Orbital Debris Modeling

J.-C. Liou, PhD
NASA Orbital Debris Program Office
Johnson Space Center, Houston, Texas

Canadian Space Agency
St Hubert, Quebec, Canada, 28 March 2012
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 ($5^\circ \times 5^\circ \times 50$ km) with spatial density and velocity distributions of debris of 6 different sizes.
ORDEM2000 Graphical User Interface (GUI)

- Telescope Assessment
- Spacecraft Assessment

Messages:
choose either telescope or spacecraft buttons

Graphical User Interface (GUI)

Display of Average Flux vs. Size for Spacecraft

AVERAGE CROSS SECTIONAL FLUX VS. SIZE

Graph showing average cross sectional flux vs. size with a graph of cumulative cross section vs. diameter.

Spacecraft Input

- Orbit: Apogee: 522.000000 km, Perigee: 522.000000 km
- Inclination: 61.8 (0 to 180 deg)
- Year of Observation: 2000

Messages:
enter values into fields then press the compute button

Graph showing the spatial density of particles with size categories.
• **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)**
National Aeronautics and Space Administration

ORDEM 3.0 GUI Interface

Notional Data – Not Yet Certified

The NASA Orbital Debris Program Office at Johnson Space Center has developed this computer-based orbital debris engineering model, ORDEM. This model describes the orbital debris environment in the Earth orbit region between 100 and 40,000 km altitude. The model is appropriate for those engineering solutions requiring knowledge and estimates of the orbital debris environment (debris spatial density, flux, etc.). ORDEM can also be used as a benchmark for ground-based debris measurements and observations. www.orbitaldebris.nasa.gov
Sample ORDEM 3.0 Model Output

2-D Directional Flux
Year: 2000  a = 6773.136  e = 0.000000  inc = 90.00  particle size = >10um

Velocity Distribution
Year: 2000  a = 12644.786  e = 0.042179  inc = 80.00  particle size = >10um

Notional Data – Not Yet Certified
Iode (lat,az,el)=(42,90,75)
Year = 2006

Flux vs. Yaw Angle
Year: 2000  a = 12644.786  e = 0.042179  inc = 80.00  particle size = >10um

Range (km)
>10um >100um >1mm >1cm >10cm >1m

Flux (#/m²/yr)
1E-10 1E-08 0.0001 0.000001

100 300 500 700 900 1100 1300 1500 1700 1900

10/43
<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>
</tbody>
</table>
| Altitude range with minimum debris size       | 200 to 2000 km (>10 \(\mu\)m) | 100 to 2000 km(>10 \(\mu\)m)  
2000 to 33,000 (>1 cm)  
33,000 to 40,000 km (>10 cm) |
| Model population breakdown                    | No                         | Intacts and mission related debris  
Fragments  
RORSAT NaK coolant droplets  
Degradation/ejecta |
| Material density breakdown                    | No                         | Low-density(<2 g/cm\(^3\)) : fragments  
Medium-density(2-6 g/cm\(^3\)) : fragments, degrad/ejecta  
High-density(>6 g/cm\(^3\)) : fragments, degrad/ejecta  
RORSAT NaK coolant droplets (0.9 g/cm\(^3\)) |
| Model cumulative size thresholds              | 10 \(\mu\)m, 100 \(\mu\)m, 1 mm,  
1 cm , 10 cm, 1 m | 10 \(\mu\)m, 31.6 \(\mu\)m, 100 \(\mu\)m, 316 \(\mu\)m, 1 mm, 3.16 mm,  
1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m |
| Population uncertainties                      | No                         | Yes                        |
| File size                                     | 16 MB                      | 1.4 GB                     |
| Run time                                      | Seconds                    | Minutes to hours            |
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 \( \geq 10 \) 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_{cum}, A/M, A_\Delta, \Delta V distributions

Generate breakup clouds

Generate element arrays

\[ t_{i+1} = t_i + \Delta t \]

L400
Add in NaK, SRM, etc.

