Measurement of Satellite Impact Test Fragments for Modeling Orbital Debris

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Outline

• Overview of orbital debris
• Purpose of measuring hypervelocity impact test fragments
• Overview of hypervelocity impact testing
• Hand measurement techniques
• Computerized measurement system
• Conclusions
• Questions
Orbital Debris

Is it safe out there?
Principal Orbital Debris Data Sources

Potential Shuttle Damage

Window Replacement
EVA Suit Penetration
Radiator Penetration
RCC Penetration
TPS Tile Penetration
Cabin Penetration
Cargo Bay Damage

Space Surveillance Network
Goldstone Radars
Haystack Auxiliary Radar
Haystack Radar

Debris Diameter in Centimeters

0.001 0.01 0.1 1 10 100 1000

Cowardin, 2008

2009 AIAA Technical Symposium
Orbital Debris Overview

- There are over 13,000 catalogued objects in orbit
- Over 18,000 tracked objects >10 cm
- Fragmentation debris are a problem
  - Risk to current and future operating satellites

Monthly Number of Objects in Earth Orbit by Object Type

- Total Objects
- Fragmentation Debris
- Spacecraft
- Mission-related Debris
- Rocket Bodies

Orbital Debris Quarterly Newsletter, April 2009
Purposes of Impact Testing

- **Size and shape distribution of fragments on orbit**
  - Measure size
  - Determine shape
    - Accurate area calculation for irregular shapes
  - Determine cross-sectional area
  - Find area-to-mass (A/M) distributions as functions of size
  - Incorporate into computer codes

- **3-D Model of fragment**
  - Compare with optical lab measurements
Many impact tests have been performed
- Realistic nonfunctional micro-satellites
- Projectiles
- Hyper- and low-velocity impacts
- Differing impact directions

Courtesy of Kyushu University and Simadzu Corporation for the high-speed video camera HyperVision HPV-1
• **Purpose:** Improve our ability to predict what debris will result from an on orbit collision or explosion
  
  - Size and shape determination of collision debris
    
    • Standard size determination is Characteristic Length $L_c$

Shot 3 fragments
Measurement Techniques

- $x =$ longest projection dimension
- $y =$ longest projection orthogonal to $x$
- $z =$ longest projection orthogonal to both $x$ and $y$
- Characteristic length is the standard size comparison variable.

$$L_C = \frac{x + y + z}{3}$$

Projection measurements, Hill, Stevens ODQN 2007
Hand Measurement Techniques

- Ruler and grid paper
- Rely on memory and eyes to determine orthogonal directions
- Uncertainty unknown
  - Variation between users
- Not always repeatable

Shot 3 fragment #282, GFRP
• **Hand held laser scanner**
  - Two cameras triangulate position of object against reference board
  - 8 LEDs to light up reference dots
  - Crosshair lasers
• Measurement techniques

*y = 49.27 mm*

\[ x = 104.32 \, \text{mm} \]
\[ L_0 = 52.43 \, \text{mm} \]

\[ z_1 = 1.27 \, \text{mm} + z_2 \]

\[ z_2 = 2.42 \, \text{mm} + z_1 \]
\[ z = 3.69 \, \text{mm} \]
Uncertainties

• Measured three qualitative types of fragments:
  – Easy
  – Moderate
  – Difficult

• Performed maximum reasonable human error ranges on each

• Compared results
### Aluminum Cube

<table>
<thead>
<tr>
<th></th>
<th>Initial Measurements</th>
<th>Careful Measurements</th>
<th>Underestimate</th>
<th>Overestimate</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>49.15</td>
<td>49.43</td>
<td>49.12</td>
<td>49.43</td>
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<tr>
<td>(y)</td>
<td>46.47</td>
<td>47.35</td>
<td>45.89</td>
<td>47.7</td>
<td>1.81</td>
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<td>(z)</td>
<td>41.27</td>
<td>40.08</td>
<td>40.96</td>
<td>40.29</td>
<td>1.19</td>
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<tr>
<td>(L_c)</td>
<td>45.63</td>
<td>45.62</td>
<td>45.32</td>
<td>45.81</td>
<td>0.49</td>
</tr>
</tbody>
</table>

- Maximum reasonable human error used for under- and over-estimates
- Range in characteristic length is less than 0.5 mm for an easy fragment
Shot 3 Fragment 282 – Moderate Fragment
Computer vs. Hand Measurement

Shot 3 Fragment 282  
*All values reported in millimeters*

*user adjusted to 2.5 giving Lc of 51.6 – computerized technique ‘discovered’ true curvature*

