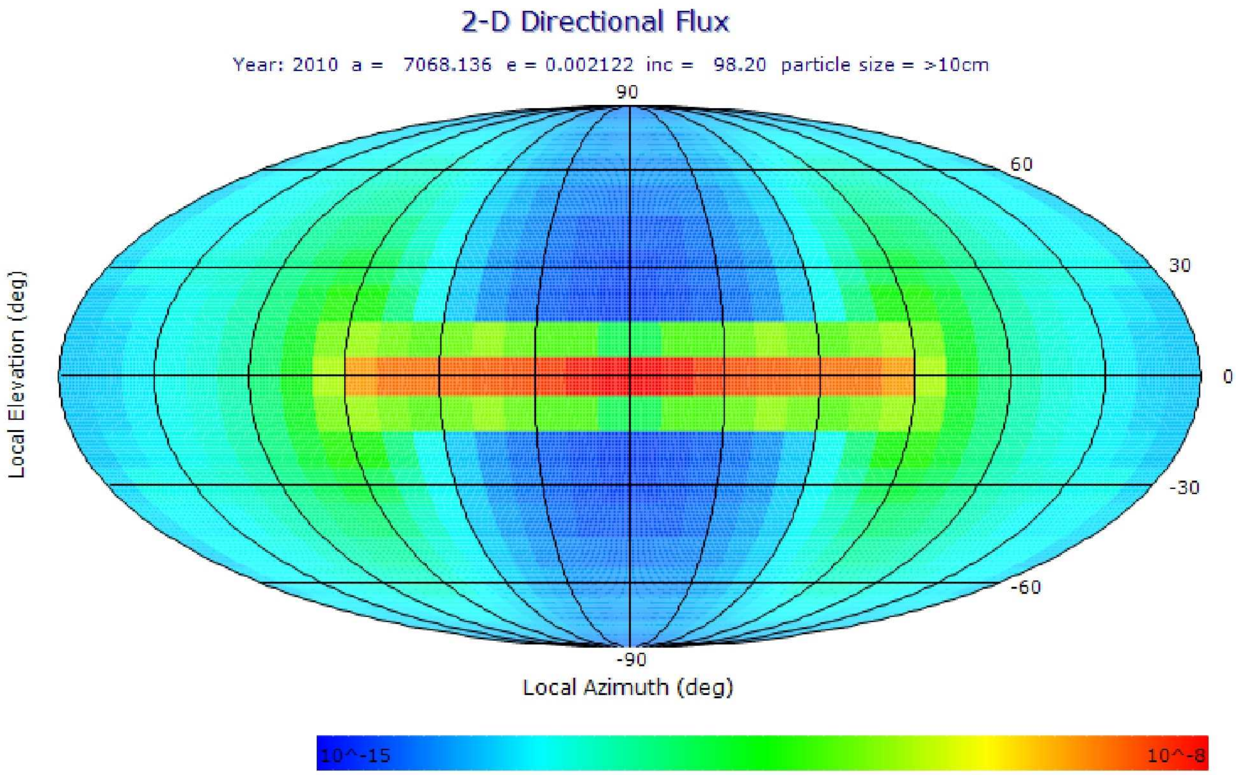

Figure 10a. GUI output of 2-D flux larger than 10 cm for Aura in 2010

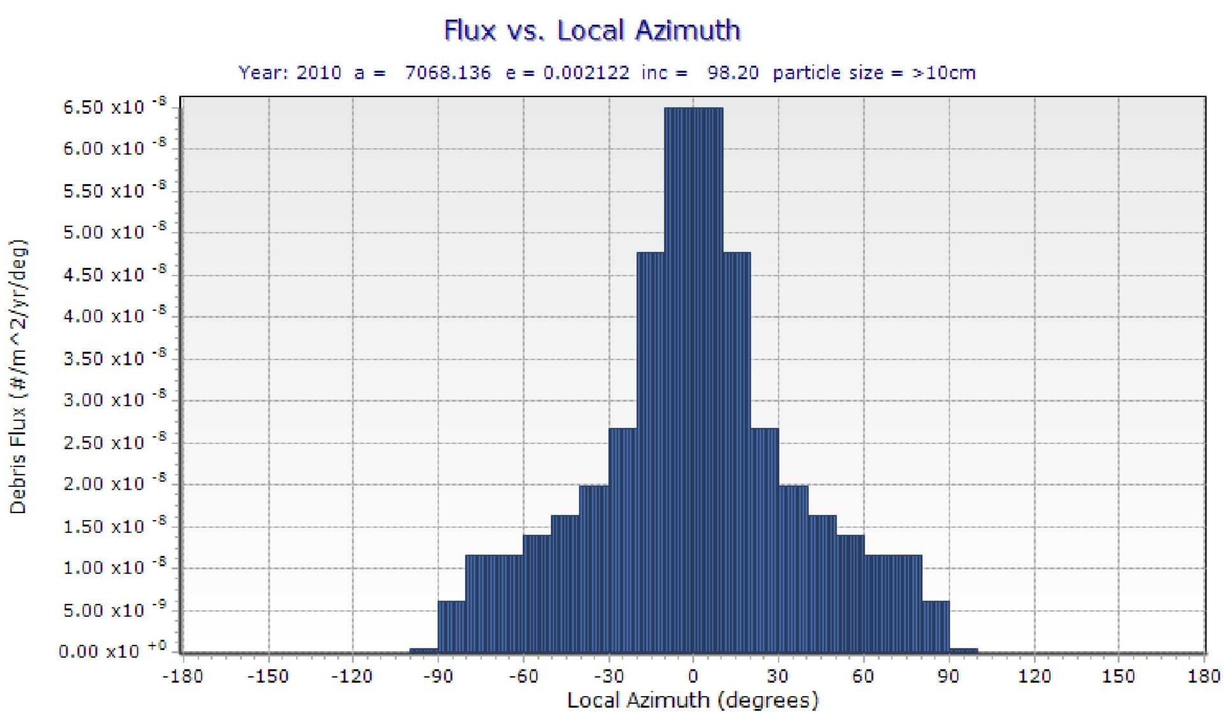

Figure 10b. GUI output of flux collapsed to horizontal plane larger than 10 cm for Aura in 2010

