COMPARISON of ORSAT and SCARAB Reentry Analysis Tools for a Generic Satellite Test Case

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ORSAT SCARAB Description

- **NASA ORSAT**
  - “Object-oriented” model
    - Reentering spacecraft are modeled as a set of simplified geometric shapes
      - Spheres
      - Cylinders
      - Boxes
      - Flat Plates
  - 3 degrees-of-freedom equations of motion
    - Stable attitude
    - No assumed lift
  - Aerodynamic and aerothermodynamic models based on shape, motion and Knudsen number dependent functions for drag and heating
  - Thermal analysis with a 1-D heat conduction model
  - Assumed break-up altitude of 78 km

- **ESA SCARAB**
  - “Spacecraft-oriented” model
    - Reentering spacecraft modeled as close to real geometry as possible using triangular panelized surfaces
  - 6 degrees-of-freedom equations of motion
    - Integration of attitude motion
  - Aerodynamic and aerothermodynamic models based on local panel methods
  - Thermal analysis with 2-D heat conduction model
  - Break-up model based on stress and structural integrity checks
Previous Comparisons

• **1998 – 1999 IADC**
  – Comparison of 1 meter diameter spheres
    • Materials consisted of Titanium, Aluminum, and Iron
  – Results were in good agreement

• **2002-2003 ROSAT**
  – Compared results for a complete, real spacecraft (~2400 kg mass)
    • Assumed uncontrolled, naturally decaying reentry
  – Showed significant difference in predicting surviving debris casualty area (DCA)
    • ORSAT DCA = 13.62 m²  • SCARAB DCA = 31.78 m²
  – Differences attributed to:
    • Different material properties
    • Different fragmentation processes
    • Differences in the simulation and assumptions of attitude dynamics

• **2004 -2005 4th European Conference on Space Debris**
  – Test Matrix of simple Geometries
    • Spheres  • Cylinders (L/D: 2 and 5)  • Boxes (L/W: 2 and 5)
  – 4 Materials; Aluminum, Titanium, and 2 types of Graphite Epoxy
  – Results were in good agreement
    • Deviation for surviving mass < 0.2%
Test Sat Design

- Joint Development between ORSAT Team at JSC and the SCARAB Team at HTG
  - 35 unique objects representing simplified models of typical satellite components
  - Approximately 400 kg mass
    - ORSAT – 391.641 kg
    - SCARAB – 401.531 kg
    - Difference +9.89 kg (+2.53% w.r.t. ORSAT mass)
    - Differences result from 3 primary effects
      - SCARAB requires all connection elements to be modeled
      - Material densities are slightly different
      - Masses in SCARAB are calculated based on the mass of the triangular panels each object is comprised of
  - Initial trajectory conditions
    - Altitude – 122 km
    - Velocity – 7.41 km/s
    - Inclination – 52°
    - Flight Path Angle – -0.1°
  - Environmental Conditions
    - Zonal Harmonics up to J4
    - Earth Flattening
      - Eccentricity of Earth = 0.08182
    - U.S. Standard 1976 Atmosphere
Modeling Results

• **ORSAT**
  – 21 Surviving components representing a mass of 47.22 kg (12.1%) \( \text{DCA} = 15.377 \text{ m}^2 \)
    • Debris footprint begins at 678 km (LH2 Tank) and ends at 849 km (Command Box)
      ➢ Footprint Length = 171 km

• **SCARAB**
  – 6 Surviving components representing a mass of 40.91 kg (10.19%) \( \text{DCA} = 4.428 \text{ m}^2 \)
    • Debris footprint begins at 744.53 km (LH2 Tank) and ends at 1013.1 km (Battery Box Contents)
      ➢ Footprint Length = 268.7 km

• **Differences**
  – Compared to SCARAB, ORSAT Predicts:
    • 15 more surviving objects
    • A DCA 10.949 m² higher
    • 6.31 kg more surviving mass
    • A Footprint 97.57 km shorter beginning 66.53 km sooner

• **Surviving fragments can be divided into 3 areas for study**
  1. Objects which survive in both codes
    • There are five of these objects; LH2 Tank and (4) RWA Flywheels
  2. Objects which only survive in one code
    • Command box survives only in ORSAT
  3. Objects which survive differently
    • The Battery Cells and Battery Box Frames survive in both codes, but in different ways
Modeling Results Comparison

- **Objects Surviving in Both Codes**

<table>
<thead>
<tr>
<th>Object</th>
<th>Surviving Mass (kg)</th>
<th>DCA (m²)</th>
<th>Downrange (km)</th>
<th>Surviving Mass (kg)</th>
<th>DCA (m²)</th>
<th>Downrange (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH2 Tank</td>
<td>10.000</td>
<td>1.088</td>
<td>678</td>
<td>9.958</td>
<td>1.088</td>
<td>744.53</td>
</tr>
</tbody>
</table>

- LH2 Tank
  - 0.5 m titanium spherical tank
  - Only significant difference is the downrange distance
    - ORSAT components decelerate faster due to kinetic energies which result from lower mass (e.g. modeling only tank, not including brackets)
    - Tank represents heel (shortest downrange distance) of debris footprint for both codes
Modeling Results Comparison

Objects Surviving in Both Codes

<table>
<thead>
<tr>
<th>Object</th>
<th>ORSAT</th>
<th>SCARAB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surviving Mass (kg)</td>
<td>DCA (m²)</td>
</tr>
<tr>
<td>Flywheel 1</td>
<td>3.136</td>
<td>0.750</td>
</tr>
<tr>
<td>Flywheel 2</td>
<td>3.136</td>
<td>0.750</td>
</tr>
<tr>
<td>Flywheel 3</td>
<td>3.136</td>
<td>0.750</td>
</tr>
<tr>
<td>Flywheel 4</td>
<td>3.136</td>
<td>0.750</td>
</tr>
</tbody>
</table>

