National Aeronautics and Space Administration

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
    - Size
    - Latitude
    - 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

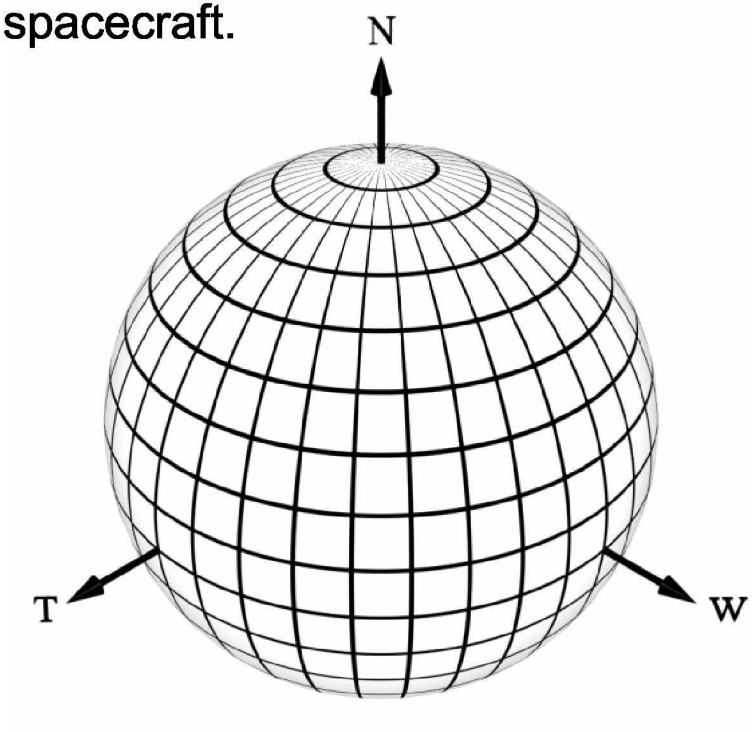
- Fluxes are computed at reference sizes and intermediate values interpolated (10 μm – 1 m)
  - ORDEM2000 – one reference size per decade (6 steps)
  - ORDEM2010 – one reference size per half decade (11 steps)

- 5 discrete material populations
  - RORSAT Sodium-Potassium coolant droplets (1 g/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)

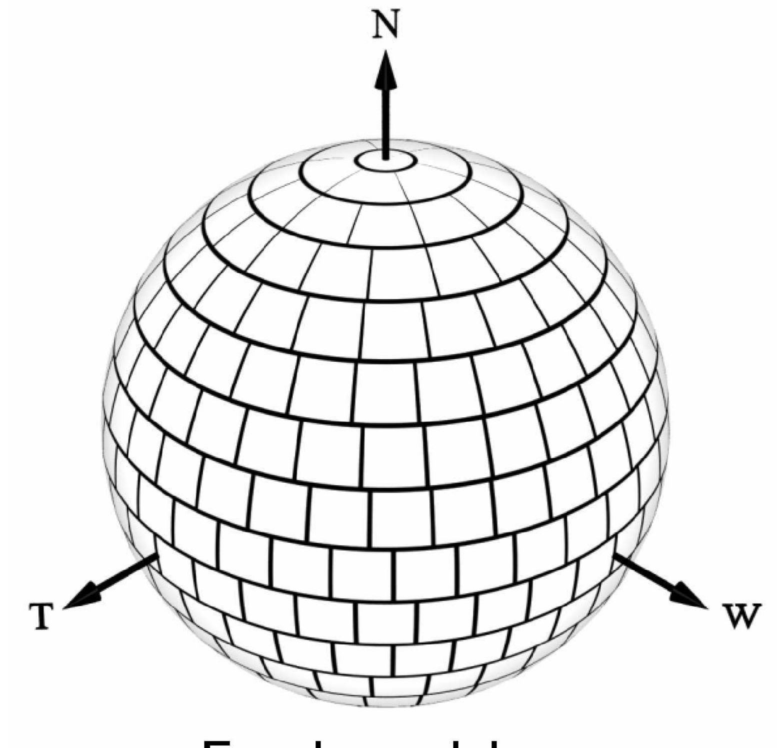
- 3 dimensional Orbital parameter finite element bins
  - Perigee Altitude
  - Eccentricity
  - Inclination

Spacecraft Flux Computation

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.



