Modeling of the Orbital Debris Environment Risks in the Past, Present, and Future

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Orbital Debris Types

- **Intact objects, > 1 m**
  - Old rocket bodies
  - Spacecraft
  - “Operational” debris – shrouds, mounts, lens caps, etc

- **Fragmentation debris, 1 mm – 1 m**
  - Deliberate or accidental explosions from on-board energy sources
    - Unvented rocket fuel
    - Active batteries
    - Self-destruct mechanisms
  - Deliberate or accidental collisions
    - Weapons tests
    - Random collisions
  - Solid rocket motor slag

- **Degradation debris, < 1 mm**
  - Deterioration of satellite surfaces in space environment
    - Micrometeoroid and small debris impact ejecta
    - Paint deterioration in harsh space environment
Modeling

- NASA and the U.S. Dept. of Defense dedicate a tremendous amount of resources to measuring and monitoring the debris environment, but measurements do not always provide all the information we need
  - Radars provide radar cross section (RCS), not size, material, shape, or mass
  - Similarly, optical telescopes provide brightness of reflected sunlight
  - NASA uses a number of telescopes and radars to statistically sample only a subset of the environment
    - Statistical sampling is the only way to measure objects <10 cm too small to track
  - No matter how good or complete are our measurements, the orbital debris environment is dynamic. We cannot know with certainty what the environment will look like in the future

- The solution to these limitations is modeling
  - Modeling is the use of mathematical and compute tools to use the incomplete data we do have and determine the information we truly need
LEGEND

• One of NASA’s “workhorse” models is LEGEND

• 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 (R/Bs and S/C), mission-related debris (payload fairings, 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
  – Uses a deterministic approach to “recreate” the historical debris environment based on recorded launches and breakups
  – Uses a Monte Carlo approach and a pair-wise collision probability evaluation algorithm to simulate future collision activities
  – Analyzes future debris environment based on user-specified launch traffic, post-mission disposal, and active debris removal options
LEGEND Supporting Models

• **LEGEND actually ties in many NASA models to do its calculations**

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

• **U.S. Space Surveillance Network (SSN) catalogs**
  - Daily records of the historical growth of the ≥10 cm debris population
  - Orbit histories are used to derive empirical area-to-mass ratio (A/M) distributions of 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

- **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 24 (1944 – present)
    - Similar to projections developed for long-term debris evolutionary models by other space agencies (ASI, UKSA, etc.)
LEGEND Supporting Models

- **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 tesserral \((J_{2,2}, J_{3,1}, J_{3,3}, J_{4,2}, \text{ and } J_{4,4})\) 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 reasonably well with the evolution of the SSN cataloged objects
LEGEND Supporting Models

- 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

![Graph showing cumulative number of fragments vs. characteristic size](image)
Breakup Model

• NASA’s Breakup Model can be used to simulate the evolution of individual breakups

• On August 6, 2012, the Russians attempted to launch two communications satellites using a Proton rocket

• The BRIZ-M upper stage failed to burn properly, and was left stranded in an elliptical orbit with about 5 metric tons of its propellant still aboard

• On October 16, the rocket body exploded, creating at least 700 trackable pieces of debris (and probably many more too small to be tracked) in orbits that cross ISS altitude

• Observed by astronomers at the Siding Springs Observatory
BRIZ-M Explosion
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)
Mass Accumulation in Orbit – Based on DBS

Monthly Mass of Objects in Earth Orbit by Object Type

- **Total Objects**
- **Spacecraft**
- **Rocket Bodies**
- **Fragmentation Debris**
- **Mission-related Debris**
Sample LEGEND Output – Collisions in LEO

LEGEND Projections (averages from 100 MC runs)

- Reg Launches, No PMD
- Reg Launches + 90% PMD
- No Future Launches
- Historical Data (excl. Cerise)
Growth with no future launches
Kessler Syndrome

Effective Number of Objects (>10cm, LEO)

- Total
- Intacts + mission related debris
- Explosion fragments
- Collision fragments
"Well, I'll be ... I guess the little chicken was right."
Gravity
Gravity
Fix the Problem? – Remove Mass

LEO Environment Projection (averages of 100 LEGEND MC runs)

- Red: Reg Launches + 90% PMD
- Blue: Reg Launches + 90% PMD + ADR2020/02
- Green: Reg Launches + 90% PMD + ADR2020/05

Effective Number of Objects (>10 cm)

Year

(Liou, Adv. Space Res, 2011)
Active Debris Removal Cartoon, 1965 (!)
• An Engineering Model is a tool (primarily) for spacecraft designers and users to understand the long-term risks of debris collisions with their spacecraft