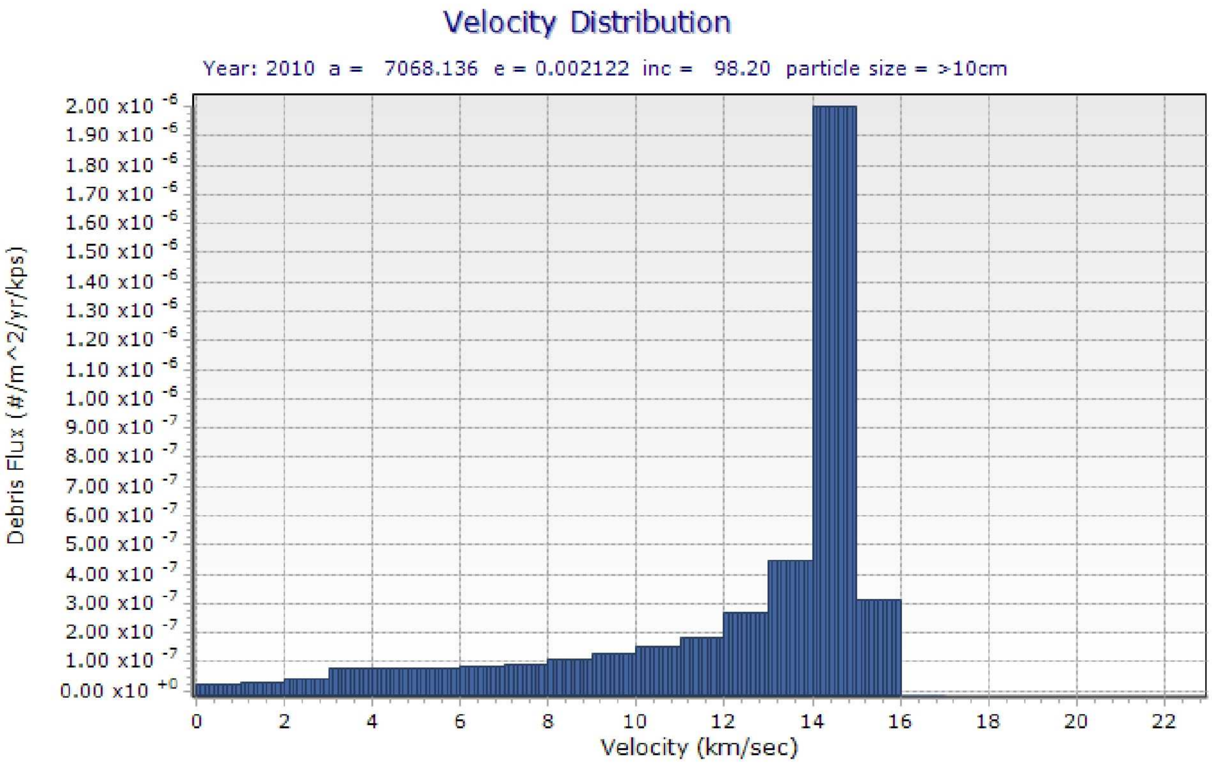

Figure 10c. GUI output of flux velocity distribution for debris larger than 10 cm for Aura in 2010

Summary

The release of ORDEM2010 will represent a significant improvement in the NASA ODPO's empirically-based debris assessment modeling program. This version of the long-running series includes ten years of additional data, new validated high-fidelity environment models, new statistical processes for data and model analysis, the extension of the modeling through GEO, the inclusion of debris material density, and a new spacecraft-encompassing igloo analysis package, with an advanced companion GUI. Comparisons with ORDEM2000 fluxes show justifiably higher populations in the sub-millimeter region. In the super-centimeter sizes the older ORDEM2000 is shown to overestimate the populations crossing the LEO high-traffic regions, but to underestimate the populations of 10 cm fragments generated by the FY-1C anti-satellite test and the Iridium 33/Cosmos 2251 accidental collision.

Sample cases of ORDEM2010 analysis for debris fluxes on the ISS and the Aura spacecraft are presented in this paper. The 2-D flux or Mollweide projection charts provide an intuitive view of the debris fluxes on these vehicles. Future implementation of ORDEM2010 into BUMPER (risk analysis code for crewed vehicles) and DAS (risk analysis code for robotic vehicles) will provide those analysis communities with an advanced reliable picture of the orbital debris environment.

REFERENCES

1. Liou J-C et al, The New NASA Orbital Debris Engineering Model ORDEM2000, NASA/TP—2002-210780, May 2002
2. Xu Y-L, 'Statistical inference in modeling the orbital debris environment', presented at IAC 2006, IAC-06-B6.2.03
3. Xu Y-L et al, 'Modeling of LEO orbital debris populations for ORDEM2008', Advance in Space Research, 43 (2009) 769-782
4. Xu Y-L et al, 'Modeling of LEO orbital debris populations in centimeter and millimeter size regimes', submitted to IAC 2010
5. Xu Y-L et al, 'Simulation of micron-sized debris populations in low Earth orbit', submitted to COSPAR 2010
6. Mulrooney M and Matney M, Derivation and Application of a Global Albedo Yielding an Optical Brightness to Physical Size Transformation Free of Systematic Errors, 2007 AMOS Technical Conference, Kihei, HI. September 2007
7. Krisko PH et al, 'Geosynchronous environment for ORDEM2010', presented at IAC 2009, IAC-09.A6.2.2
8. Opiela JN, 'A study of material density distribution of space debris', Advances in Space Research 43 (2009) 1058–1064
9. Krisko PH, Horstman M, Fudge ML. SOCIT4 collisional-breakup test data analysis: With shape and materials characterization, Advances in Space Research, 2008, 41(7), 1138-1146
10. Krisko PH et al, 'Material density distribution of small debris in Earth orbit', accepted by Advances in Space Research
11. Christiansen EL, 'Meteoroid/debris Shielding', TP-2003-210788, August 2003
12. Opiela JL, E Hillary, DO Whitlock, M Hennigan, Debris Assessment Software Version 2.0 User's Guide, JSC 64047, November 2007
13. NASA Aura Press Kit, Joint Assembly 2004 Meeting ,Release: 04-158, May 17, 2004

ORDEM2010

- **ORDEM2010 will represent a significant improvement in the NASA ODPO's empirically-based debris assessment modeling program**
  - new statistical processes for data and model analysis
  - includes ten years of additional data
  - new validated high-fidelity environment models
  - extension of the modeling through GEO
  - inclusion of debris material density
  - new spacecraft-encompassing igloo analysis package
  - advanced companion GUI

- **ORDEM2010 will supersede ORDEM2000 as the NASA Orbital Debris Program Office (ODPO) Orbital Debris Engineering Model this summer**

- **The ODPO plans to implement ORDEM2010 in the risk analysis models BUMPER (for crewed spacecraft) and DAS (for robotic spacecraft) this year**

National Aeronautics and Space Administration

NASA's new orbital debris engineering model, ORDEM2010

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ORDEM2010

- **ORDEM2010 will supersede ORDEM2000 as the NASA Orbital Debris Program Office (ODPO) Orbital Debris Engineering Model this summer**
- **ORDEM2010 includes,**
  - **New Bayesian statistical approach to debris population analysis**
    - Ten additional years of data including,
      - Statistical datasets → Haystack, HAX radars
      - Individual event datasets → FY-1C anti-satellite test, Iridium 33/Cosmos 2251 from SSN radar observation
    - High–fidelity models
      - LEGEND 3-D debris long-term environment model replaces the 1-D EVOLVE
      - NaKModule for RORSAT sodium potassium droplets
      - Degradation/Ejecta (D/E) for sub-millimeter particles
  - **Resulting high-fidelity population file structure of the yearly debris populations from 1995 - 2035**
    - Sizes 10 μm - 1 m (LEO - GTO)
    - Sizes 10 cm - 1 m (GEO)
    - Stable orbital elements (i.e., those that do not randomize on a sub-year timescale)
      - LEO – GTO → Hp, Ecc, Inc
      - GEO → MM, ECC, Inc, RAAN
    - Debris material density
  - **High-fidelity spacecraft analysis program**
    - Compares the populations with a spacecraft-encompassing 'igloo' to achieve a 3-D output of the flux on the spacecraft
  - **Advanced graphical user interface (GUI)**
    - Allows visualization of spacecraft flux in 2-D and 1-D

