Orbital Debris and Future Environment Remediation

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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 21st 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 despins 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**
Impact Kinetic Energy:
golf ball @ 10 km/sec ≈
midsize sedan @ 120 mile/hr

Threat Regime
Shuttle Vulnerabilities

Potential Shuttle Damage

- Window Replacement
- EVA Suit Penetration
- Radiator Penetration

- Shuttle Loss of Crew and Vehicle (LOCV) risks from MMOD impact damage are in the range of 1 in 250 to 1 in 300 per mission
  - The risks vary with altitude, mission duration, and attitude
  - OD to MM is about 2:1 at ISS altitude

Debris Diameter in Centimeters

0.001  0.01  0.1  1  10  100  1000
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**

Key Events:
- **FY-1C ASAT Test**
- **Iridium-Cosmos**
- **~1000 are operational**

Year:
- 1958
- 1960
- 1962
- 1964
- 1966
- 1968
- 1970
- 1972
- 1974
- 1976
- 1978
- 1980
- 1982
- 1984
- 1986
- 1988
- 1990
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012
Mass in Orbit

Monthly Mass of Objects in Earth Orbit by Object Type

- LEO to GEO: ~6300 tons
- LEO only: ~2500 tons

Year:
- 1956
- 1958
- 1960
- 1962
- 1964
- 1966
- 1968
- 1970
- 1972
- 1974
- 1976
- 1978
- 1980
- 1982
- 1984
- 1986
- 1988
- 1990
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012

Mass in Orbit (millions of kg):
- 0.0
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
- 4.5
- 5.0
- 5.5
- 6.0
- 6.5

- Total
- Spacecraft
- Rocket Bodies
- Mission-related Debris
- Fragmentation Debris
Sources of the Catalog Population – All

Number Breakdown
- CIS, 37.8%
- USA, 30.8%
- China, 21.7%
- others, 9.7%

Mass Breakdown
- CIS, 48.3%
- USA, 27.6%
- others, 18.9%
- France, 5.3%

CIS = Russian Federation
Sources of the Catalog Population – LEO Only

Number Breakdown
- China, 27.7%
- USA, 28.4%
- CIS, 39.0%
- Others, 4.8%

Mass Breakdown
- USA, 23.4%
- CIS, 62.4%
- Others, 10.0%
- China, 4.2%

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

LEO to GEO

Spatial Density (no/km³)

Altitude (km)

LEO

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

![Graph showing spatial density of catalog population in LEO. Peaks indicate ASAT tests and collisions.]
Mass Distribution in LEO

ISS (~400 tons) not included
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)

Year (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.”

- Liou and Johnson, Science, 20 January 2006
Average Collisions in the Next 200 Years

- i-i collisions: 10 / 0
- i-f collisions: 11 / 21
- f-f collisions: 3 / 2
- total: 24 / 23
International Consensus

• 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
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)
A good implementation of the commonly-adopted mitigation measures and an ADR of ~5 objects per year can only reduce the collisions by ~50%
Potential Active Debris Removal Targets

Top 500 Current R/Bs and S/Cs

- SL-16 R/B (8900 kg) Cosmos (3300 kg)
- SL-8 R/B (1400 kg)
- SL-8 R/B (1400 kg) METEOR (2000 kg)
- SL-8 R/B (1440 kg) METEOR (2200-2800 kg)
- Various R/Bs and S/Cs (SL-16 R/B, Envisat, etc., 1000-8900 kg)
- Cosmos (1300 kg)
- Cosmos (1400 kg)
- Cosmos (2500 kg)
- Cosmos (2000 kg)

Inclination (deg) Altitude (km)

60 65 70 75 80 85 90 95 100 105

600 700 800 900 1000 1100 1200 1300 1400 1500 1600

Apogee
Perigee

(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:

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>
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- **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

2 years
11 years
25 years

Year
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060

Semiaxis (km)
6500 6700 6900 7100 7300 7500
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
• 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

- 10,000,000
- 1,000,000
- 100,000
- 10,000
- 1,000

Size (cm)

- 0.1
- 1
- 10
- 100

- 5 mm
- 1 cm
- 5 cm
- 10 cm
- 50 cm
- 1 m
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 \( \sim 5 \) 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
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