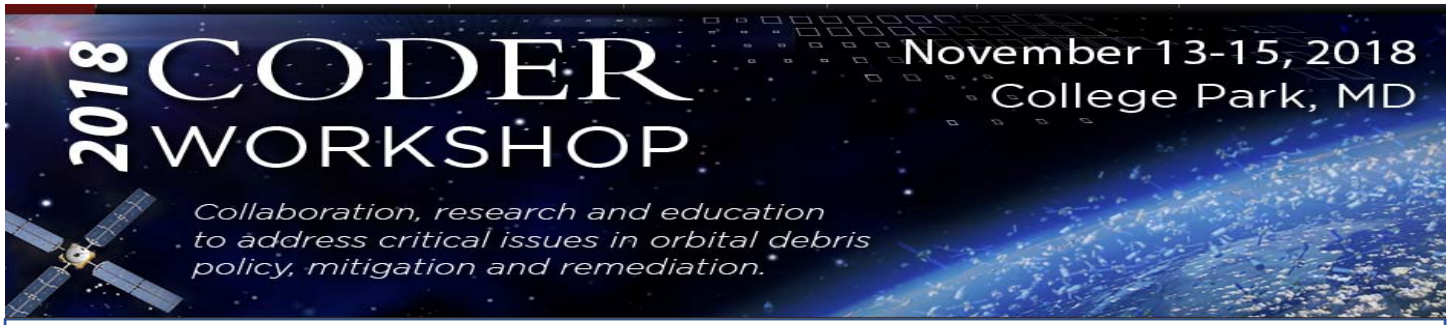

Two-Dimensional Space Debris Management and Control

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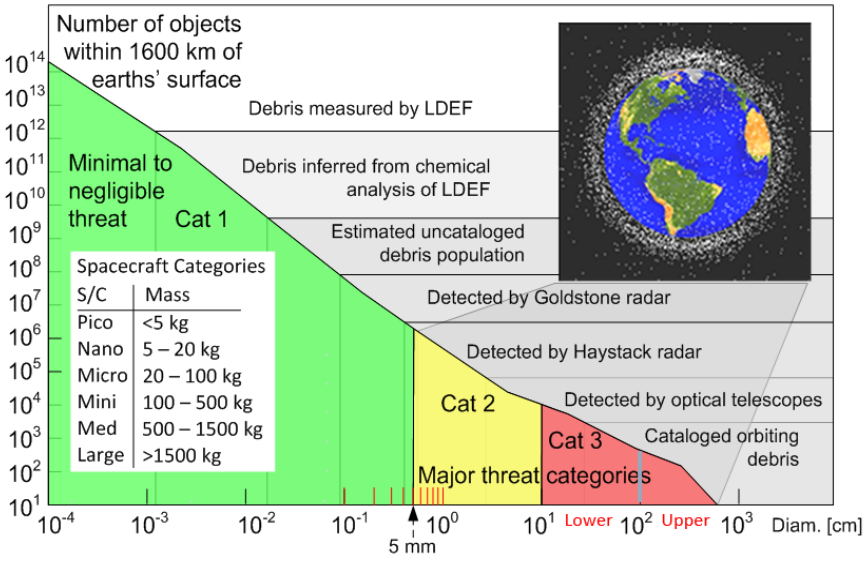
A Realistic Assessment of the LEO Problem

In LEO, it all has to do with debris sizes and quantities:

- **Cat 1:** Cannot be sensed or tracked and can do little damage to shielded spacecraft, but will eventually clog the LEO zone (Ultimately will act like sandpaper)
- **Cat 2:** More than $1x10^6$ debris objects that can be sensed but not tracked and are too small to be collected individually (However, such objects can cause considerable damage and/or destruction to operating satellites)
- **Cat 3:** largest debris objects - can cause devastating damage (Current population is estimated at ~29,000 objects with only several hundred larger than ~1 meter)