ORDEM2010 vs. ORDEM2000

Parameter	ORDEM2000	ORDEM2010
Spacecraft and Telescope/Radar analysis modes	YES	YES
Time range	1991 to 2030	1995 to 2035
Altitude range with minimum debris size	200 to 2000 km (>10 μm)	200 to 34,000 km (>10 μm)* 34,000 to 38,000 km (>10 cm)
Model population breakdown	NO	Intacts Low-density fragments Medium-density fragments and degradation/ejecta High-density fragments and degradation/ejecta RORSAT NaK coolant droplets
Population material density breakdown	NO	Low-density (<2 g/cc) Medium-density (2-6 g/cc) High-density (>6 g/cc) RORSAT NaK coolant (0.9 g/cc)
Population cumulative size thresholds	10 μm, 100 μm, 1 mm, 1 cm , 10 cm, 1 m	10 μm, 31.6 μm, 100 μm, 316 μm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m
Population storage	LEO Bins – Alt, Lat, Inc, Vel(horiz)	LEO-to-GTO bins - Hp, Ecc, Inc GEO bins - MM, Ecc, Inc, RAAN
Population extension	Max Likelihood Estimation	Bayesian statistics with ODPO models
Model S/C flux analysis method	S/C orbit segments	Igloo surrounding S/C
Model T/R flux analysis method	Segments along line-of-sight	Segments along line-of-sight

*sub-millimeter population has been validated for LEO only

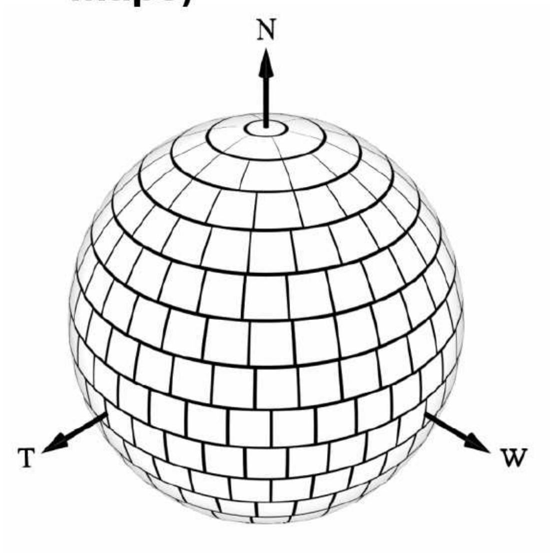
ORDEM2010 Models and Datasets

Model	Usage	Corroborative Data
LEGEND	LEO Fragments > 1mm GEO Fragments > 10cm	Haystack, SSN MODEST
NaKModule	NaK droplets > 1 mm	Haystack
Degradation/ejecta model	1mm > Degradation/ejecta > 10μm	STS windows & radiators

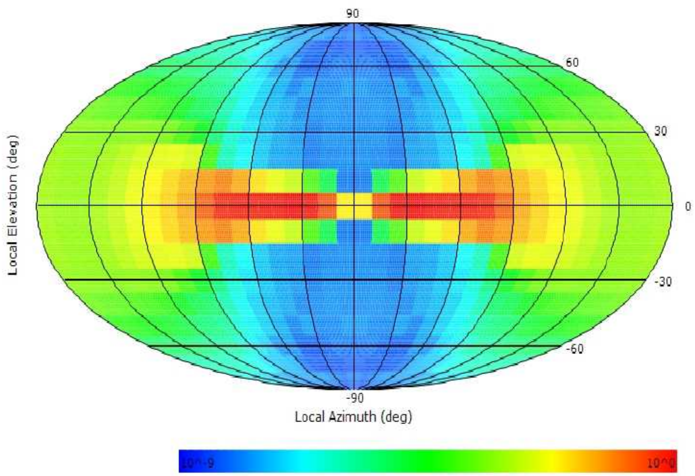
Observational Data	Role	Region/Size
SSN catalog (radars, telescopes)	Intacts & large fragments	LEO > 10 cm, GEO > 70 cm
Cobra Dane (radar)	Compare with SSN	LEO > 4 cm
Haystack (radar)	Statistical populations	LEO > 5.5 mm
Goldstone (radar)	Compare with Haystack	LEO > 2 mm
STS windows & radiators (returned surfaces)	Statistical populations	LEO < 1 mm
HST solar panels (returned surfaces)	Compare with STS	LEO < 1 mm
MODEST (telescope)	Only GEO data set	GEO > 30 cm

ORDEM2010 Spacecraft Flux Analysis

- **ORDEM2010 spacecraft encounters debris flux via a spacecraft-encompassing 3-D igloo**
  - Population flux is tested for each igloo element in an igloo coordinate system of debris size, velocity, azimuth, and elevation with respect to spacecraft ram direction
  - Flux is summed within an element, all element fluxes are summed together for the total yearly spacecraft encounter
  - Highest fidelity igloo presently in ORDEM2010 is 10°x10°x1km/s (Az x EL x Vel)
- **This directional debris flux calculation is supported by an updated graphical user interface (GUI) package designed for ORDEM2010 that includes a 2-D directional flux chart (a.k.a. Mollweide projection, pseudo-cylindrical equal-area map projection used for global or sky maps)**



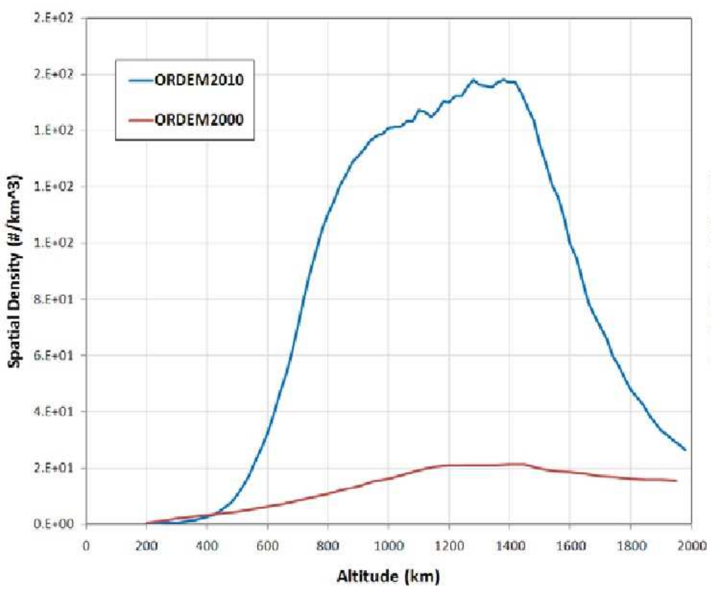
equal-area
spacecraft-encompassing igloo



