Orbital Debris and Future Environment Remediation

J.-C. Liou, PhD
NASA Orbital Debris Program Office
Johnson Space Center, Houston, Texas

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Outline

• An overview of the historical and current orbital debris environment
• Projected growth of the future debris population
• The need for active debris removal (ADR)
• A grand challenge for the 21\textsuperscript{st} century
• The forward path
An Overview of the Orbital Debris Environment
The Near-Earth Environment (1957-2010)

- Only objects in the US Space Surveillance Network (SSN) catalog are shown
- Sizes of the dots are not to scale
What Is Orbital Debris?

• Orbital debris is any man-made object in orbit about the Earth that no longer serves a useful purpose

• Examples
  – Spent upper stages (i.e., rocket bodies), retired spacecraft (i.e., payloads)
  – Mission-related debris: objects released during normal mission operations (engine covers, yo-yo despinn weights, etc.)
  – Breakup fragments (via explosions or collisions)
  – Solid rocket motor effluents (Al₂O₃ slag and dust particles)
  – NaK droplets (coolant leaked from Russian nuclear reactors)
  – Surface degradation debris (paint flakes, etc.)
The Orbital Debris Family

Objects in the Near-Earth Environment

- S/Cs, R/Bs
- Breakup Fragments
- Mission-related Debris
- NaK
- Al₂O₃
- Al₂O₃ (slag)
- Paint Flakes
- MLI Pieces
- Meteoroids

Size (diameter): 10 μm, 100 μm, 1 mm, 1 cm, 10 cm, 1 m, 10 m
How Much Junk Is Currently Up There?

- Softball size or larger (≥10 cm): ~22,000
  (tracked by the Space Surveillance Network)
- Marble size or larger (≥1 cm): ~500,000
- Dot or larger (≥1 mm): ~100,000,000
  (a grain of salt)

- Total mass: ~6300 tons LEO-to-GEO (~2500 tons in LEO)
- Debris as small as 0.2 mm pose a realistic threat to Human Space Flight (EVA suit penetration, Shuttle window replacement, etc.) and critical national space assets
The Environment

Impact Kinetic Energy:
golf ball @ 10 km/sec ≈ midsize sedan @ 120 mile/hr
**Shuttle Vulnerabilities**

- **Potential Shuttle Damage**
  - Window Replacement
  - EVA Suit Penetration
  - Radiator Penetration

- **Shuttle Loss of Crew and Vehicle (LOCV) risks from MMOD impact**
  - The risks vary with altitude, mission duration, and attitude
  - OD to MM is about 2:1 at ISS altitude

- Damage are in the range of **1 in 250 to 1 in 300 per mission**

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![Debris Diameter Chart](chart.png)

- Debris Diameter in Centimeters
- Range: 0.001 to 1000

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**JCL**
Growth of the Historical Catalog Populations

Monthly Number of Objects in Earth Orbit by Object Type (SSN Catalog)

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

FY-1C ASAT Test
Iridium-Cosmos

~1000 are operational
Mass in Orbit

Monthly Mass of Objects in Earth Orbit by Object Type

- LEO to GEO: ~6300 tons
- LEO only: ~2500 tons
Sources of the Catalog Population – All

Number Breakdown

- USA, 30.8%
- China, 21.7%
- CIS, 37.8%
- Others, 9.7%

CIS = Russia

Mass Breakdown

- USA, 27.6%
- Others, 18.9%
- CIS, 48.3%
- France, 5.3%

CIS = Russian Federation

LEO-to-GEO
Sources of the Catalog Population – LEO Only

Number Breakdown

- USA: 28.4%
- CIS: 39.0%
- China: 27.7%
- Others: 4.8%

Mass Breakdown

- CIS: 62.4%
- USA: 23.4%
- China: 10.0%
- Others: 4.2%

CIS = Russian Federation
Spatial Density of the Catalog Population (1/2)

LEO to GEO

Spatial Density (no/km³)

Altitude (km)

1.0e-07
1.0e-08
1.0e-09
1.0e-10
1.0e-11
1.0e-12
1.0e-13

0 10000 20000 30000 40000

LEO

GEO
Spatial Density of the Catalog Population (2/2)

Spatial Density of the Catalog Population

- LEO
  - FY-1C ASAT test
  - Iridium 33 / Cosmos 2251 collision

Altitude (km)

Spatial Density (no/km³)

200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000

0.0E+00 1.0E-08 2.0E-08 3.0E-08 4.0E-08 5.0E-08 6.0E-08
Mass Distribution in LEO

ISS (~400 tons) not included

- All
- Rocket Bodies (46% of All)
- Spacecraft (51% of All)
- Others
Projected Growth of the Future Debris Environment
Debris Environment Modeling

