Modeling the Space Debris Environment with MASTER-2009 and ORDEM2010

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Outline

- ESA MASTER-2009 Population Generation
  (Meteoroid and Space Debris Terrestrial Environment Reference)

- NASA ORDEM2010 Population Generation
  (Orbital Debris Engineering Model)

- (Software Feature Comparison)
Object Data Acquisition & Processing
- Data for tracked objects is collected from multiple sources & brought into unified format

Simulation & Data Fusion
- All debris sources are simulated
- Simulation results are fused with data for tracked objects

Population Validation
- Large objects > ~10 cm: comparison of real and simulated measurement campaigns (PROOF)
- Small objects < ~1 mm: comparison of real and simulated impact craters (MASTER)
Acquisition of object bulk:

*Input:* Two-Line Elements (USSTRATCOM)
*Acquired data:* single mean orbit parameters
*Output:* Quarterly orbit snapshots between 1957 and 2009

Additional objects:

*Input:* Satellite Catalog (Jonathan McDowell)
*Acquired data:* Objects not included with TLE data
*Output:* Extended quarterly orbit snapshots

Object properties:

*Input:* Database and Information System Characterising Objects in Space (ESA: DISCOS) & Satellite Situation Report (USSTRATCOM)
*Acquired data:* Object size, mass and mass-to-area ratio
*Output:* Quarterly population snapshots subdivided into fragments & launch- and mission related objects (payloads, rocket bodies and mission debris)
**POEM (Program for Orbital Debris Environment Modeling)**

- Compendium of individual debris models for each source

**List based debris sources:**
- Individual events are simulated
- List data includes e.g.: event epoch, orbit location, event magnitude

**Continuous debris sources:**
- All LMRO are analysed wrt. paint flakes, delaminated MLI and ejecta which they would have produced
**MASTER-2009**

**Large Object Validation**

- Detection campaigns offer information on the number of objects, RCS or magnitude and orbit properties
- **PROOF** (ESA **Program for Radar and Optical Observation Forecasting**) applies filters for:
  - geometry (e.g. field of view, viewing direction)
  - performance (e.g. radar: wavelength, power; optical: CCD type, integration time)

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**Validation of amount of debris**

![Graph showing detection rate vs. altitude](image)

**Validation of orbit distribution**

![Graph showing inclination vs. RAAN](image)
MASTER-2009
Small Object Validation

- Impact craters offer information on the impactor size/impact velocity, impact direction and total number of objects
- MASTER applies filters for e.g.:
  - target orbit evolution/maneuvers
  - rotation of target orbit line of apsides and line of nodes
  - target surface orientation
  - damage equations

**Small object validation schematic**

- Real population
- Simulated population

- Real Impact craters
- Simulated Impact craters

**Simulating mission parameters**

**Validation of impact fluence**
The Orbital Debris Engineering Model, ORDEM2010, includes:

- High-fidelity population file structure of the yearly debris populations from 1995 - 2035
  - Sizes 10 µm - 1 m (LEO - GTO); sizes 10 cm - 1 m (GEO)
  - Stable orbital elements (i.e., those that do not randomize on a sub-year timescale)
    - LEO – GTO \( \rightarrow \) Hp, Ecc, Inc ; GEO \( \rightarrow \) MM, ECC, Inc, RAAN
  - Debris material density

- High-fidelity spacecraft analysis program compares the populations with a spacecraft-encompassing ‘igloo’ to achieve a 3-D output of flux on the spacecraft

- Advanced graphical user interface (GUI) allows visualization of spacecraft flux in 2-D and 1-D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORDEM2010</th>
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</thead>
<tbody>
<tr>
<td>Spacecraft and Telescope/Radar analysis modes</td>
<td>YES</td>
</tr>
<tr>
<td>Time range</td>
<td>1995 to 2035</td>
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<tr>
<td>Altitude range with minimum debris size</td>
<td>200 to 34,000 km (&gt;10 µm)* ; 34,000 to 38,000 km (&gt;10 cm)</td>
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<tr>
<td>Model population breakdown</td>
<td>Intacts, Low-density fragments ; Medium-density fragments and degradation/ejecta ; High-density fragments and degradation/ejecta ; RORSAT NaK coolant droplets</td>
</tr>
<tr>
<td>Population material density breakdown</td>
<td>Low-density (&lt;2 g/cc) ; Medium-density (2-6 g/cc) ; High-density (&gt;6 g/cc) ; RORSAT NaK coolant (0.9 g/cc)</td>
</tr>
<tr>
<td>Population cumulative size thresholds</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 extension</td>
<td>Bayesian statistics with ODPO models</td>
</tr>
<tr>
<td>Model S/C flux analysis method</td>
<td>Igloo surrounding S/C</td>
</tr>
<tr>
<td>Model T/R flux analysis method</td>
<td>Segments along line-of-sight</td>
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</table>
ORDEM2010
Population Generation Process

