AutoORSAT Parametric Studies: a Step Toward Incorporating Uncertainty into Reentry Simulation

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Introduction

• **ORSAT**: Object oriented approach to reentry casualty risk
  – Spacecraft is modeled as a collection of nested shape primitives
  – Each object is released and begins aerodynamic heating when its container fully demises

• **AutoORSAT**: Python wrapper for ORSAT to extend object nesting and parametric study functionality
  – Allows arbitrary number of nesting levels
  – Parametric study of an arbitrary number of variations in an arbitrary number of input variables
  – Output to CSV files and to a SQLite3 database file for simple cross-referencing of variables
Questions

• How much is demisability affected by (realistic) initial conditions?
• How much does the change in demisability realistically affect the total Debris Casualty Area (DCA) and Expectation of Casualty ($E_c$)?
• Which initial conditions affect the DCA and $E_c$ the most?
• How best to interpret a Monte Carlo analysis of the range of realistic entry conditions?
Parameter Space Study

REPRESENTATIVE COMPONENTS
Parameter Space

• Each spacecraft component can have up to 65 independent parameters
  – Geometry
  – Initial trajectory
  – Materials
  – Computation model flags

• To study the effect of $n$ variations in all parameters of $m$ components of a spacecraft requires $m \times 65^n$ separate ORSAT runs

• Some of these variables have a greater impact on the demise of a given component than others
Parameter Space Study

• **Design limited parameter space study to relative influence of parameters**
  – Restrict inputs to realistic values
  – Components represent typical components of a spacecraft
  – Measure outcome as Demise/Survive Only/Survive with Casualty

• **Parameters Studied**
  – Initial trajectory
  – Shape
  – Dimensions
  – Mass
Realistic Initial Trajectory

- **Assumptions:**
  - Spacecraft starts at a 300 km circular orbit
  - A random reentry could occur at any RAAN, at any time of year, and will be uniformly distributed along the mean anomaly

- **Use the NASA General Mission Analysis Tool (GMAT) to simulate trajectories from 300 km altitude to the standard ORSAT 122 km entry altitude**
  - Uniform distribution of initial RAAN
  - Uniform distribution of entry day of year
  - Uniform distribution of entry argument of latitude

- **Use the final trajectory at 122 km as the ORSAT input trajectory**

- **Generate entry trajectories for**
  - 10 orbit inclinations between 10° and 100°
  - 2 spacecraft ballistic numbers: 50 kg/m² and 150 kg/m²
Components

- **Screws**
  - M6 and M8 size
  - 15 mm to 40 mm long
  - Aluminum, Steel, and Titanium

- **Magnetorquers**
  - Copper windings
  - Iron cores

- **Structural Panels**
  - 1 m and 0.5 m square
  - Aluminum and Steel

- **Spherical Tanks**
  - 0.2, 0.5, and 1 m
  - 5 mm – 25 mm thick
  - Aluminum, Steel, Titanium, Carbon Overwrapped Titanium

- **PCBs**
  - Fiberglass
  - 3 mm thick
  - 25, 50, and 100 mm square
## Unchanged Outcomes

<table>
<thead>
<tr>
<th>Always Demised</th>
<th>Always Survived</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 25 mm and 50 mm PCB</td>
<td>• Steel structural panels</td>
</tr>
<tr>
<td>• All magnetorquer copper windings</td>
<td>• 1 m titanium spherical tank</td>
</tr>
<tr>
<td>• M8 aluminum screws</td>
<td>• 1 m carbon overwrapped titanium tank</td>
</tr>
<tr>
<td>• 15 mm and 25 mm long M8 steel screws</td>
<td></td>
</tr>
<tr>
<td>• 25 mm long M8 titanium screws</td>
<td></td>
</tr>
</tbody>
</table>
Marginal Outcomes

Iron Rod

Titanium Screw (approx. M8x40)

Spherical Tank (0.2 m) (Titanium)

Spherical Tank (0.2 m) (Aluminum)
Marginal Outcomes
Parameter Space Study

REPRESENTATIVE SPACECRAFT
Representative Spacecraft

• Hypothetical 2100 kg Spacecraft
  – Carbon fiber solar array substrate
  – Aluminum structural panels
  – Magnetorquer, reaction wheels
  – Propulsion system & tank
  – Communication antennas
  – Telescope
  – 18650 Li-ion battery pack
  – Various sizes of printed circuit board

• Variation in demise altitude of parent spacecraft between 74 km and 82 km
Effect on DCA of Representative Spacecraft
Effect on DCA of Representative Spacecraft

Higher inclinations result in fewer surviving fragments.

