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The Long-Term Stability of the LEO Debris Population and the Challenges for Environment Remediation

J.-C. Liou (NASA)

The near-Earth space environment has been gradually polluted with orbital debris (OD) since the beginning of human space activities in 1957. The OD problem was highlighted by the collision between Cosmos 2251 and the operational Iridium 33 in 2009. This accidental collision underlined the potential of an ongoing collision cascade effect (also known as the “Kessler Syndrome”) in low Earth orbit (LEO, the region below 2000 km altitude). Recent modeling studies conducted by major space agencies around the world indicated that the current LEO environment had already reached the level of instability. Mitigation measures commonly adopted by the international space community, such as the 25-year decay rule, will be insufficient to stabilize the LEO debris population. To better limit the OD population growth, more aggressive actions must be considered.

There are three options for OD environment remediation: (1) removal of massive intact objects with high collision probabilities to address the root cause of the long-term OD population growth problem, (2) removal of the ~5-mm-to-1 cm debris to mitigate the main mission-ending threats for the majority of operational spacecraft, and (3) prevention of major debris-generating collisions as a temporary means to slow down the OD population increase. The technology, engineering, and cost challenges to carry out any of these three options are monumental. It will require innovative ideas, game-changing technologies, and major collaborations at the international level to address the OD problem and preserve the near-Earth environment for future generations.

Biography - - - - -

Dr. **J.-C. Liou** is a member of the NASA Orbital Debris Program Office. He is the Lead Scientist for long-term environment modeling, and for MMOD in-situ measurements. He also serves as the Chief Technologist for the Astromaterials Research and Exploration Science (ARES) Directorate at the NASA Johnson Space Center.

Dr. Liou led the development of the NASA Orbital Debris Engineering Model, ORDEM2000, and NASA’s long-term debris evolutionary model, LEGEND. He has authored more than 80 technical publications, including 40 papers in peer-reviewed journals, and is the Technical Editor for the NASA Orbital Debris Quarterly News. Dr. Liou was the recipient of NASA Exceptional Engineering Achievement Medal in 2012.

Dr. Liou earned his B.S. degree in Physics from the National Central University in Taiwan, and his M.S. (1991) and Ph.D. (1993) degrees in Astronomy from the University of Florida.



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Outline



- **Buildup of the Orbital Debris (OD) Population**
- **Projected Growth of the OD Population**
- **Options for Environment Remediation**
- **Challenges Ahead**



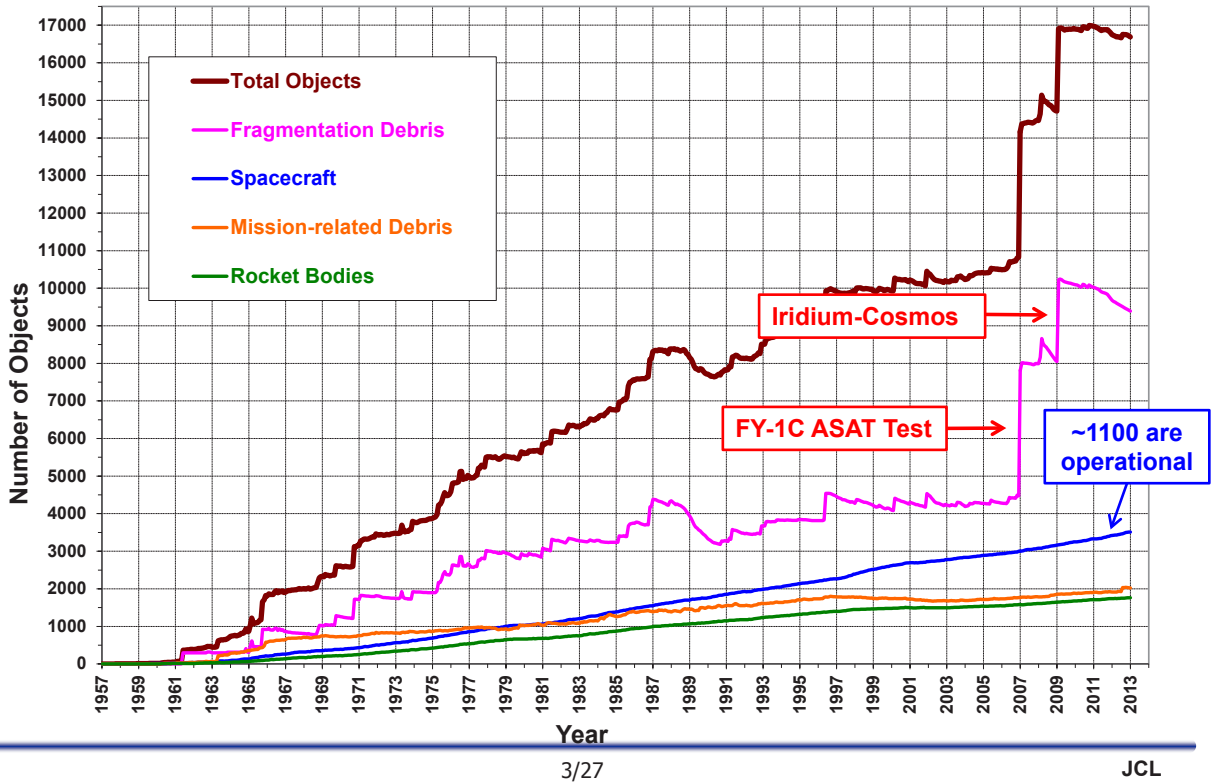
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Growth of the Cataloged Populations

