Meteoroid and Orbital Debris Risk and Mitigation

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Introduction

My Background

Principal Engineer for the NASA Engineering and Safety Center (NESC)

- 32 years with NASA
- 17 years with the NESC at NASA Langley Research Center, Hampton, VA
- Previous 15 years at Kennedy Space Center in Space Shuttle engineering
  - Environmental Control and Life Support System
  - Power Reactant Supply and Distribution/Fuel Cells System

NESC Meteoroid and Orbital Debris (M/OD) Technical Expert

- Led several teams addressing aspects of M/OD including :
  - M/OD environment modeling
  - Failure criteria determination
  - Shield design
  - M/OD risk assessment and mitigation

Past AIAA Space Operations and Support Technical Committee Chair

Meteoroids and Orbital Debris (M/OD or MMOD)

Meteoroids

- Small (<~1 m), naturally occurring bodies in space
- Primarily dust or ice particles originating from comets or asteroids
- Micrometeoroid = meteoroid smaller than grain of sand

Orbital Debris

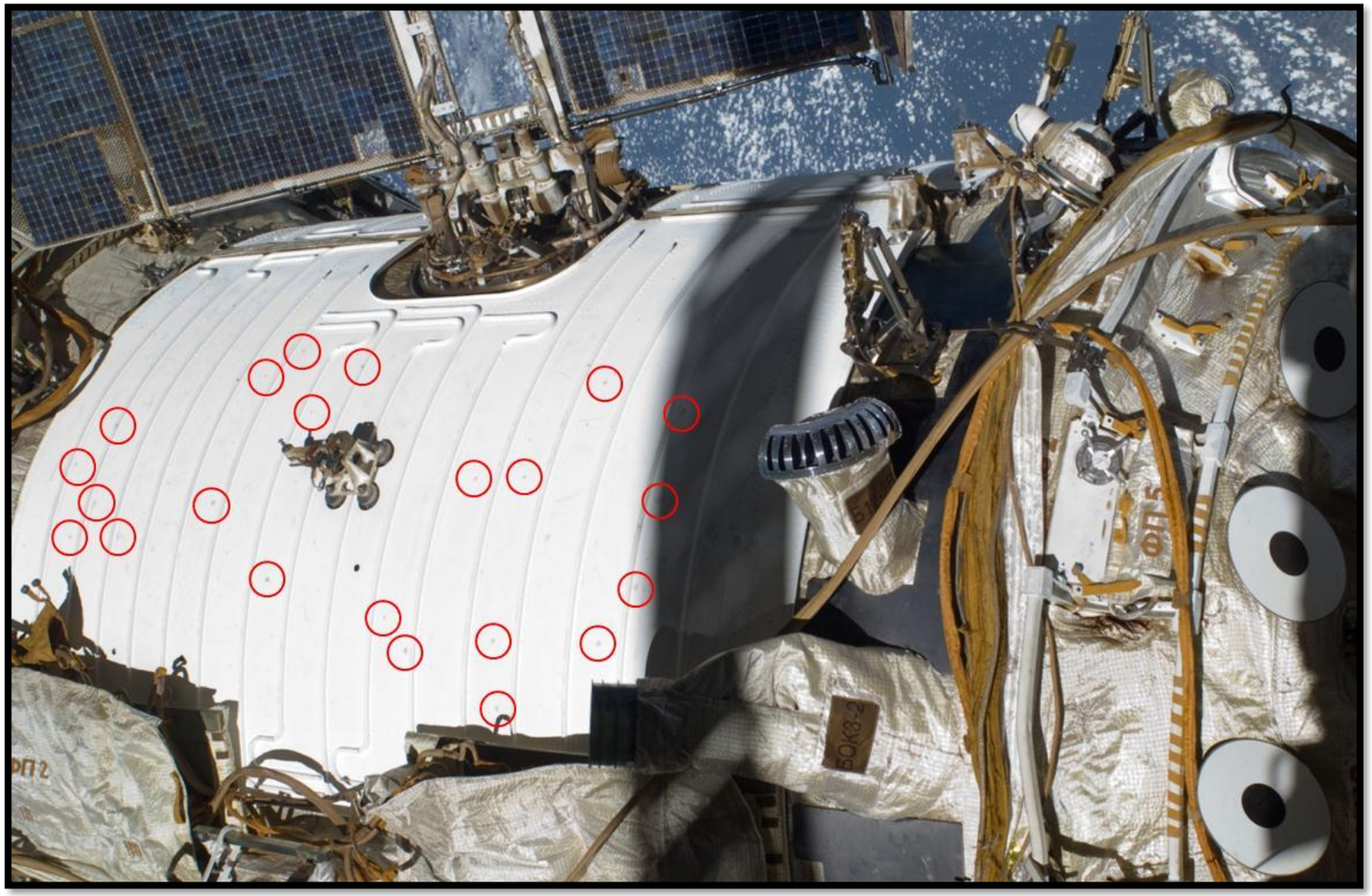
- Manmade objects not carrying out a useful function
- Examples: intact objects (nonoperational satellites, rocket bodies), fragmentation debris, mission debris (tools, covers, deployment mechanisms)

M/OD pose hazards to space assets due to possibility of hypervelocity impact

- Up to 20 km/s for orbital debris
- Up to 70 km/s for meteoroids

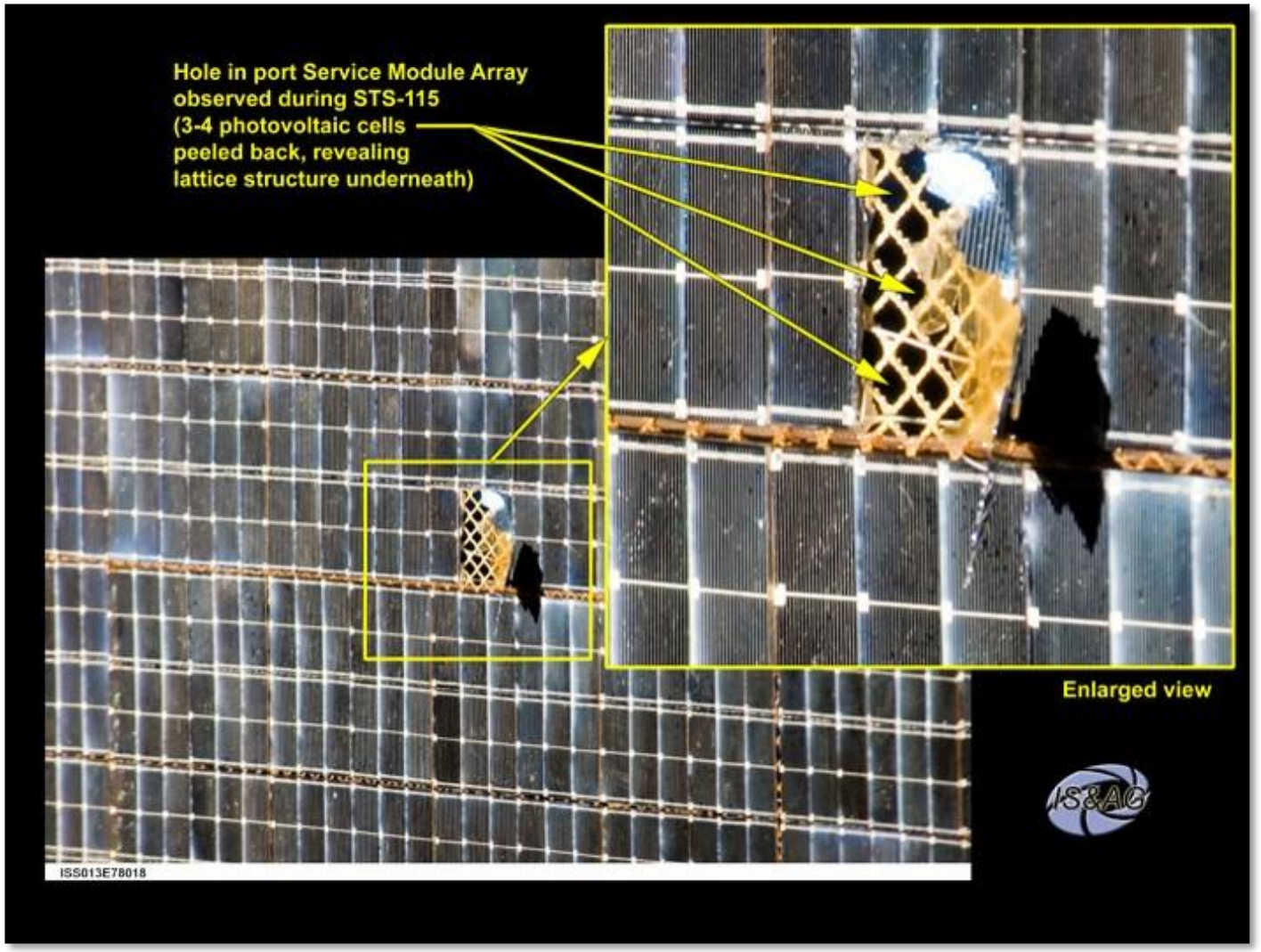
M/OD typically highest risk for crewed and robotic missions

M/OD Damage: ISS



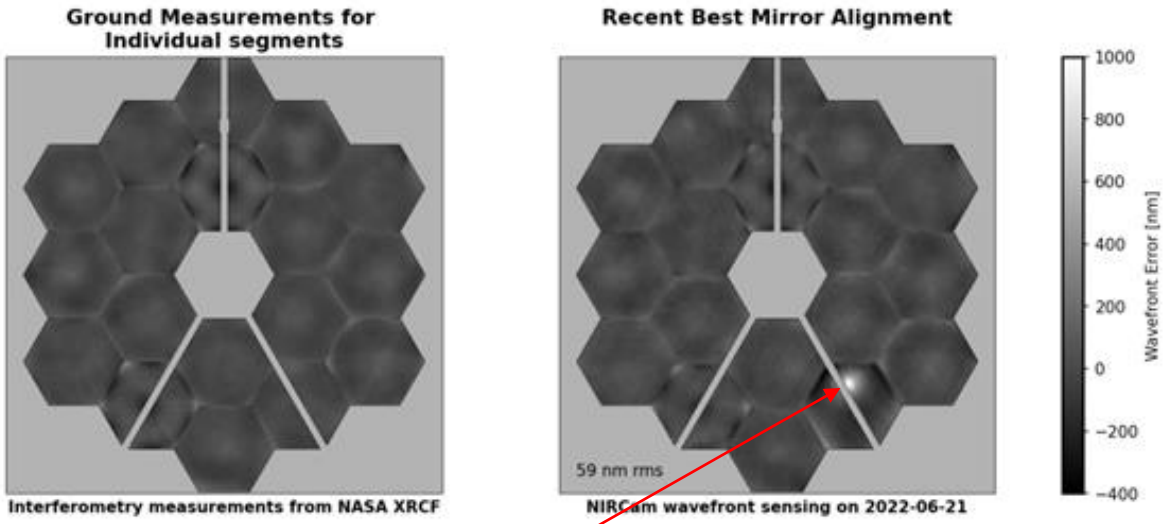
Multiple M/OD Impact Sites on ISS Service Module