• All environment simulations are based on LEGEND (an LEO-to-GEO Environment Debris model)
  – LEGEND is the high fidelity orbital debris evolutionary model developed by the NASA Orbital Debris Program Office
  – LEGEND simulates objects individually, incorporates major perturbations in orbit propagation, and includes major source and sink mechanisms (launches, breakups, decays)
  – Ten peer-reviewed journal papers have been published on LEGEND and its applications since 2004
  – This seminar will focus on ≥10 cm objects and limit the future projection to 200 years


Future Projection – The **Worst Case Scenario**
(Regular Satellite Launches, but No Mitigation Measures)

Non-Mitigation Projection (averages and 1-σ from 100 MC runs)

- **LEO** (200-2000 km alt)
- **MEO** (2000-35,586 km alt)
- **GEO** (35,586-35,986 km alt)

![Graph showing the increase in effective number of objects (≥1 cm) from 1950 to 2210.](image)

(Liou, 2010)
Assessments of the Non-Mitigation Projection

- **LEO:** the non-mitigation scenario predicts the debris population (≥10 cm objects) will have a rapid non-linear increase in the next 200 years
  - This is a well-known trend (the “Kessler Syndrome”) that was the motivation for developing the currently-adopted mitigation measures in the last 15 years

- **MEO and GEO:** the non-mitigation scenario predicts a moderate population growth
  - Only a few accidental collisions between ≥10 cm objects are predicted in the next 200 years
  - The currently-adopted mitigation measures (including EOL maneuvers in GEO) will further limit the population growth
  - Environment remediation is not urgent
Will the Commonly-Adopted Mitigation Measures Stabilize the Future LEO Environment?
Future Projection – The Best Case Scenario
(No New Launches Beyond 1/1/2006)

- 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.
Assessments of the No-New-Launches Scenario

• In reality, the situation will be worse than the “no new launches” scenario as
  – Satellites launches will continue
  – Major breakups may continue to occur (e.g., Fengyun-1C)

• Postmission disposal (such as a 25-year decay rule) will help, but will be insufficient to prevent the self-generating phenomenon from happening

• To preserve the near-Earth space for future generations, ADR must be considered
Conclusions of the 2006 Paper

• “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.”

Average Collisions in the Next 200 Years

<table>
<thead>
<tr>
<th>Type</th>
<th>cat /non-cat</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-i collisions</td>
<td>10 / 0</td>
</tr>
<tr>
<td>i-f collisions</td>
<td>11 / 21</td>
</tr>
<tr>
<td>f-f collisions</td>
<td>3 / 2</td>
</tr>
<tr>
<td>total</td>
<td>24 / 23</td>
</tr>
</tbody>
</table>
The LEO environment instability issue is under investigation by the Inter-Agency Space Debris Coordination Committee (IADC) members.

An official “Stability of the Future LEO Environment” comparison study, was initiated in 2009.

- Six participating members: NASA (lead), ASI, ESA, ISRO, JAXA, and UKSA.
- Results from the six different models are consistent with one another, i.e., even with a good implementation of the commonly-adopted mitigation measures, the LEO debris population is expected to increase in the next 200 years.
- Study summary was presented at the April 2011 IADC meeting.
Preserving the Environment with Active Debris Removal (ADR*)

*ADR = Removing debris beyond guidelines of current mitigation measures
Key Questions for ADR

- Where is the most critical region for ADR?
- What are the mission objectives?
- What objects should be removed first?
  - The debris environment is very dynamic. Breakups of large intacts generate small debris, small debris decay over time,…
- What are the benefits to the environment?
- How to do it?

→ The answers will drive the top-level requirements, the necessary technology development, and the implementation of ADR operations
How to Define Mission Success?

• Mission objectives guide the removal target selection criteria and the execution of ADR

• Common objectives
  – Follow practical/mission constraints (in altitude, inclination, class, size, etc.)
  – Maximize benefit-to-cost ratio

• Specific objectives
  – Control population growth (≥10 cm or others)
  – Limit collision activities
  – Mitigate mission-ending risks (not necessarily catastrophic destruction) to operational payloads
  – Mitigate risks to human space activities
  – And so on

Target large & massive intacts
Target small debris
Target Small Debris
One Example: Risks From Small Debris