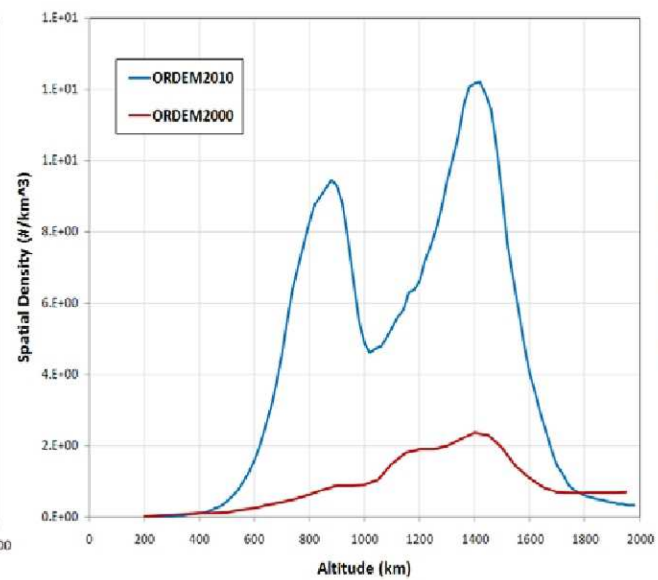
- Spacecraft velocity vector (ram direction) is defined by the azimuth, elevation coordinates (0°,0 °)
- Anti-ram is defined where (180°,0°) and (-180°,0°) meet
- Zenith is defined at (0°,90°), and nadir at (0°,-90°).

ORDEM2010 vs. ORDEM2000
(Small Debris Spatial Densities in LEO in 2010)

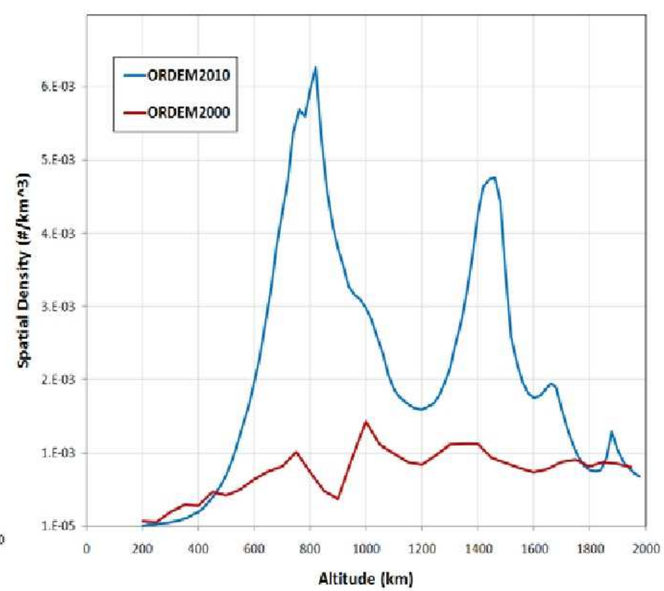
- **ORDEM2010 - debris smaller than 1 mm are derived from in-situ STS impact data (radiators and windows) and a degradation/ejecta model throughout LEO to GTO**
  - ORDEM2010 small debris peaks in regions of high traffic (700 km to 1000 km, and 1200 km to 1600 km)
- **ORDEM2000 - debris smaller than 1 mm are derived from in-situ STS impact data (radiators and windows) and extended into other altitude regimes in LEO via a Maximum Likelihood Estimator (MLE)**
- **In both models 1 mm population is a bridge between small and large debris**



>10 μm



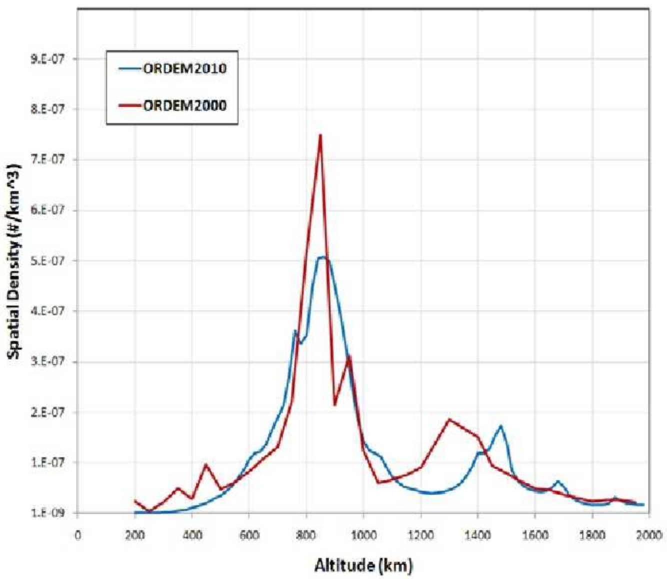
>100 μm



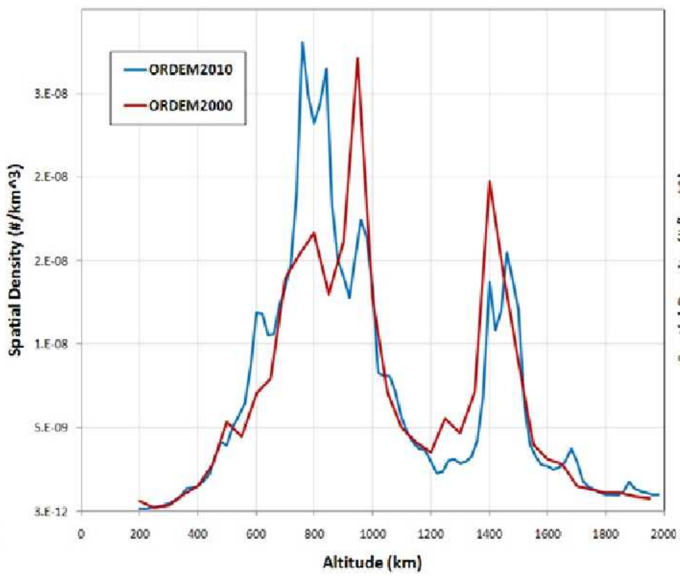
>1 mm

ORDEM2010 vs. ORDEM2000 (Large Debris Spatial Densities in LEO in 2010)

