Orbital Debris Modeling

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Outline

• The NASA OD Engineering Model
  – A mathematical model capable of predicting OD impact risks for the ISS and other critical space assets

• The NASA OD Evolutionary Model
  – A physical model capable of predicting future debris environment based on user-specified scenarios

• The NASA Standard Satellite Breakup Model
  – A model describing the outcome of a satellite breakup (explosion or collision)
Orbital Debris Engineering Models
What Is an Engineering Model?

• An OD engineering model is a mathematical tool
  – Designed to describe the current and near-future OD flux in the environment
  – Created primarily for spacecraft designers/operators to reliably assess spacecraft risk due to OD impacts
  – Has been used to estimate sensor flux for radar/telescope observers

• There is a need to update the model on a regular basis
  – New data
  – Better techniques
  – Changes in the environment
  – Need for expanded capabilities
History of the NASA OD Engineering Models

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

• 1994 Space Station Freedom model and ORDEM96 – obtained Haystack radar data for debris in the 1 cm to 10 cm regime
  – Used simple equations to describe debris populations in 6 inclination and 2 eccentricity groups

• ORDEM2000 – used new techniques and improved computer capabilities to describe the LEO environment
  – Populations were derived from data and then processed to generate the model environment
The LEO environment is described by a finite element model (5° × 5° × 50 km) with spatial density and velocity distributions of debris of 6 different sizes.
Highlights of the New Model – ORDEM 3.0

• Expand data sources in time, altitude, and particle size
  – Altitude: 100 to 40,000 km (LEO through GEO)
  – LEO-GTO: Use SSN catalog, Haystack, HAX, Goldstone, STS windows/radiators to develop OD populations
  – GEO: use the MODEST GEO survey data to develop ≥10 cm populations

• Utilize higher fidelity supporting environmental models
  – LEGEND replaces EVOLVE 4.0
  – Material density breakdown included
  – NaK droplet and degradation/ejecta product models added

• Use Bayesian statistics to derive debris populations from data
  – Model uncertainties are included in the output

• Maintain two analysis modes: spacecraft and telescope/radar
  – Debris fluxes through ‘igloo’ in pitch, yaw, impact velocity elements (in spacecraft mode) and through cylinder in range elements (in telescope/radar mode)

• Update Graphical User Interface (GUI)
ORDEM 3.0 GUI Interface

Notional Data – Not Yet Certified
Sample ORDEM 3.0 Model Output

Notional Data – Not Yet Certified

Iode (lat,az,el)=(42,90,75)
Year = 2006
## ORDEM2000 versus ORDEM 3.0

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORDEM2000</th>
<th>ORDEM 3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft and Telescope/Radar analysis modes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Time range</td>
<td>1991 to 2030</td>
<td>2010 to 2035</td>
</tr>
<tr>
<td>Altitude range with minimum debris size</td>
<td>200 to 2000 km (&gt;10 μm)</td>
<td>100 to 2000 km (&gt;10 μm)</td>
</tr>
<tr>
<td></td>
<td>2000 to 33,000 (&gt;1 cm)</td>
<td>2000 to 33,000 (&gt;1 cm)</td>
</tr>
<tr>
<td></td>
<td>33,000 to 40,000 km (&gt;10 cm)</td>
<td></td>
</tr>
<tr>
<td>Model population breakdown</td>
<td>No</td>
<td>Intacts and mission related debris</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fragments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RORSAT NaK coolant droplets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Degradation/ejecta</td>
</tr>
<tr>
<td>Material density breakdown</td>
<td>No</td>
<td>Low-density(&lt;2 g/cm³): fragments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium-density(2-6 g/cm³): fragments, degrad/ejecta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High-density(&gt;6 g/cm³): fragments, degrad/ejecta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RORSAT NaK coolant droplets (0.9 g/cm³)</td>
</tr>
<tr>
<td>Model cumulative size thresholds</td>
<td>10 μm, 100 μm, 1 mm, 1 cm, 10 cm, 1 m</td>
<td>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</td>
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<tr>
<td>Population uncertainties</td>
<td>No</td>
<td>Yes</td>
</tr>
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<td>File size</td>
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<td>1.4 GB</td>
</tr>
<tr>
<td>Run time</td>
<td>Seconds</td>
<td>Minutes to hours</td>
</tr>
</tbody>
</table>
Status of ORDEM 3.0