Monthly Number of Objects in Earth Orbit by Object Type

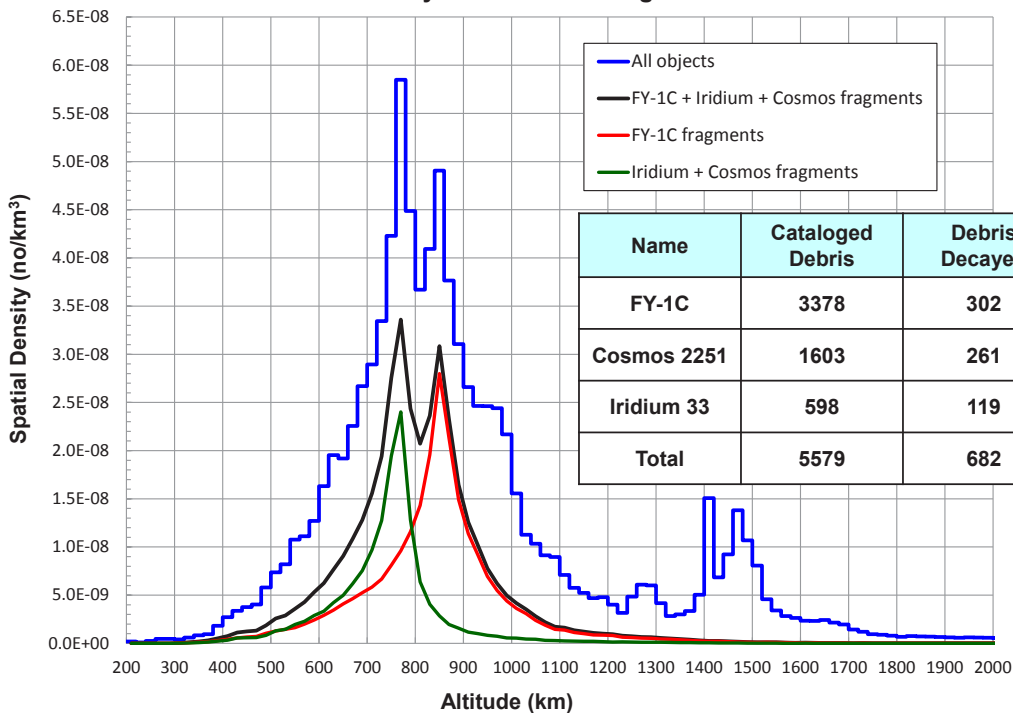


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The LEO Environment

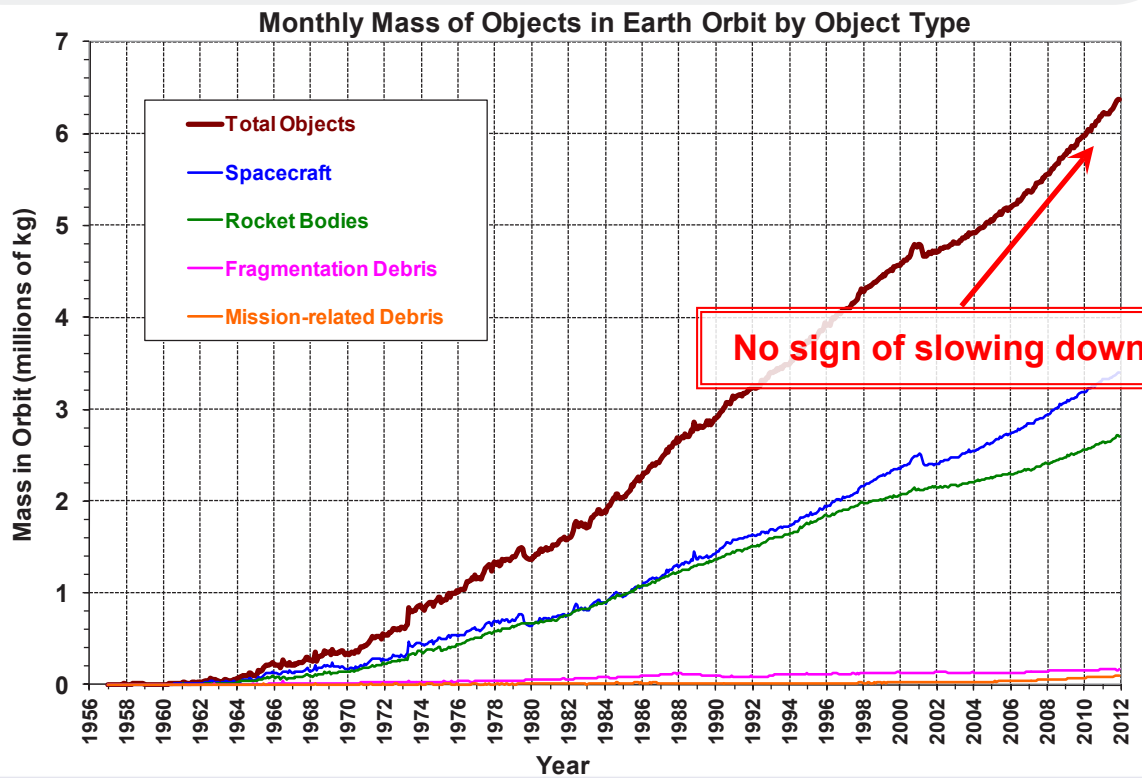
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Mass in Orbit



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The Big Sky Is Getting Crowded

- **Four accidental collisions between cataloged objects have been identified**
 - The collision between Cosmos 2251 and the operational Iridium 33 in 2009 underlined the potential of the Kessler Syndrome
- **The US Joint Space Operations Center (JSpOC) is currently providing conjunction assessments for all operational spacecraft (S/C)**
