Introduction to Space Debris and Hypervelocity Impact Test Facilities at Kyushu Institute of Technology

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Introduction to Space Debris

Space Debris?
**Space Debris?**

**Useless man-made space objects** in Earth’s orbit or re-entering the Earth’s atmosphere

<table>
<thead>
<tr>
<th>Spent satellites, upper stages, fuel tanks</th>
<th>Explosions and Collisions Fragments</th>
<th>Mission Related Objects</th>
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<tbody>
<tr>
<td><img src="Image" alt="Cerise" /> Upper stages</td>
<td><img src="Image" alt="Explosions and Collisions Fragments" /> Credit: NASA</td>
<td><img src="Image" alt="Mission Related Objects" /></td>
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<td><img src="Image" alt="Discovery STS-124" /></td>
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</table>
Introduction to Space Debris

How Many Are Out There?
How Many are Out There?

- Space debris vs. Catalog objects

**Catalog objects** are space debris that can be tracked by ground observations.

Source: The Greening of Orbital Debris – NASA Academy of Program/Project and Engineering Leadership[1]
How Many are Out There?

2009 – Iridium and Cosmos accidental collision

~17,000 objects

How Many are Out There?

Space debris > 100 μm

Introduction to Space Debris

Are Space Debris an Urgent Threat?
Are Space Debris an Urgent Threat?

Are space debris a threat?

Large space debris (>10 cm) case

- Since Sputnik about 38,000 catalogued objects in orbit
- 22,000 objects have re-entered in the atmosphere without causing damage
- Re-entries with fragments reaching the ground
  - Kosmos-954, 1978
  - Skylab, 11 July 1979
  - Kosmos-1402, 1984
  - Salyut-7 / Kosmos-1686, 7 Feb. 1991
  - Numerous rocket bodies

Fragment of a Delta second stage found in Texas on 22 Jan. 1997 (main propellant tank made of stainless steel, 250 kg)
Are Space Debris an Urgent Threat?

- Are space debris a threat?

**Large space debris (>10 cm) case**

- Since Sputnik about 38,000 catalogued objects in orbit
- 22,000 objects have re-entered in the atmosphere without causing damage
- Re-entries with fragments reaching the ground
- Risk on ground can be minimised by controlled re-entry

January 2011 – Successful re-entry of H-IIB upper stage[4]
Are Space Debris an Urgent Threat?

Small space debris case

- Average orbiting velocity: 7 - 8 km.s\(^{-1}\)
- Average impact velocity: 10~15 km.s\(^{-1}\)
- Energy equivalences (aluminum sphere)
  - Ø 1 mm: tennis ball at 70 km.h\(^{-1}\)
  - Ø 1 cm: 181 kg safe at 95 km.h\(^{-1}\)
  - Ø 10 cm: small car at 1,300 km.h\(^{-1}\)
Are Space Debris an Urgent Threat?

Small space debris case

- Example

Projectile diameter: 0.3 mm, velocity: 4 km.s\(^{-1}\)[5]
Are Space Debris an Urgent Threat?

- Are space debris a threat?

  Large or small, debris possible impact on our lives cannot be neglected

- Television
- Telephones
- Navigation
- Business and finance
- Weather
- Climate and environmental monitoring
- Safety
- Science

All pictures’ credit: JAXA
Are Space Debris an Urgent Threat?

Are space debris an *urgent* threat?

- Operational spacecraft = 6%
  - 94% of debris in space…
  - Area-to-mass ratio factor

<table>
<thead>
<tr>
<th>Operational satellites</th>
<th>6%</th>
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<tbody>
<tr>
<td>Intact spacecraft</td>
<td>22%</td>
</tr>
<tr>
<td>Rocket bodies</td>
<td>11%</td>
</tr>
<tr>
<td>Mission-related objects</td>
<td>7%</td>
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<tr>
<td>Fragments</td>
<td>60%</td>
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</tbody>
</table>

45% of total debris mass is in LEO, 28.8% in GEO\[^6\]

34.8% of total debris’ cross-section in LEO, 40.9% in GEO\[^6\]
Are Space Debris an Urgent Threat?

- Are space debris an **urgent** threat?
  - Kessler syndrome

![Non-Mitigation Projection (averages and 1- from 100 MC runs)](image_url)

Future debris population growth (no mitigation measures)\textsuperscript{[7]}
Are Space Debris an Urgent Threat?