Equal-angle Igloo



Equal-area Igloo

"Telescope mode" uses a much simpler 1-dimensional igloo in altitude

Mapping Matrix

- There exists a mapping matrix that converts the orbital population finite element bins to "igloo" flux finite element bins

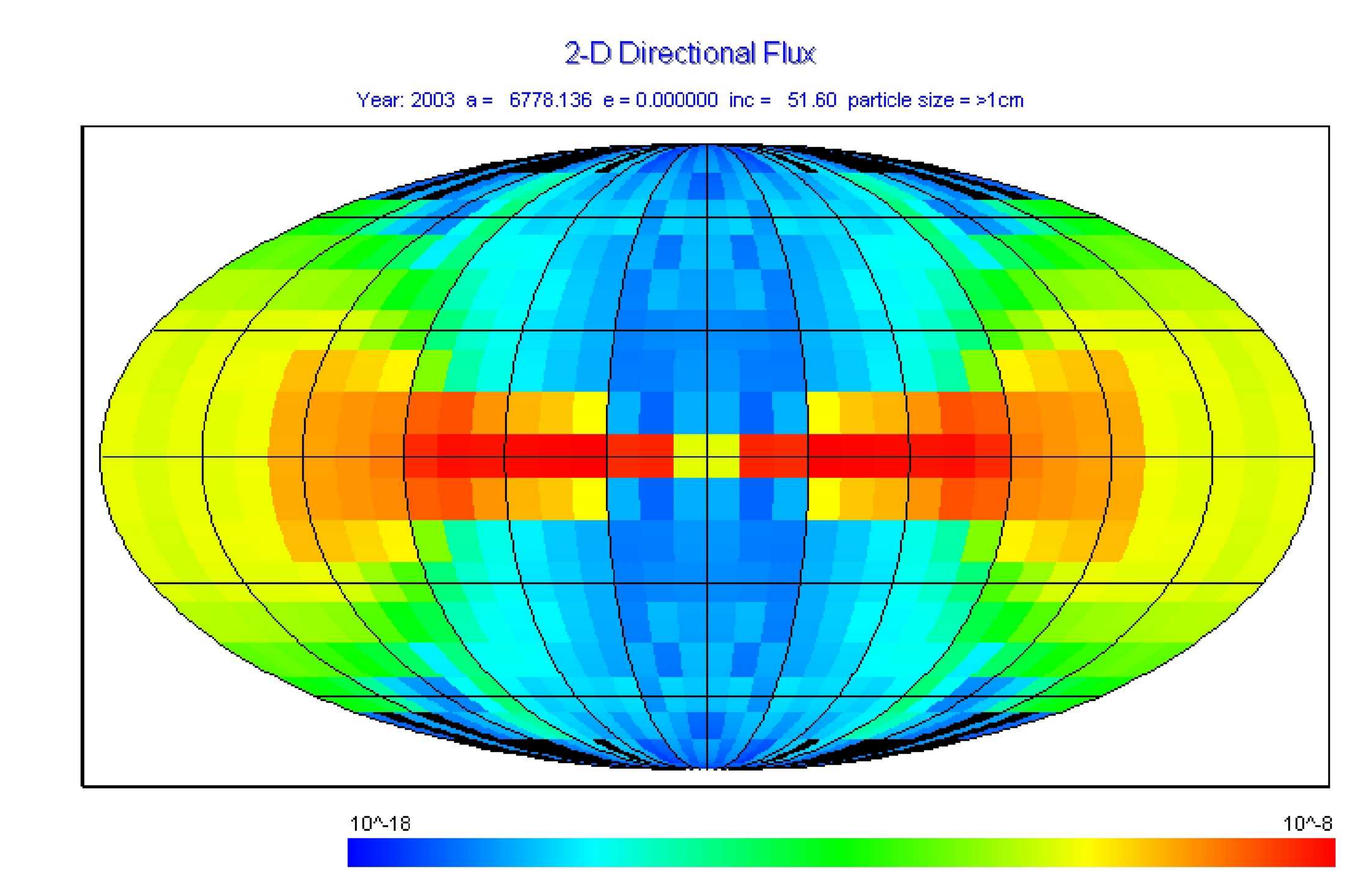
- This matrix must be computed numerically, but is independent of material type, size, etc. It is only dependent on the details of the spacecraft orbit / telescope pointing mode