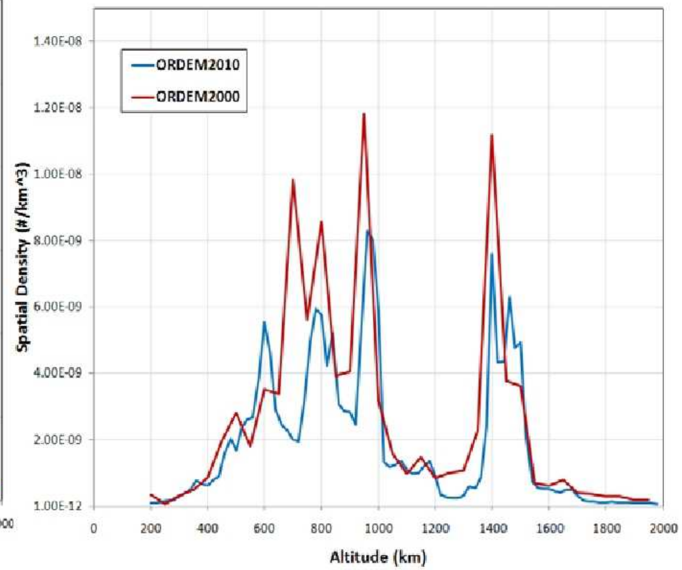
- **ORDEM2010 – last historical population is 2009, FY-1C anti-satellite test and Iridium 33/ Cosmos 2251 fragments are explicitly included**
- **ORDEM2000 – last historical population is 1999, population extended into projection period via ‘growth factors’ based on EVOLVE model environments**
  - general overestimation of spatial density in the LEO high traffic regions due to changes in space traffic since the year 2000
  - underestimates the 10 cm spatial density in the range 700 km to 900 km, the regions where the FY-1C and Iridium 33/ Cosmos 2251 fragments are presently located
- **In both models the larger heavily-observed debris environment are derived using copious Haystack, HAX and SSN radar data coupled with environmental models.**



>1 cm



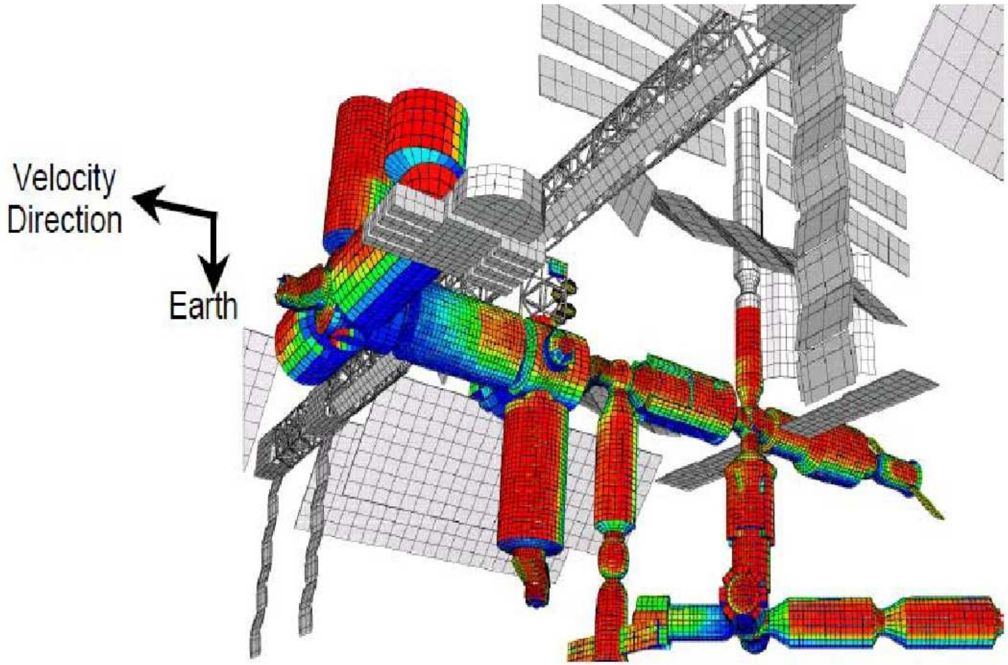
>10 cm



>1 m

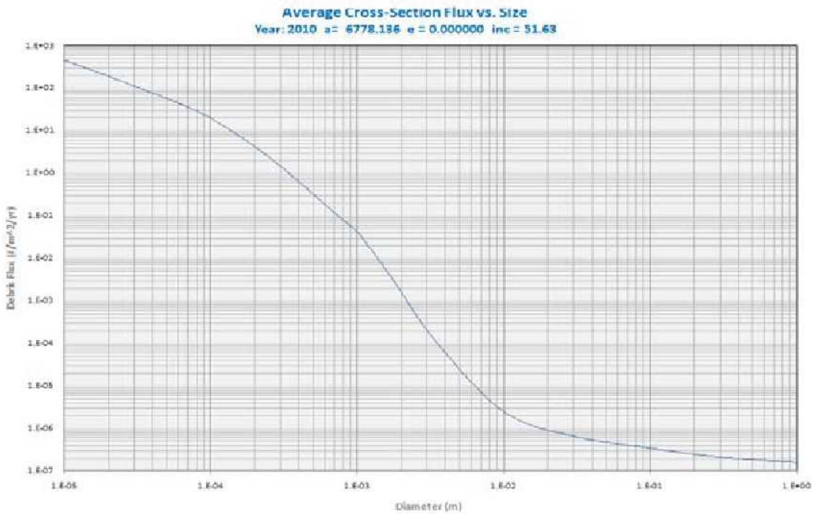
ORDEM2010 Study of Crewed Spacecraft (International Space Station)

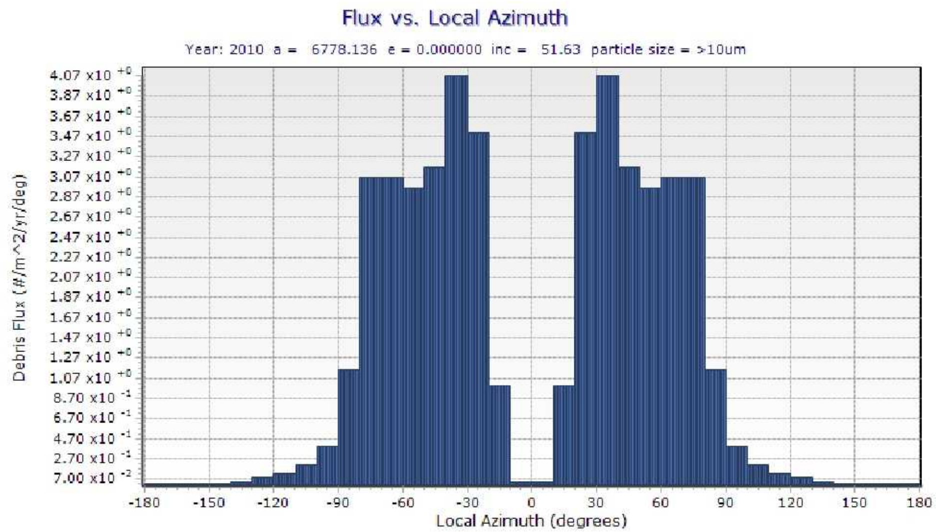
- **Original purpose for development and upkeep of ORDEM series is for safety analysis of crewed spacecraft**
- **NASA BUMPER finite element risk assessment code – presently ORDEM2000 for artificial debris environment + NASA meteoroid model**
  - debris and meteoroid fluxes applied to over 150,000 elements describing the surface geometry and shielding of the ISS
- **As noted in previous slides, ORDEM2000 population bins ignore debris radial velocity**
  - The horizontal plane of a LEO spacecraft carries the main source of orbital debris
  - The ORDEM2000 debris flux in BUMPER is therefore restricted to that plane