N_{cum}, A/M, A_\Delta, \Delta V distributions

Generate element arrays

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? yes

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

no

stop

(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

L600
Generate breakup fragments

L500
Generate element arrays

Constellations, special satellites, etc.

breakup yes

breakup no

Generate element arrays

L200
Existing fragments

Postmission disposal or removal

breakup yes

breakup no

Generate element arrays

\[ t_{i+1} = t_i + \Delta t \text{ (5 days)} \]

Propagate to the end of the time step

End-of-year output

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

• Debris distributions (1-D, 2-D, 3-D)
• Element arrays, etc.
• **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
LEGEND Supporting Models (2/4)

- **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
NASA Breakup Model for Explosions

- 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

\[ N_{\text{cum}} = sf \times 6 \times L_c^{-1.6} \]

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

- 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

Cumulative Number vs. Characteristic Size (m)

Characteristic Size (m): 0.01 to 10
Cumulative Number: 1 to 1000
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)
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>
</tr>
</thead>
<tbody>
<tr>
<td>0501H</td>
<td>15</td>
<td>740</td>
<td>4.03 / 1.4</td>
<td>4.44</td>
<td>53.7</td>
<td>⊥</td>
</tr>
<tr>
<td>0502L</td>
<td>15</td>
<td>740</td>
<td>39.2 / 3.0</td>
<td>1.45</td>
<td>55.7</td>
<td>⊥</td>
</tr>
<tr>
<td>0701L</td>
<td>20</td>
<td>1300</td>
<td>39.2 / 3.0</td>
<td>1.66</td>
<td>41.5</td>
<td>⊥</td>
</tr>
<tr>
<td>0702L</td>
<td>20</td>
<td>1283</td>
<td>39.2 / 3.0</td>
<td>1.66</td>
<td>42.0</td>
<td>//</td>
</tr>
<tr>
<td>0703L</td>
<td>20</td>
<td>1285</td>
<td>39.2 / 3.0</td>
<td>1.72</td>
<td>45.1</td>
<td>⊥</td>
</tr>
<tr>
<td>0801F</td>
<td>20</td>
<td>1515</td>
<td>39.2 / 3.0</td>
<td>1.74</td>
<td>39.2</td>
<td>⊥</td>
</tr>
<tr>
<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°, 90°)
    - 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
<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>
</tr>
</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>
<td>2.014E-01</td>
</tr>
<tr>
<td>2</td>
<td>CFRP+Aluminum</td>
<td>Medium</td>
<td>Plate_Square</td>
<td>0.28284</td>
<td>0.28284</td>
<td>0.02186</td>
<td>8.873E-02</td>
</tr>
<tr>
<td>3</td>
<td>CFRP</td>
<td>Low</td>
<td>Plate_Square</td>
<td>0.28284</td>
<td>0.28284</td>
<td>0.00167</td>
<td>6.263E-02</td>
</tr>
<tr>
<td>4</td>
<td>CFRP+Aluminum</td>
<td>Medium</td>
<td>Plate_Square</td>
<td>0.28284</td>
<td>0.28284</td>
<td>0.06762</td>
<td>7.567E-02</td>
</tr>
<tr>
<td>5</td>
<td>GFRP+Metal</td>
<td>Medium</td>
<td>Plate_Square</td>
<td>0.28230</td>
<td>0.19110</td>
<td>0.08777</td>
<td>5.075E-02</td>
</tr>
<tr>
<td>6</td>
<td>CFRP+Aluminum+Metal</td>
<td>Medium</td>
<td>Cube_Complex_Oblong</td>
<td>0.34520</td>
<td>0.14032</td>
<td>0.05755</td>
<td>6.910E-02</td>
</tr>
<tr>
<td>7</td>
<td>CFRP</td>
<td>Low</td>
<td>Plate_Square</td>
<td>0.14846</td>
<td>0.13875</td>
<td>0.02689</td>
<td>2.192E-02</td>
</tr>
<tr>
<td>8</td>
<td>CFRP</td>
<td>Low</td>
<td>Plate_Square</td>
<td>0.14953</td>
<td>0.14678</td>
<td>0.01391</td>
<td>1.668E-02</td>
</tr>
<tr>
<td>9</td>
<td>CFRP</td>
<td>Low</td>
<td>Plate_Oblong</td>
<td>0.20080</td>
<td>0.02619</td>
<td>0.00406</td>
<td>1.234E-03</td>
</tr>
<tr>
<td>10</td>
<td>Aluminum</td>
<td>Medium</td>
<td>Cube_Complex_Oblong</td>
<td>0.15790</td>
<td>0.03335</td>
<td>0.02576</td>
<td>1.464E-02</td>
</tr>
</tbody>
</table>
Upcoming Ground-based Impact Test

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

<table>
<thead>
<tr>
<th></th>
<th>SOCIT</th>
<th>Proposed Test</th>
</tr>
</thead>
<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>
<tr>
<td>Impact Energy to Target Mass ratio (EMR)</td>
<td>78 J/g</td>
<td>86 J/g</td>
</tr>
</tbody>
</table>
Questions?