M/OD Damage: ISS

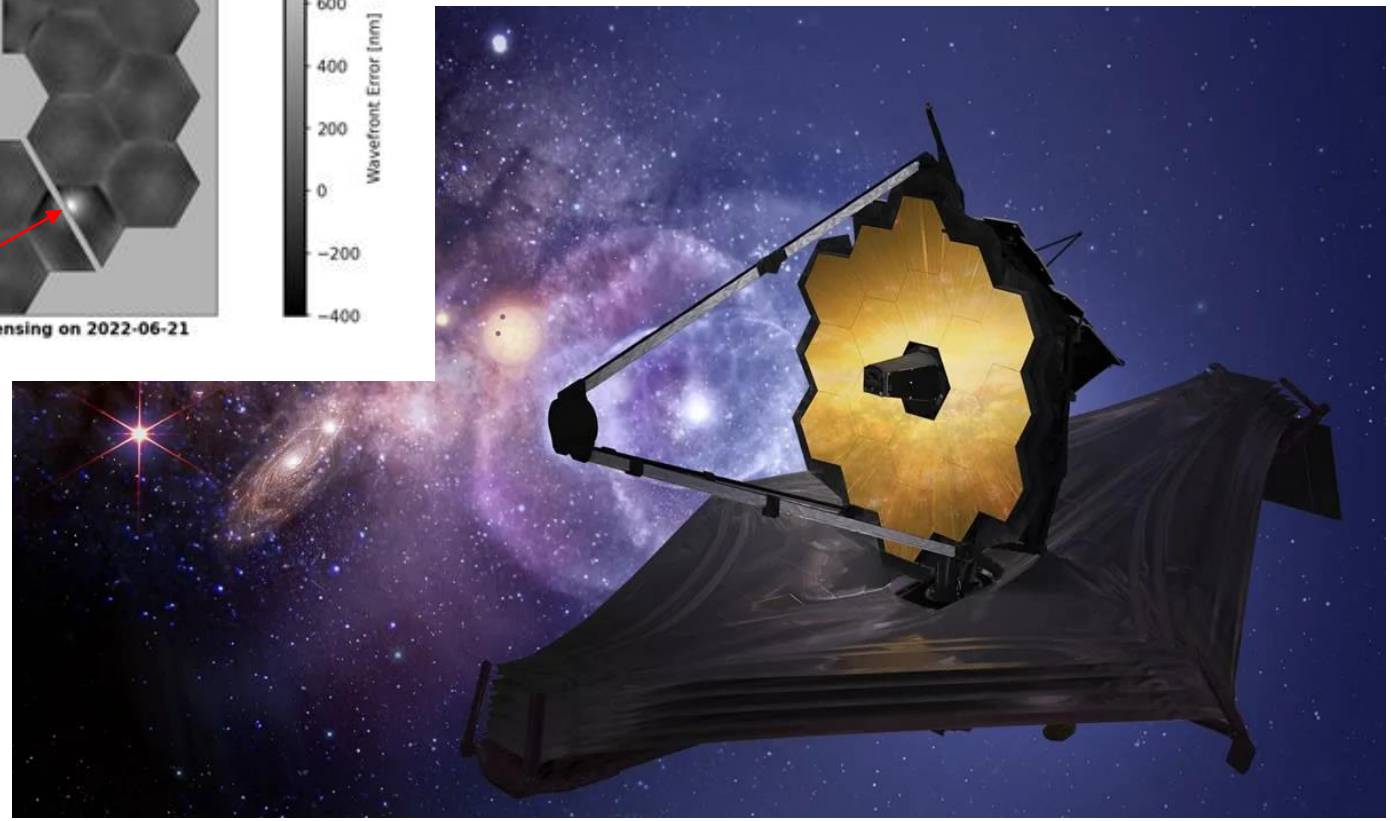


ISS Solar Array Damage

M/OD Damage: James Webb Space Telescope

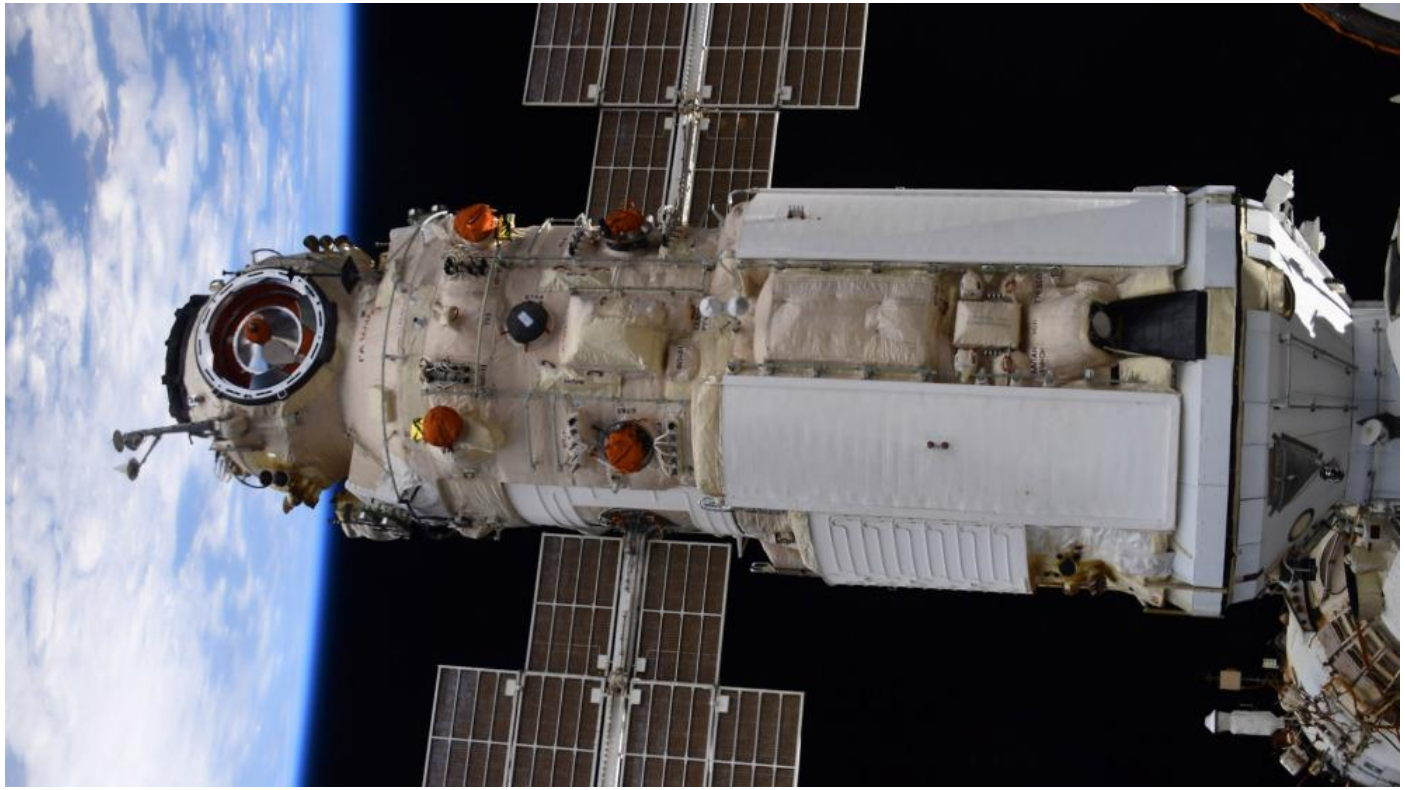


Meteoroid Damage to JWST



- As of March 2023, 37 meteoroid impacts detected
- Avg of 2.6 impacts per month
- C3 mirror impact in March 2022 was the largest and resulted in uncorrectable damage

M/OD Damage:Russian ISS Vehicles



Russian ISS Multipurpose Laboratory Module

In less than a year, Russian ISS modules and visiting vehicles have developed three coolant leaks—all attributable to M/OD

M/OD Damage:ISS Tool Damage



Damage on ISS EVA D-Handle Tool Stored on Z1 Truss

Meteoroids/Micrometeoroids

Meteoroid Environment

Definitions

- Meteoroid: small naturally occurring body in space
- Meteor: light and ionization produced when meteoroid enters atmosphere
- Meteoroid Stream: trail of meteoroids left in the wake of a comet (or rarely an asteroid)
- Meteor Shower: visible manifestation from Earth of meteoroid stream encounter

Sporadic Meteoroids

- Background meteoroids providing constant risk
- Not associated with meteoroid streams or meteor shower
- Long-term risk driven by sporadics, not showers/streams

Local meteoroid flux affected by location

- Planets can shield or focus meteoroids
- Meteoroids have preferential radiants (source directions)
- Varies with distance from the sun