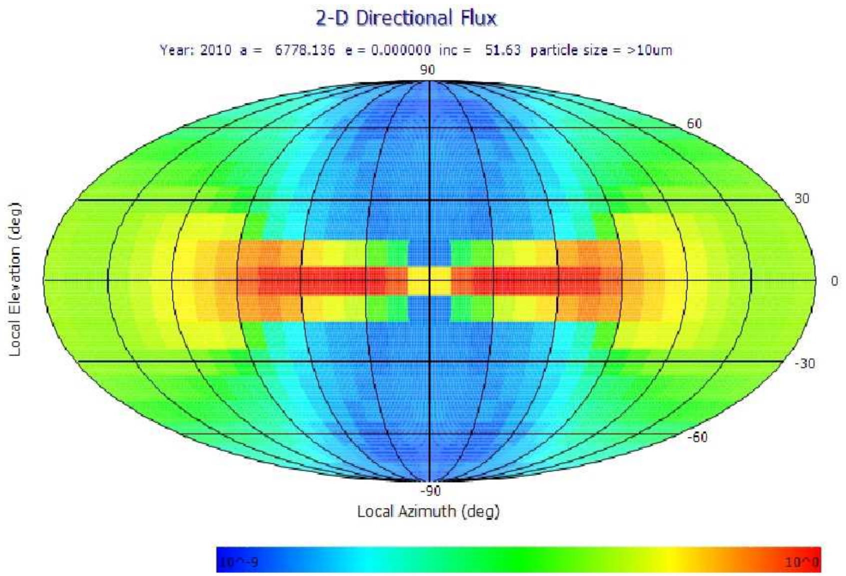


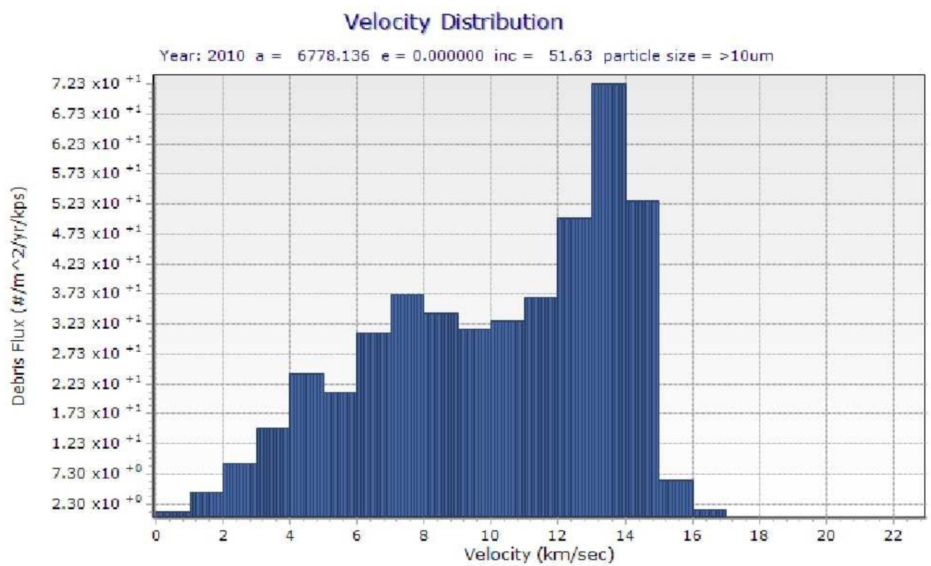
- BUMPER finite elements, high probability of impact is in red, low probability of impact is in blue
- Most critical components in the velocity ram and port/starboard sides are shielded to 1 cm debris at typical impact velocities of 9 km/s and impact angles of 45 deg
  - artificial debris environment the most important source of catastrophic impact threat to the ISS, as the natural meteoroid environment has a much lower flux by this size

ISS ORDEM2010 GUI Outputs for Debris larger than 10 µm (Inc = 51.63°, Hp = Ha = 400 km, year = 2010)