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

Mapping Matrix | Orbit Population Densities = Igloo Element Fluxes

$$\sum_j M_{ij} P_j = I_i$$

ORDEM Igloo Fluxes – Mollweide Plot

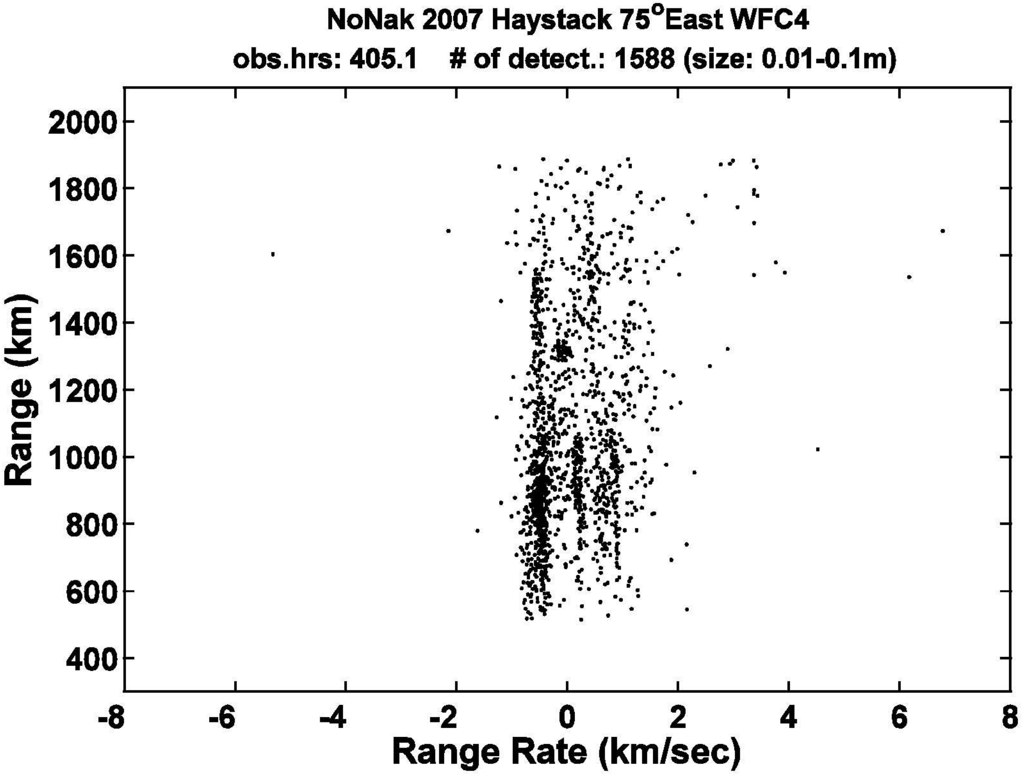


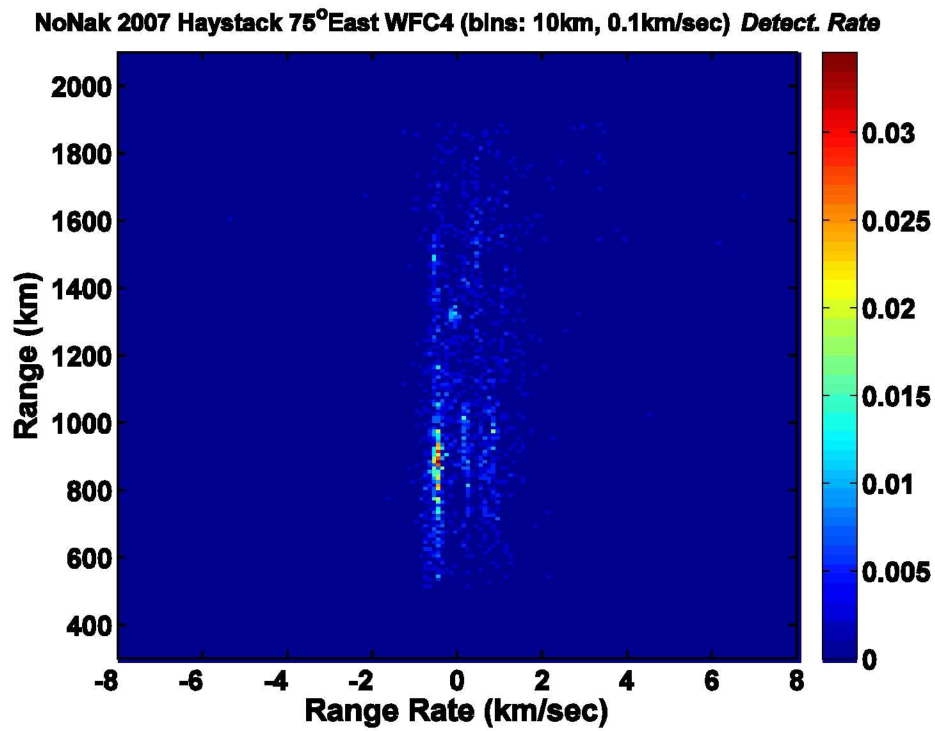
- Each direction bin is also subdivided into velocity bins
- Center of 2-D chart is yaw/pitch = 0/0 – the spacecraft direction