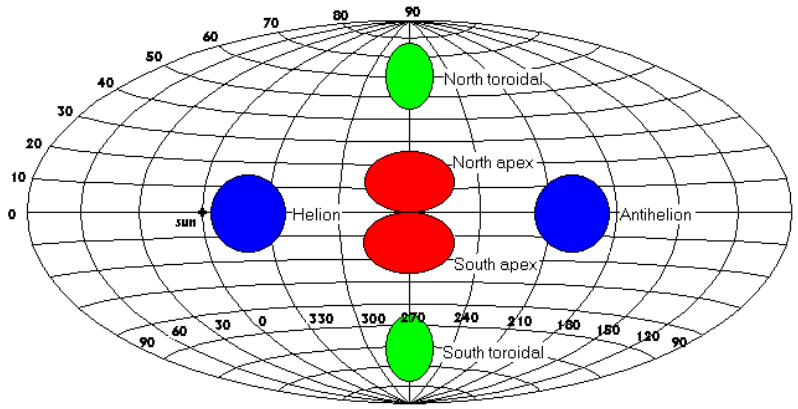


Meteor

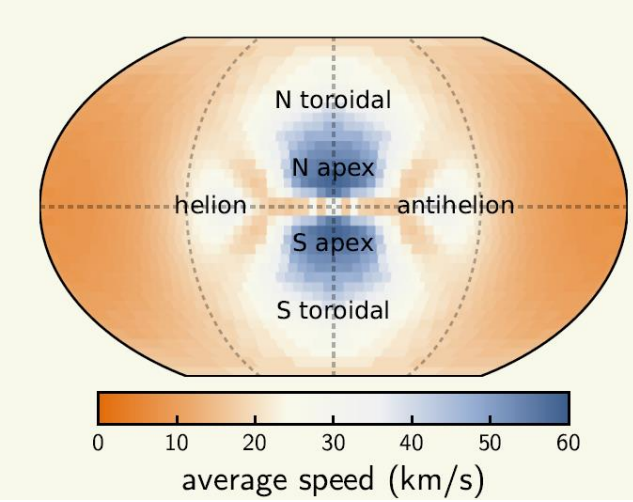
Sporadic Meteoroids

Sporadic Meteoroid Environment Models

- Meteoroid Engineering Model (MEM)
  - Model used by NASA
  - MEM Version 3 currently in use
  - Developed and Maintained by NASA's Meteoroid Environment Office (MEO) at the Marshall Space Flight Center
- Other Models
  - LunarMEM for near-Moon environment
  - ESA's Meteoroid and Space Debris Terrestrial Environmental Reference (MASTER)
  - Grun Flux Model, Divine-Staubach (older models)



Sporadic meteoroid radiants



Sporadic meteoroid speed distribution

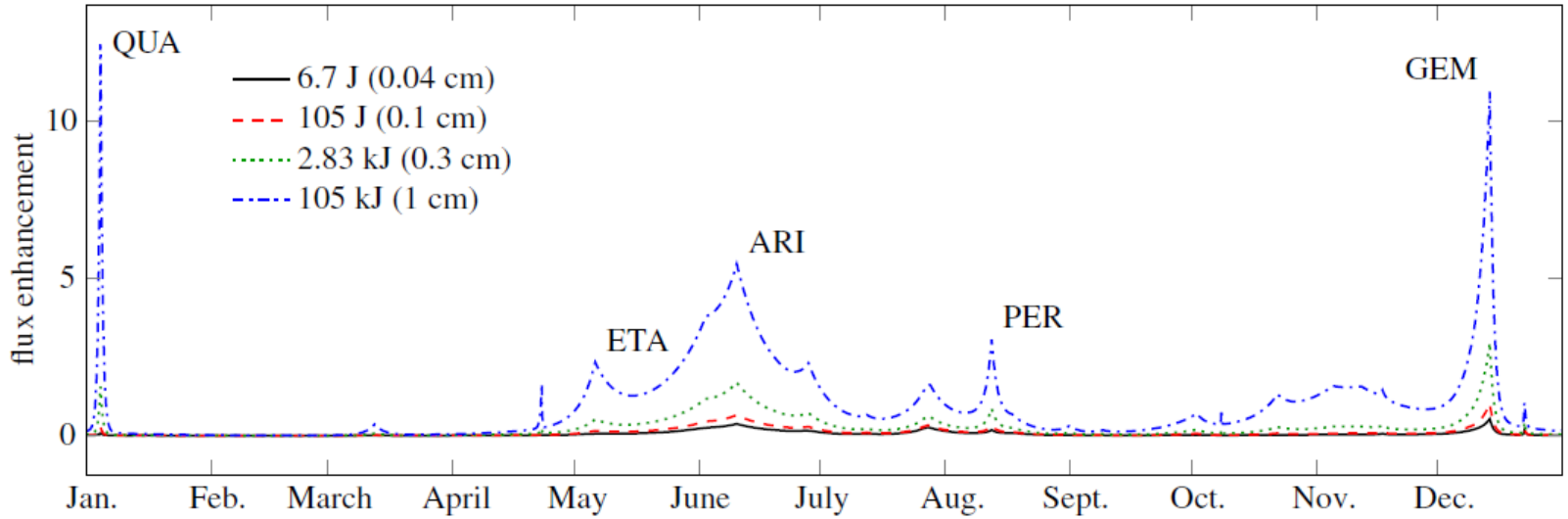
Meteoroid Streams/Meteor Showers

Meteoroid streams/meteor showers not included in MEM

- Risk for long-term assessments negligible compared to sporadics
- Elevated flux can increase risk for duration of shower

Strength expressed as flux enhancement factor over sporadic flux (graph below)

- Calculated for energy levels to account for expected damage independent of velocity
- Higher energy levels have higher flux enhancement (i.e., higher proportion of higher energy particles in showers than sporadics



Meteor Showers

Meteor shower intensity measured by zenith hourly rate (ZHR)—number of naked-eye meteor observations from Earth under ideal conditions

Shower intensity can vary from year-to-year

- Occasionally outbursts (ZHR higher than average) and storms (ZHR>1000) can occur

Table shows largest meteor showers predicted for 2023

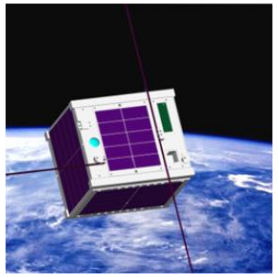
shower name	ID	max time (UT)	max ZHR
Quadrantids	QUA	2023-01-04 00:25	120
eta Aquariids	ETA	2023-05-04 12:31	129
Daytime zeta Perseids	ZPE	2023-06-03 12:08	20
Daytime Arietids	ARI	2023-06-11 04:46	50
Southern mu Sagittariids	SSG	2023-06-20 09:19	2
beta Taurids	BTA	2023-06-28 23:36	2
Southern delta Aquariids	SDA	2023-07-28 13:49	30
alpha Capricornids	CAP	2023-07-29 03:38	4
Perseids	PER	2023-08-13 08:50	80
kappa Cygnids	KCG	2023-08-18 12:27	5
Daytime Sextantids	DSX	2023-10-03 05:45	5
October Draconids	DRA	2023-10-09 07:48	3
Orionids	ORI	2023-10-23 04:25	30
Southern Taurids	STA	2023-11-06 00:32	5
Northern Taurids	NTA	2023-11-12 23:47	5
Geminids	GEM	2023-12-14 19:59	140
Ursids	URS	2023-12-22 16:23	12

Orbital Debris

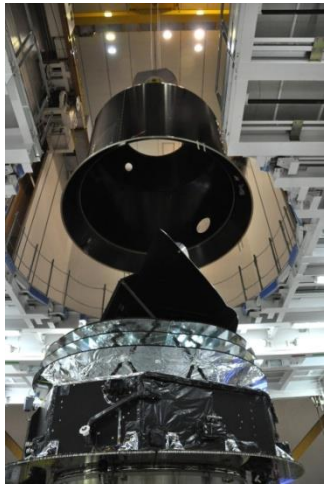
Orbital Debris

Any man-made object in space not serving a useful purpose

Intact Objects (>1 m)
- Non-operational spacecraft
- Spent launch vehicle stages

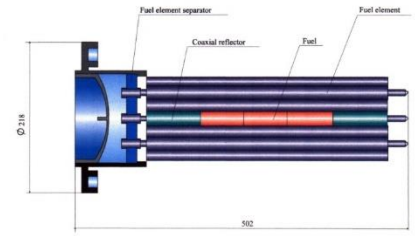




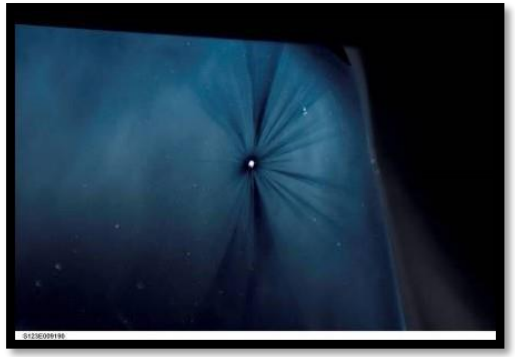


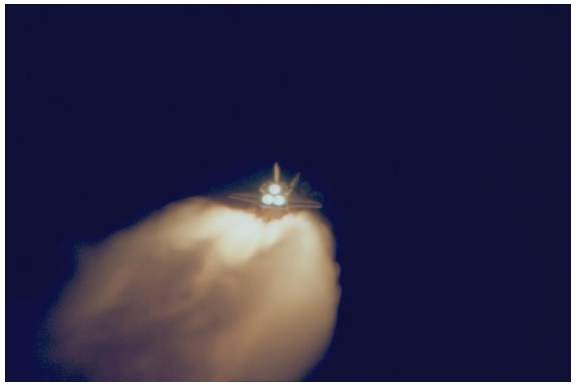


Fragmentation Debris (<1 m)
- Caused by deliberate or accidental collisions
- Fragmentation events also due to on-board energy sources
  - E.g., propellants, batteries, pyrotechnic devices