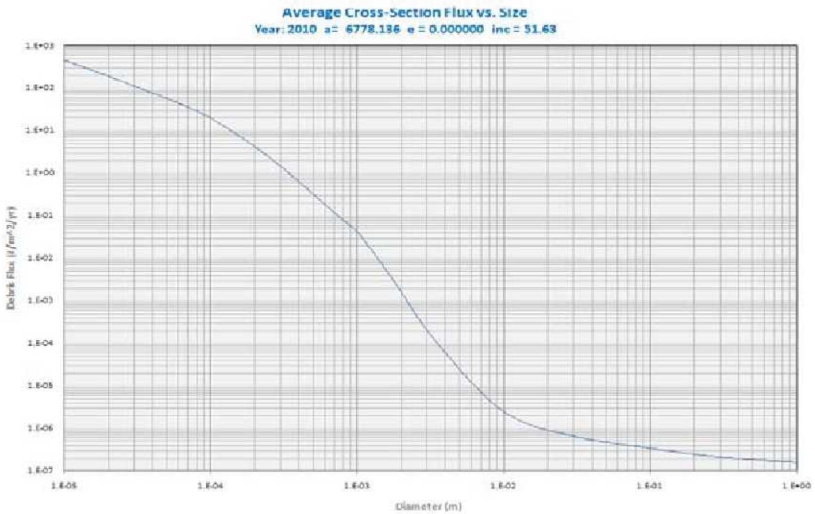


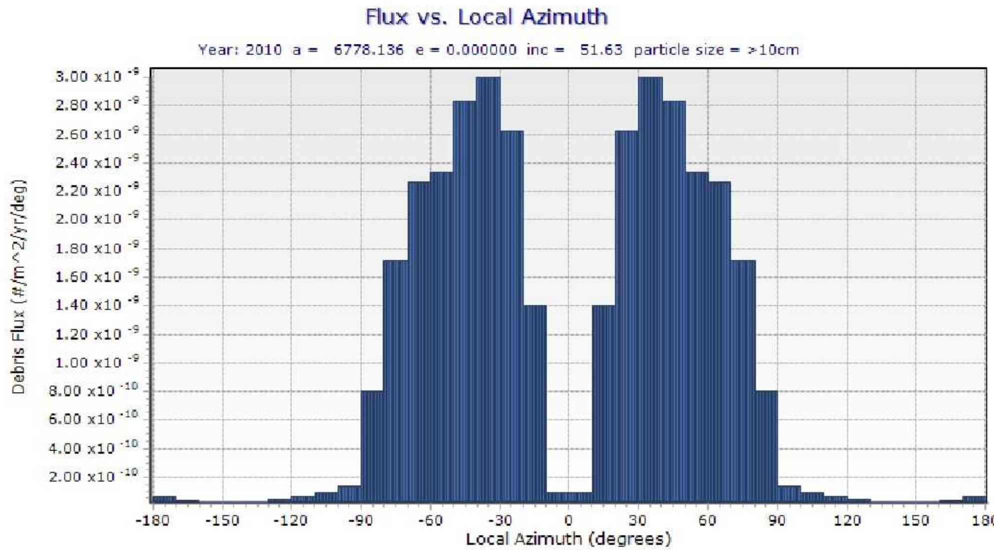


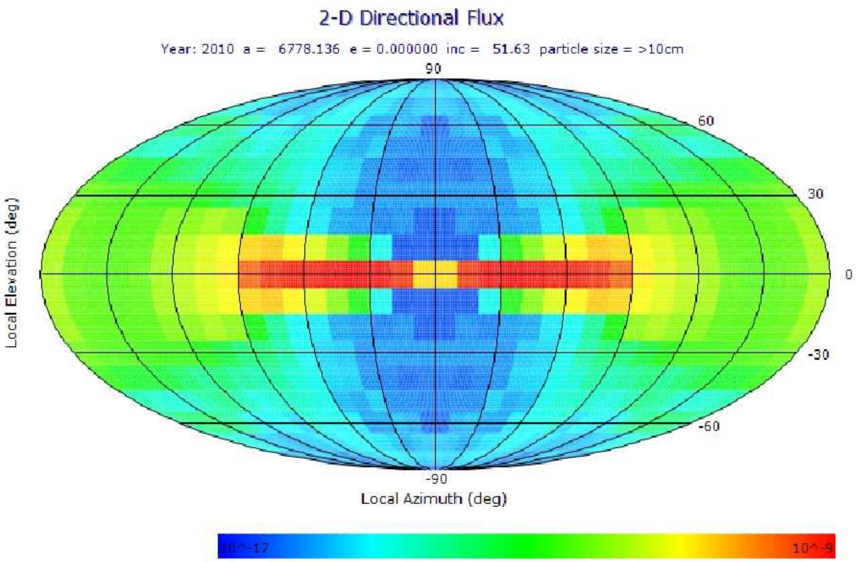


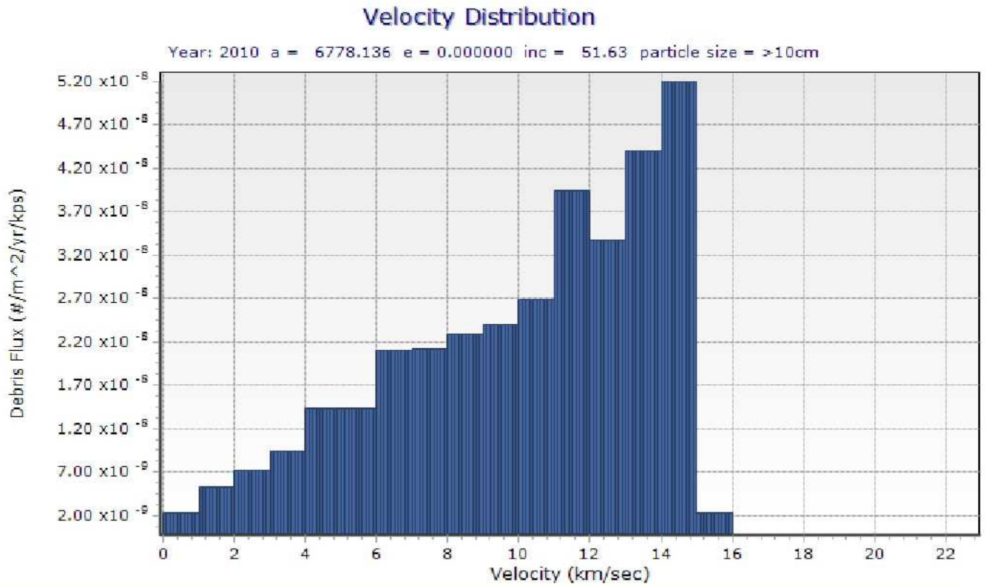


ISS ORDEM2010 GUI Outputs for Debris larger than 10 cm (Inc = 51.63°, Hp = Ha = 400 km, year = 2010)



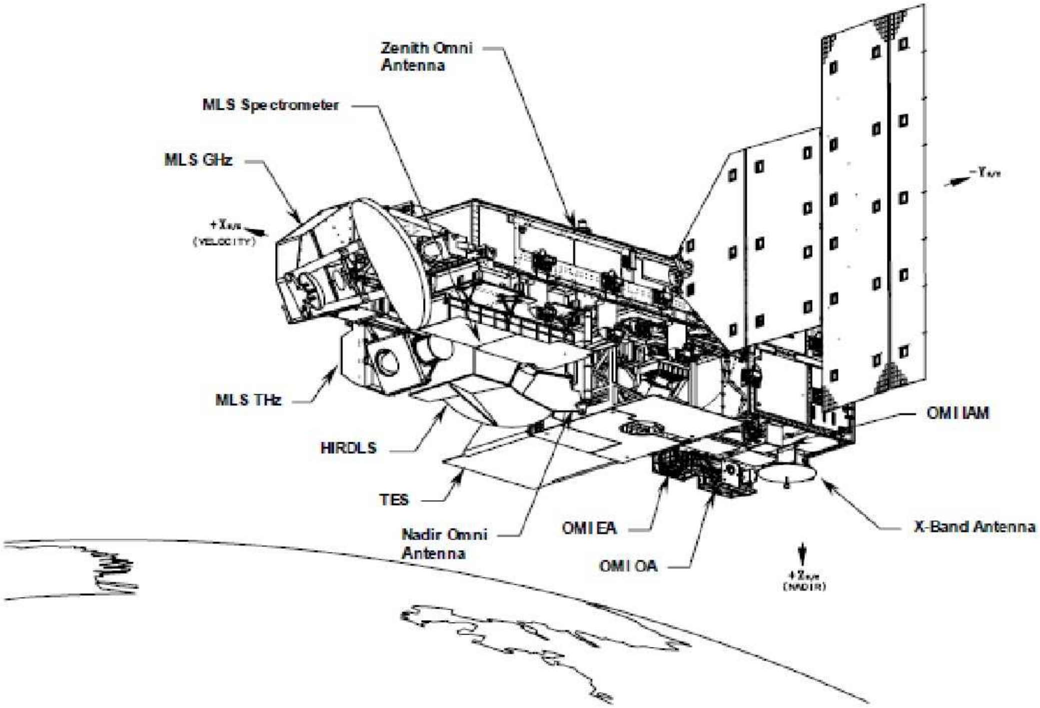






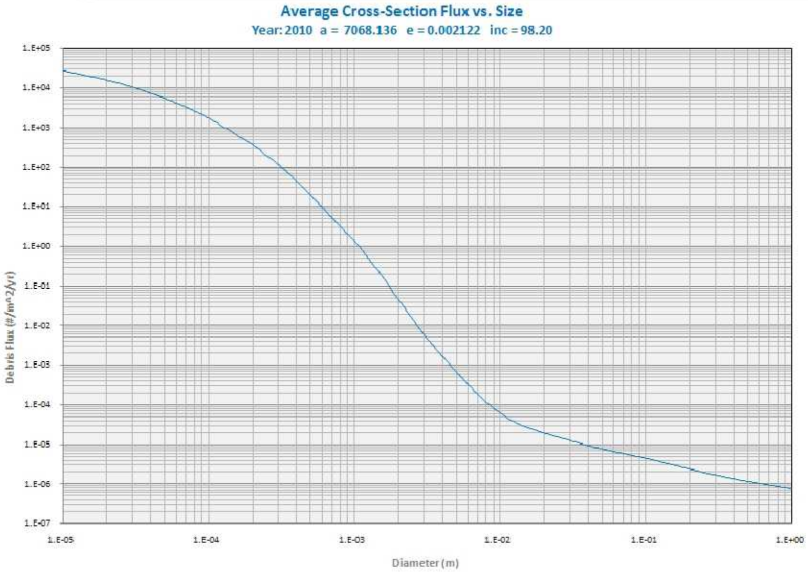
ORDEM2010 Study of Robotic Spacecraft (EOS-Aura)