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

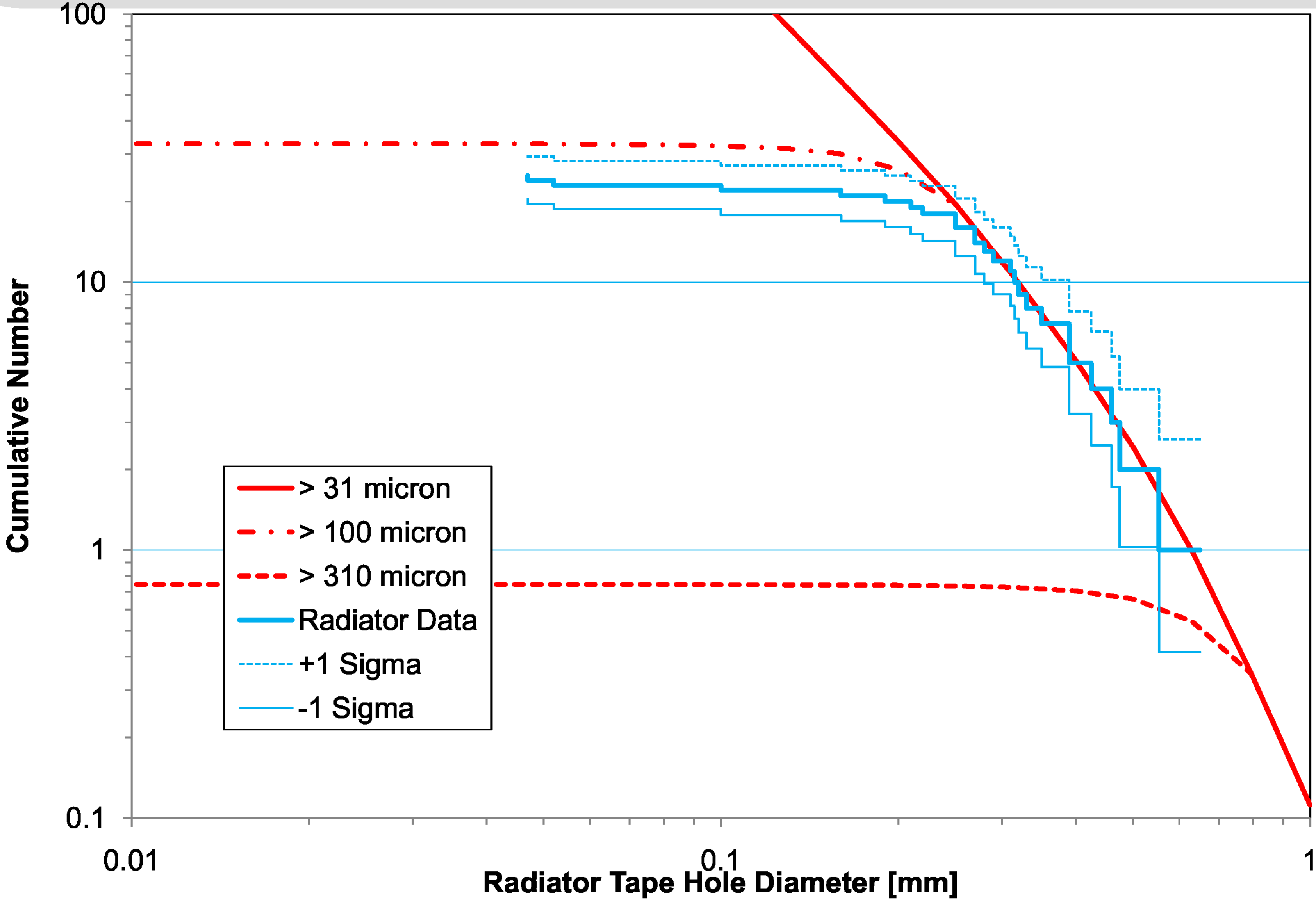
Haystack Data





- 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



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**