• Model in final validation and verification process

• Official release is scheduled for later this year
  – Will be available for download from the NASA Orbital Debris Program Office website
NASA Orbital Debris Evolutionary Model
• LEGEND, A LEO-to-GEO environment debris model
  – Is a high fidelity, three-dimensional numerical simulation model for long-term orbital debris evolutionary studies
  – Replaces the previous one-dimensional, LEO only model, EVOLVE
  – Includes intacts (rocket bodies and spacecraft), mission-related debris (rings, caps, etc.), and explosion/collision fragments
  – Handles objects individually
  – Is capable of simulating objects down to 1 mm in size, but the focus has been on ≥10 cm objects
  – Covers altitudes up to 40,000 km
  – Can project the environment several hundred years into the future
• LEGEND, an orbital debris evolutionary model
  – Uses a deterministic approach to mimic the historical debris environment based on recorded launches and breakups
  – Uses a Monte Carlo approach and an innovative, pair-wise collision probability evaluation algorithm to simulate future collision activities
  – Analyzes future debris environment based on user-specified launch traffics, postmission disposal, and active debris removal options
  – Ten peer-reviewed journal papers have been published about LEGEND and its applications since 2004


Development History

• **History**
  – 2003: Completed the historical component
  – 2005: Developed the “Cube” collision probability evaluation algorithm
  – 2006: Completed the future projection component
  – 2006: Added the postmission disposal mitigation options
  – 2007: Added the new capabilities to evaluate and identify individual objects for removal
  – 2008: Added additional options and output information for debris removal

• **Future Improvements**
  – Increase the computational speed of the two orbit propagators
  – Validate model predictions for sub-10 cm populations
The LEGEND Code

• LEGEND is written in Fortran
  – Includes ~18,000 lines of Fortran code

• LEGEND runs on Unix/Linux-based workstations
  – Typical runtime: ~days to weeks

• LEGEND is only available to a few well-trained Orbital Debris Program Office scientists
Set up constants, parameters, arrays

---

1957

L500
Read in breakup events
N\text{cum}, A/M, A₂, ΔV distributions
Generate breakup clouds
Generate element arrays

\[ t_{i+1} = t_i + Δt \]

L400
Add in NaK, SRM, etc.
N\text{cum}, A/M, A₂, ΔV distributions
Generate element arrays

L300
Read in traffic data

L200
Existing objects

L100
Maneuvers if necessary

Propagate to the end of the year

- Atmosphere model
- Solar activity model
- Radiation pressure
- Solar-lunar, \( \oplus \)'s perturbations
- \( \oplus \)'s shadow

output

2011?

no

yes

stop

- Element arrays, etc.
- Debris distributions (1-D, 2-D, 3-D)

(Liou et al., 2004)
LEGEND Architecture (2/2)

From the end of historical simulation

2012

L400

A selected historical traffic cycle

Read in traffic data

L100

Existing intacts

Postmission disposal or removal

L200

Existing fragments

L600

Generate breakup fragments

L500

Generate element arrays

β

Generate element arrays

β

Yes

No

Yes

No

Propagate to the end of the time step

• Atmosphere model
• Solar activity model
• Radiation pressure
• Solar-lunar, $\oplus$’s perturbations
• $\oplus$’s shadow

End-of-year output

• Debris distributions (1-D, 2-D, 3-D)
• Element arrays, etc.