 - JSpOC issues ~10 to 30 conjunction warnings on a daily basis, and more than 100 collision avoidance maneuvers were carried out by satellite operators in 2010
- **The International Space Station has conducted 16 debris avoidance maneuvers (DAMs) since 1999**
 - 3 DAMs and 1 shelter-in-Soyuz in 2012

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Projected Growth of the Debris Population



Uncertainties In Environment Projection

- **Future launches**
 - Orbits, masses, materials, mission lifetimes, etc
- **Solar activity projection**
 - Orbit propagation
- **Breakup frequency and outcome**
 - Explosions
 - Collisions
- **Postmission disposal implementation**

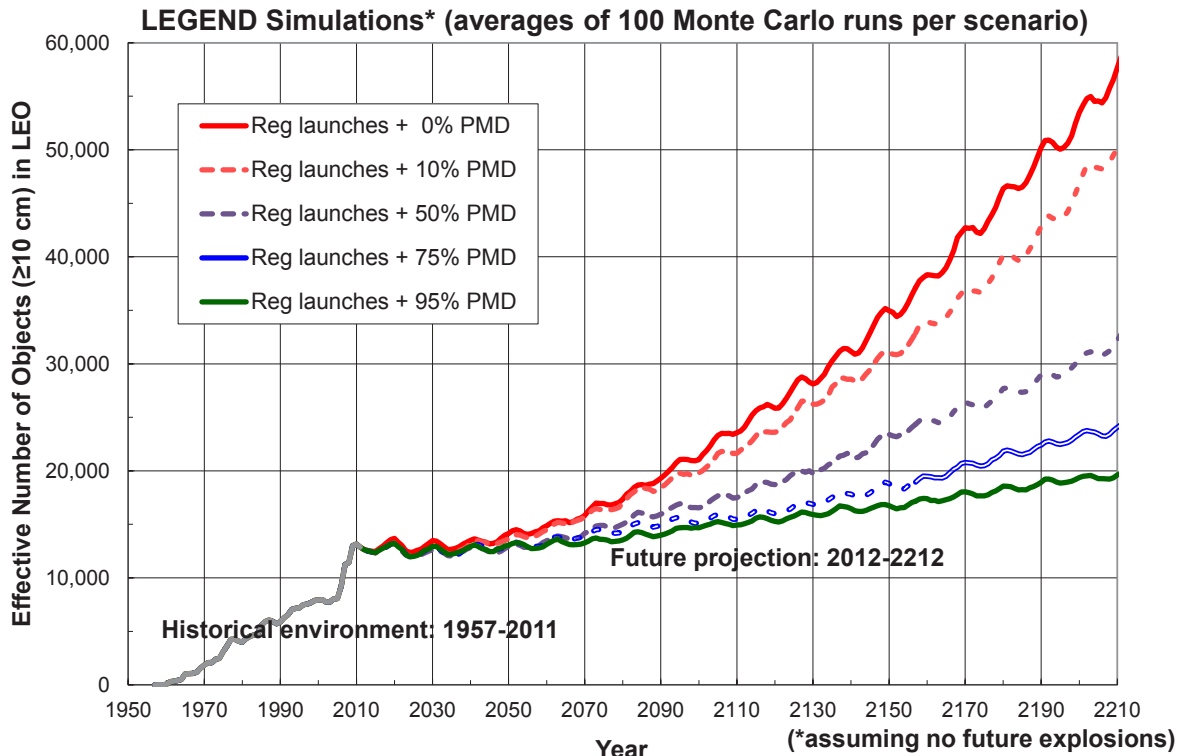
Two general approaches for future projection:

