Orbital Debris, Space Situational Awareness, and Space Traffic Management

− Managing Risks from Orbital Debris

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Definitions

- ***SPD-3*: Sec. 2. Definitions***

"(a) Space Situational Awareness shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities."

(b) Space Traffic Management shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment."

(c) Orbital debris, or space debris, shall mean any human-made space object orbiting Earth that no longer serves any useful purpose."

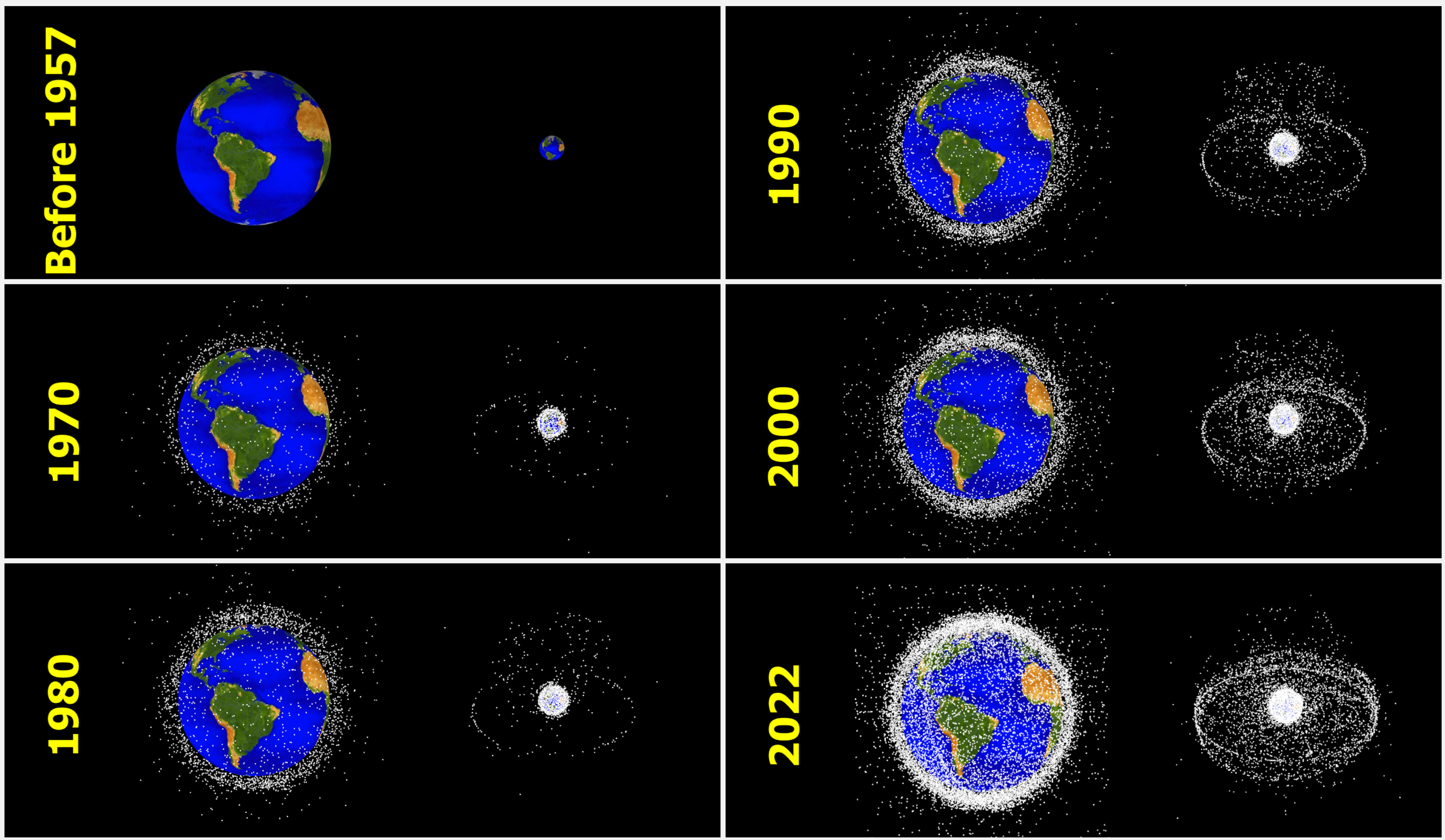
*Space Policy Directive-3 (SPD-3), U.S. National Space Traffic Management Policy, 21 June 2018

The Space Age

- **The first human-made satellite, Sputnik, was launched to study the atmosphere by the Soviet Union on October 4, 1957**
- **Since then, more than 5800 launches have been conducted worldwide**
- **Benefits of space activities**
  - Communications
  - Environment monitoring
  - Explorations
  - Technology advancements
  - Many others
- **But…**