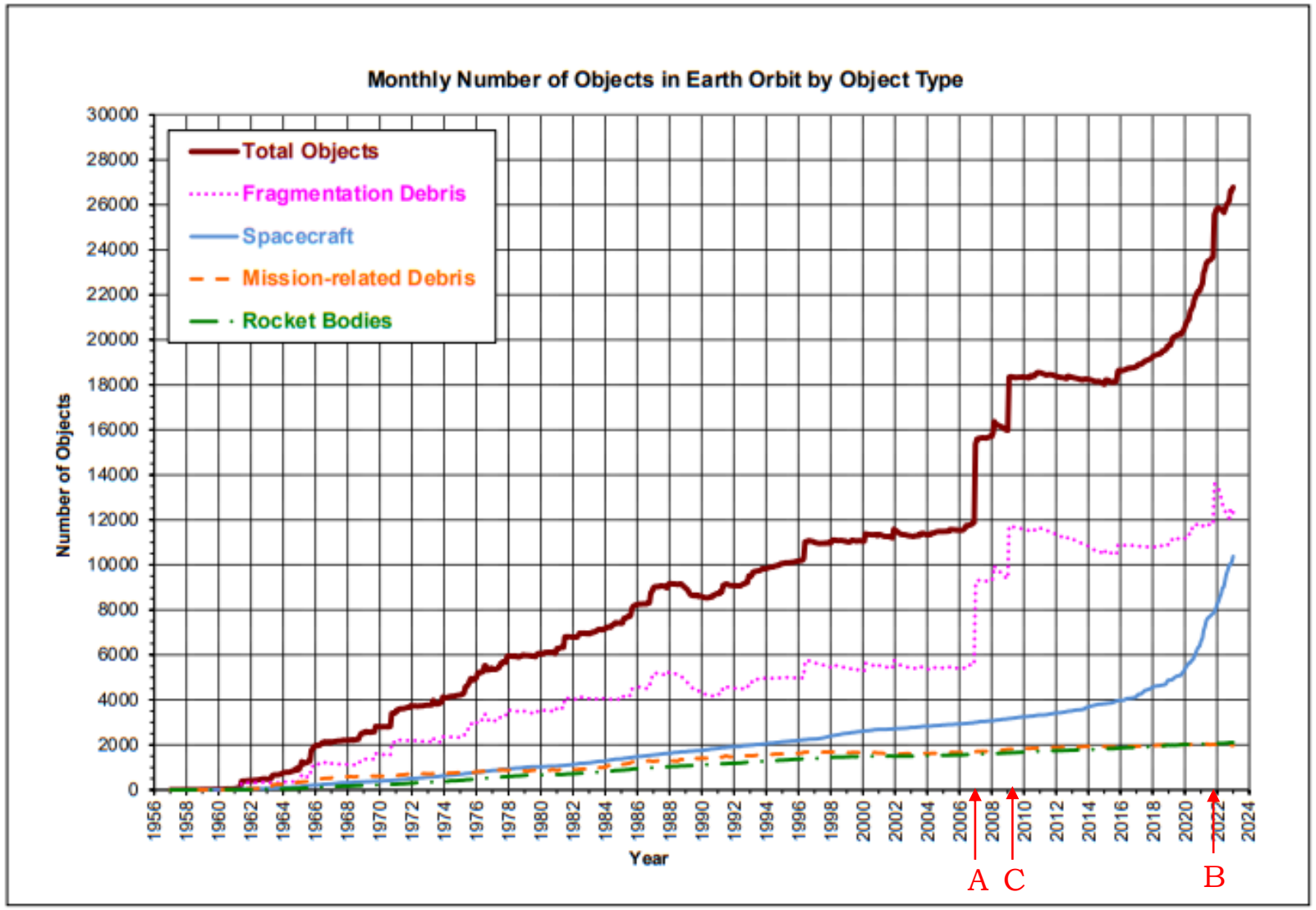
Mission-related Debris (<1 m)
- Deployment mechanisms
- Inadvertent jettisons (e.g., tools)
- Solid rocket motor slag
- Coolant droplets





Surface Degradation Debris (<1 mm)
- Small debris impact ejecta
- Paint flakes

Orbital Debris Growth by Number of Cataloged Objects

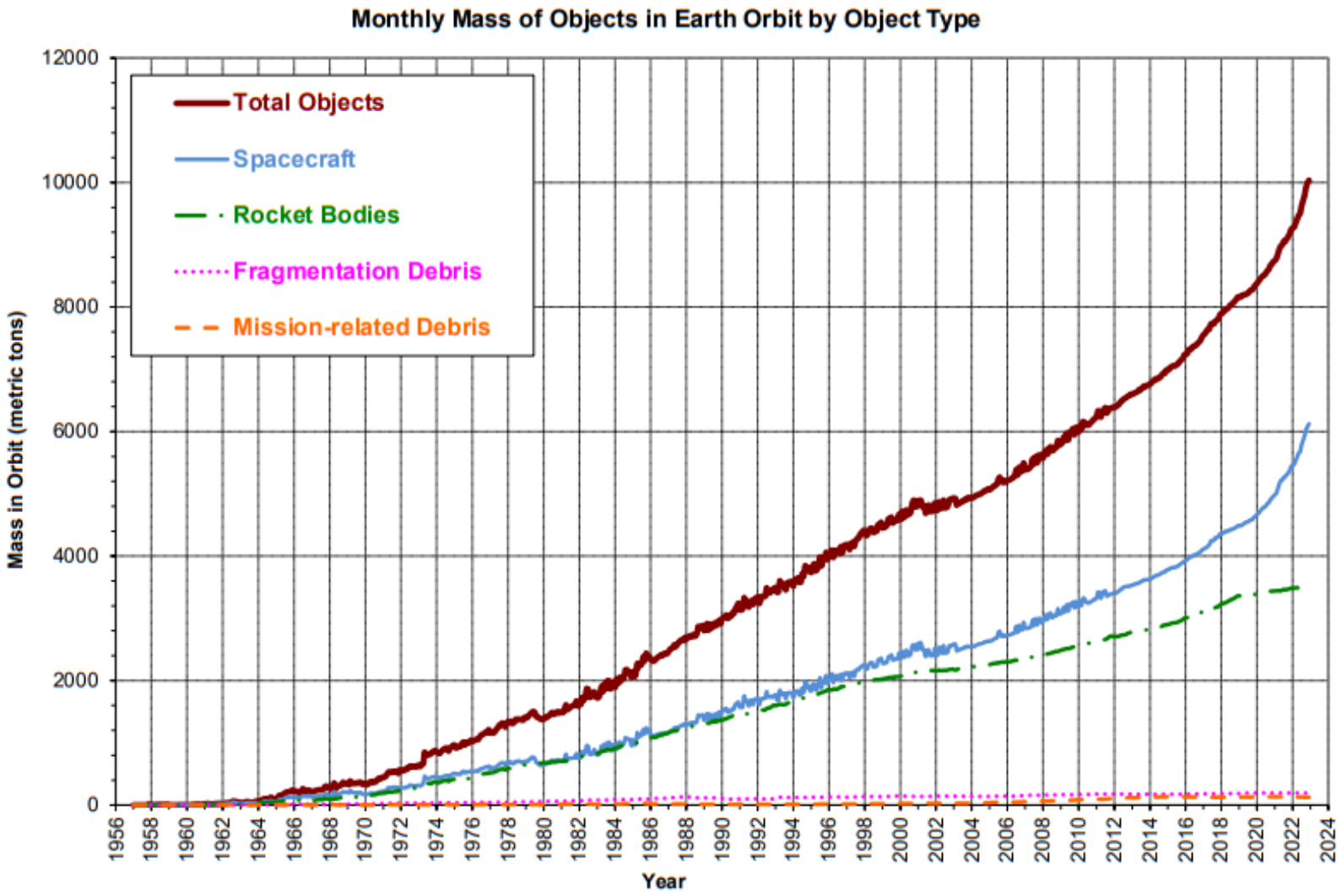


Three Worst Fragmentation Events

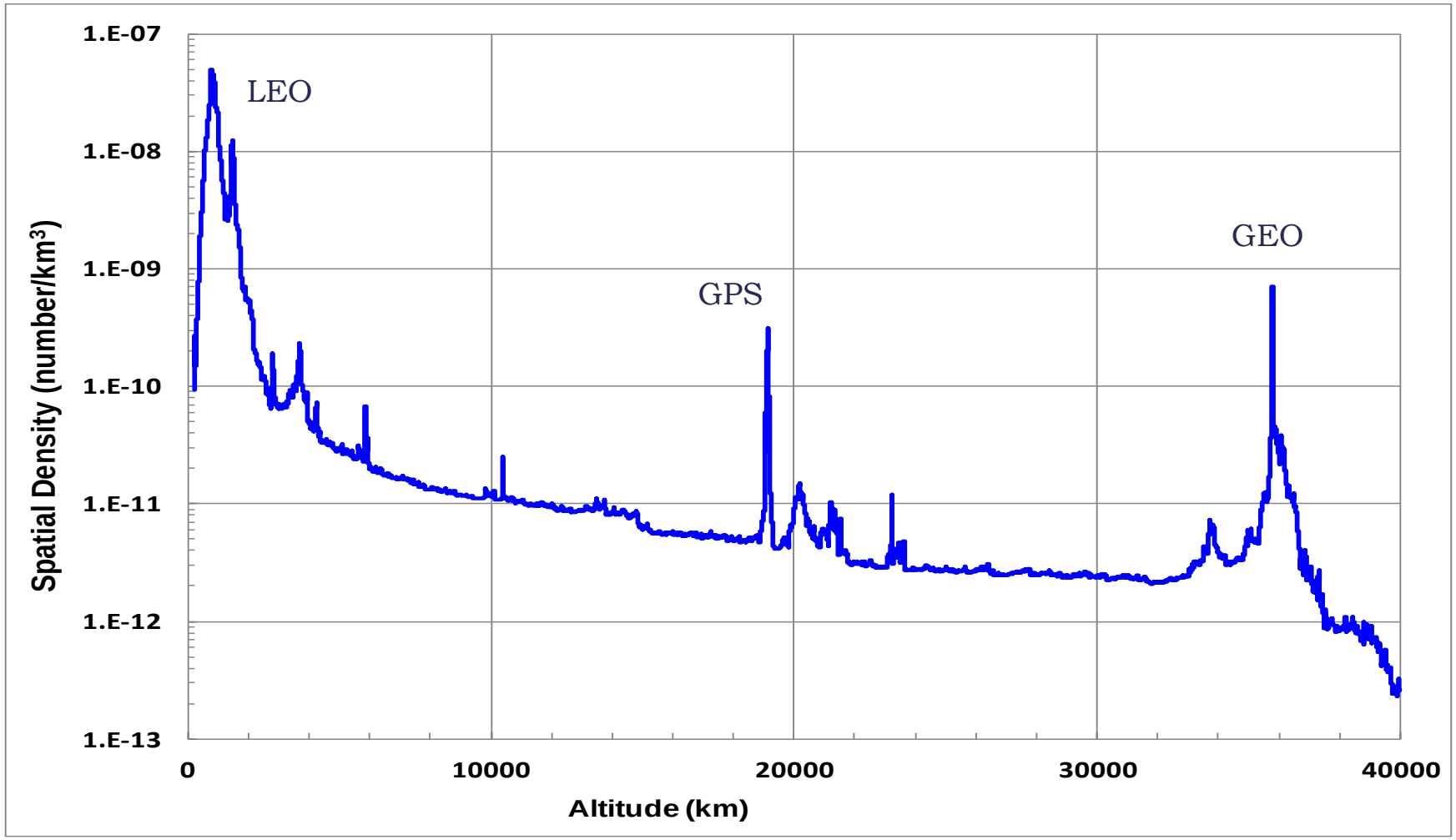
- A: Fengyun-1C ASAT
  - 3532 DC/2793 SIO
- B: Cosmos 1408 ASAT
  - 1785 DC/364 SIO
- C: Iridium-33/Cosmos-2251 Collision
  - 1715 DC/1021 SIO

Key:
ASAT=Anti-satellite Test
DC=Debris Cataloged
SIO=Cataloged Debris Still in Orbit