<table>
<thead>
<tr>
<th></th>
<th>Hand user 1</th>
<th>Hand user 2</th>
<th>Hand user 3</th>
<th>Hand user 4</th>
<th>Computer</th>
<th>Computer Underestimate</th>
<th>Computer Overestimate</th>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>104.35</td>
<td>104</td>
<td>104</td>
<td>104.03</td>
<td>104.32</td>
<td>102.54</td>
<td>105</td>
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<tr>
<td>y</td>
<td>41.7</td>
<td>40</td>
<td>48.4</td>
<td>49.16</td>
<td>49.27</td>
<td>47.66</td>
<td>50.32</td>
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<tr>
<td>z</td>
<td>2.1775</td>
<td>1</td>
<td>1*</td>
<td>1.43</td>
<td>3.69</td>
<td>2.64</td>
<td>4.48</td>
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<tr>
<td>L_c</td>
<td>49.4</td>
<td>48.33</td>
<td>51.1</td>
<td>51.54</td>
<td>52.43</td>
<td>50.95</td>
<td>53.27</td>
</tr>
</tbody>
</table>

Difference in characteristic length:

- Between hand measurements 4.29mm 8.3%
- Between computerized measurements 2.32mm 4.4%
- Between hand and computer 0.83mm 1.6%

Maximum error assessed to be less than 2.5 mm  
– LESS THAN USER ERROR
Computerized Measurement Techniques

• Advantages
  – Uncertainty is more consistent
    • Maximum error ~ 0.25 mm
  – Allows for additional calculations / analysis
    • All calculations are repeatable
  – Decreases the risk of damaging the fragment (less handling)

• Disadvantages
  – Some objects are difficult to measure (equally true for hand measurements)
    • Light reflection / scattering
  – Unreliable for small objects
    • Determined Lc=5.2 mm is smallest nugget we can scan
  – Measurements are time-consuming
Future Work

- **MATLAB® model**
  - Measure cross-sectional area at any 2D slice of 3D model
    - A/M results
      - Irregular objects
    - Shape determination
  - Volume

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2009 AIAA Technical Symposium
Future Work

• **MATLAB® model**
  – Tumbling model for comparison with photometric studies
    • Establish a model which will support an optical database to aid in the interpretation of telescopic data
  – Many other research and analysis possibilities
Conclusions

- The computerized measurement system creates a 3D model of a satellite impact fragment.

- This model is more consistent than hand measurement techniques and is repeatable.

- By manipulation of the saved model, this technique allows for further analyses without having to redo any work with the physical fragment.

- This model supports size and shape determination for the understanding of the corresponding distributions of the on orbit debris population.
Questions?
References


   DOI: 10.1126/SCIENCE.1121337
### Back-up: Difficult Fragment

**Shot 3 Fragment 30**

<table>
<thead>
<tr>
<th></th>
<th>Initial computer</th>
<th>Detailed computer</th>
<th>Computer underestimate</th>
<th>Computer overestimate</th>
<th>Hand user 1</th>
<th>Hand user 2</th>
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<tbody>
<tr>
<td>x</td>
<td>63.61</td>
<td>64.24</td>
<td>63.57</td>
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<td>y</td>
<td>23.56</td>
<td>31.70</td>
<td>23.30</td>
<td>32.25</td>
<td>33.09</td>
<td>37.50</td>
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<td>z</td>
<td>19.84</td>
<td>17.78</td>
<td>19.29</td>
<td>18.04</td>
<td>14.86</td>
<td>19.00</td>
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<tr>
<td>$L_c$</td>
<td>35.67</td>
<td>37.91</td>
<td>35.39</td>
<td>38.17</td>
<td>40.02</td>
<td>42.83</td>
</tr>
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</table>

**Difference in $L_c$:**

- Between hand measurements 0.25 mm 0.3%
- Between computerized measurements 2.78 mm 6.5%
- Between hand and computer 4.92 mm 11.5%
Back-up slides – test 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,
Back up slide - Impact Test
## Back up slide - Impact Tests

<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>
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<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>
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<tr>
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<td>20</td>
<td>1285</td>
<td>39.2 / 3.0</td>
<td>1.66</td>
<td>42.0</td>
<td>//</td>
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<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>
</tbody>
</table>
Back up slide - Orbital Debris Growth

Before 1957 = 0 objects

Cataloged objects (>10 cm diameter) represented by white dots (not to scale)
Back up slide - Orbital Debris Growth

1960 = 10+ objects

Cataloged objects >10 cm diameter
Back up slide - Orbital Debris Growth

1970 = 1400+ objects

Cataloged objects > 10 cm diameter
1980 = 3700+ objects

Cataloged objects >10 cm diameter
Back up slide - Orbital Debris Growth

1990 = 6000+ objects

Cataloged objects >10 cm diameter

LEO

GEO ring, Molniya, Polar orbit, GTO

2009 AIAA Technical Symposium
National Aeronautics and Space Administration

Back up slide - Orbital Debris Growth

2000 = 8900+ objects

Cataloged objects >10 cm diameter
Orbital Debris = all space objects non-functional and human-made

- First launch in 1957 started growth of the orbital debris population (R/B from Sputnik Launch = SSN 1)
- First satellite break-up in 1961
- Low Earth Orbit (LEO) debris can travel at speeds of ~7 km/s and ~3 km/s in Geosynchronous Earth Orbit (GEO)
• Space Surveillance Network (SSN) routinely tracks targets >10 cm
  – Catalogued objects: objects with multiple detections, orbits established (~12,500)
  – Tracked objects: detected at least once, may not be included in catalogue (~17,000)
Other Ground-Based Sensors

- Ground-based remote systems able to detect objects as small as 2 mm in LEO and 10 cm in the GEO regime.