- Are space debris an urgent threat?
  - Kessler syndrome

Future debris population growth (no new launches from January 1, 2006) \[(\text{Liou and Johnson, Science, 2006})\]
Are Space Debris an Urgent Threat?

- Are space debris an urgent threat?

  Even without new launches, debris population will critically increase in LEO and active measures have to be taken and applied.

  “The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future.”

  “Only remediation of the near-Earth environment – the removal of existing large objects from orbit – can prevent future problems for research in and commercialization of space.”

  Liou and Johnson, *Science, 20 January 2006*
Introduction to Space Debris

Research on Space Debris
Research on Space Debris

- Mitigation
  - IADC guidelines
    - 25-year rule
    - Passivation

![Non-Mitigation Projection (averages and 1 - from 100 MC runs)](image)

Future debris population growth (no mitigation measures)[7]
Research on Space Debris

- **Mitigation**
  - IADC guidelines
    - 25-year rule
    - Passivation

Projection of LEO population with 90% compliance with mitigation measures\(^8\)
Research on Space Debris

- Mitigation measures needed, but not sufficient...

<table>
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<tr>
<th>2007 - ASAT</th>
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<tr>
<td>Feng-Yun 1C</td>
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<td>(Source: globalsecurity.org)</td>
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- 3,000 new objects

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<th>2009 - Accidental Collision</th>
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<td>Iridium 33</td>
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<tr>
<td>(Source: space.skyrocket.de)</td>
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</table>

| Cosmos 2851 |
| (Source: nationalgeographic.com) |

- 2,000 new objects

- Active debris removal needed!
Research on Space Debris

- Active debris removal (ADR)
  - In which portion of space should it be applied?
  - Which object to target first?
  - What are the objectives?
  - How to do it?
  - Who will pay?
  - Technical vs. economical vs. political challenges

Need a few more years for technical maturity and economic viability

Source: ISU SSP12 Space Debris Team Project’s executive summary[9]
Research on Space Debris

- Small space debris oriented research
  - Better assess small space debris population
  - Better assess small space debris threat
  - Hypervelocity impact testing
Research on Space Debris

- Small space debris oriented research
  - Better assess small space debris population
  - Better assess small space debris threat
  - Hypervelocity impact testing
  - Modeling

Debris flux vs. altitude (adapted from Kanemitsu et al. [11])

Role of HVI experiments [10]
Research on Space Debris
Introduction to KIT’s Hypervelocity Impact Test Facilities

What is Hypervelocity?
Hypervelocity?

- **Velocity** greater than the sound velocity in a given material, $\sim 7$ km.s$^{-1}$

- Impact regime definition
  - **Velocity** (Jonas and Zukas, 1979)

Is the velocity alone sufficient to characterize an impact?
Hypervelocity?

- Velocity greater that the sound velocity in a given material, \( \sim 7 \text{ km.s}^{-1} \)

- Is the velocity alone sufficient to characterize an impact?

*Increasing velocity*

- Low velocity – Projectile slightly deformed
- Projectile erodes – Crater depth increases and start to enlarge
- High velocity – Projectile completely disintegrated, crater *enlarges BUT DOESN’T go deeper*
- Crater enlarges
Hypervelocity?

- **Velocity greater that the sound velocity in a given material, \( \sim 7 \text{ km.s}^{-1} \)**

- **Impact regime definition**
  - Velocity (Jonas and Zukas, 1979)
  - Material (Johnson, 1972)

\[
\frac{\rho v^2}{Y}
\]

\( \rho \): material density, \( v \): impact velocity; \( Y \): mean flow stress

- **Projectile and target strength (Wilbeck, 1985)**

\[
\frac{\rho v^2}{\sigma_p} \quad \frac{\rho v^2}{\sigma_T}
\]

\( \sigma \): yield stress; \( \rho v^2 = P \), hydrodynamic pressure
Hypervelocity?

- Velocity greater that the sound velocity in a given material, $\sim 7 \text{ km.s}^{-1}$

- Impact regime definition
  - Velocity
  - Material
  - Projectile and target strength

- Materials considered as fluids

<table>
<thead>
<tr>
<th>$\frac{P}{\sigma_p}$</th>
<th>$\ll 1$</th>
<th>$\sim 1$</th>
<th>$\gg 1$</th>
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<tbody>
<tr>
<td>$\frac{P}{\sigma_T}$</td>
<td>1</td>
<td>2</td>
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<td>$\frac{P}{\sigma_T}$</td>
<td>4</td>
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<td>6</td>
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<tr>
<td>$\frac{P}{\sigma_T}$</td>
<td>7</td>
<td>8</td>
<td>9</td>
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Hypervelocity regime