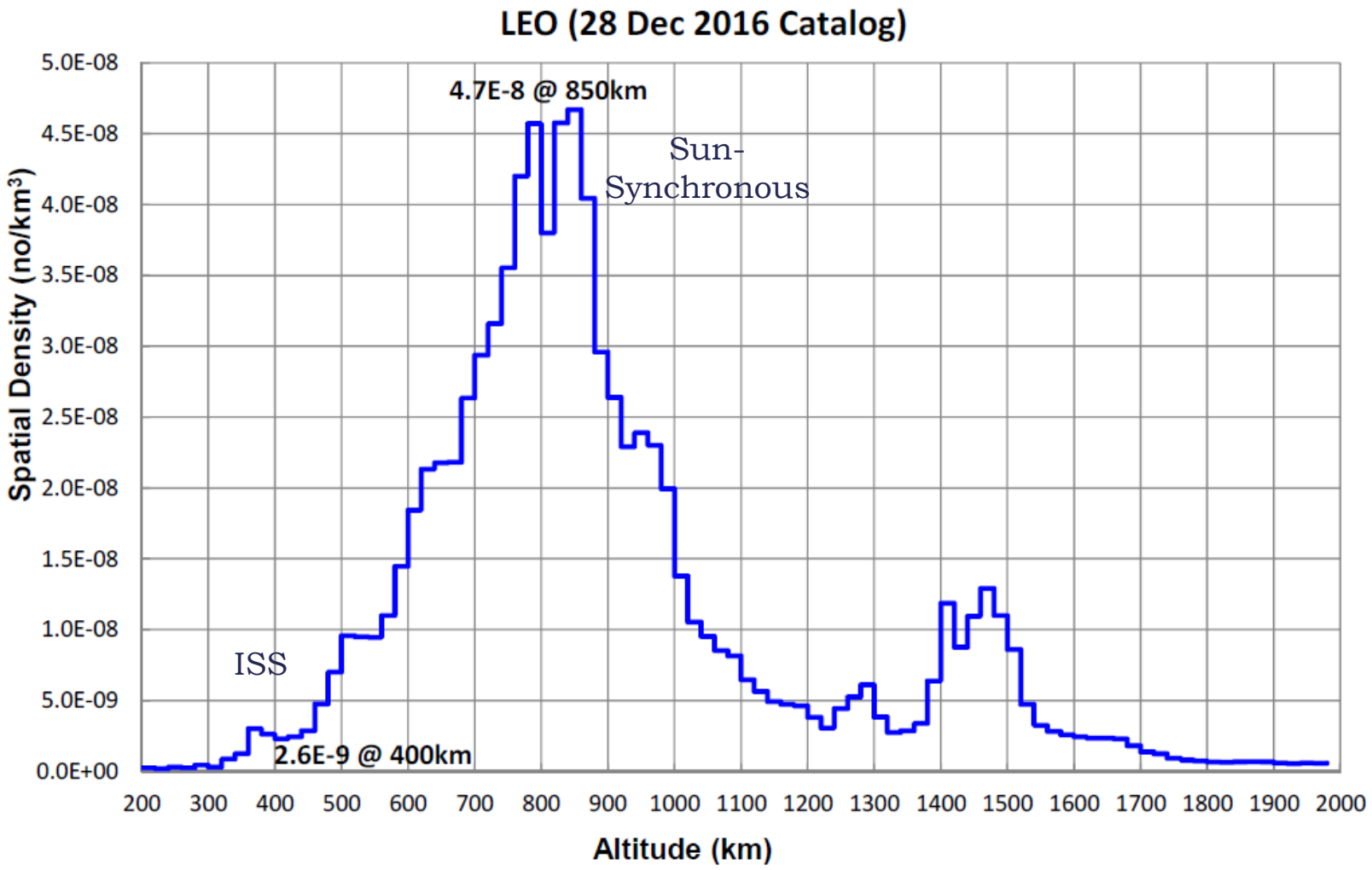
Orbital Debris Growth by Mass



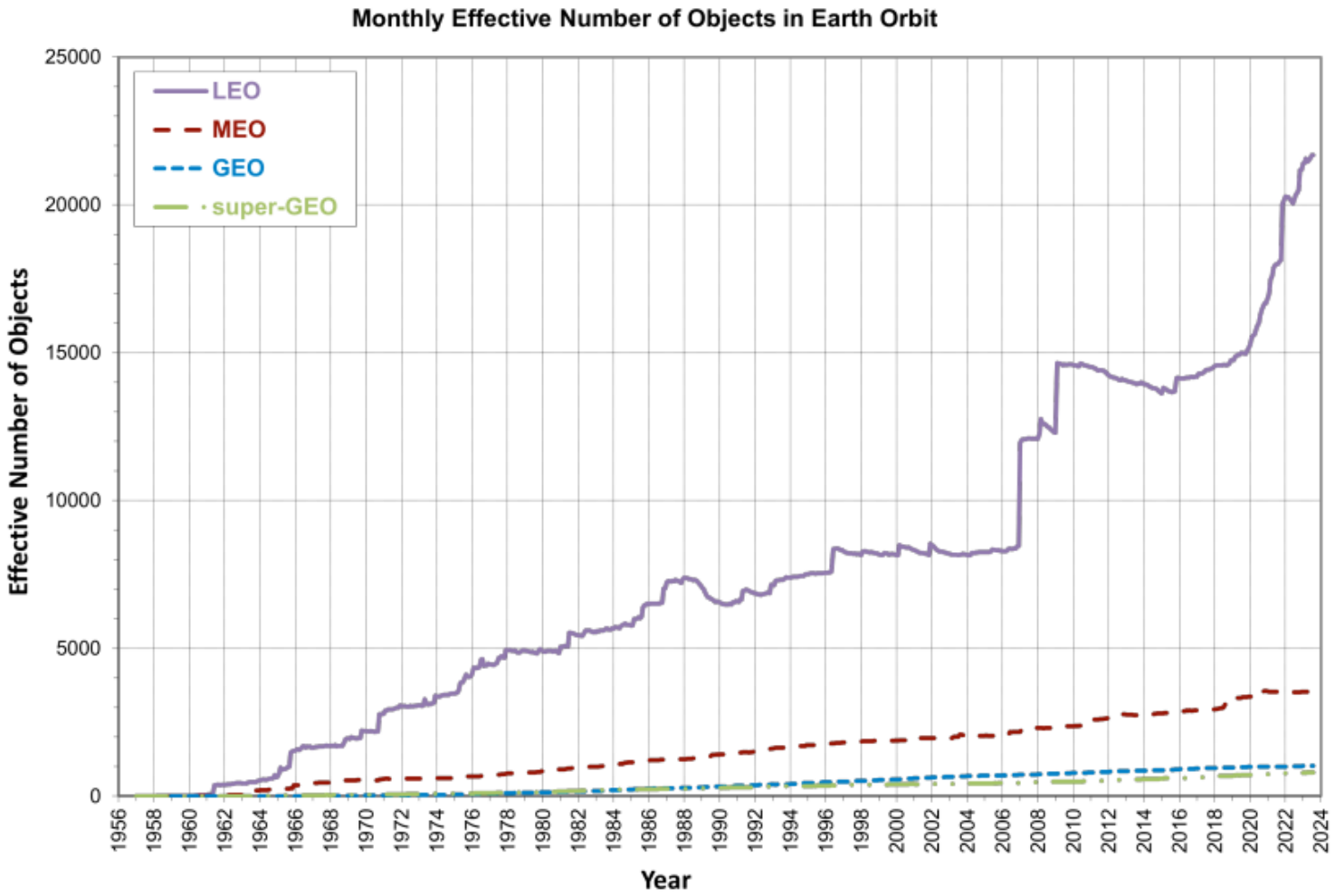
Orbital Debris Spatial Density



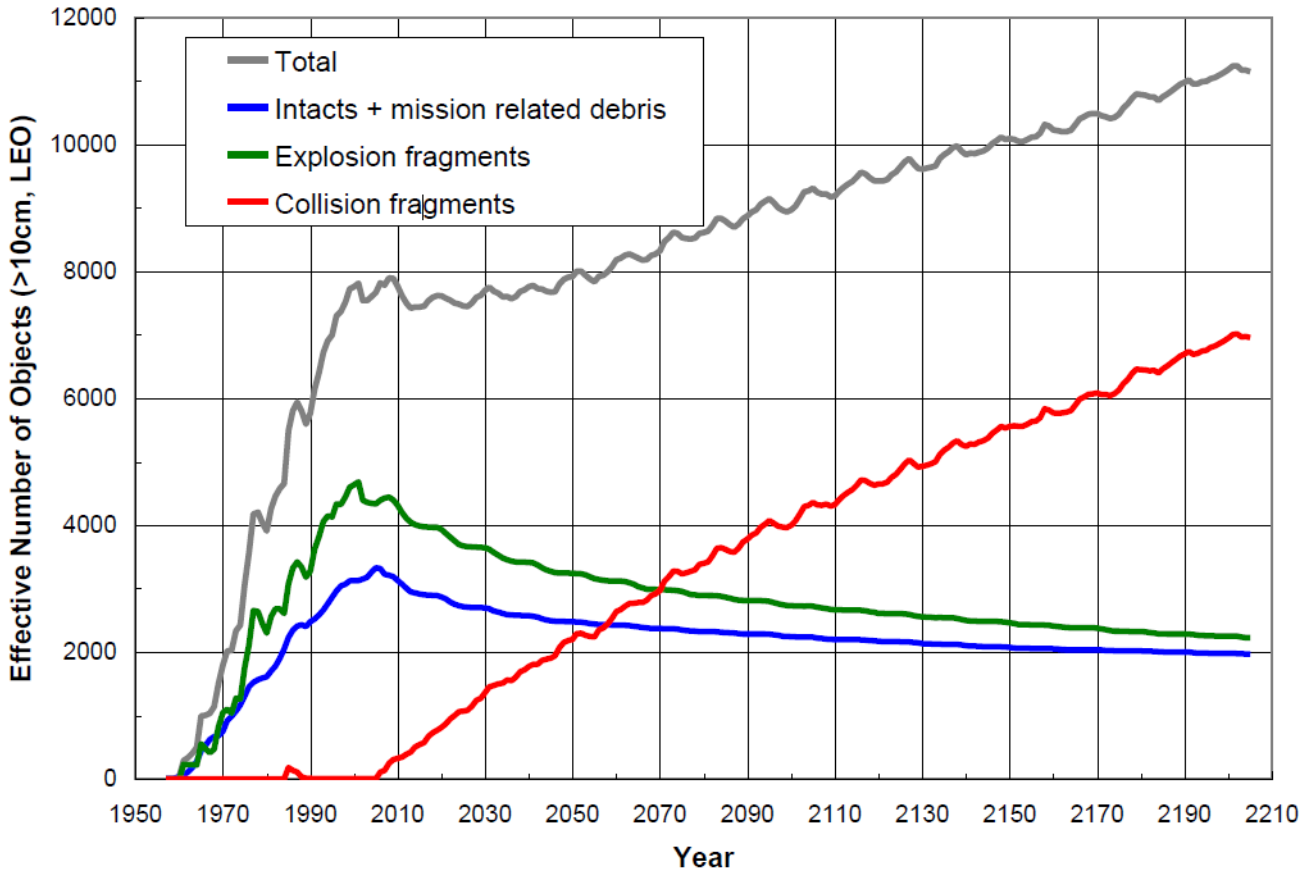
Orbital Debris Spatial Density in LEO



Orbital Debris Growth by Region



Kessler Syndrome



Self-sustaining growth in orbital debris population even with no new launches

- Due solely to collisions
- Named after NASA astrophysicist Don Kessler

Orbital Debris Models

NASA Orbital Debris Environment Models--Maintained by NASA's Orbital Debris Program Office (ODPO)