• NASA’s Orbital Debris Engineering Model ORDEM 3.0 represents NASA’s best estimate of the current and near future orbital debris environment.
  – The environment is dynamic and must be updated periodically

• ORDEM 3.0 has significant new capabilities over past ORDEM models
  – Uncertainties
  – Material density categories
  – Model extended to GEO
  – Can easily calculate flux for satellites in highly elliptical orbit
# ORDEM 3.0 vs. ORDEM2000

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORDEM2000</th>
<th>ORDEM 3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft &amp; 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) (LEO)</td>
<td>200 to 38,000 km (&gt;10 μm) (LEO to GTO) 34,000 to 38,000 km (&gt;10 cm) (GEO)</td>
</tr>
<tr>
<td>Orbit types</td>
<td>Circular (radial velocity ignored)</td>
<td>Circular to highly elliptical</td>
</tr>
<tr>
<td>Model populations divided by type &amp; material density</td>
<td>No</td>
<td>Intacts Low-density (&lt;2 g/cc) – e.g., plastic Medium-density (2-6 g/cc) – e.g., aluminum High-density (&gt;6 g/cc) – e.g., steel RORSAT NaK coolant droplets (0.9 g/cc)</td>
</tr>
<tr>
<td>Special model populations</td>
<td>No</td>
<td>Yes (ASAT, Iridium/Cosmos, Snapshot, Transit)</td>
</tr>
<tr>
<td>Model cumulative size thresholds (<em>fiducial points</em>)</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>
</tr>
<tr>
<td>Flux uncertainties</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Meteoroids</td>
<td>No</td>
<td>No*</td>
</tr>
</tbody>
</table>

* a separate meteoroid environment model (MEM) is available from NASA's Meteoroid Environment Office
ORDEM Process
Creating the Current Environment

• Initial environment created by using database of known space activity and tools such as the NASA Standard Breakup Model (to model breakup clouds) & PROP3D (to model long-term orbit evolution)

• Environment-dominating events such as the Chinese ASAT (~850 km) and the Iridium/COSMOS collision (~775 km) were modeled separately as were a few unique non-breakup populations

• Debris material densities
  – For sub-mm debris - determined from analysis of residue in impact features from returned spacecraft surfaces (specifically, Shuttle windows and radiators)
  – For larger debris - directly measured from ground impact tests

• Maximum Likelihood Estimator used to empirically fit the environment to measurement data, creating a final “Current” debris environment
  – This resulted in adjusting model populations to fit data using size-dependent “weighting factors”
  – Size-dependent weighting factors derived from these data-fitting processes are used to project into the future
  – Uncertainties computed using Bayesian and other techniques
February 10, 16:56 GMT two satellites collided near 789 km altitude

**Iridium 33 (24946, 97051C)**
- 779 x 808 km, 86.4° orbit, 556 kg
- Operational US Commercial Communication Satellite

**Kosmos 2251 (22675, 93036A)**
- 786 x 826 km, 74.0° orbit, 900 kg
- Non-operational Russian Communication Satellite
2009 Collision
2009 Collision
Shuttle *In Situ* Data

- Facesheet hole ($d_{\text{max}}$)
- Facesheet hole ($d_{\text{min}}$)

- Conchoidal spell
- Central pit defined by densely packed crushed glass
- Large, shallow crater (roughly circular in this example)
- Outer limits of larger crater and impact event influence
### ORDEM 3.0 Datasets and Supporting Models

<table>
<thead>
<tr>
<th>Observational Data</th>
<th>Role</th>
<th>Region/Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSN catalog (radars, telescopes)</td>
<td>Intacts &amp; large fragments</td>
<td>LEO &gt; 10 cm, GEO &gt; 70 cm</td>
</tr>
<tr>
<td>HAX (radar)</td>
<td>Statistical populations</td>
<td>LEO &gt; 3 cm</td>
</tr>
<tr>
<td>Haystack (radar)</td>
<td>Statistical populations</td>
<td>LEO &gt; 5.5 mm</td>
</tr>
<tr>
<td>Goldstone (radar)</td>
<td>Statistical populations</td>
<td>LEO &gt; 3 mm</td>
</tr>
<tr>
<td>STS windows &amp; radiators (returned surfaces)</td>
<td>Statistical populations</td>
<td>10 μm &lt;LEO ≤ 1 mm</td>
</tr>
<tr>
<td>MODEST (telescope)</td>
<td>GEO data set</td>
<td>GEO &gt; 30 cm</td>
</tr>
</tbody>
</table>

- Note that the US Space Shuttle is no longer an active data source.
STS Radiator Data