- The U.S. segments of the ISS are protected against orbital debris about 1.4 cm and smaller
  - “Currently,” the number of objects between 1.5 cm and 10 cm, with orbits crossing that of the ISS, is approximately 1200
    - ~800 of them are between 1.5 cm and 3 cm
    - To reduce 50% of the ISS-crossing orbital debris in this size range (1.5 cm to 3 cm) will require, for example, a debris collector/remover with an area-time product of ~1000 km² year
The Small Debris Environment is highly dynamic. In the region 50-500 km, from 2009 to 2019, there was a decrease in the number of objects, with a peak in 2011. At the ISS altitude, 1.5- to 3 cm debris continue to spiral toward lower altitude, and the region continues to be replenished by debris spiraling down from higher altitude on a rapid (yearly) timescale.
The small debris environment is highly dynamic and could have strong short-term (i.e., monthly to yearly) episodic variations.
Target Large Debris
Targeting the Root Cause of the Problem

A 2008-2009 NASA study shows that the two key elements to stabilize the future LEO environment (in the next 200 years) are

- A good implementation of the commonly-adopted mitigation measures (passivation, 25-year rule, avoid intentional destruction, *etc.*)

- An active debris removal of *about five objects per year*
  - These are objects with the highest \[ M \times P_{\text{coll}} \]
  - Many (but not all) of the potential targets in the current environment are spent Russian SL upper stages
    - **Masses:** 1.4 to 8.9 tons
    - **Dimensions:** 2 to 4 m in diameter, 6 to 12 m in length
    - **Altitudes:** ~600 to ~1000 km regions
    - **Inclinations:** ~7 well-defined bands
A good implementation of the commonly-adopted mitigation measures and an ADR of ~5 objects per year can “stabilize the future environment” (Liou, Adv. Space Res, 2011)
Projected Collision Activities in LEO

A good implementation of the commonly-adopted mitigation measures and an ADR of ~5 objects per year can only reduce the collisions by ~50% (Liou, Adv. Space Res, 2011)
Potential Active Debris Removal Targets

Top 500 Current R/Bs and S/Cs

- SL-8 R/B (1400 kg)
- Cosmos (1300 kg)
- SL-8 R/B (1400 kg)
- SL-16 R/B (8900 kg)
- Cosmos (3300 kg)
- SL-3 R/B (1440 kg)
- METEOR (2000 kg)
- SL-3 R/B (1440 kg)
- METEOR (2200-2800 kg)
- Cosmos (1300 kg)
- cosmos (2000 kg)
- Various R/Bs and S/Cs (SL-16 R/B, Envisat, etc., 1000-8900 kg)

Inclination (deg)

(SL-8 2nd stage)

Envisat

(Liou, Adv. Space Res, 2011)
Orbital debris is mentioned on 4 different pages for a total of 10 times in this 14-page policy document.

On page 7:

**Preserving the Space Environment and the Responsible Use of Space**

**Preserve the Space Environment.** For the purposes of minimizing debris and preserving the space environment for the responsible, peaceful, and safe use of all users, the United States shall:

- ...  
- Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment; and
- ...
### Challenges for ADR Operations

<table>
<thead>
<tr>
<th>Operations</th>
<th>Technology Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>Single-object removal per launch is not feasible from cost perspective</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Solid, liquid, tether, plasma, laser, drag-enhancement devices, others?</td>
</tr>
<tr>
<td>Precision Tracking</td>
<td>Ground or space-based</td>
</tr>
<tr>
<td>GN&amp;C and Rendezvous</td>
<td>Autonomous, non-cooperative targets</td>
</tr>
<tr>
<td><strong>Stabilization (of the tumbling targets)</strong></td>
<td>Physical or non-physical, how</td>
</tr>
<tr>
<td>Capture or Attachment</td>
<td>Physical (where, how) or non-physical (how), do no harm</td>
</tr>
<tr>
<td>Deorbit or Graveyard Orbit</td>
<td>When, where, reentry ground risks</td>
</tr>
</tbody>
</table>

- **Other requirements:**
  - Affordable cost
  - Repeatability of the removal system (in space)
The First Step

- **Identify top-level requirements for an end-to-end ADR operation**
  - Launch, propulsion, precision tracking, GN&C, rendezvous, stabilization, capture/attachment, and deorbit/graveyard maneuvers
  - Define stakeholders and their expectations to drive the development of a concept of operations

- **Conduct mission design analyses and establish a feasible forward plan**
  - Identify TRLs of existing technologies
  - Evaluate pros and cons of different technologies (*e.g.*, space tug vs. drag-enhancement devices)
  - Identify technology gaps (*e.g.*, ways to stabilize a massive, non-cooperative, fast spinning/tumbling target)
  - Perform trade studies (*e.g.*, physical vs. non-physical capture; deorbit vs. graveyard orbit)
An Example – Deorbit With Drag-Enhancement Devices