- Orbital Debris Engineering Model (ORDEM)
  - Primary orbital debris environment model
  - Currently version 3.2
- LEO-to-GEO Environmental Debris (LEGEND) model
  - Three-dimensional, long-term evolutionary model
- Object Reentry Survival Analysis Tool (ORSAT)
  - Predicts the reentry survivability of satellite and launch vehicle upper stage components

Other Models

- MASTER (ESA)
- Debris Risk Assessment and Mitigation Analysis (DRAMA) (ESA)
- Debris Environment Long-term Analysis (DELTA) (ESA)

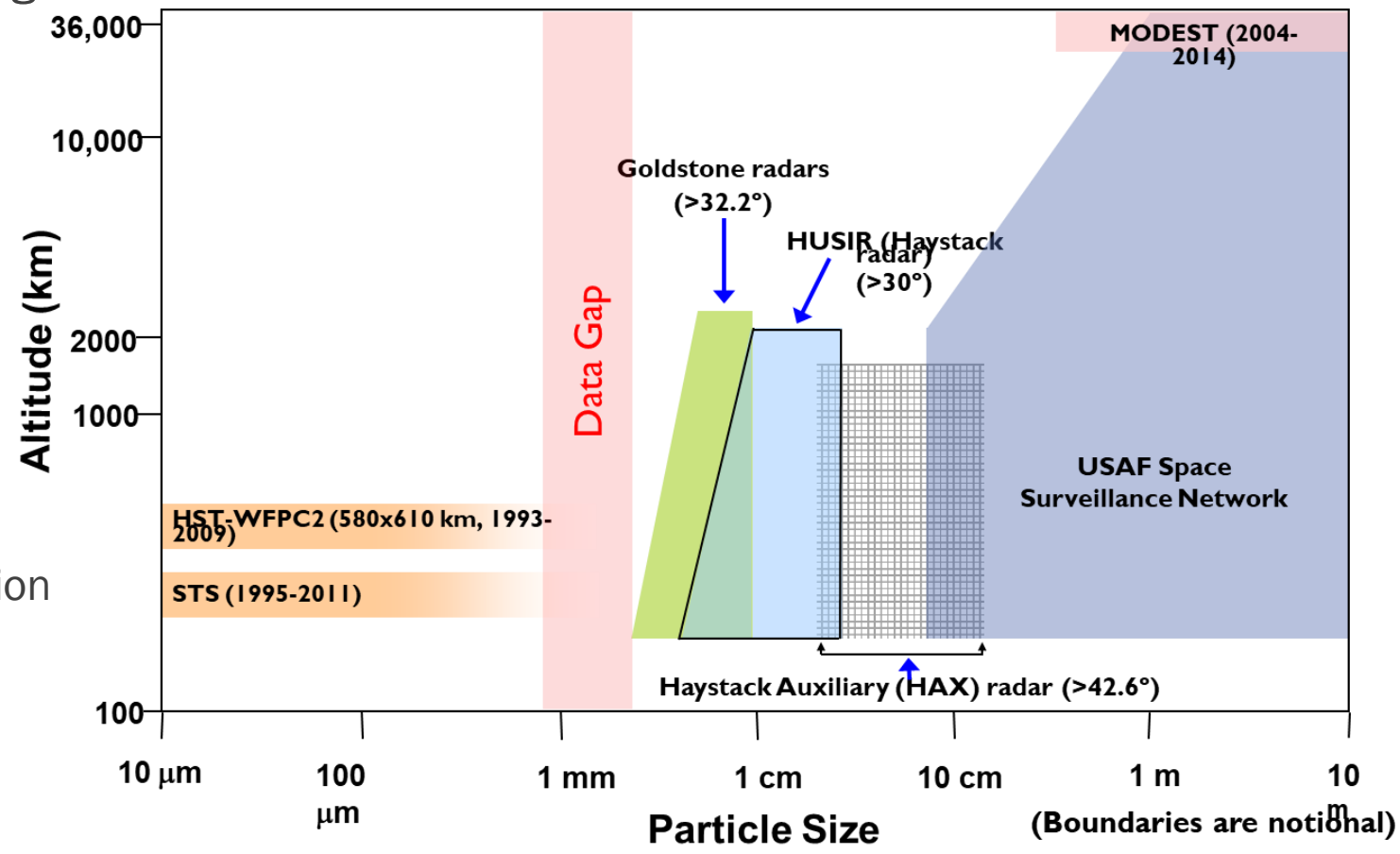
Measuring Orbital Debris

Space Surveillance Network Tracking and Cataloging
- Debris >5 cm diameter in LEO
- Debris > 1 m in GEO

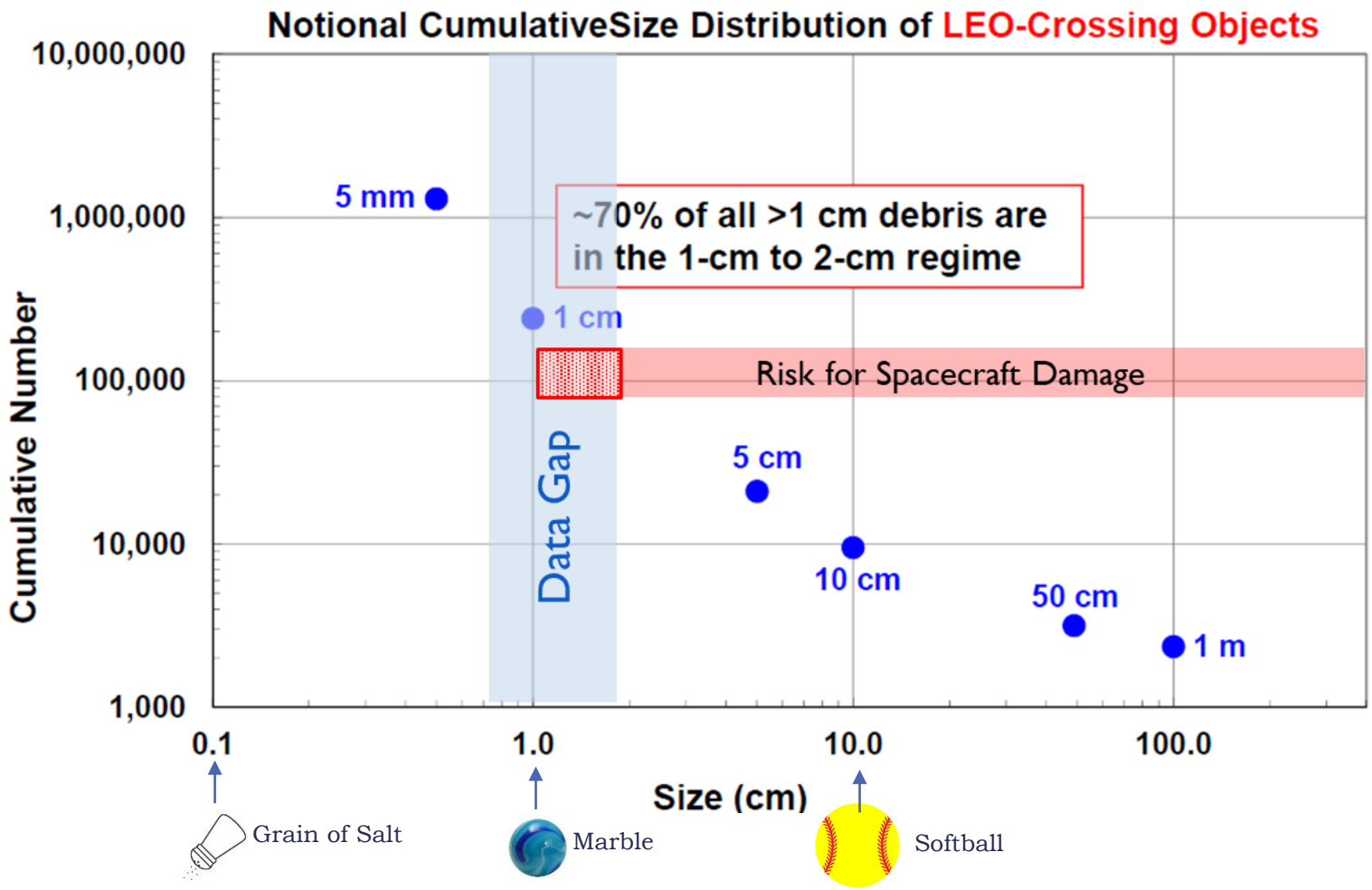
Radar and Optical Tracking
- Debris >5 mm

Returned Spacecraft Surface Inspection
- Debris and meteoroids <1 mm
- Impacting particle material information possible

Data Gap ~1 to 5 mm
- Models must interpolate based on available data sources



Orbital Debris Size Distribution



Remote Data Measurement

Data Source	Region (Debris Size)	Location	Description
Space Surveillance Network (SSN)	LEO (>5 cm) GEO (>1 m)	Worldwide ground- and space-based	Phased-array and mechanical radars, optical systems, operated by DoD
Haystack Auxiliary Radar (HAX)	LEO (>3 cm)	Massachusetts	15 m diameter, 1.8 cm wavelength (Ku band) radar, operated by MIT Lincoln Laboratory
Haystack Ultrawide Satellite Imaging Radar (HUSIR)	LEO (>5 mm)	Massachusetts	36 m diameter, 3 cm wavelength (X band) radar, operated by MIT Lincoln Laboratory
Goldstone Radar	LEO (>3 mm)	Southern California	70 m + 35 m dishes, part of Deep Space Network (limits use for OD)
Meter-Class Autonomous Telescope (MCAT)	GEO (<20 cm)	Ascension Island	1.3 m aperture Ritchey-Chretien reflecting telescope
Michigan Orbital Debris Survey Telescope (MODEST)	GEO (>30 cm)	Chile	0.61 m aperture Curtis Schmid optical telescope, operated by Univ. of Michigan