Debris Population vs Size in LEO – Circa 1997

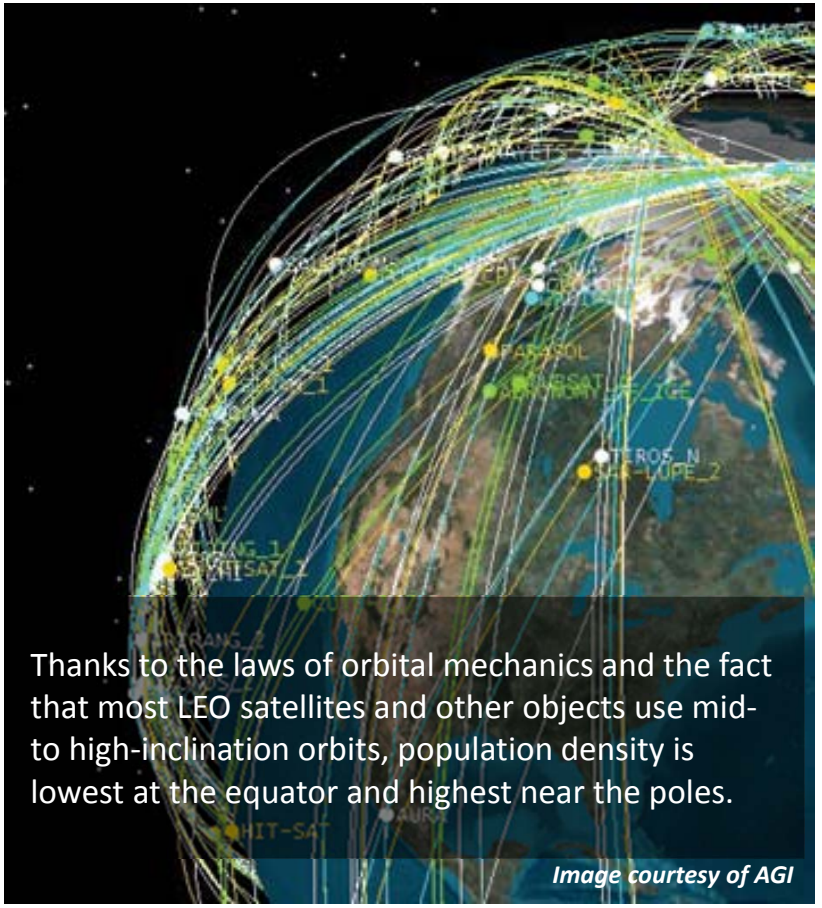
➢Three size categories: Cat 1: up to 0.5 cm
Cat 2: 0.5 to 10 centimeters
Cat 3: 10 cm and larger



LEO debris represents the greatest threat and will likely require different remediation approaches as opposed to MEO and GEO debris approaches.

A Realistic Solution to the LEO Problem

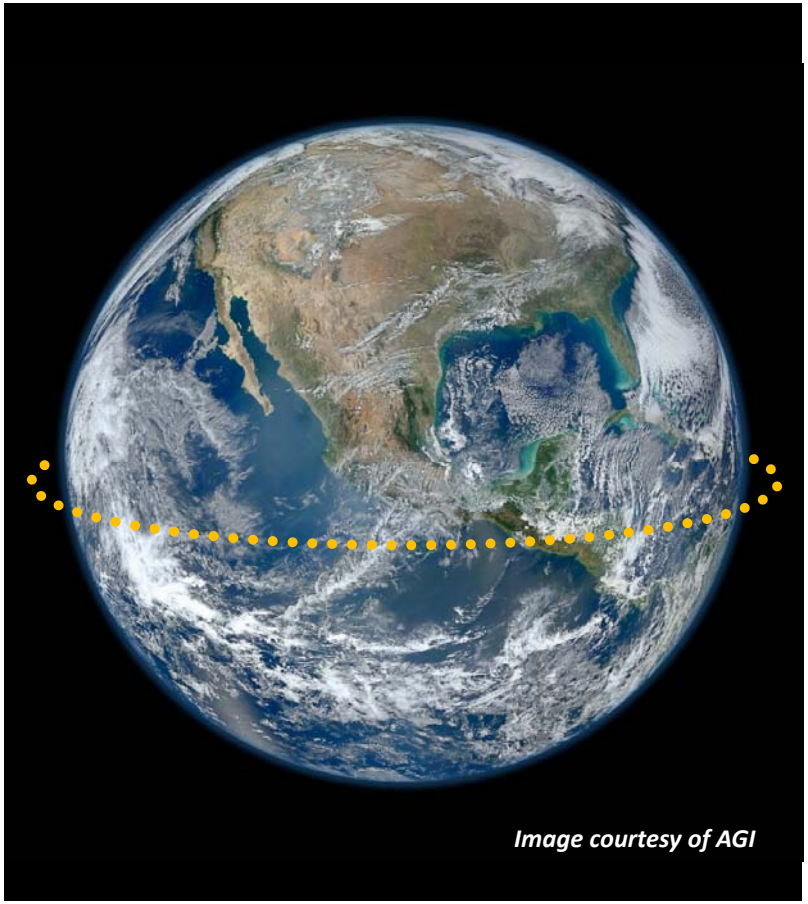
- Dealing with Large Cat 3 RSOs
  - Few, if any, of these need be removed, because they do not pose a high-probability threat to active spacecraft and will become Cat 1 and 2 objects
  - Removal needs to be considered only on a case-by-case basis
- Dealing with Cat 1 & 2 Objects
  - Cat 1 objects do not pose a short-term threat to properly shielded satellites but do pose a long-term clogging problem
  - Cat 1 & 2 objects may be collected by pseudo-passive* devices
- Over a sustained period, permanent pseudo-passive devices may be used to continuously remove sufficient debris to assure safe flight operations