- Reaction Wheel Assembly Flywheel
  - 0.3 m diameter X 0.01 m thick titanium disk
  - Flywheels illustrate a diversion in modeling approach
    - ORSAT’s “object oriented” method for modeling the components treats duplicate components such that the flywheels experience identical reentry scenarios
    - SCARAB “S/C oriented” approach models the trajectory and ablation of flywheels individually as they break apart from the parent object at different times
  - DCA difference is a result of differing method for determining area
    - ORSAT uses maximum cross section for disks
    - SCARAB uses mean cross section
  - Downrange distance variance is a result of differing masses as SCARAB predicts the shaft to remain attached and ORSAT does not
Objects which only survive in one code
- ORSAT predicts the command box to survive
  - Impacts with a mass of 3.89 kg (15.6% of original mass) and a DCA of 0.691 m²
- Differences between ORSAT and SCARAB fragmentation modeling make the source of the prediction difference difficult to identify
  - ORSAT begins modeling reentry of the command box at 78 km break-up of parent S/C
  - SCARAB has a more complex fragmentation history (below):

- In addition, the ORSAT analysis also shows that > 96% of the total energy required for this object to demise is absorbed, and that it will be predicted to demise if the oxidation heating efficiency is increased
Objects which survive differently

- The battery box and its fragments partially survive in both codes
  - ORSAT assumes the inner frames of the battery box and the battery cells to be separate fragments of the battery box
    - Once the outer box demises, these are assumed reenter individually
  - The SCARAB analysis assumes the battery box, inner frame, and battery cells are strongly attached
    - As portions of the battery box assembly demise, the rest remain connected

- ORSAT predicts the survival of 3 aluminum frame pieces and 12 nickel batteries
  - Total DCA = 2.798 m$^2$ and mass of 9.37 kg for aluminum frame pieces
  - Total DCA = 7.8 m$^2$ and mass of 11.4 kg for battery cells

- SCARAB predicts 1 surviving component
  - DCA = 1.002 m$^2$ and mass 17.697 kg
    - Of this mass 11.616 kg are Nickel and 6.081 kg are aluminum
Objects which survive differently (cont.)

- The differences in the battery box survival reveal both striking variances and similarities between the results of the two codes
  - The ORSAT assumption that all of the objects impact separately results in a much higher DCA due the large number of objects impacting
    - In both codes DCA values include an added area to account for the proximity of a standing person for each individual object
  - If the total mass of each material which impacts the ground is compared the results are quite similar
    - For the inner frames and battery cells, ORSAT predicts:
      - 11.4 kg of nickel survives compared to 11.616 kg for SCARAB
      - 9.37 kg of aluminum survives compared to 6.081 kg for SCARAB
  - If the surviving mass of aluminum and nickel in ORSAT are combined into a box shaped fragments with a volume equal to the inner dimension of the parent battery box the following would result
    - 1 Fragment with an impacting mass of 20.77 kg and a DCA of 1.254 m²
    - This is in much better agreement with the SCARAB value
### Modeling Results Comparison

#### Looking back at the final results

<table>
<thead>
<tr>
<th>Surviving Mass (kg)</th>
<th>ORSAT Reported Values</th>
<th>ORSAT Assuming Battery Box Remains Intact</th>
<th>ORSAT Ignoring Command Box</th>
<th>SCARAB Reported Values</th>
<th>SCARAB Using Maximum Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47.220</td>
<td>47.220</td>
<td>43.330</td>
<td>40.91</td>
<td>40.91</td>
</tr>
<tr>
<td>DCA (m²)</td>
<td>15.377</td>
<td>6.033</td>
<td>5.342</td>
<td>4.428</td>
<td>5.226</td>
</tr>
</tbody>
</table>

- By adjusting some of the methods and assumptions in each code the comparison becomes more clear and results begin to converge
  - Adjust ORSAT results to account for the fused battery cell and inner frame as in SCARAB
    - Reduces ORSAT DCA by 9.344 m²
  - Adjust SCARAB cross-sectional area calculation to match those in ORSAT
    - Use maximum area for RWA Flywheels
    - Use 0.5*(L*D)+(L*H)) for Battery Box contents
    - Increases DCA by 0.797
  - The end result is that the DCA’s between the codes differ by 0.116 m² (2.12% w.r.t. ORSAT) when considering only objects surviving in both codes
    - Difference is 0.807 m² (13.37%) when the command box is included
Conclusions

- Careful examination reveals that ORSAT and SCARAB arrive at very similar results
  - Of 33 unique objects modeled both codes strongly agree on 31 of those
    - Predict 29 to demise in a similar fashion
    - Predict 2 (LH2 tank, RWA flywheels) to demise in much the same way
  - Only 2 objects (as modeled in SCARAB) show significant variance
    - For the command box ORSAT’s prediction of a high demise factor were very close to the results predicted by SCARAB, and may have demised in ORSAT after evaluating the oxidation effects

- The large difference in the debris casualty area which resulted form the battery box contents (1 item in SCARAB, 3 unique items in ORSAT) are not an effect of the differing methods employed to model the reentry physics, but are instead a difference in safety philosophy associated with geometric description of components

- It is not possible to deem either method as “correct” or better
  - Either scenario is equally plausable