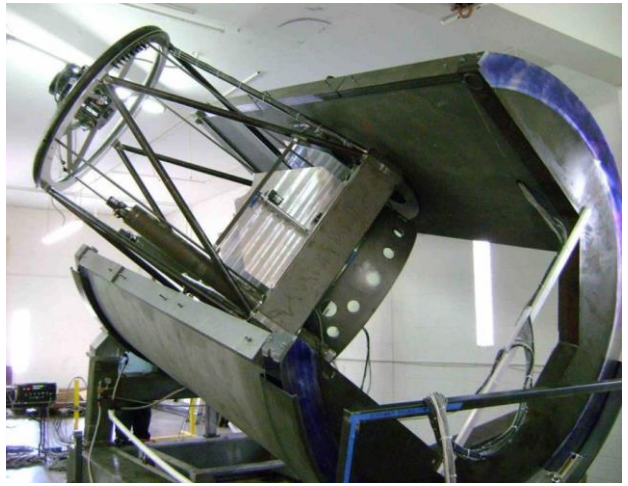
Remote Data Measurement



MODEST



HUSIR (left) and HAX (right)

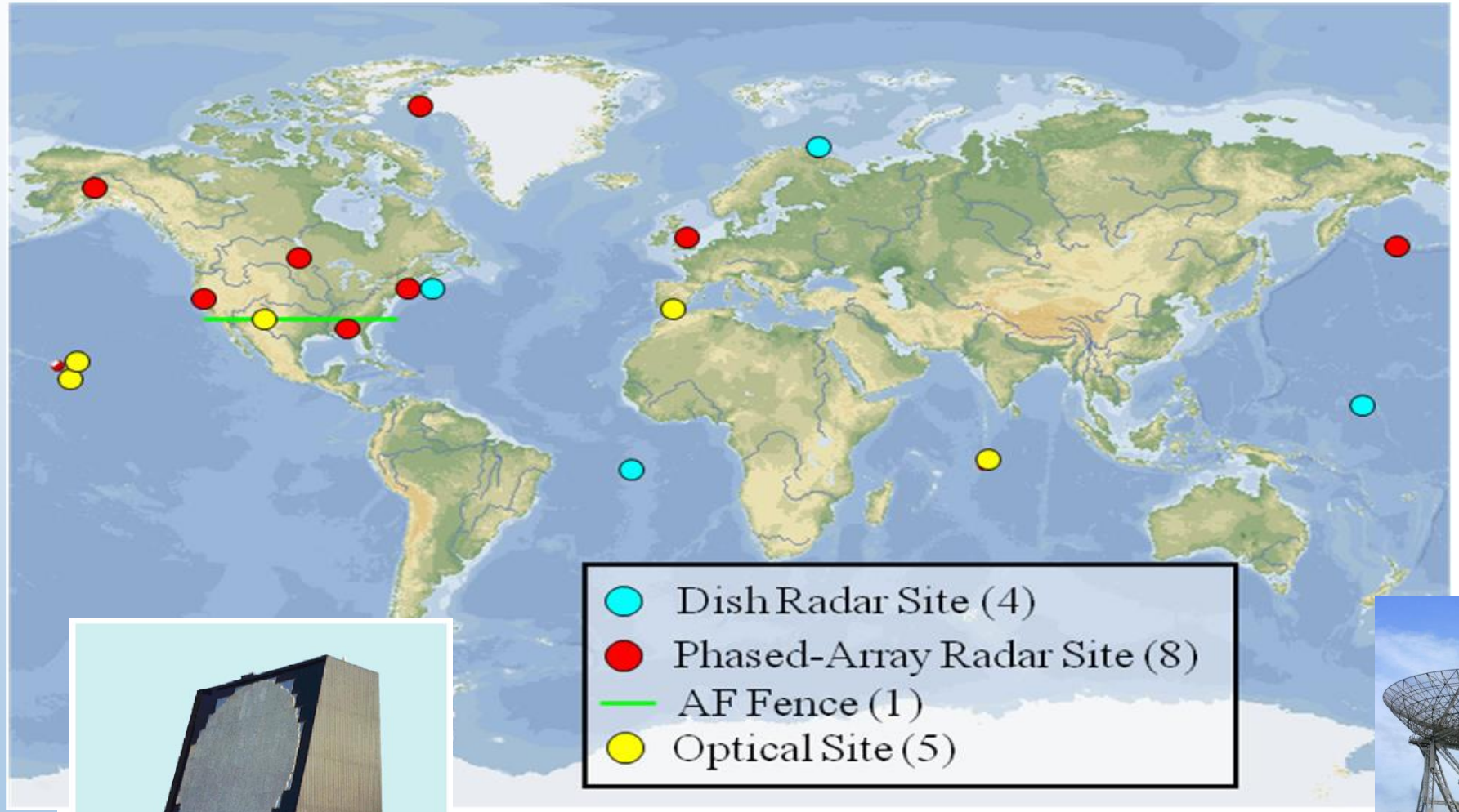


MCAT



Goldstone

SSN



SATELLITE BOX SCORE
(as of 04 September 2023, cataloged by the U.S. SPACE SURVEILLANCE NETWORK)

Country/ Organization	Spacecraft*	Spent Rocket Bodies & Other Cataloged Debris	Total
CHINA	620	4399	5019
CIS	1570	5673	7243
ESA	97	35	132
FRANCE	88	533	621
INDIA	113	104	217
JAPAN	203	108	311
UK	695	1	696
USA	6734	5096	11830
OTHER	1202	84	1286
Total	11322	16033	27355

* active and defunct

Phased-array Radar

Dish Radar

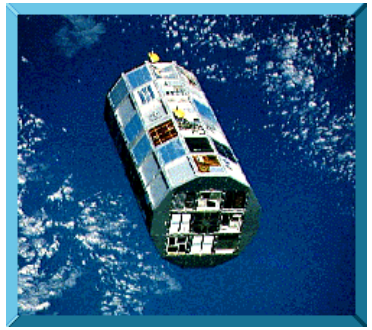


Analysis of Returned Surfaces

For particle sizes smaller than ~2 mm

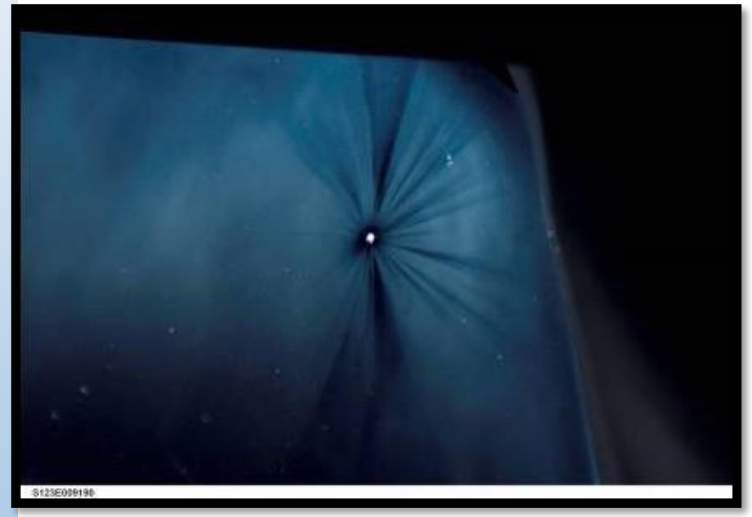
Damage features (i.e., hole or crater) are functions of:

- Particle size, mass, shape, density, speed, impact angle
- Characteristics of impacted surface

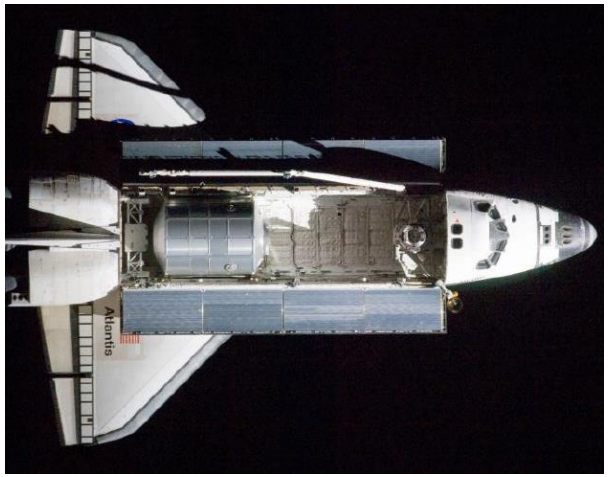


Long Duration Exposure Facility (LDEF)

ORDEM uses data primarily from analyzing Space Shuttle orbiter windows and radiators