NASA

The Historical Orbital Debris Environment

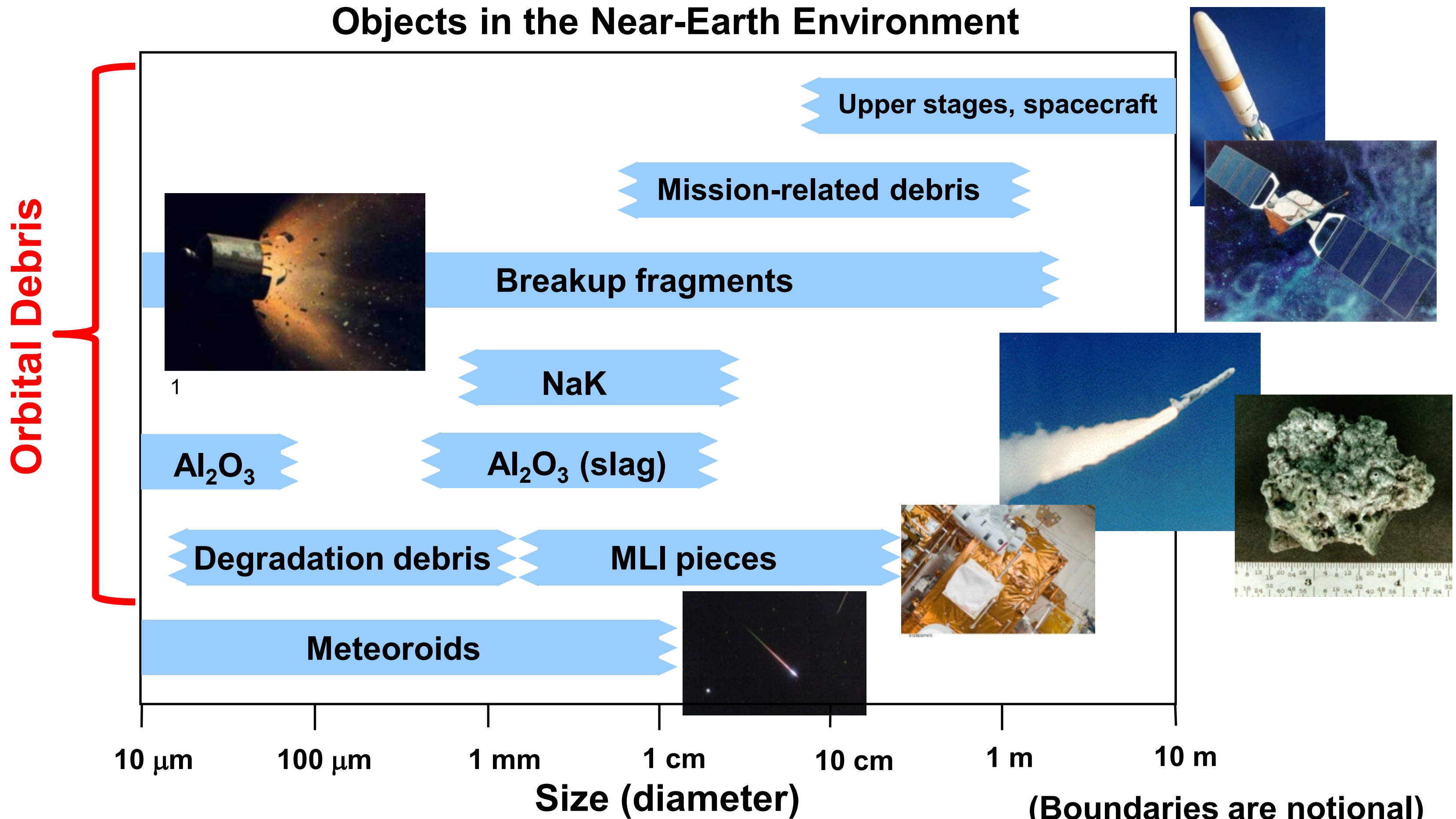


NASA ODPO

- **Only objects in the US satellite catalog (~10 cm and larger) are shown**
- **Sizes of the dots are not to scale**

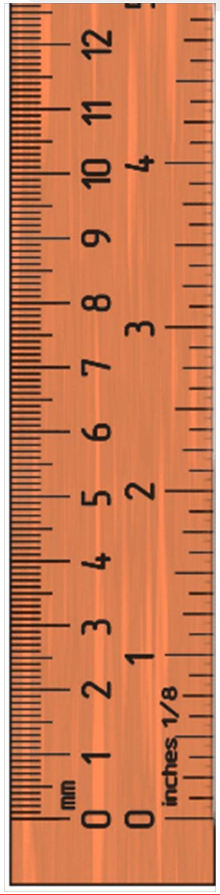
What Is Orbital Debris?

- **Orbital debris is any human-made object in orbit about the Earth that no longer serves any useful function**



[1] 1981 painting copyright William K. Hartmann, Senior Scientist Emeritus, Planetary Science Institute

How Much Orbital Debris Is Up There?



Somewhat larger than a cricket ball (≥10 cm): ~27,000
(tracked by Space Force's 18th Space Defense Squadron, 18 SDS)

Public domain images

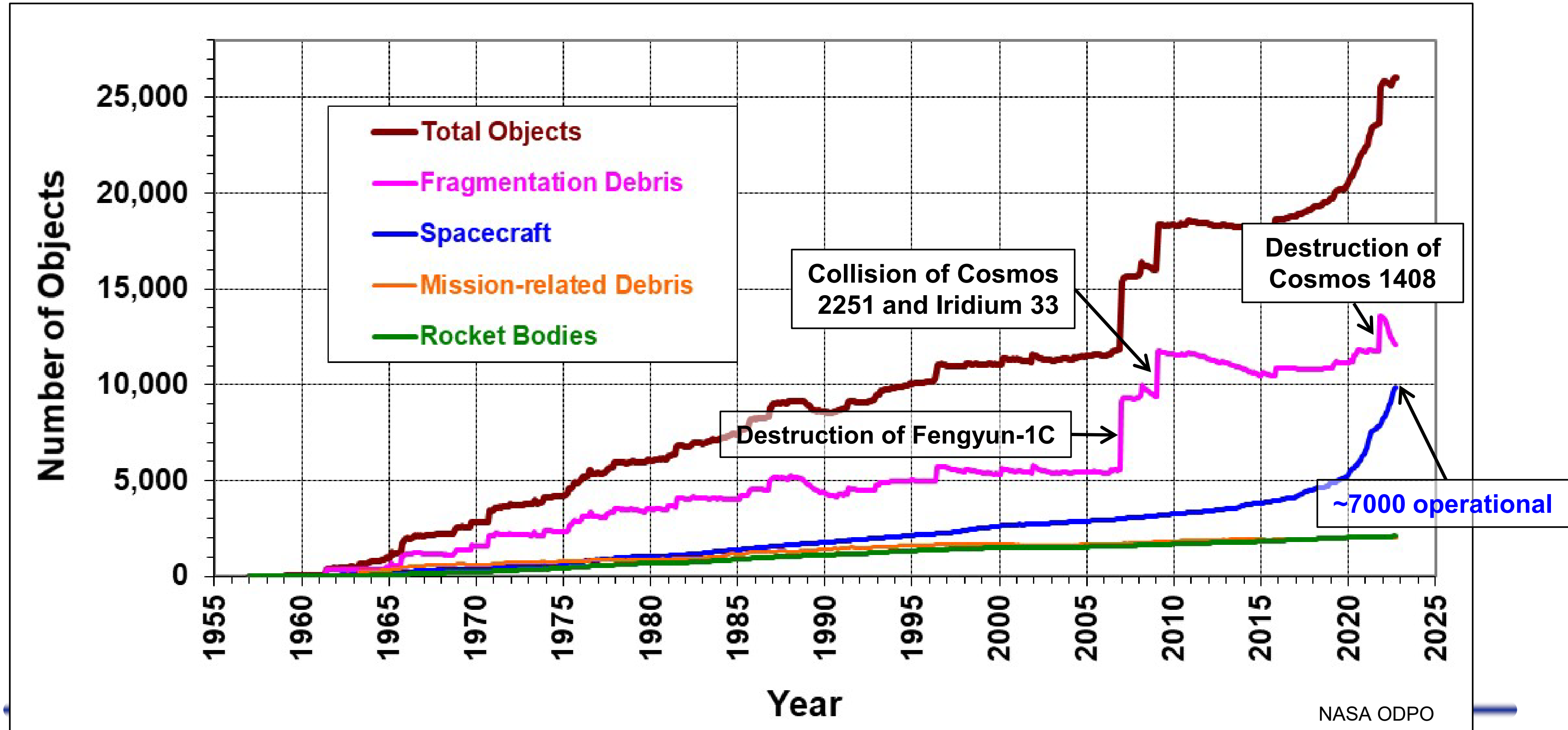
Marble size or larger (≥1 cm): ~500,000

Dot or larger (≥1 mm): >100,000,000
(a grain of salt)

- **Due to high impact speed in space (~10 km/sec in low Earth orbit, LEO), even sub-millimeter debris pose a realistic threat to human spaceflight and robotic missions**
  - **10 km/sec = 22,000 miles per hour (the speed of a bullet ~1,500 miles per hour)**
- **Mission-ending threat is dominated by small (mm-to-cm sized) debris impacts**
- **Total mass: >9500 tons LEO-to-GEO (~4000 tons in LEO)**