$t_{i+1} = t_i + \Delta t$ (5 days)

2212

JCL

20/43
LEGEND Supporting Models (1/4)

• **DBS database**: a comprehensive record of historical launches and breakup events
  – Time, type, orbit, physical properties (mass, area), *etc.*
  – The database is updated annually

• **Space Surveillance Network (SSN) catalogs**
  – Daily records of the historical growth of the ≥10 cm debris population
  – Basis of empirical area-to-mass ratio (A/M) distributions of large breakup fragments
  – New files are downloaded from “Space Track” website daily

• **Future launch traffic model**
  – Typically a repeat of the last 8-year cycle, as commonly adopted by the international debris modeling community
• **Atmospheric drag model**
  – Jacchia atmospheric density model (1977)
  – Drag perturbation equations based on King-Hele (1987)
• **Solar flux (at 10.7 cm wavelength) model consisting of three components**
  – Historical daily records available from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC)
  – Short-term projection provided by NOAA/SWPC – currently through 2019
  – Long-term projection is a repeat of a 13th-order sine and cosine functional fit to Solar Cycles 18 to 23 (1944 – 2010)
    • Similar to projections developed for long-term debris evolutionary models by other space agencies (ASI, UKSA, etc.)
• GEOprop orbital propagator
  – Propagates objects near geosynchronous (GEO) region
  – Perturbations include solar and lunar gravitational forces, solar radiation pressure, and Earth’s gravity-field zonal \((J_2, J_3, \text{ and } J_4)\) and tesseral \((J_{2,2}, J_{3,1}, J_{3,3}, J_{4,2}, \text{ and } J_{4,4})\) harmonics

• Prop3D orbit propagator
  – Propagates orbits of objects in LEO and GTO regions
  – Perturbations include atmospheric drag, solar and lunar gravitational forces, solar radiation pressure, and Earth’s gravity-field zonal harmonics \(J_2, J_3, \text{ and } J_4\)

• Both propagators compare well with similar tools used by other space agencies
• **NASA Standard Satellite Breakup Model**
  - Describes the outcome of an explosion or collision
    • Fragment size, A/M, and ΔV distributions
  - Based on seven, well-observed on-orbit explosions, several ground-based impact experiments, and one on-orbit collision
LEGEND Applications

• **LEGEND** is the tool the NASA Orbital Debris Program Office uses to
  
  – Provide debris environment projection for the next 200 years
    • Based on user-specified scenarios (launch traffics, postmission disposal, active debris removal options, etc)
  – Evaluate the instability of the current debris environment
  – Assess the growth of the future debris populations
  – Characterize the effectiveness of the NASA, U.S., and international debris mitigation measures
  – Quantify the benefits of active debris removal (ADR)
Sample LEGEND Output

LEO Environment Projection (averages of 100 LEGEND MC runs)

- Reg Launches + 90% PMD
- Reg Launches + 90% PMD + ADR2020/02
- Reg Launches + 90% PMD + ADR2020/05
NASA Standard Satellite Breakup Model
What Is a Satellite Breakup Model?

• A satellite breakup model describes the outcome of a satellite breakup (explosion or collision)
  – Fragment size, area-to-mass ratio (A/M), and ΔV distributions

• The key to provide good short- and long-term debris impact risk assessments for critical space assets is the ability to reliably predict the outcome of a satellite breakup

• There are two options to develop the model
  – Theoretical
  – Empirical
• Based on the fragment distribution of 7 well-observed on-orbit R/B explosions
• Fragments are described by a single power law distribution
• Explosions are classified into 6 different groups with different scaling factors (sf) assigned to their fragment distribution

\[ \text{N}_{\text{cum}} = \text{sf} \times 6 \times L^{-1.6} \]

\( \text{N}_{\text{cum}} \): number of fragments \( \geq L_c \),
\( L_c \): characteristic length in (m)
Size Distribution of Explosion Fragments

Cumulative Number

Characteristic Size (m)

- LANDSAT 1 R/B
- LANDSAT 2 R/B
- LANDSAT 3 R/B
- Nimbus 6 R/B
- Nimbus 4 R/B (Agena D)
- OPS 7613 R/B (Agena D)
- Long March 4 R/B
- NASA: Ncum=6 Lc^-1.6
NASA Breakup Model for Collisions

• Based on ground-based impact experiments and one well observed on-orbit collision (P78/SOLWIND)
• A catastrophic collision occurs when the ratio of impact energy to target mass exceeds 40 J/g
• Fragments are described by a single power law distribution

\[ N_{\text{cum}} = 0.1 \times (M_{\text{tot}})^{0.75} \times L_c^{-1.71} \]

- \( N_{\text{cum}} \): number of fragments \( \geq L_c \)
- \( L_c \): characteristic length in (m),
- \( M_{\text{tot}} = m_{\text{tar}} + m_{\text{proj}} \) (catastrophic) or
- \( M_{\text{tot}} = m_{\text{proj}} + m_{\text{proj}} \times V^2/(\text{km/sec})^2 \) (non-catastrophic)
Mass Distribution of Collision Fragments

![Graph showing mass distribution of collision fragments with different symbols and lines representing various datasets and the NASA BU Model.](https://example.com/graph.png)
Improving the NASA Breakup Model

• The NASA satellite breakup model has been adopted by major international space agencies for various OD environment studies.