Orbital Lifetime of a Typical SL-8 2nd Stage (950 km, 83°)

- Actual A/M (0.015 m²/kg)
- Enhanced A/M, 0.4 m²/kg → ~30 m balloon
- Enhanced A/M, 1.4 m²/kg → ~50 m balloon
- Enhanced A/M, 5.5 m²/kg → ~100 m balloon
Recent ADR Activities at the National and International Levels
• The 2.5-day conference included 10 sessions
  – Understanding the Problem; Solution Framework; Legal & Economic; Operational Concepts; Using Environmental Forces; Capturing Objects; Orbital Transfer; Technical Requirements; In Situ vs. Remote Solutions; Laser Systems
  – Had 275 participants from 10 countries; 52 presentations plus 4 keynote speeches
• The conference reflected a growing concern for the future debris environment
• It represented the first joint effort for different communities to explore the issues and challenges of active debris removal
Other Major ADR Events (1/2)

• **International Science and Technology Center (ISTC) Space Debris Mitigation Workshop**
  - A two-day workshop in Moscow in April 2010
  - An international group of experts (IGOE) panel was formed to develop plans for ISTC’s participation in future ADR activities
  - ISTC provides a good potential mechanism for Russian contributions

• **1st European Workshop on Active Debris Removal**
  - A one-day event hosted by CNES in Paris in June 2010
  - Included more than 100 participants
  - Solidified CNES’ plan to move forward with an ADR demonstration mission

• **ADR sessions at AIAA, COSPAR, EUCASS, IAC, etc.**
Other Major ADR Events (2/2)

- **International Academy of Astronautics**
  - Is conducting a study to survey existing ADR technologies (led by ESA and NASA)

- **Inter-Agency Space Debris Coordination Committee**
  - Has just completed a LEO environment instability study (led by NASA)
  - Is drafting a white paper on the future LEO debris environment and the need for ADR
Summary
• The LEO debris population will continue to increase even with a good implementation of the commonly-adopted mitigation measures
  – The increase is driven by catastrophic collisions involving large and massive intacts
  – The major mission-ending risks for most operational satellites, however, comes from impacts with debris just above the threshold of the protection shields (~5 mm to 1 cm)
Concluding Remarks (2/4)

Size Distribution of the Current LEO-Crossing Objects

- Degradation threat to operational S/Cs
- Main threat to operational S/Cs
- Main driver for population growth

Cumulative Number

Size (cm)

- 5 mm
- 1 cm
- 5 cm
- 10 cm
- 50 cm
- 1 m

50/53
Concluding Remarks (3/4)

- To address the root cause of the population growth
  → Target objects with the highest \( M \times P_{\text{coll}} \)
  - To maintain the future LEO debris population at a level similar to the current environment requires an ADR of ~5 massive intacts per year

- To address the main threat to operational satellites
  → Target objects in the 5-mm-to-1-cm regime
  - The small debris environment is highly dynamic and will require a long-term operation to achieve the objective

- Targeting anything in between will NOT be the most effective means to remediate the environment nor mitigate risks to operational satellites
Concluding Remarks (4/4)

• There is a need for a top-level, long-term strategic plan for environment remediation
  – Define “what is acceptable”
  – Define the mission objectives
  – Establish a roadmap/timeframe to move forward

• The community must commit the necessary resources to support the development of low-cost and viable removal technologies
  – Encourage dual-use technologies

• Address non-technical issues, such as policy, coordination, ownership, legal, and liability at the national and international levels
Preserving the Environment for Future Generations

Pre-1957 → 2011 → 2211

National Aeronautics and Space Administration

NASA
Backup Charts
Why Should Satellite Owners/Operations Care?

• JSpOC is providing conjunction assessments for all operational satellites, but

• The major risk for operational satellites actually comes from impacts with small debris

• As the debris population increases
  – More frequent conjunction assessments will be needed
  – More collision avoidance maneuvers (i.e., $\Delta V$) will be needed
    • “Now, once every couple of weeks we do a maneuver” – S. Smith, Iridium EVP, December 2010
    • A total of 126 COLA maneuvers were conducted by satellite owners in 2010
  – More debris impact shields (i.e., mass) will be needed to meet the same requirement for probability of no penetration (PNP)
  – The risks for potential critical failure will increase
    • Number of impacts by 0.5 cm debris (with an average impact speed of 10 km/sec) to all operational satellites in LEO is about 1 to 2 per year in the current environment
Four Essential “Cs” for ADR

- Consensus
- Cooperation
- Collaboration
- Contributions