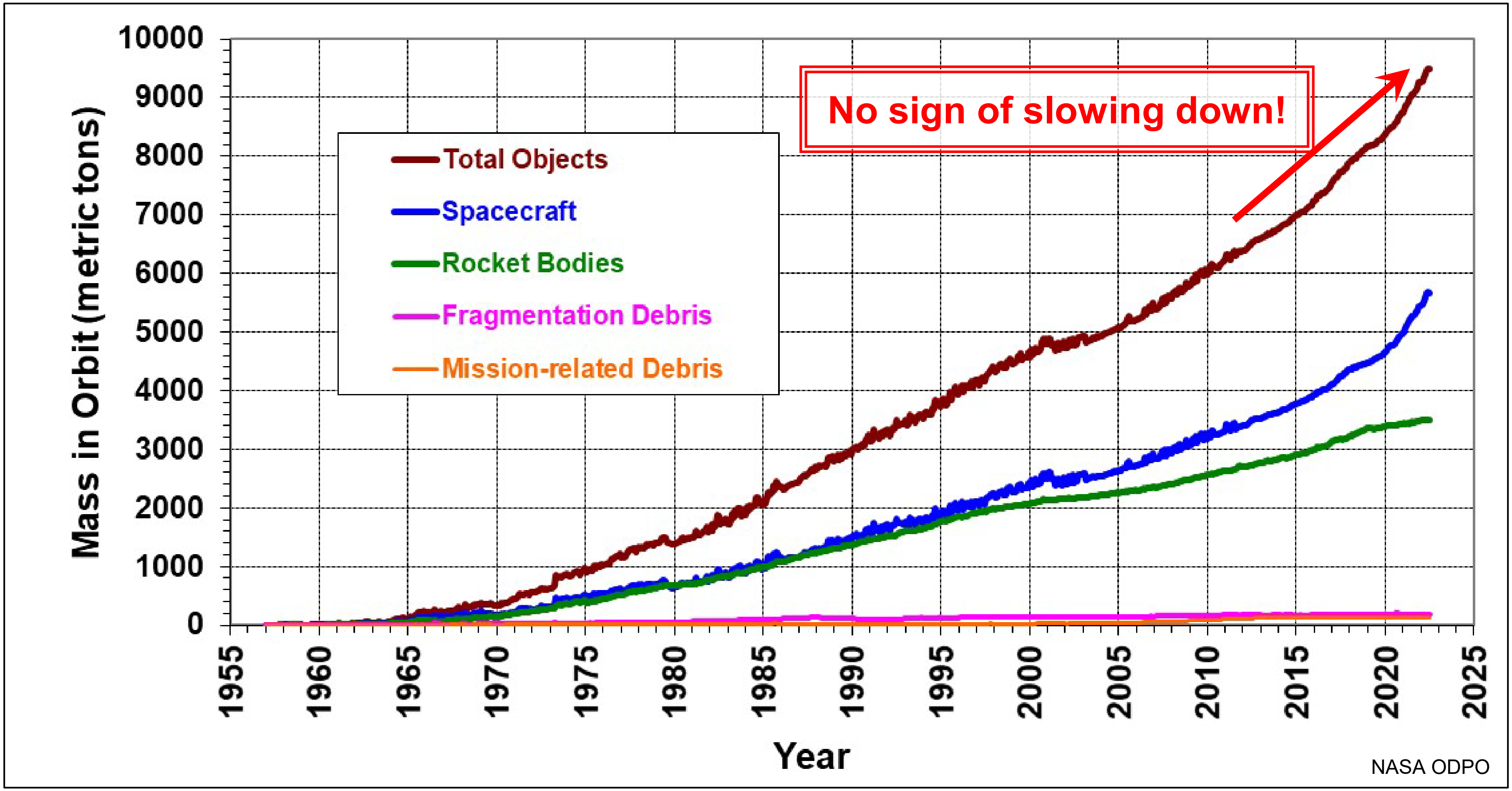
Growth of the Cataloged Populations

- **The USSF 18 SDS tracks/catalogs the largest objects in space**
  - Such objects only represent the tip of the iceberg for the orbital debris population
  - ~100,000,000 additional debris too small to be tracked but large enough to threaten human spaceflight and robotic missions exist in the environment

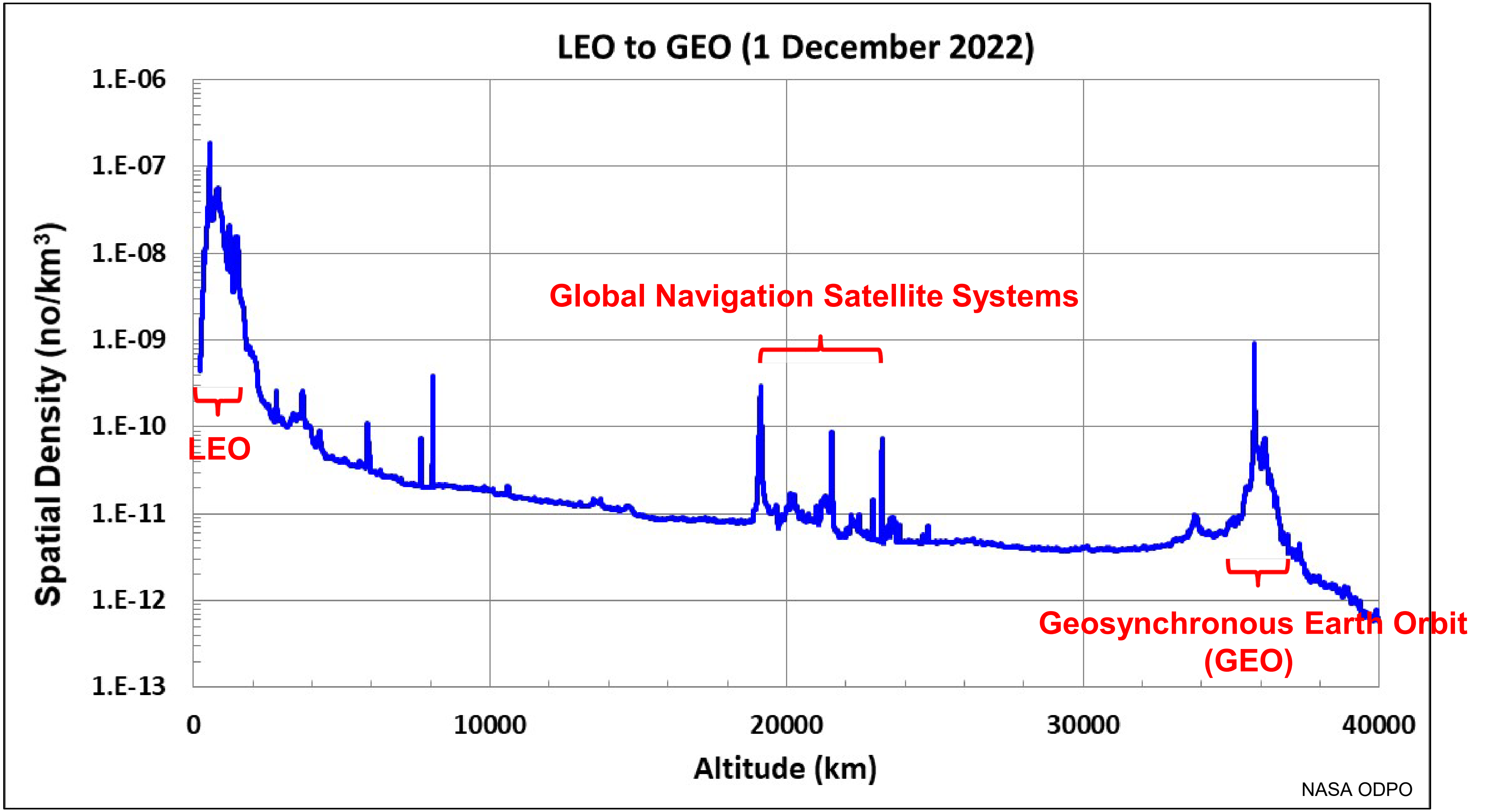


Mass in Orbit Continues to Increase

- **The total mass of material has exceeded 9500 metric tons**
  - About 4000 tons of material is in LEO (the region below 2000 km altitude)

