AN Overview of NASA’s Orbital Debris Engineering Model

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Engineering Models

• Orbital debris engineering models are mathematical tools to assess orbital debris flux
  – Created primarily for spacecraft designers to accurately assess spacecraft risk
  – Also have been used historically to estimate sensor flux (e.g., predicted counts in a radar beam)

Need to be updated periodically
  – New data
  – New techniques
  – Unanticipated changes in the environment
  – Need for expanded capabilities

• Need to predict some distance into the future
Engineering Model History

- Pre-1990 – simple flux curve based mostly on model results

1994 Space Station Freedom model and ORDEM96 – used new Haystack data to describe 1 cm – 10 cm regime accurately for the first time
  - Finite inclination and eccentricity bands still described by analytic formulae

ORDEM2000 – used new techniques and computer improvements to describe complicated orbit distributions
  - Populations now saved as digital populations rather than analytic functions
ORDEM2010 New Features

- Expanded environment past LEO
  - New GEO data
  - Allow elliptical spacecraft orbits
  - Requires expanding flux directionality

- Include uncertainties
  - Primarily uncertainties in population estimates
  - Need to propagate to final flux values

- Include material density types
  - Material densities influence damage equations

- Debris shape was analyzed carefully, but is not explicitly included in the model
Structure

• ORDEM2000
  – Used finite element cells to describe spatial density in space around Earth
    • Altitude
    • Latitude
    • Size
    • Time
    • 2-dimensional velocity (parallel to Earth’s surface)
  – 6 dimensions of data storage

• ORDEM2010
  – In order to extend beyond LEO, need to add radial velocity term
  – Breaking up population into material types adds another dimension
  – 8 dimensions of data storage!
  – Solution - store orbit populations in terms of orbital elements
  – Altitude + Latitude + 3D Velocity
    → Perigee Altitude + Eccentricity + Inclination
  – This trades off storage space (6D) with run time
Structure

- Fluxes are computed at reference sizes and intermediate values interpolated (10 \( \mu \text{m} \)-1 m)
  - ORDEM2000 – one reference size per decade (6 steps)
  - ORDEM2010 – one reference size per half decade (11 steps)

- 5 discrete material populations
  - RORSAT Sodium-Potassium coolant droplets (1 g/cm\(^3\))
  - Intact objects (>10 cm, 2.8 g/cm\(^3\))
  - Low-density debris (1.4 g/cm\(^3\))
  - Medium-density debris (2.8 g/cm\(^3\))
  - High-density debris (8.0 g/cm\(^3\))

- 3-dimensional Orbital parameter finite element bins
  - Perigee Altitude
  - Eccentricity
  - Inclination
Spacecraft flux uses the concept of the encompassing “igloo” finite elements. Dimensions are “pitch/latitude”, “yaw/longitude”, and relative velocity in the frame of the spacecraft.

“Telescope mode” uses a much simpler 1-dimensional igloo in altitude.
There exists a mapping matrix that converts the orbital population finite element bins to “igloo” flux finite element bins.

- This matrix must be computed numerically, but is independent of material type, size, etc. It is only dependent on the details of the spacecraft orbit / telescope pointing mode.

- This mapping matrix is used to map population uncertainties into flux uncertainties.

\[ \sum_j M_{ij} P_j = I_i \]
• Each direction bin is also subdivided into velocity bins
• Center of 2-D chart is yaw/pitch = 0/0 – the spacecraft direction
Data

• The computed orbit populations are empirically driven as much as possible

> 10 cm : data is based on the catalog work of the US Space Surveillance Network

1 mm – 10 cm : data is based on measurements by the Haystack and HAX radars, and supplemented by the Goldstone radar. Shape/material information from ground tests, especially SOCIT4

10 mm – 1 mm : data is based primarily on Shuttle window and radiator impacts (material information included)

GEO (>10 cm) : data based on MODEST optical telescope analysis

Chinese ASAT test and Iridium-Cosmos cloud populations explicitly added based on empirical radar data analysis and modeling of future cloud evolution
A Bayesian method is used to adjust population parameters so that the predicted pattern of data (in this case range and Doppler range-rate) best match the data. Uncertainties are a by-product of this analysis.
Radiator Fit - HD data only

Radiator Data

- > 31 micron
- > 100 micron
- > 310 micron

Radiator Tape Hole Diameter [mm]

Cumulative Number

- 1 Sigma
- +1 Sigma
- -1 Sigma
Future Populations

- ORDEM2010 populations are projected out to 2035

Future populations based on LEGEND model runs using nominal assumptions for breakup rates, launch rates, and solar activity

100 Monte Carlo runs
- Mean represents “average” future
- Spread in results represents range of possible futures, treated as uncertainty value
Uncertainties

- Great effort was put into estimating and tracking uncertainties in the ORDEM2010 populations

For simplification, uncertainties are of two types – random (uncorrelated) and population (correlated) uncertainties
  - Random uncertainties are those that are uncorrelated between different orbit value finite element bins within a population
  - Population uncertainties are those correlated across the total sub-population

- Uncertainties in estimating populations from measurements
  - Conversion of measurements to size
  - Material distributions (Multinomial errors)
  - Distributions in orbital parameters (Poisson-like errors)
  - Total Population in orbit family (Poisson-like errors)
    • These last two are handled by a multidimensional Bayesian method taking advantage of the Poisson nature of the measurements
Uncertainties

- **Modeling uncertainties**
  - Future projections (Monte Carlo)

- **Uncertainties in model construction**
  - Orbit distributions created from discrete “objects” (Monte Carlo)
  - Numerical integration errors – orbit distributions must be numerically mapped to “igloo” using mapping matrix

- Uncertainty values are preserved for each “igloo” bin in final output files for use by user
Conclusions

ORDEM2010 represents the latest generation of orbital debris engineering models

• New features:
  – Extension beyond LEO
  – Full 2D directionality for spacecraft flux
  – Material density breakdowns
  – Computes uncertainties in flux calculations