Shuttle Radiator Hole Data
STS-71 - STS-133 (except STS-75 and STS-100)
1995-2011

Filled points are impactors identified by chemistry
Hollow points are "Unknowns" with impactor size estimated using MD density

Cumulative Number

Estimated Particle Size [mm]
STS Radiator Data

Shuttle Radiator Hole Data
STS-71 - STS-133 (except STS-75 and STS-100)
1995-2011
Data and Size Regimes

- Small particle populations are fit separately from large particle populations
ORDEM
Projecting Into the Future – Debris > 3 mm

- LEGEND used to propagate the “Current” environment into the future
- Populations empirically adjusted to match radar and optical measurement data, then propagated in the future
- Launch rate, solar activity, and explosion rate are independent inputs into the model
- 120 Monte Carlo future environments are created
  - Future collisions simulated stochastically
- Reported future environment is the average of the 120 possible future environments, “spread” of possible futures preserved as population uncertainties
• LEGEND used to characterize the population of intact objects in the future as source objects for small debris

• The surface degradation model “creates” particles with zero delta-velocity at different sizes and material types proportional to the area of the parent body

• These debris are propagated under solar radiation pressure and atmospheric drag to compute flux on in situ surfaces

• Damage equations (based on empirical tests) are used to “predict” distribution in feature size (e.g., crater diameter) on the in situ surface using reference debris population

• Production rates at the parent bodies adjusted to match empirical data, and rates projected into the future
Average Cross-Sectional Flux vs. Size

Year: 2013  Perigee Altitude = 400.000  Apogee Altitude = 400.000  inc = 51.60
Material Distributions - ISS

ORDEM Populations for 2013 ISS Flux as a Function of Debris Size

- ORDEM 3.0 LD Population
- ORDEM 3.0 MD Population
- ORDEM 3.0 HD Population
- ORDEM 3.0 Total Population
- ORDEM 2000
ORDEM Flux for A-Train 705km

Average Cross-Sectional Flux vs. Size

Year: 2013  Perigee Altitude = 705.000  Apogee Altitude = 705.000  Inc = 98.00

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Debris Flux (#/m²-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$1 \times 10^{-3}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$1 \times 10^{-2}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$1 \times 10^{-1}$</td>
<td>$1 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Flux

±1σ Error
Material Distribution – A-Train

ORDEM Populations for 2013 98° 705 km Orbit Flux as a Function of Debris Size

- ORDEM 3.0 LD Population
- ORDEM 3.0 MD Population
- ORDEM 3.0 HD Population
- ORDEM 3.0 Total Population
- ORDEM 2000

Flux [m²·yr⁻¹]

Debris Size [m]
2-D Directional Flux

Year: 2013  Perigee Altitude = 400.000  Apogee Altitude = 400.000  inc = 51.60  particle size = >1mm

Local Elevation (deg)

Local Azimuth (deg)

7/23/2013 5:06:05 PM

10^-12 to 10^-4
ORDEM 3.0 Outputs
BUMPERS
NASA/JSC BUMPERS-II Meteoroid/Debris Threat Assessment Code

Spacecraft Configuration (l-DEAS Finite Element Model)
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions
- Approximately 120,000 elements in ISS assembly complete mated configuration FEM

Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing
- 90 debris threat cases and 149 meteoroid threat cases assessed for each element in the FEM

Critical Particle Diameter Calculation (RESPONSE)
- Protection capability

Computation of Penetrating Flux and PNP (SHIELD)
Graphical Interpretation of Results (EXCEL & l-DEAS)

<table>
<thead>
<tr>
<th>Station Region</th>
<th>Impact Risk From Local Debris</th>
<th>Probability of No Impact</th>
<th>Odds of Impact</th>
<th>Probability of No Penetration</th>
<th>Odds of Penetration</th>
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</thead>
<tbody>
<tr>
<td>ISS</td>
<td>0.986939</td>
<td>1.9/14</td>
<td>0.998951</td>
<td>1/148</td>
<td>0.998951</td>
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<tr>
<td>Service Module</td>
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<td>0.998951</td>
<td>1/148</td>
<td>0.998951</td>
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<tr>
<td>Node 2</td>
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<td>Lab Module</td>
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<td>CNV</td>
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<td>0.998951</td>
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<tr>
<td>TOTALS</td>
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<td>1/115</td>
<td>0.998951</td>
<td>1/148</td>
<td>0.998951</td>
</tr>
</tbody>
</table>

Whipple Shield Ballistic Limit
(failure above lines)

0.00  0.25  0.50  0.75  1.00

critical aluminum dia. (cm)

0.0  3  6  9  12  15

velocity (km/sec)
Questions?