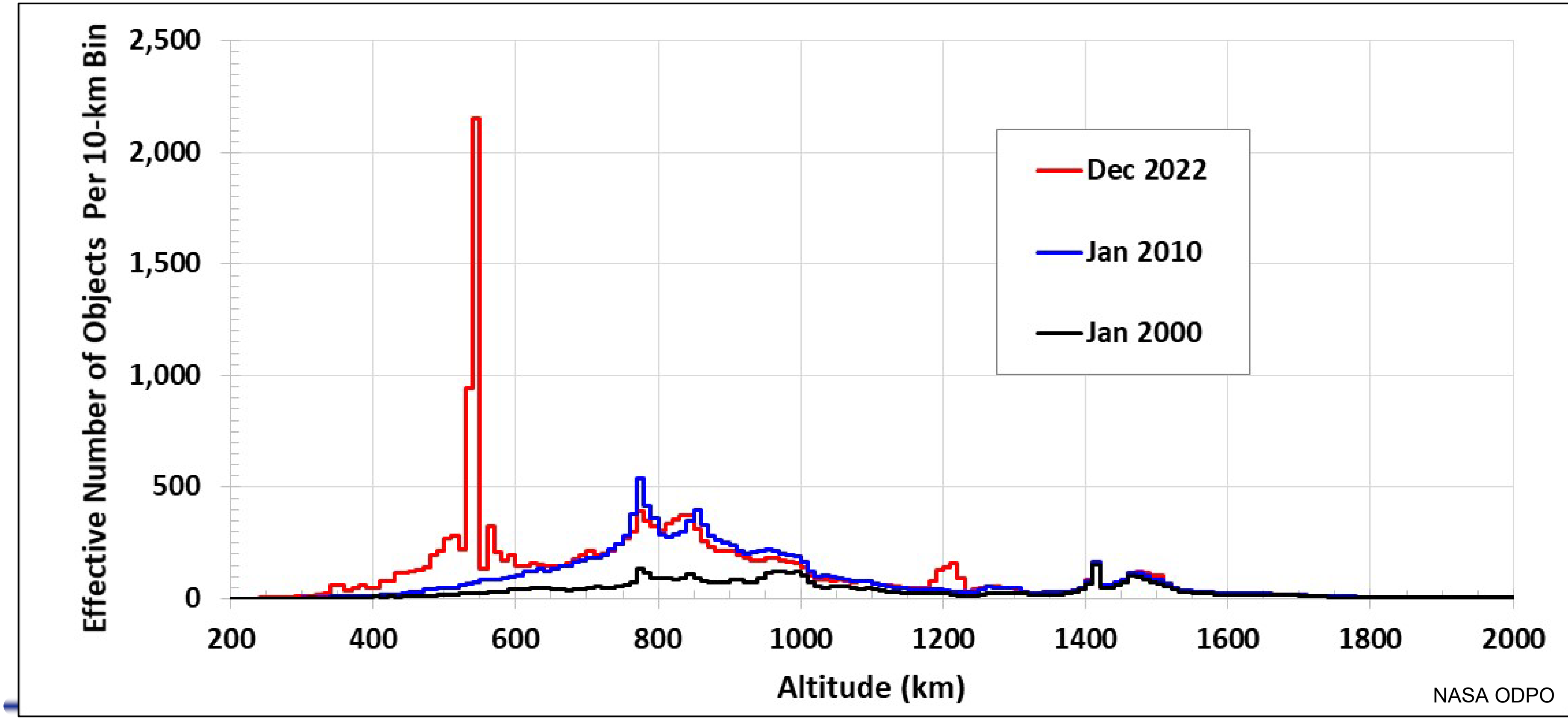


Distribution of the Cataloged Objects
– LEO-to-GEO



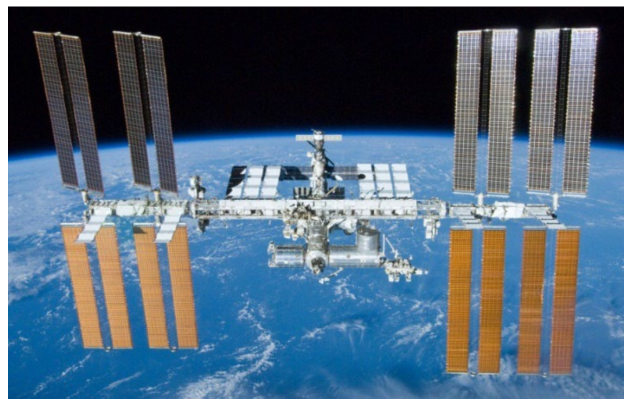
LEO Environment
– from the year 2000 to 2022

- **The LEO cataloged objects have significantly increased in 20 years**
  - 2000 to 2010: The Fengyun-1C anti-satellite (ASAT) test and the collision between Iridium 33 and Cosmos 2251 drove most of the increase
  - 2010 to 2022: Proliferation of CubeSats and deployments of large constellations were primarily responsible for the increase below ~700 km



Protecting NASA Assets From Large Debris

- **NASA has established conjunction assessment processes for its human spaceflight and robotic missions to avoid accidental collisions with objects tracked by the 18 SDS**
  - NASA also assists other U.S. government spacecraft owners with conjunction assessments and subsequent maneuvers
- **The International Space Station (ISS) has conducted 32 debris collision avoidance maneuvers since 1999**
  - Twice in 2021: The avoided objects were (1) a fragment generated from the 2007 Fengyun-1C ASAT test and (2) a fragment from the explosion of a Pegasus upper stage in 1996
  - Twice in 2022: Both were against fragments generated from the Nov 2021 Russian Cosmos 1408 ASAT test



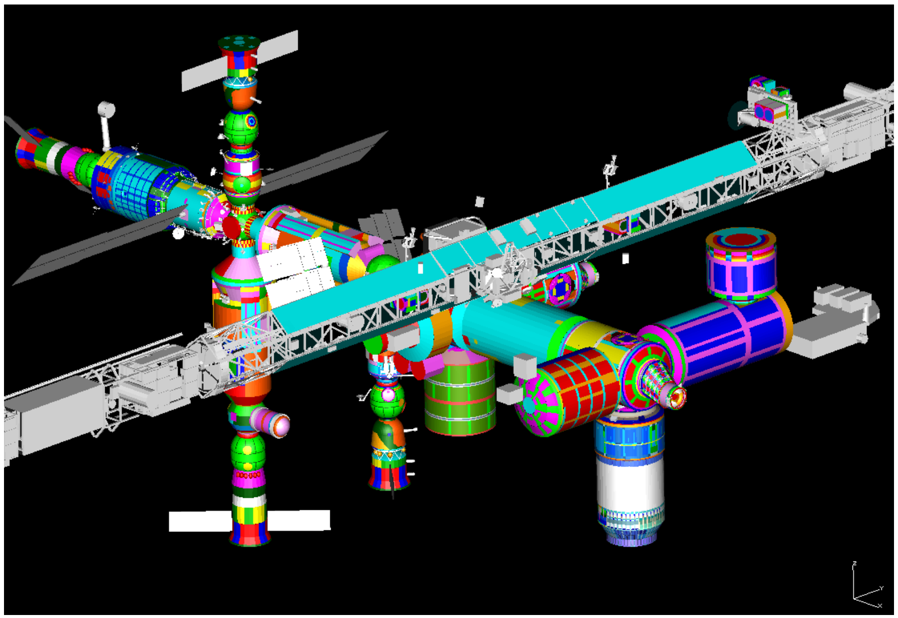
- **During 2021 NASA also executed or assisted in the execution of 13 collision avoidance maneuvers by robotic spacecraft**