*Pseudo-passive devices have maneuverability in a single plane.

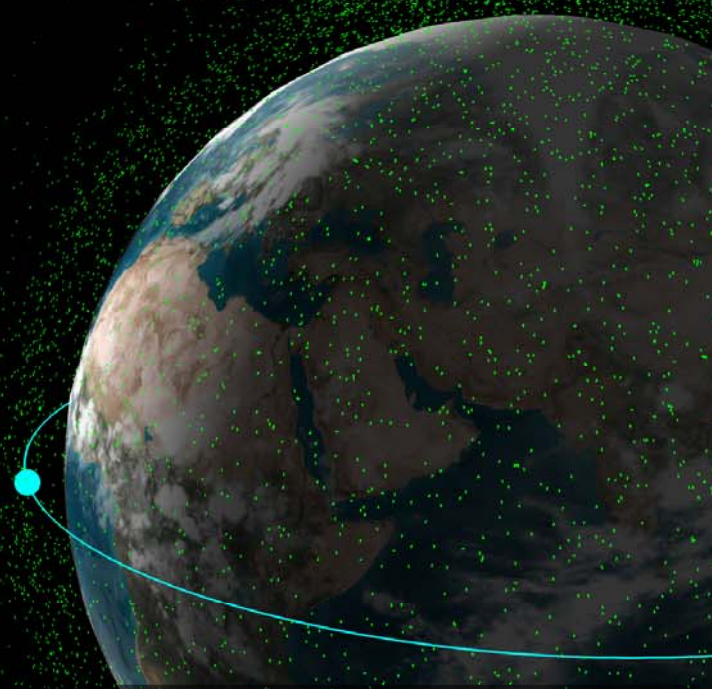
The Problem is Three-Dimensional, but the Solution is Two-Dimensional

- By placing a space system entirely in low-earth **equatorial** orbits, plane changes are not required and all maneuvers are two-dimensional
- This results in minimal propellant expenditures for maneuvering, plus other important advantages:
  - Ascent-to-orbit requires **minimal energy** from equatorial launch sites, because you can take maximum advantage of the Earth's spin and no plane rotations are required
  - There are **no launch window constraints** associated with equatorial rendezvous operations
  - Reentry disposal operations are simple and safe
  - Ideal for intercepting small debris because all LEO objects **cross the equator every 55 minutes**
  - **Object population density is lowest** at equatorial crossings, allowing easy avoidance of large objects



Here is the Planar Solution to LEO Debris Challenges

- Two satellite constellations in equatorial orbits: One for **sensing** and one for direct small-debris **collection:**
  - o Sensor satellites provide precision tracking of **large LEO objects** for individual removal plus detection of **small-debris fields** which can be selectively targeted by debris collectors
  - o Debris collector satellites intercept debris < ~10 cm and are highly maneuverable in small-debris fields while avoiding objects that are > ~10 cm



A single debris collector orbits about the equator while it performs in-plane maneuvers allowing small debris to impact its collector pads and avoiding objects large enough to be tracked.

Image courtesy of AGI

This is How the System Works

- Precision space-based sensor data are merged with ground-based sensor outputs to assist in:
  - Generating highly-accurate conjunction alerts for constellation operators
  - Operations for individual large-debris removal
  - Guiding and maneuvering debris collector satellites
- Debris collector satellites target small-debris zones such that subscribing constellations are protected from these debris