- Bayesian statistical approach to debris population analysis
  - Ten additional years of data including,
    - Catalog datasets → SSN
    - Statistical datasets → Haystack, HAX radars
    - Individual event datasets → FY-1C anti-satellite test, Iridium 33/Cosmos 2251 from SSN radar observation
  - NASA Orbital debris Program Office (ODPO) models used as prior conditions
    - LEGEND 3-D debris long-term environment model replaces the 1-D EVOLVE
    - NaK Module for RORSAT sodium potassium droplets
    - Degradation/Ejecta (D/E) for sub-millimeter particles

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<tr>
<th>Model</th>
<th>Usage</th>
<th>Corroborative Data</th>
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<tr>
<td>LEGEND</td>
<td>LEO Fragments &gt; 1mm ; GEO Fragments &gt; 10cm</td>
<td>Haystack, HAX, SSN ; MODEST</td>
</tr>
<tr>
<td>NaK Module</td>
<td>NaK droplets &gt; 1 mm</td>
<td>Haystack</td>
</tr>
<tr>
<td>Degradation/ejecta model</td>
<td>1mm &gt; Degradation/ejecta &gt; 10µm</td>
<td>STS windows &amp; radiators</td>
</tr>
</tbody>
</table>
Large object (>1mm) validation is ongoing.

Small object (<1mm) validation

- A degradation/ejecta source model is constructed to provide the desired reference populations for the micro-debris population derivations.
- Catalog (>10 cm) objects are taken as parent bodies of the small micron-sized particles.
  - Number of micro-debris objects created by a surface degradation process is proportional to the surface area of a parent body.
  - Micro-debris objects created in a surface degradation process share the same orbit with its parent body at the creation time. Every orbit of the degradation/ejecta particles is propagated independently under the influence of solar radiation pressure and atmospheric drag, in addition to gravitational perturbations.

- The production rates of micro-debris are honed to be compatible with data.
Window and radiator impact data from 38 STS missions. Window data is identified by the metric crater depth, radiator data by metric tape-hole diameter.

Impactor are identified by material density when available. MD = medium density (aluminum, paint). HD = high density (steel)
Degradation/ejecta model medium density population is adjusted to both window data and radiator data simultaneously.

Detailed presentation, ‘Simulation of Micron-Sized Debris Populations in Low Earth Orbit’ will be given later at this conference, by Dr. Yu-Lin Xu.
ORDEM2010
Spacecraft Analysis Program

- ORDEM2010 spacecraft encounters debris flux via a spacecraft-encompassing 3-D igloo
  - Population flux is tested for each igloo element in an igloo coordinate system of debris size, velocity, azimuth, and elevation with respect to spacecraft ram direction
  - Flux is summed within an element, all element fluxes are summed together for the total yearly spacecraft encounter
  - Highest fidelity igloo presently in ORDEM2010 is \(10^\circ\times10^\circ\times1\text{km/s (Az x EL x Vel)}\)
ORDEM2010
Graphical User Interface (GUI)

- This directional debris flux calculation is supported by an updated graphical user interface (GUI) package designed for ORDEM2010 that includes a 2-D directional flux chart (a.k.a. Mollweide projection, pseudo-cylindrical equal-area map projection used for global or sky maps).

- Spacecraft velocity vector (ram direction) is defined by the azimuth, elevation coordinates (0°,0°).
- Anti-ram is defined where (180°,0°) and (-180°,0°) meet.
- Zenith is defined at (0°,90°), and nadir at (0°,-90°).
ORDEM2010 GUI Example

ISS ORDEM2010 GUI Outputs for Debris larger than 10 µm (Inc=51.63°, Hp=Ha= 400 km, yr=2010)
Summary

• Spacecraft analysis using ORDEM2010 uses a high-fidelity population model to compute risk to on-orbit assets
• The ORDEM2010 GUI allows visualization of spacecraft flux in 2-D and 1-D
• The population was produced using a Bayesian statistical approach with measured and modeled environment data
• Validation of sizes < 1mm were performed using Shuttle window and radiator impact measurements
• Validation of sizes > 1mm is on-going
Backup Slide
MASTER-2009
Population Generation Process

Simulated Campaign

Validation of LARGE Objects

Validation of small objects

Deterministic

Probabilistic

POEM

TLE

User Interface

FLUX BROWSER

PROOF

PROOF 2009

PROBDENS

Population

2D spatial density distribution vs latitude (ESA MASTER-2009 Model)