Protecting the ISS From Small Debris

- **The ISS is equipped with various micrometeoroids and orbital debris (MMOD) impact protection shields**
  - The U.S. segments of the ISS are protected against orbital debris approximately 1 cm and smaller
  - The biggest threat to the ISS comes from orbital debris too small to be tracked by the 18 SDS but large enough to penetrate the protection shields (*i.e.*, debris between 1 cm and 10 cm for U.S. modules)

The ISS MMOD shielding models: each color represents a different MMOD shield configuration

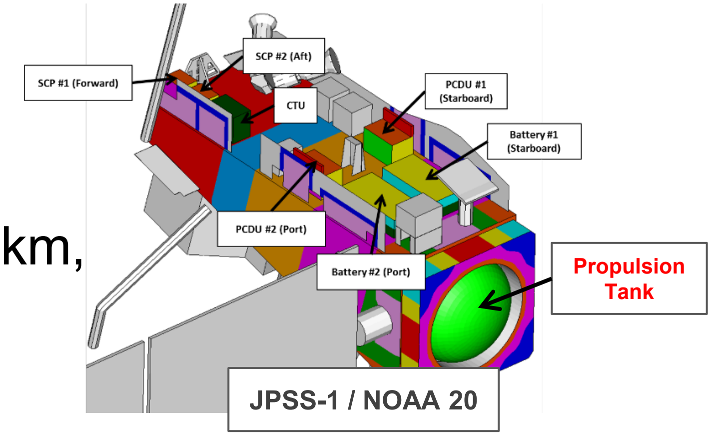
About 500 different shields protect ISS modules and external pressure vessels



NASA

Risk From Small Debris to Robotic Spacecraft

- **Millimeter-sized orbital debris represents the highest penetration risk to most operational spacecraft in LEO**
  - As concluded by a NASA Engineering and Safety Center panel study (NASA/TM 2015-218780)
- **Currently, more than 400 spacecraft operate at 600–900 km altitudes**
  - Including 18 NASA missions (A-Train@705km, NOAA@825km, IXPE@600km, *etc.*)



- **There is a lack of measurement data on millimeter-sized orbital debris above 600 km altitude**
  - Direct measurement data on such small debris is needed to support the development and implementation of cost-effective, protective measures for the safe operations of future missions

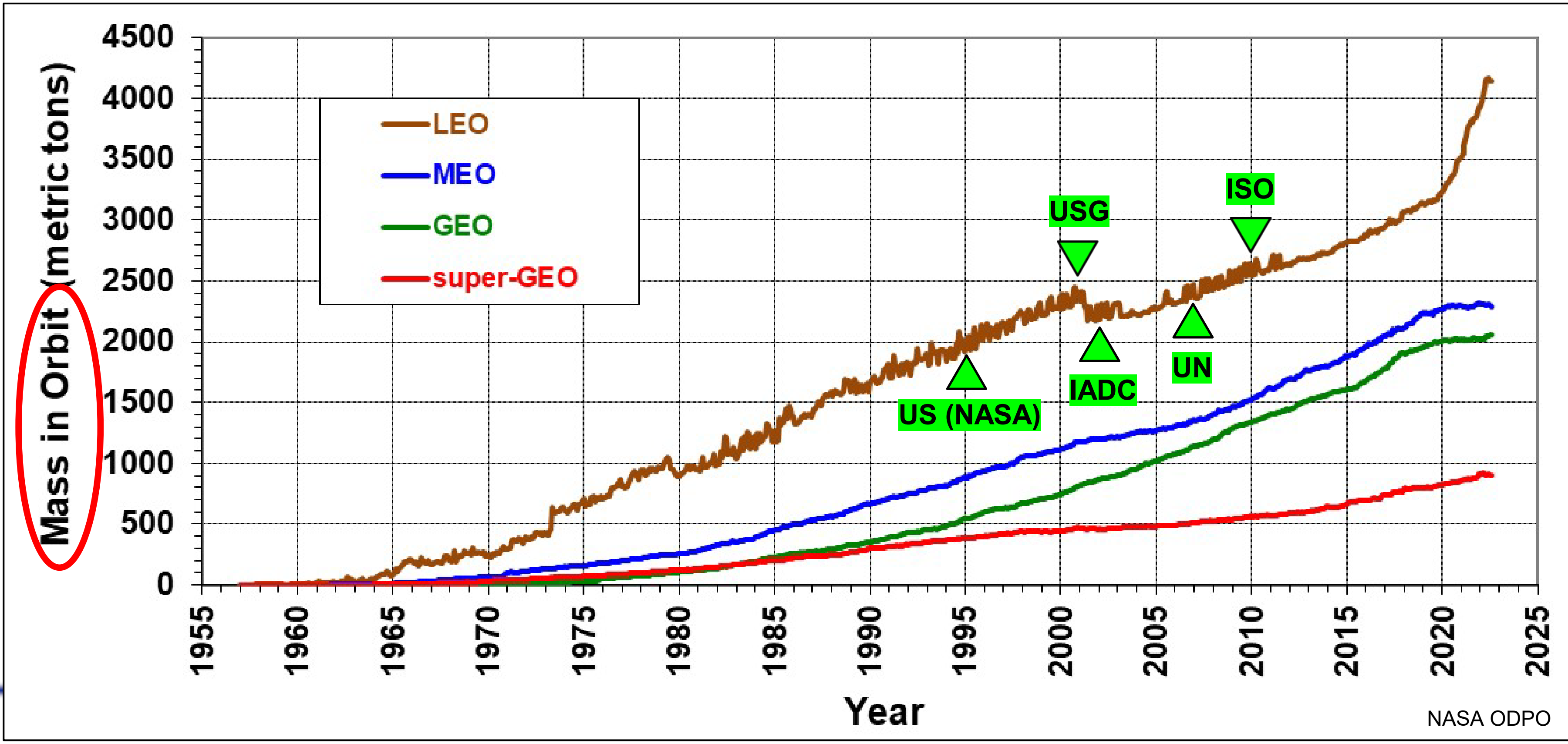
The Orbital Debris Problems

- **The long-term problem:** The orbital debris population continues to increase over time despite decades of efforts to limit the generation of new debris

- **The near-term problem:** Mission-ending risk for most operational spacecraft is driven by small, millimeter-sized orbital debris

The Long-term Orbital Debris Problem

- **The orbital debris population continues to increase over time despite decades of efforts to limit the generation of new debris**
  - Green triangles indicate when key OD mitigation guidelines and standard practices were first established
  - The global 25-year-rule compliance level has been <40% over the past 15 years



Examples of Guidelines and Best Practices
− Postmission Orbital Lifetime Limit in LEO

- **UN COPUOS Space Debris Mitigation Guidelines (2007)**
  - *"Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region…"*
- **UN COPUOS LTS Guidelines (2019)**
  - None
- **IADC Space Debris Mitigation Guidelines (2021 revision)**
  - *"Spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate manoeuvred into an orbit with an expected residual orbital lifetime of 25 years or shorter.."*

Examples of Guidelines and Best Practices
− Reentry Human Casualty Risk

- **UN COPUOS Space Debris Mitigation Guidelines (2007)**
  - *"Spacecraft and launch vehicle orbital stages…due consideration should be given to ensuring that debris that survives to reach the surface of the Earth does not pose an undue risk to people or property…"*