- Examine extreme cases to bound the problem
- Analyze nominal cases based on reasonable assumptions

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Effectiveness of Postmission Disposal (PMD)



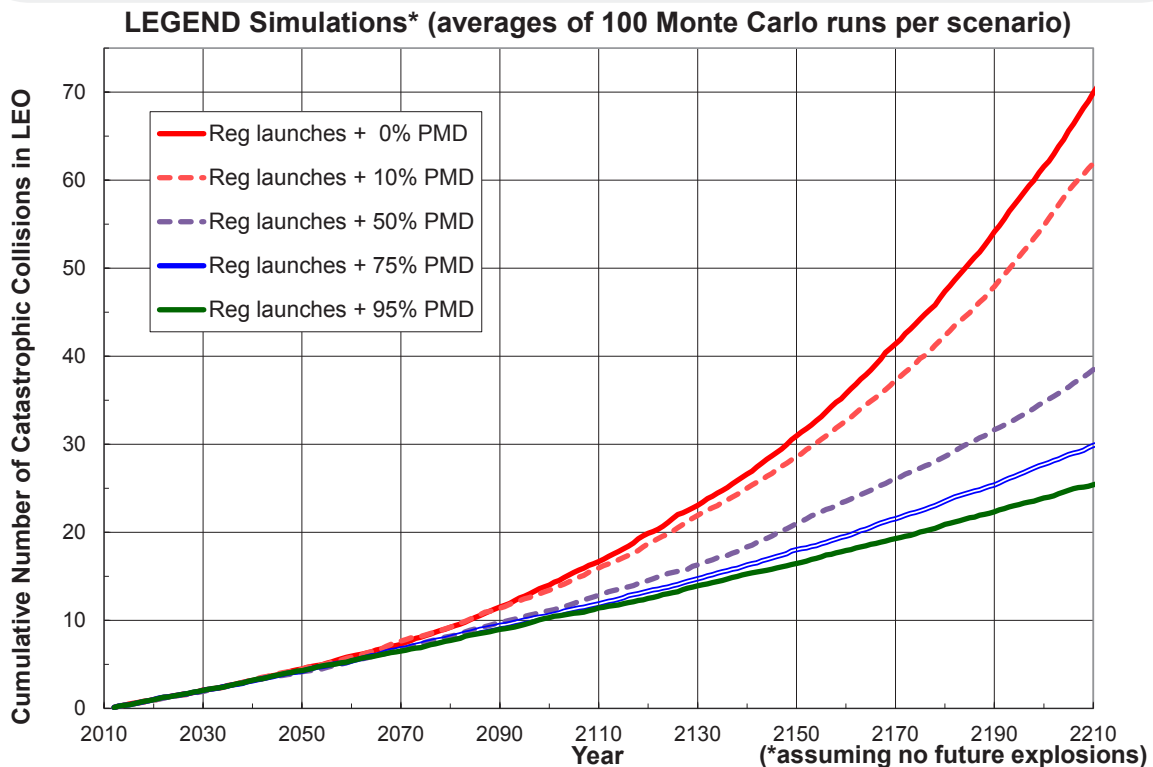
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Projected Catastrophic Collisions in LEO



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Assessments of the Future Projections

- **Postmission disposal (PMD), including passivation and the 25-year decay rule, can significantly limit the future population growth, but PMD will be insufficient to stabilize the LEO environment**
- **To preserve the near-Earth space for future generations, more aggressive measures, such as active debris removal (ADR), should be considered**