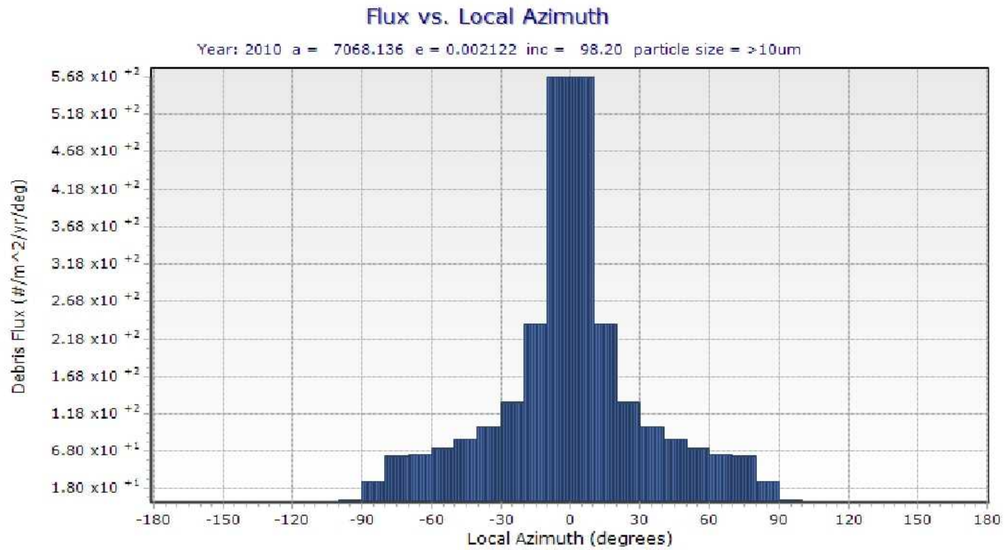
- **Since 1995 all NASA programs have been required to perform orbital debris assessments per the NASA Safety Standard 1740.14 and its successor NASA Standard 8719.14, at several stages of development (PDR, CDR)**
- **Debris Assessment Software (DAS) package developed by the ODPO to assist in this task**
  - DAS 2.0.1 - NASA orbital propagators for long-term mission analysis, ORDEM2000 with its artificial debris flux calculations, penetration probability codes, reentry survivability prediction code, and resulting ground casualty calculations
    - downloadable from NASA ODPO website, http://orbitaldebris.jsc.nasa.gov/mitigate/das.html
    - ORDEM2000 to be replaced by ORDEM2010 this year

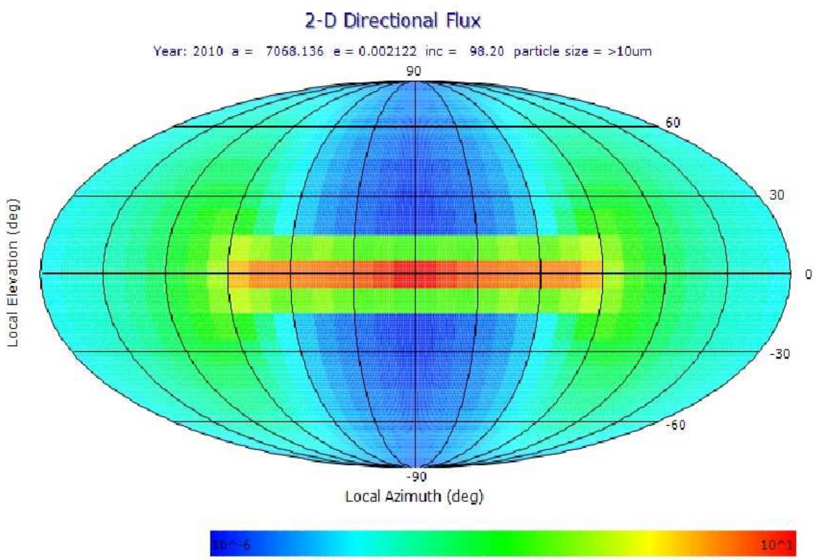


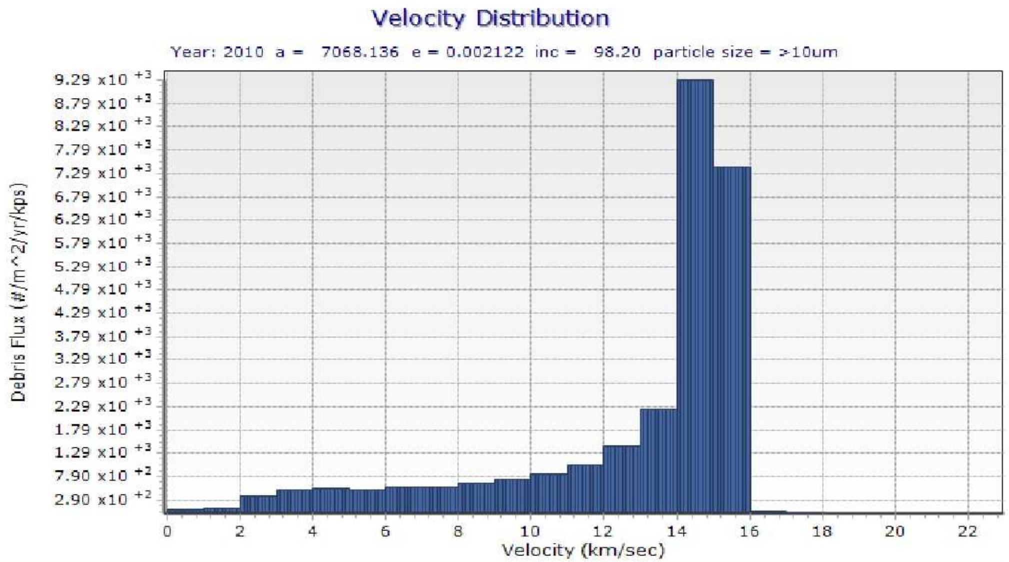
- Aura launched in July 2004 joining two other members of the EOS project, Terra and Aqua, all three in sun synchronous orbits
- Aura spacecraft configuration (deployed), +X to the left in the figure is the spacecraft velocity (ram) direction. The solar panel extends in +Y. Only 1 ½ panels are shown in the figure out of 12 panels
- Deployed Advanced Microwave Scanning Radiometer (AMSR) dish is the ram direction (+X)

Aura ORDEM2010 GUI Outputs for Debris larger than 10 µm (Inc = 98.2 °, Hp = Ha = 705 km, year = 2010)









Aura ORDEM2010 GUI Outputs for Debris larger than 10 cm (Inc = 98.2 °, Hp = Ha = 705 km, year = 2010)