- **UN COPUOS LTS Guidelines (2019)**
  - "*States and international intergovernmental organizations should consider applying design techniques to minimize the risk associated with fragments of space objects surviving uncontrolled re-entry…*"

- **IADC Space Debris Mitigation Guidelines (2021 revision)**
  - "*Using 10^{-4} as the upper limit for the expected number of human casualties per re-entry is recommended. This may be accomplished by limiting the amount of surviving debris or confining the debris to uninhabited regions, such as broad ocean areas.*"

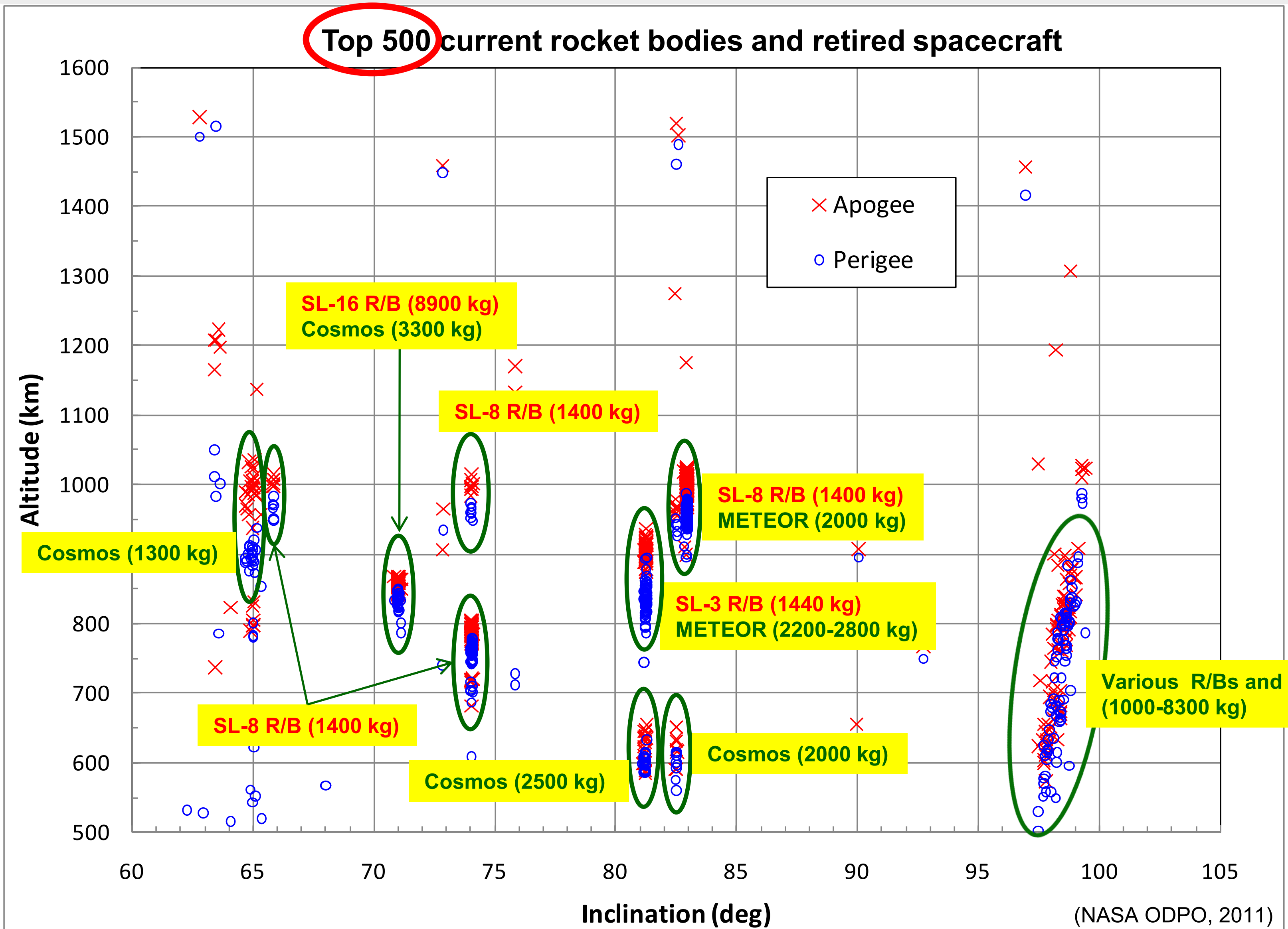
Managing the Long-term Orbital Debris Problem

- **Orbital Debris Mitigation = Prevention**
  - Limiting the generation of new debris
- **Orbital Debris Remediation = Cure**
  - Dealing with objects that already exist in the environment (*i.e.*, active debris removal, ADR)

> - **"An ounce of prevention is worth a pound of cure"**
>   - (*Prov.*) It is better/cheaper to stop something bad from happening than it is to deal with it after it has happened.

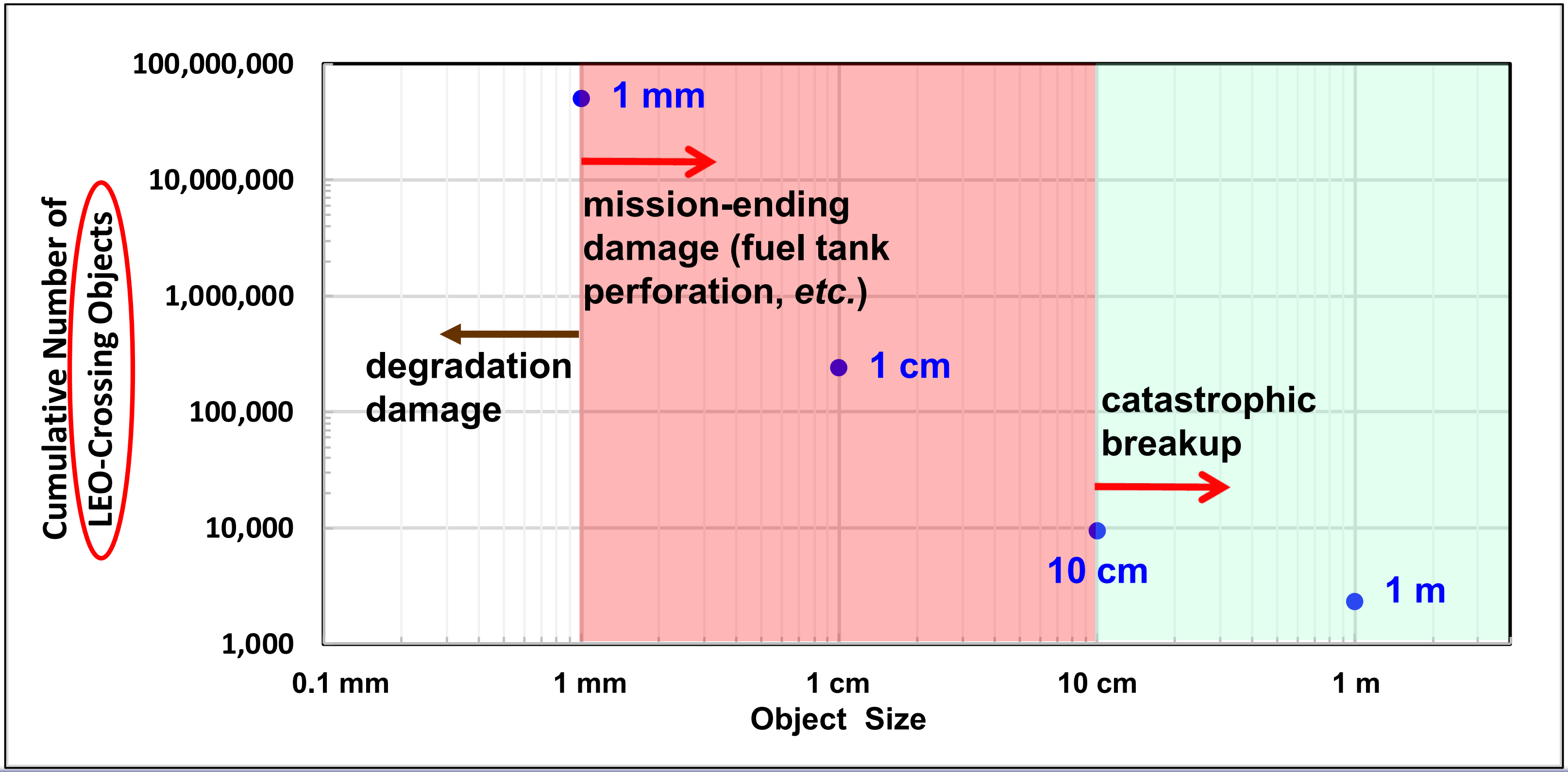
- **Cost of ESA's ClearSpace-1 mission to remove a 112 kg payload adapter: €100M**
- **Between 600 and 2000 km altitudes:**
  - Number of spent upper stages and retired spacecraft : **>2200**
  - Total mass of spent upper stages and retired spacecraft: **>1,700,000 kg**
    - **Approximately 58% Russia, 20% U.S., 11% China, 11% others**