Options for Environment Remediation*

***Remediation = Removal of pollution or contaminants (*i.e.*, old and new debris) to protect the environment**



Problems and Solutions

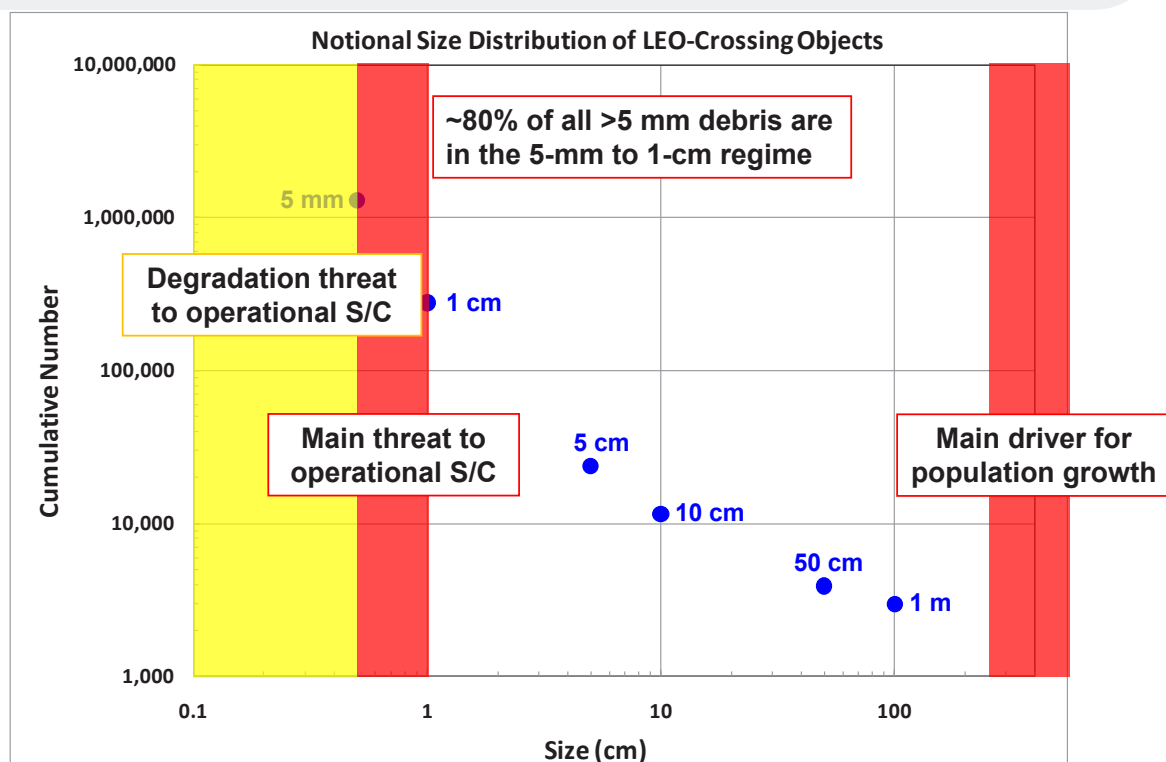
- **LEO debris population will continue to increase even with a good implementation of the commonly-adopted mitigation measures**
 - The root-cause of the increase is catastrophic collisions involving large/massive intact objects (R/Bs and S/C)
 - The major mission-ending risks for most operational S/C, however, come from impacts with debris just above the threshold of the protection shields (~5-mm to 1-cm)
- **A solution-driven approach is to seek**
 - Concepts for removal of massive intacts with high $P_{\text{collision}}$
 - Concepts capable of preventing collisions involving intacts
 - Concepts for removal of 5-mm to 1-cm debris

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Targets for Environment Remediation



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Options for LEO Environment Remediation

- **Removal of massive intact objects with high collision probabilities to address the root cause of the future debris population growth problem**
- **Removal of 5-mm to 1-cm debris to mitigate the main threat for operational spacecraft**
- **Prevention of major debris-generating collisions involving massive intact objects as a potential short-term solution**

These three options

- have different objectives, benefits, and timeframes
- are not mutually exclusive



Challenges for Environment Remediation





Challenges for Small Debris Removal

- **Targets are small**
 - Approximately 5-mm to 1-cm
- **Targets are numerous (>500,000)**
 - For any meaningful risk reduction, removal of a significant number of targets is needed
- **Targets are not tracked by the U.S. SSN or other space surveillance systems**
- **Targets are highly dynamic**
 - Long-term operations are needed
- **Concepts proposed by various groups: large-area collectors, laser removal, tungsten dust, etc.**



Challenges for Collision Prevention

- **To allow for actionable prevention operations involving uncontrolled objects**
 - Conjunction assessments should include R/Bs and retired S/C
 - Improvements to assessment accuracy would be beneficial
- **To be an effective means to reduce debris growth**
 - Prevention operations should be applied to most predicted events with probabilities exceeding acceptable threshold
- **Targets are limited in number, but many are massive R/Bs or S/C (up to 9 metric tons dry mass)**
- **Concepts proposed by various groups: ballistic intercept, frozen mist, laser-nudging, etc.**