Source: CNES

Source: Mendo Coast Current
Introduction to KIT’s Hypervelocity Impact Test Facilities

Launchers Overview
Launchers Overview

- Pneumatic launcher
- Blast launcher
- Hybrid launcher
- Electromagnetic launcher
Launchers Overview

- Pneumatic launcher
  - One-stage light gas guns (~2 to 3 km.s\(^{-1}\))

![Diagram of one-stage light gas gun](image-url)
Launchers Overview

- Pneumatic launcher
  - One-stage light gas guns (~2 to 3 km.s\(^{-1}\))
  - Two-stage light gas guns (~ 7 km.s\(^{-1}\))
Launchers Overview

- Blast launcher – Shaped charge (∼12 km.s⁻¹)

Conical shaped charge launcher[10]

Liner (made of Al)

Jet shape[13]

Computer simulation of shaped charge projectile[14]
Launchers Overview

- Hybrid launcher – Flyer plate launcher (≈ 15 km.s\(^{-1}\))
  - Additional stage to two-stage guns
  - Graded-density materials focus shock wave on flyer plate
  - Disk-shaped projectiles only

Flyer place launch schematic\(^{[15]}\)
Launchers Overview

- Electromagnetic launcher – Rail guns (~ 15 to 20 km.s\(^{-1}\))
  - Lorenz force used to accelerate metallic or plasma armature, which will then propel the projectile
  - 3rd stage of light gas gun to increase final output velocity
  - Arc formation must be synchronized to the propellant exhaustion

Electromagnetic launcher working principle – Rail Gun\(^{[10]}\)
Introduction to KIT’s Hypervelocity Impact Test Facilities

KIT Launchers and Associated Researches
KIT Launchers

- Two-stage light gas gun
  - Large two-stage light gas gun (transformable into one-stage gun)
  - Small two-stage light gas gun
KIT Launchers – *Large TSLGG*

- Large two-stage light gas gun
  - **Asteroid deflection** - Study of near-Earth object deflection by hypervelocity impact

![Image of asteroid with spacecraft](image-url)
KIT Launchers – Large TSLGG

Test Chamber → Free Flight Section → High Pressure Coupling Section → Ignition Chamber

Velocity Measurement Section · Launch Tube · Pump Tube

Flight direction

Projectile: PE · Target: plaster · Velocity: 200 m.s⁻¹
KIT Launchers – Small TSLGG

- Small two-stage light gas gun
  - Secondary space debris (= ejecta) evaluation - Study on ejecta evaluation experiment for international standardization

Credit: ESA. Projectile: 5 mm Al sphere • Velocity: 5.2 km.s⁻¹
KIT Launchers – Small TSLGG

Projectile (1 mm Al sphere)

Targets. Top left: glass • Top right: solar cell • Bottom left: CFRP/Al honeycomb • Bottom right: Al honeycomb

Projectile: 14 mm Al sphere • Velocity: 4 km.s\(^{-1}\) • Video: 460 kfps
Kit Launchers

- Plasma gun
  - Accelerate small particles up to 10 km.s⁻¹ - Development of a plasma gun to accelerate micro-particles
**KIT Launchers**

- **Plasma gun**

Under high current changes, Al sheet transformed into Al plasma

The plasma is accelerated by its own diffusion and the Lorenz force

Projectiles are pushed out and accelerated by the plasma
KIT Launchers

- Besides hypervelocity launchers...

Aeronautical Applications

- Rail gun
- Gas gun

Automotive Applications

- Crash Box Testing
In a nutshell...

**Space debris**

- **Useless man-made space objects** in Earth’s orbit or re-entering the Earth’s atmosphere
- **Catalog objects (> 10 cm):** 17,000 debris
- **All (> 100 μm):** 5,800,000,000,000 debris!
- **Ø 1 mm debris** ≅ tennis ball at 70 km.h⁻¹ · soccer ball at 65 km.h⁻¹
- Mitigation and active debris removal

**KIT HVI facilities**

- 2 two-stage light gas guns: asteroid deflection and ejecta evaluation
- 1 plasma gun under development (objective: 10 km.s⁻¹)
- Other launcher: 1 gas gun (bird strikes on fan case investigation), 1 powder gun (crash box design for better energy absorption)
References


References

[9] International Space University Space Studies Program (2012). Space Debris Team Project Executive Summary


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