AN Overview of NASA’s Orbital Debris Engineering Model

Mark Matney
Orbital Debris Program Office
NASA Johnson Space Center
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
National Aeronautics and Space Administration

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 µm – 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/cm³)
  - Intact objects (>10 cm, 2.8 g/cm³)
  - Low-density debris (1.4 g/cm³)
  - Medium-density debris (2.8 g/cm³)
  - High-density debris (8.0 g/cm³)

- 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

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

Cumulative Number vs. Radiator Tape Hole Diameter [mm]

- Radiator Data
- +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
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