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 which produces long-lived debris, *etc.*)

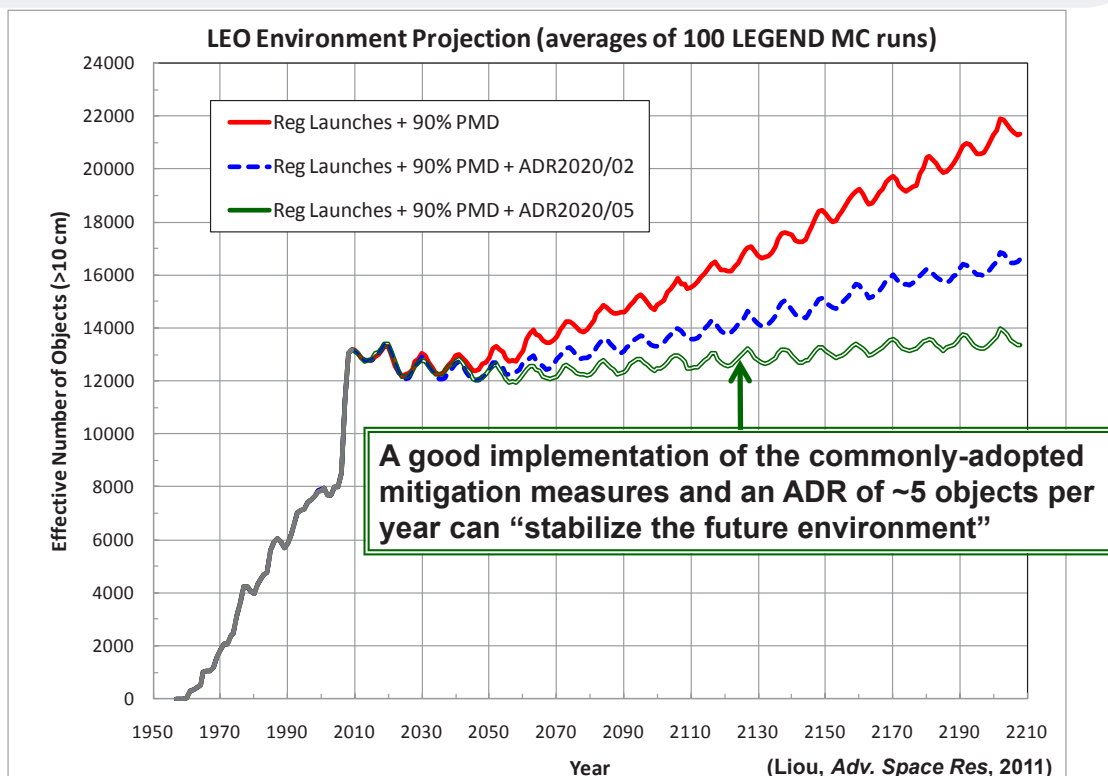
- An active debris removal of about five objects per year
 - These are objects with the highest [$M \times P_{coll}$]
 - Many (but not all) of the potential targets in the current environment are spent Russian SL upper stages
 - **Masses:** 1.4 to 8.9 tons
 - **Dimensions:** 2 to 4 m in diameter, 6 to 12 m in length
 - **Altitudes:** ~600 to ~1000 km regions
 - **Inclinations:** ~7 well-defined bands

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Controlling Debris Growth with ADR