Active Debris Removal: High Priority Targets

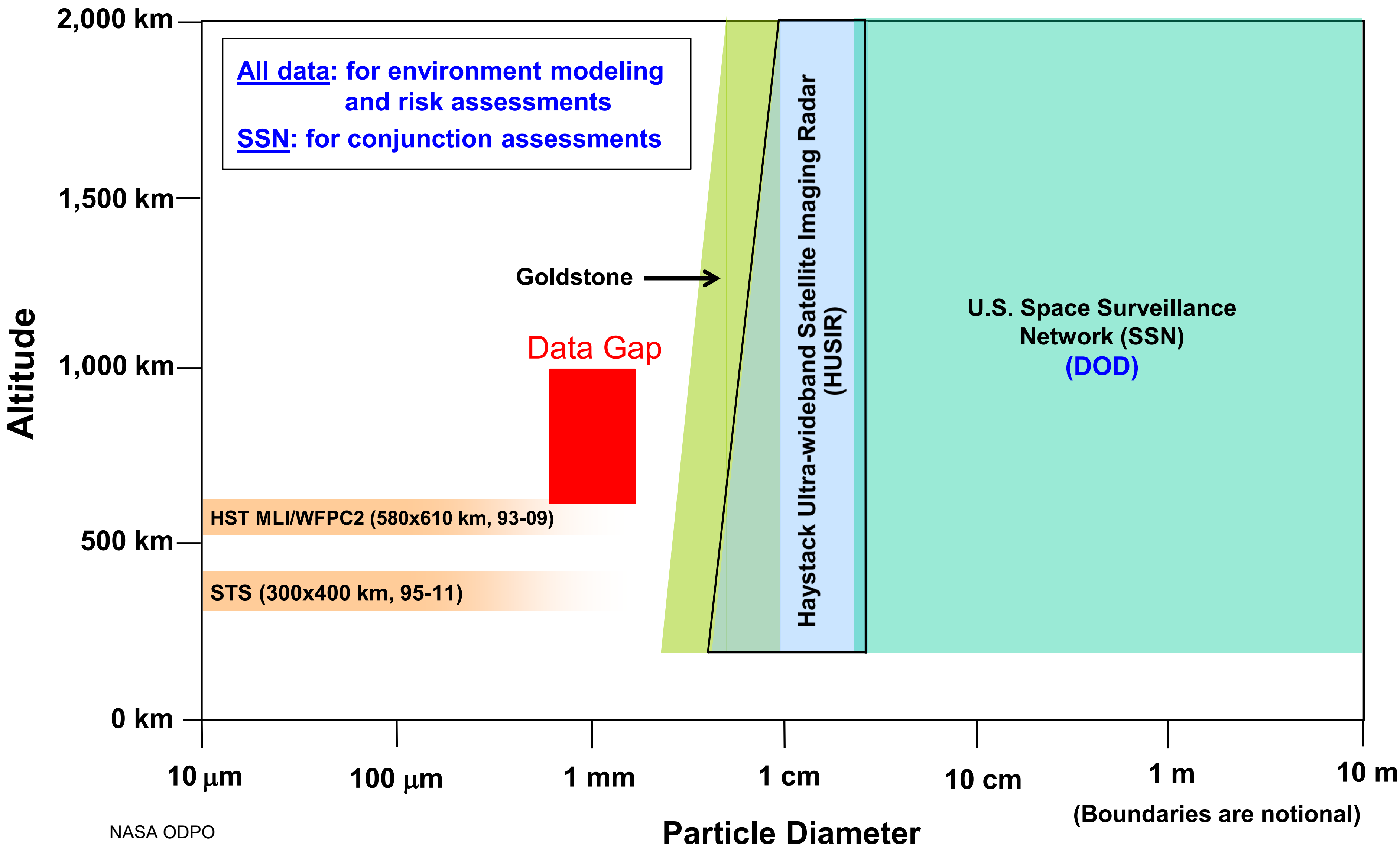


The Short-term Orbital Debris Problem

- **There is far more small debris than large debris**
  - Mission-ending risk is driven by millimeter-sized debris in LEO, but there is a lack of direct measurement data on such small debris
  - Conjunction assessments and collision avoidance against the large (≥10 cm) tracked objects only address <1% of the orbital debris mission-ending risk



Current NASA Orbital Debris Measurements in LEO



Actionable Orbital Debris Impact Risk Mitigation
- Against Large and Small Debris

	Large/trackable debris (<1% mission-ending risk)		**Millimeter-sized debris** (drives the mission-ending risk)	
Observe	Collect measurement data (radars, telescopes, *etc.*)	✓	Collect measurement data (radar, telescopes, in-situ, *etc.*)	✗
Assess	Calculate the probability of conjunction (collision)	✓	Calculate the probability of mission-ending impact collision	✓
Mitigate	1. Accept the risk or 2. Conduct an avoidance maneuver to mitigate the risk	✓	1. Accept the risk or 2. Implement cost-effective impact protective shields to mitigate the risk	✓
Time of Actions	During mission operations	✓	During mission design and development	✓

Space Situational Awareness on Orbital Debris
− Ever-changing Environment

- **Monitor the ever-changing orbital debris environment**
  - NASA has led the characterization of debris too small to be tracked by the DOD but large enough to threaten human spaceflight and robotic missions for more than 30 years
    - **Collect/analyze radar measurement data on orbital debris in LEO**
    - **Build/operate telescopes, collect/analyze optical measurement data on orbital debris from LEO to GEO**
    - **Collect/analyze space-based *in-situ* measurement data on sub-millimeter debris, develop *in-situ* sensor technologies in preparation for future mission opportunities to address the millimeter-sized OD data gap**
    - **Design/conduct laboratory experiments and collect/analyze test data for debris characterization and assess risk from orbital debris**
  - Critical data gap: millimeter-sized debris at 600-1000 km altitude; such small debris drives the mission-ending risk to LEO spacecraft