• As new materials and new construction techniques are developed for modern satellites, there is a need to conduct additional ground-based tests and use the data to further enhance the collision model.
The A/M distribution of the Cosmos 2251 fragments matches well with the NASA model prediction.
• The A/M distribution of the Iridium 33 fragments appears to be systematically higher than the NASA model prediction
• Lightweight composite materials were extensively used in the construction of the vehicle
The A/M distribution of the Iridium 33 fragments is approximately a factor of 3 higher than the NASA model prediction.
The project is a collaboration between NASA ODPO and the Kyushu University in Japan.

<table>
<thead>
<tr>
<th></th>
<th>Size (cm)</th>
<th>$M_t$ (g)</th>
<th>$M_p$ (g) / $D_p$ (cm)</th>
<th>$V_{imp}$ (km/s)</th>
<th>EMR (J/g)</th>
<th>Impact Angle</th>
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<tbody>
<tr>
<td>0501H</td>
<td>15</td>
<td>740</td>
<td>4.03 / 1.4</td>
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<td>740</td>
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<td>0801R</td>
<td>20</td>
<td>1525</td>
<td>39.3 / 3.0</td>
<td>1.78</td>
<td>40.8</td>
<td>⊥</td>
</tr>
</tbody>
</table>
Micro Satellites

• **Target satellites**
  - Cube-shaped, with 6 Carbon Fiber Reinforced Plastic (CFRP) outer walls and 3 Glass Fiber Reinforced Plastic (GFRP) boards inside
    - Direction of CFRP fiber: \((0^\circ, 90^\circ)\)
    - Thickness of the front and back CFRP walls: 2 mm
    - Thickness of other CFRP and GFRP walls: 1 mm
  - Components: lithium-ion batteries, transmitter, solar cells, power circuit board, communication circuit board, on board computer, antenna
Ground-based Impact Experiments
Impact Fragmentation

- Target: Micro satellite covered with Multi-Layer Insulation (MLI) a solar panel on one side
  - Objective: characterize satellite, MLI, and solar panel fragments
# Sample Measurement Data

<table>
<thead>
<tr>
<th>No</th>
<th>Characteristic</th>
<th>Label</th>
<th>Shape</th>
<th>x[m]</th>
<th>y[m]</th>
<th>z[m]</th>
<th>M[kg]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>CFRP+Aluminum</td>
<td>Medium</td>
<td>Plate_Square</td>
<td>0.28284</td>
<td>0.28284</td>
<td>0.03031</td>
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<td>0.00167</td>
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<tr>
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<td>0.03335</td>
<td>0.02576</td>
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# Upcoming Ground-based Impact Test

• A collaboration of NASA ODPO, AF/SMC, and University of Florida

<table>
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<tr>
<th></th>
<th>SOCIT</th>
<th>Proposed Test</th>
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<tbody>
<tr>
<td>Target dimensions</td>
<td>46 cm (dia) × 30 cm (ht)</td>
<td>50 cm</td>
</tr>
<tr>
<td>Target mass</td>
<td>34.5 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td>MLI and solar panel</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Projectile material</td>
<td>Al sphere</td>
<td>Al sphere</td>
</tr>
<tr>
<td>Projectile dimensions/mass</td>
<td>4.7 cm diameter, 150 g</td>
<td>5 cm diameter, 176 g</td>
</tr>
<tr>
<td>Impact speed</td>
<td>6.075 km/sec</td>
<td>7 km/sec</td>
</tr>
</tbody>
</table>
| Impact Energy to Target Mass ratio (EMR) | 78 J/g                       | 86 J/g
Questions?