- As few as 8 or 9 surviving fragments at over 80° inclination.
- Up to 23 surviving fragments at 20° inclination.

Higher inclinations result in fewer surviving fragments.
Effect on DCA of Representative Spacecraft

For any inclination, most likely result is between 8 and 12 unique surviving fragments.
Because many of the marginal fragments in this spacecraft have low quantities or don’t meet the casualty threshold, DCA is mostly concentrated between 12 $m^2$ and 15 $m^2$. 

Lines indicate DCA for a “Standard” ORSAT analysis at each inclination.
Effect on DCA of Representative Spacecraft

Lines indicate mean DCA at each inclination.
“Standard” ORSAT analysis:
- Altitude: 122 km
- FPA: -0.1°
- Breakup: 78 km

Standard ORSAT less conservative than mean

Usually aligns with highest-count bin
Effect on Expectation of Casualty ($E_c$)

Example Spacecraft, 60° Inclination

CDF
- Standard ORSAT
- Mean
- Median

% of Cases

$E_c$

1 in 10 million
1 in 6 billion
1 in 2 billion
1 in 8 billion
1 in 300 million
1 in 110 million
1 in 61 million
1 in 40 million
1 in 24 million
1 in 15 million
1 in 9 million
1 in 5 million
1 in 3 million
1 in 2 million
1 in 732 thousand
1 in 444 thousand
1 in 263 thousand
1 in 163 thousand
1 in 99 thousand
1 in 60 thousand
1 in 39 thousand
1 in 22 thousand
1 in 13 thousand
1 in 8 thousand
1 in 5 thousand
1 in 2 thousand
1 in 1 thousand
1 in 637
1 in 308
Effect on Expectation of Casualty ($E_c$)

$E_c$ is calculated based on the **actual latitude band** of each fragment impact, and so automatically takes into account latitudinal population variation.
Effect on Expectation of Casualty ($E_c$)

Example Spacecraft, 60° Inclination

Long tail on $E_c$ distribution
Effect on Expectation of Casualty ($E_c$)

Example Spacecraft, 60° Inclination

- CDF
- Standard ORSAT
- Mean
- Median

Standard ORSAT approximately tracks 50th percentile (true for all tested inclinations)

Long tail on $E_c$ distribution
Conclusions

• Demisability of many types of components not affected at all by even large changes in initial conditions
• Marginally demisable components can have a very large effect on the DCA of a spacecraft
• A relatively small parametric study can determine whether any of the components are marginal
• The vast majority of variability in DCA comes from
  – Release altitude of the component (unfortunately also the least well-known input)
  – Inclination of the orbit
• The vast majority of variability in \( E_c \) comes from variability in impact latitude
Future Work

• **Develop statistical model for**
  – Distribution of release altitudes
  – Distribution of initial entry trajectory

• **Implement true Monte-Carlo analysis in AutoORSAT**
  – Likely require fewer ORSAT runs to achieve representative results
  – Mean value of final DCA will be representative of likeliest DCA
BACKUP SLIDES
Steel Spherical Tanks (0.2 m - 1 m)
Example Spacecraft, 50° Inclination

- CDF
- Standard ORSAT
- Mean
- Median

% of Cases

$E_c$

1 in 251 million
1 in 170 million
1 in 115 million
1 in 52 million
1 in 24 million
1 in 11 million
1 in 5 million
1 in 2 million
1 in 1 million
1 in 624 thousand
1 in 364 thousand
1 in 214 thousand
1 in 144 thousand
1 in 97 thousand
1 in 69 thousand
1 in 44 thousand
1 in 30 thousand
1 in 20 thousand
1 in 14 thousand
1 in 9 thousand
1 in 6 thousand
1 in 4 thousand
1 in 2 thousand
1 in 1 thousand
1 in 873
1 in 590
1 in 308