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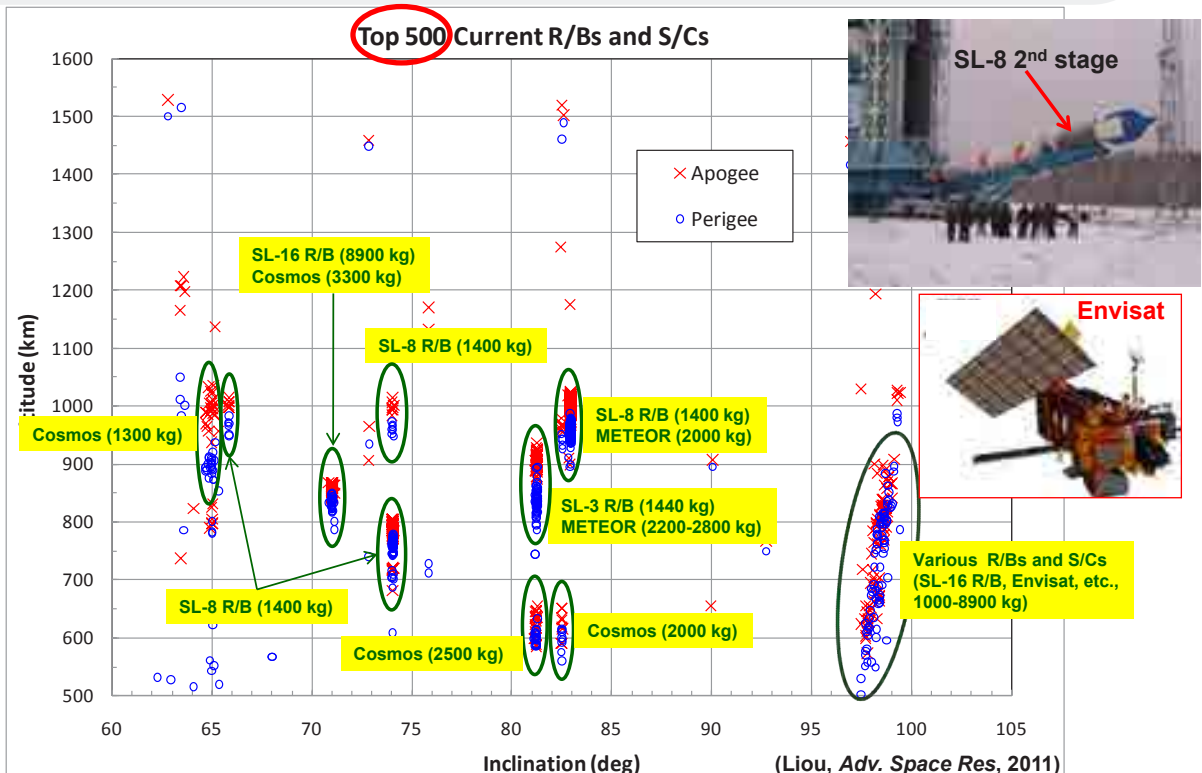


About the “Five Objects Per Year”

- The “removing five objects per year can stabilize the LEO environment” conclusion is somewhat notional. It is intended to serve as a guidance for ADR planning.
- Assumptions in the LEGEND ADR simulations
 - Nominal launches during the projection period
 - 90% compliance of the commonly-adopted mitigation measures
 - ADR operations starts in 2020
 - Target selection is based on each object’s mass and P_{coll}
 - No operational constraints on target selection
 - Immediate removal of objects from the environment
 - Average solar activity cycle



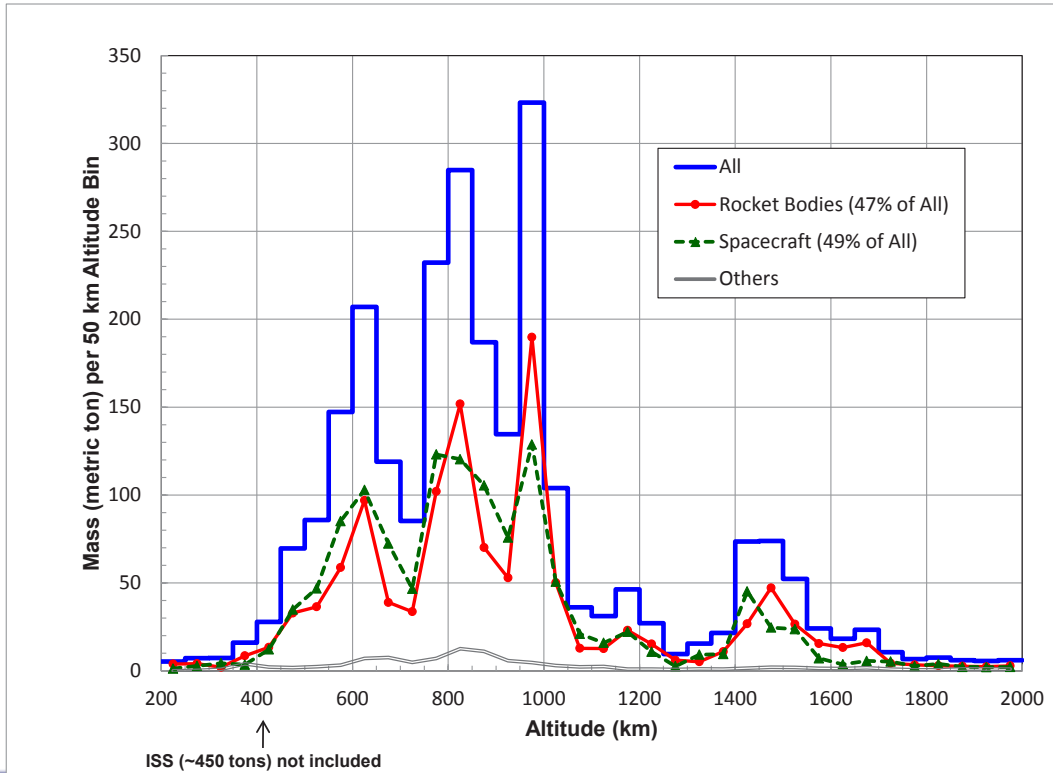
Potential Active Debris Removal Targets



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Mass Distribution in LEO (1/2)