<table>
<thead>
<tr>
<th>Observational Data</th>
<th>Region/Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSN catalog (radars, telescopes)</td>
<td>LEO &gt; 10 cm, GEO &gt; 70 cm</td>
</tr>
<tr>
<td>Cobra Dane (radar)</td>
<td>LEO &gt; 4 cm</td>
</tr>
<tr>
<td>Haystack (radar)</td>
<td>LEO &gt; 1 cm</td>
</tr>
<tr>
<td>Goldstone (radar)</td>
<td>LEO &gt; 2 mm</td>
</tr>
<tr>
<td>STS windows and radiators (returned surfaces)</td>
<td>LEO &lt; 1 mm</td>
</tr>
<tr>
<td>HST solar panels (returned surfaces)</td>
<td>LEO &lt; 1 mm</td>
</tr>
<tr>
<td>MODEST (telescope)</td>
<td>GEO &gt; 30 cm</td>
</tr>
</tbody>
</table>
Back up - Orbital Debris Seen From LMT
• Approximately 4500 launches conducted worldwide since 1957
• Known breakups = 197
  – Major events: (number of catalogued fragments, YYYY)
    • Titan Transtage (473, 1965) – U.S.
    • Agena D stage (373, 1970) – U.S.
    • COSMOS 1275 (309, 1981) – Russia
    • Ariane 1 stage (489, 1986) – Europe
    • Pegasus HAPS (709, 1996) – US
    • Long March 4 stage (316, 2000) – China
    • PSLV (326, 2001) – India
    • Fengyun 1C (>2500\(^a\), 2007) – China
    • Briz-M (>1000\(^b\), 2007) – Russia

\(^a\)on-going, \(^b\)initial report
Running into Meatball logo

LMIT-ODIN, 4/21/2009
Back up - Assessing the Problem: Involvement

The orbital debris issue is being addressed at national and international levels

- **U.S.**:
  - U.S. Government Orbital Debris Mitigation Standard Practices
  - NASA Procedural Requirements (NPR) and NASA Technical Standard (NS) on Orbital Debris

- **COPUOS**: United Nations Committee on Peaceful Uses of Outer Space
  - Started in 1959, currently has 69 member states
  - Albania, Algeria, Argentina, Australia, Austria, Belgium, Benin, Bolivia, Brazil, Bulgaria, Burkina Faso, Cameroon, Canada, Chad, Chile, China, Colombia, Cuba, Czech Republic, Ecuador, Egypt, France, Hungary, Germany, Greece, India, Indonesia, Iran, Iraq, Italy, Japan, Kazakhstan, Kenya, Lebanon, Libyan Arab Jamahiriya, Malaysia, Mexico, Mongolia, Morocco, Netherlands, Nicaragua, Niger, Nigeria, Pakistan, Peru, Philippines, Poland, Portugal, Republic of Korea, Romania, the Russian Federation, Saudi Arabia, Senegal, Sierra Leone, Slovakia, South Africa, Spain, Sudan, Sweden, Switzerland, Syrian Arab Republic, Thailand, Turkey, the United Kingdom of Great Britain and Northern Ireland, the United States of America, Ukraine, Uruguay, Venezuela & Viet Nam

- **IADC**: International Standards Organization Technical Committee "Aircraft And Space Vehicles" Sub-Committee "Space Systems And Operations"
  - Development of standards to address implementation of measures associated with debris mitigation
Orbital Debris Population Breakdown

- Breakup Fragments
- Mission-related Debris
- NaK
- Al₂O₃
- Al₂O₃ (slug)
- Paint Flakes
- Meteoroids

Size (diameter):
- 10 μm
- 100 μm
- 1 mm
- 1 cm
- 10 cm
- 1 m
- 10 m

Courtesy of Cowardin, 2008

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Collision fragments replace other decaying debris through the next 50 years, keeping the total population approximately constant. Beyond 2055, the rate of decaying debris decreases, leading to a net increase in the overall satellite population due to collisions.
Starting in 2020
PMD scenario predicts the LEO populations would increase by ~75% in 200 years
The population growth could be reduced by half with a removal rate of 2 obj/year
LEO environment could be stabilized with a removal rate of 5 obj/year
Back up – Orbit Propagation