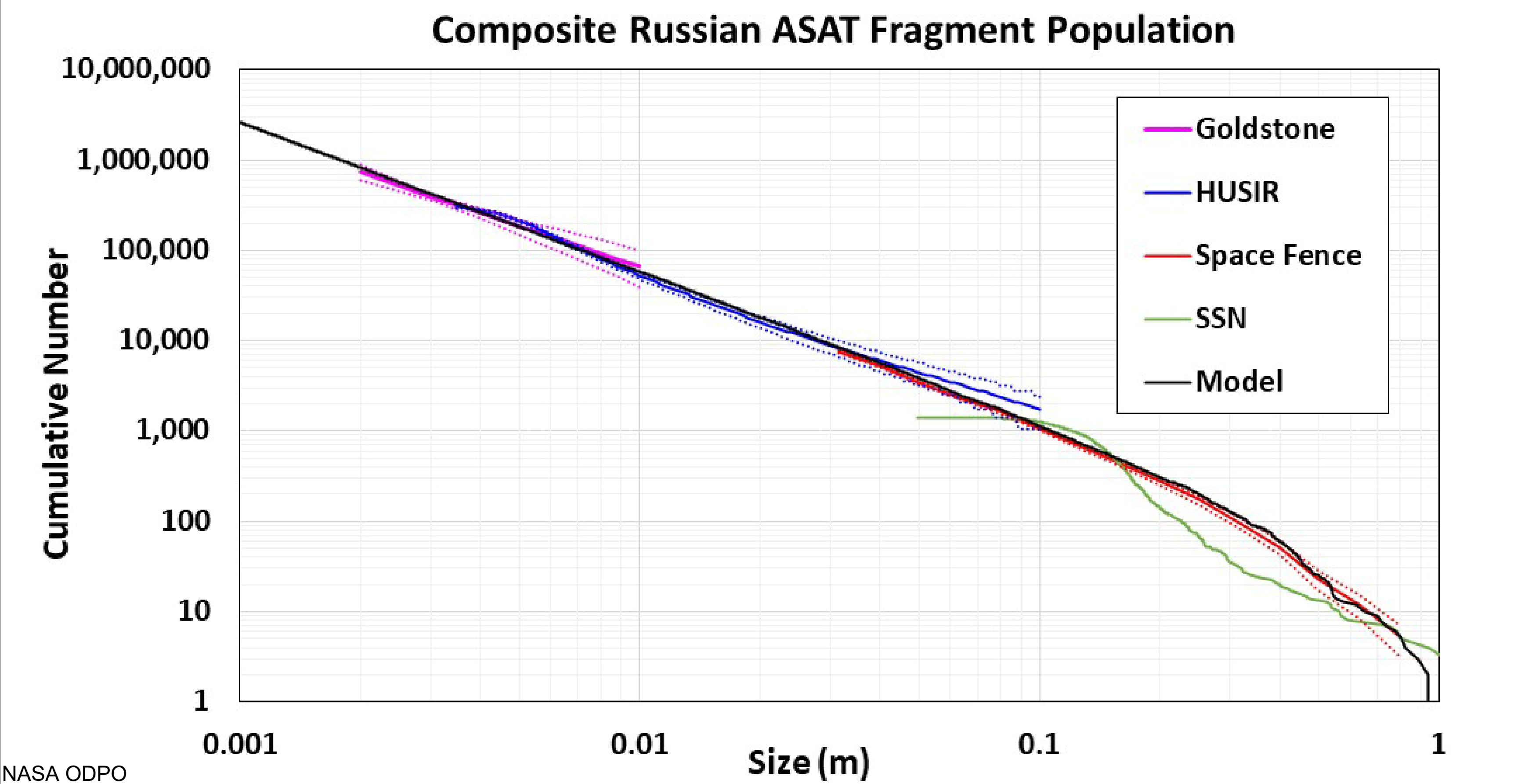
Credits, left-to-right: Reprinted with permission Courtesy of MIT Lincoln Laboratory, Lexington, Massachusetts; NASA (PIA13277); https://deepspace.jpl.nasa.gov/galleries/goldstone/#gallery; NASA ODPO; NASA (S125E007413); Arnold Engineering Development Complex/Air Force; NASA HVIT

Space Situational Awareness on Orbital Debris
− Major Breakups: Cosmos 1408 Fragments

- **The Russian ASAT test on Cosmos 1408 (1750 kg, 490 x 465 km altitude) occurred on 15 November 2021**
- **The NASA Orbital Debris Program Office (ODPO) led efforts to assess risks from Cosmos 1408 fragments to the ISS and developed mitigation measures to protect the crew**
- **The ODPO also made special arrangements to collect timely radar measurement data on small Cosmos 1408 fragments immediately after the Russian ASAT test occurred**
  - MIT/LL's Haystack Ultrawideband Satellite Imaging Radar (HUSIR)
  - JPL's Goldstone radar
  - DOD's Space Fence
- **The ODPO used the measurement data to validate its risk assessments and to update the Orbital Debris Engineering Model (ORDEM) with a new Cosmos 1408 fragment component**

Cosmos 1408 Fragments – Data and Model

- **NASA's prediction matches the radar measurement data well**
- **The updated ORDEM 3.2 with a new Cosmos 1408 fragment component was released to the space community in March 2022**



NASA ODPO

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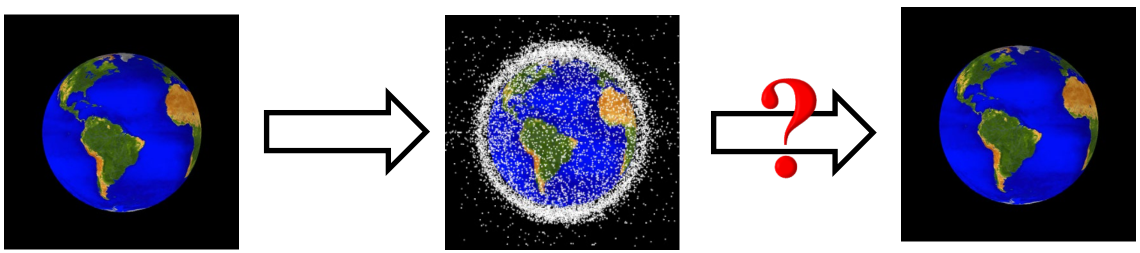
Forward Challenges
– Space Situational Awareness & Space Traffic Management

- **Key priorities to enhance the safety, stability, and sustainability of operations in the future space environment**
  - Improve space situational awareness on small debris, especially the millimeter-sized orbital debris in LEO, to better protect future space missions
  - Promote better global compliance with existing orbital debris mitigation best practices to slow down the debris population growth
  - Establish long-term goals, combining orbital debris mitigation and remediation, to preserve the near-Earth space environment



The 2nd International Orbital Debris Conference (IOC II)

- **Preparation is underway for the 2nd International Orbital Debris Conference (IOC II)**
  - This quadrennial conference will take place in Sugar Land, Texas (greater Houston area), 04-07 December 2023
  - The four-day conference will cover all aspects of micrometeoroid and orbital debris research, mission support, and other activities
    - **Measurements, modeling, hypervelocity impacts, operations and mission support, and environment management**

All are invited to attend the 2023 IOC!

https://www.hou.usra.edu/meetings/orbitaldebris2023/