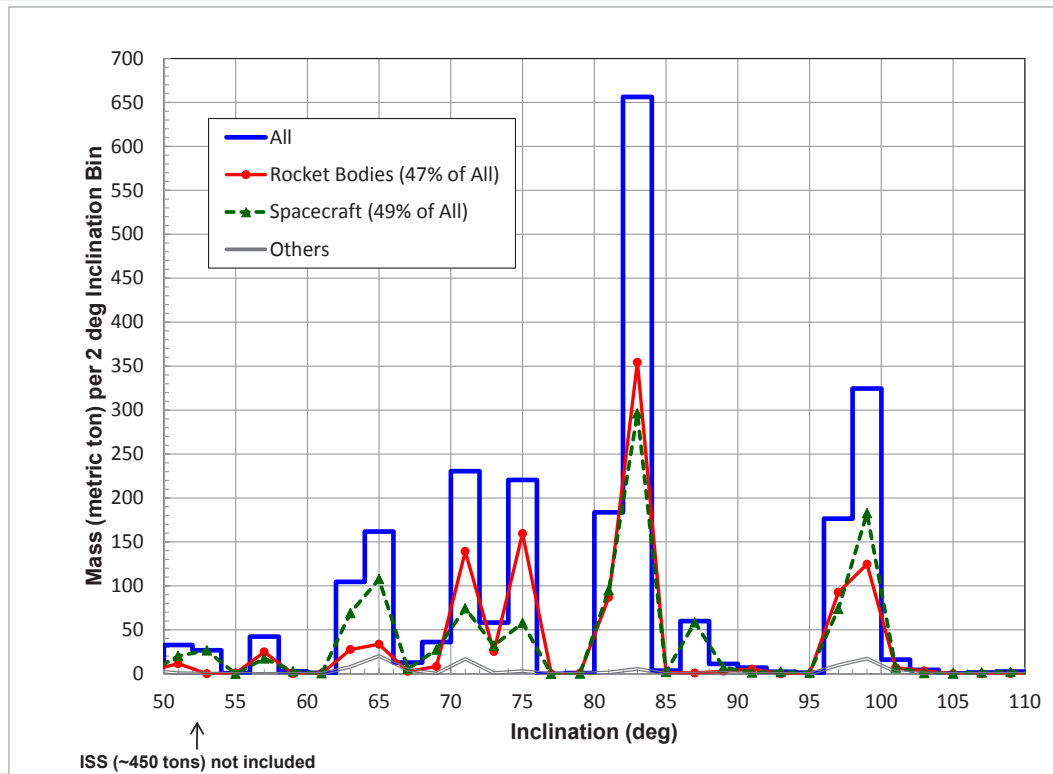
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Mass Distribution in LEO (2/2)



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Challenges for Large Debris ADR Operations



Operations	Technology Challenges
Launch	Single-object removal per launch may not be feasible from cost perspective
Propulsion	Solid, liquid, tether, plasma, laser, drag-enhancement devices, others?
Precision Tracking	Ground or space-based
GN&C and Rendezvous	Autonomous, non-cooperative targets
Stabilization (of the tumbling targets)	Contact or non-contact (how)
Capture or Attachment	Physical (where, how) or non-physical (how), do no harm
Deorbit or Graveyard Orbit	When, where, reentry ground risks

- **Other requirements:**

- Affordable cost
- Repeatability of the removal system (in space)?
- Target R/Bs first?

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Forward Path



- **There is a need for a top-level, long-term strategic plan for environment remediation**
 - Define “what is the acceptable threat level”
 - Define the mission objectives
 - Establish a roadmap/timeframe to move forward
- **The community should commit the necessary resources to support the development of innovative, low-cost, and viable removal technologies**
 - Encourage multi-purpose technologies
- **Address non-technical issues, such as policy, coordination, ownership, legal, and liability at the national and international levels**

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Preserving the Environment for Future Generations



- **Innovative concepts and technologies are key to solve the environment remediation challenges**
- **International consensus, cooperation, collaboration, and contributions are needed to move forward**