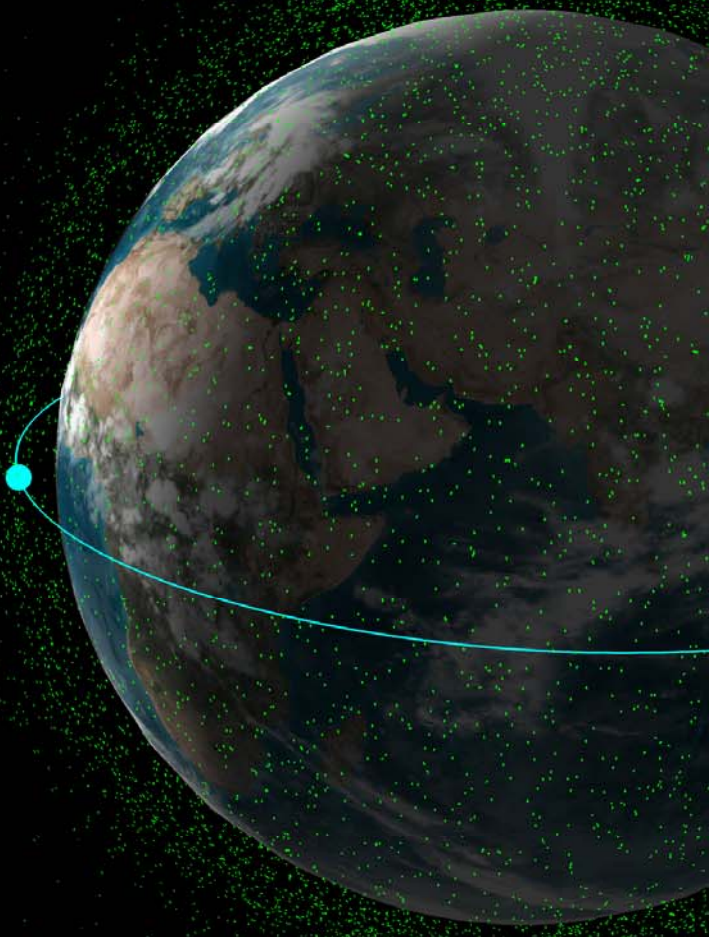


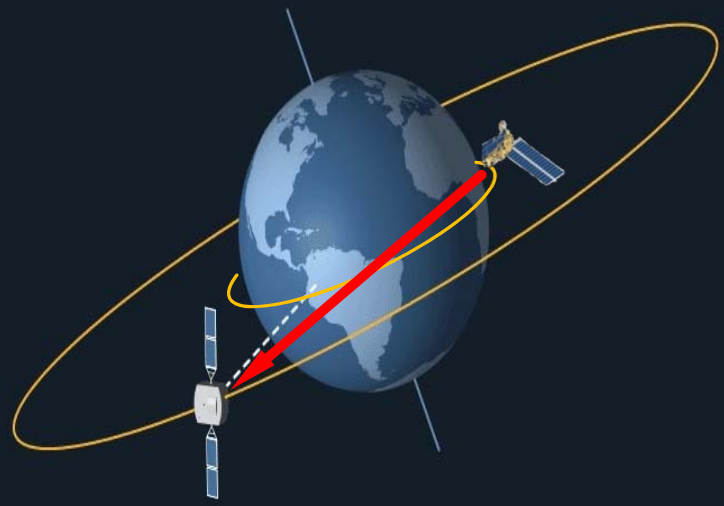
Image courtesy of AGI

Commercial Viability (Revenue Sources)

Revenue in connection with the removal of small debris and with the offering of other services is viewed as the basis for a viable commercial business operation.

Examples of Expected Revenue Sources:

- Precision LEO object tracking data and exact conjunction warnings
- Removal of small debris for the protection of LEO satellite constellations
- Precision SSA data sales
- STM support functions
- Hosted payloads on the sensor satellites



A single sensor satellite tracking a GEO bird from an equatorial LEO orbit. A constellation of these sensor satellites can accurately and continuously scan the entire GEO band.

Image courtesy of AGI

Conclusions

- LEO debris remediation and control must be resolved
- All debris need not be removed to maintain a safe environment for active satellites
  - LEO satellites have experienced few hazards from debris for the first 60 years of space flight
  - The main objective of a debris removal program should be the permanent control of the debris population at altitudes where active satellites fly
- Debris less than 5 mm (Cat 1) need not be addressed actively in a removal program:
  - Safety can be provided by individual spacecraft shielding
  - A pseudo-passive program may remove these objects
- Debris sizes from 5 mm to 10 cm (Cat 2):
  - These represent the most serious ongoing risk to operational satellites
  - The system presented here may become a cost-effective solution
- Debris sizes from 10 cm to 1+ m (Category 3, large debris):
  - This size range represents roughly 25,000 debris objects that are currently tracked
  - When removal benefits are compared to the cost of removal, the value proposition appears to be very weak