Endeavour Window Damage/STS-123

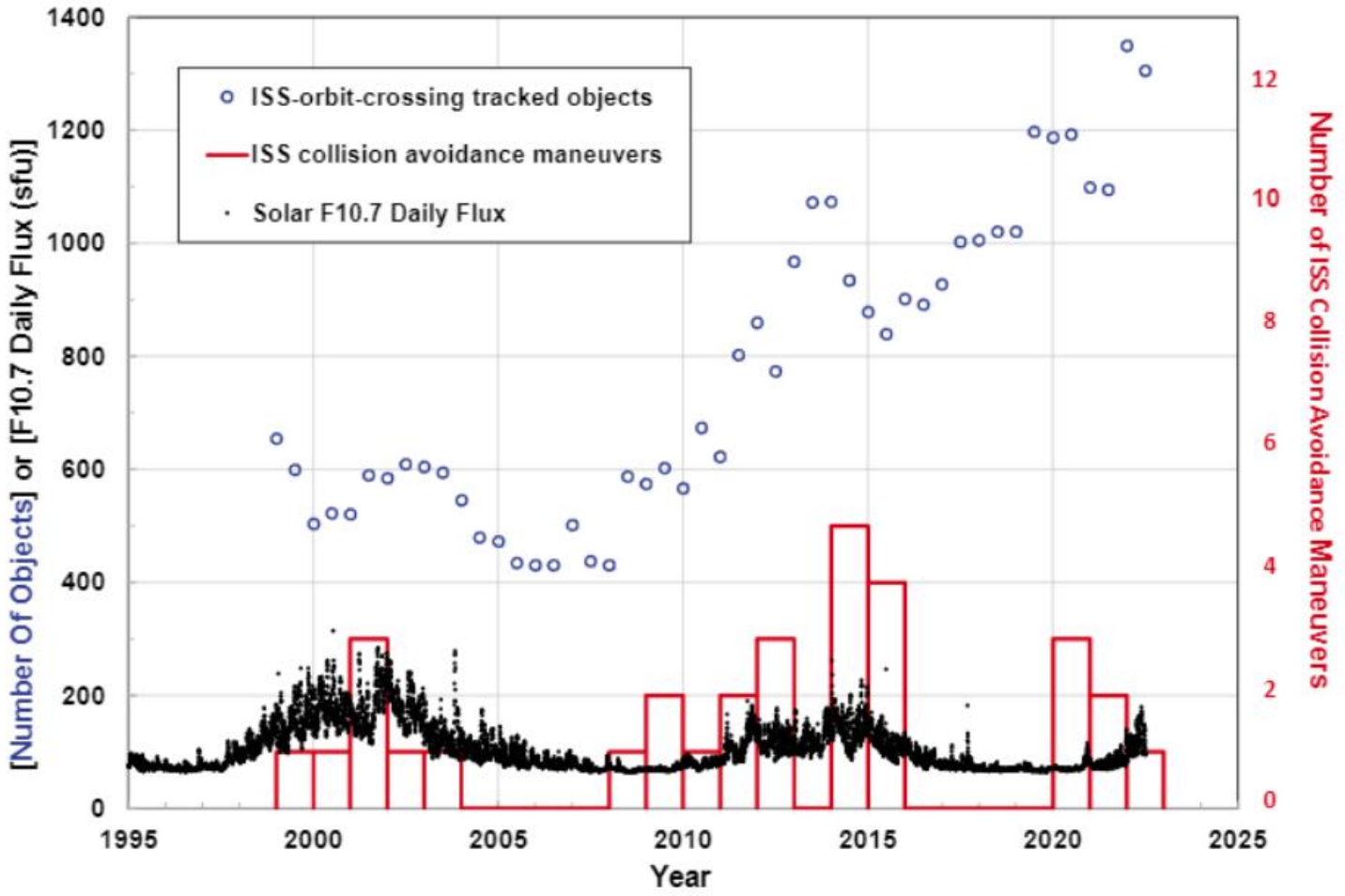




Radiator Damage on Endeavour/STS-118

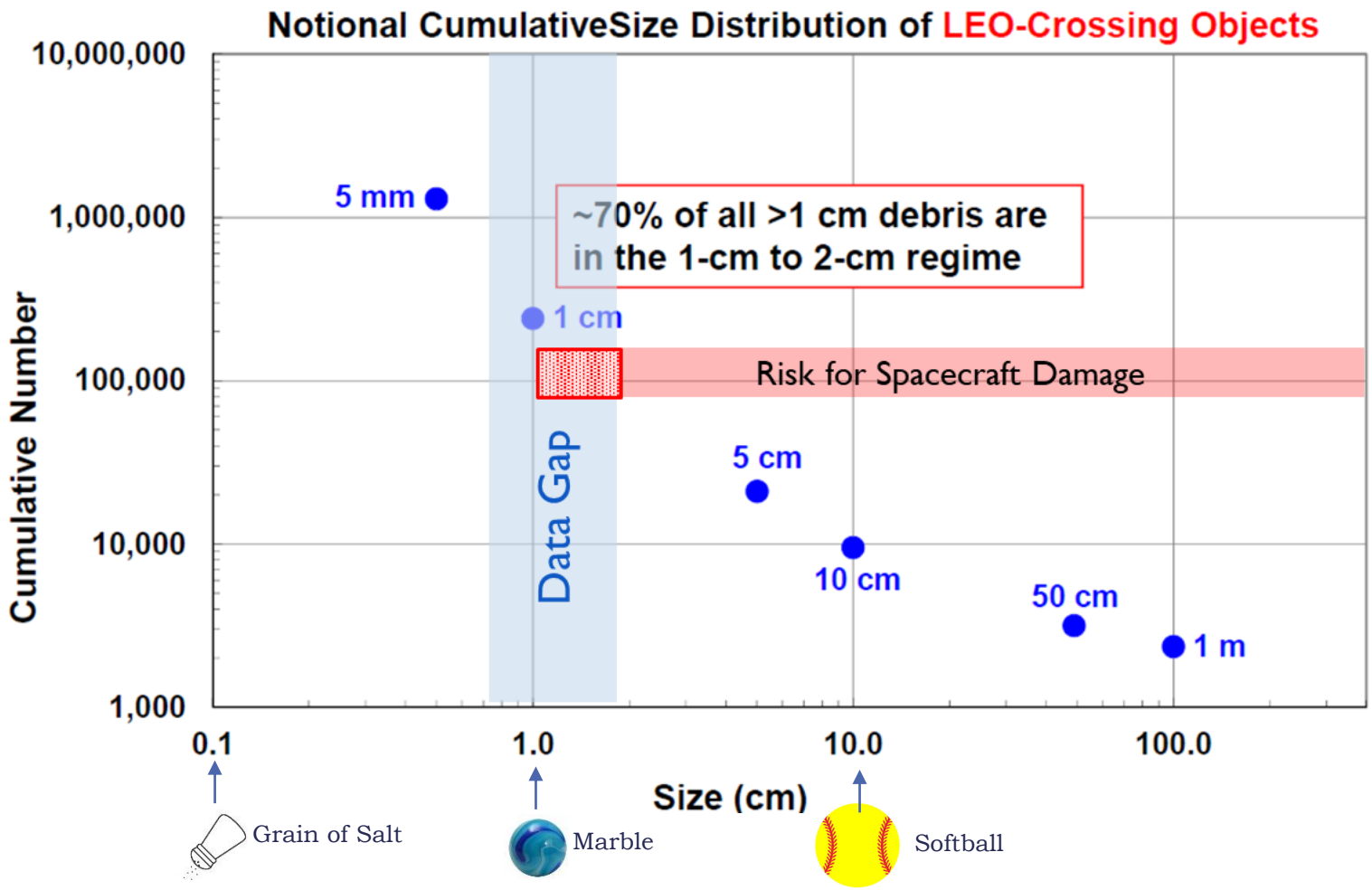
Risk Mitigation

ISS Collision Avoidance Maneuvers



Only works for tracked debris!

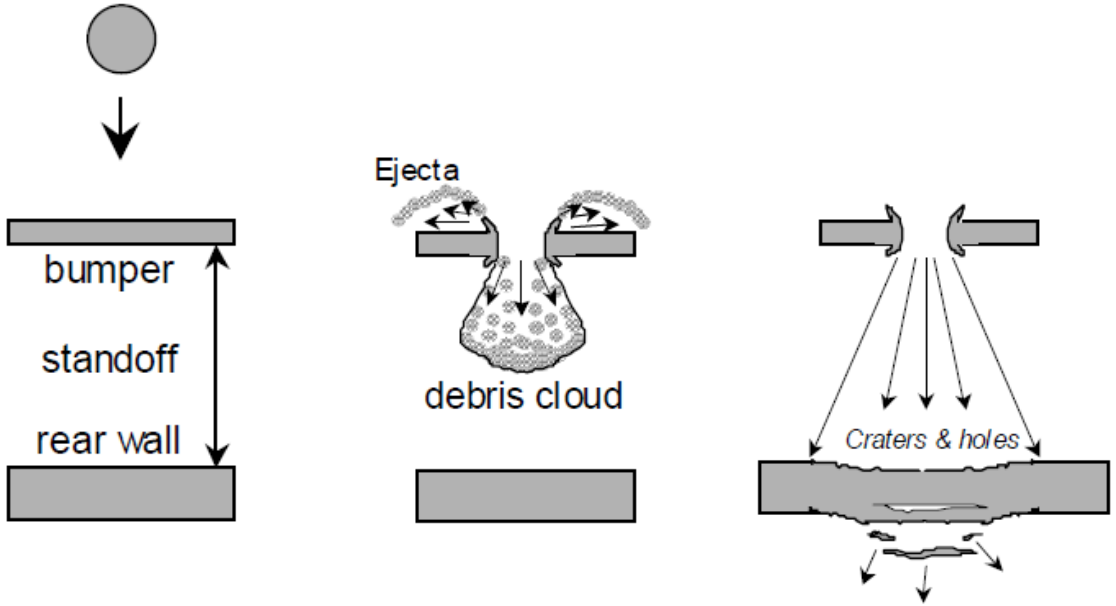
Orbital Debris Size Distribution

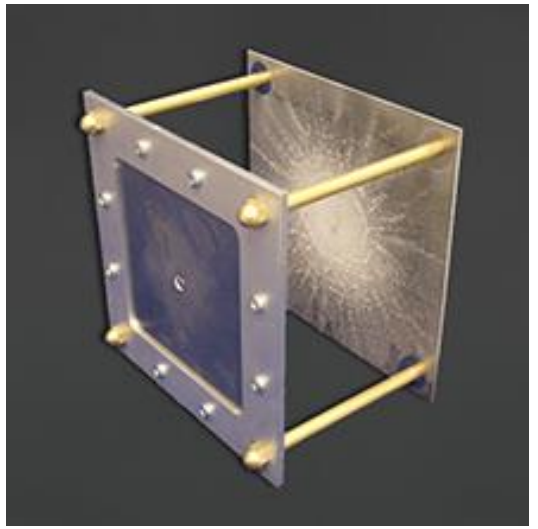


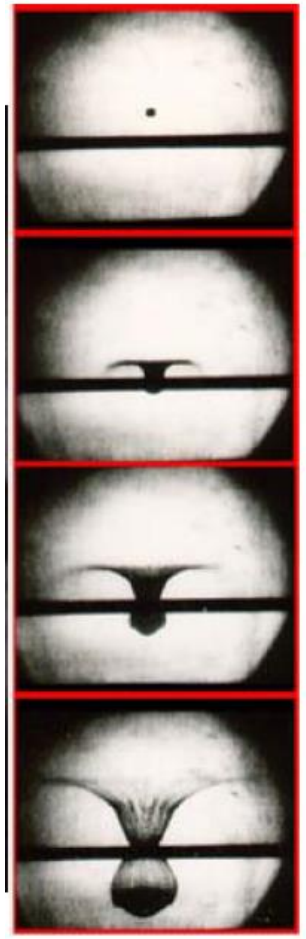
M/OD Shielding

Whipple Shields

- Consists of an outer layer (bumper), a stand-off, and the rear wall
- Bumper shocks the incoming particle, fragmenting and/or liquefying it
  - Converts much of the energy to fragmentation
  - Particle fragments disperse over a wide area on the rear wall, dispersing energy
- Much more effective than single wall (monolithic) shields

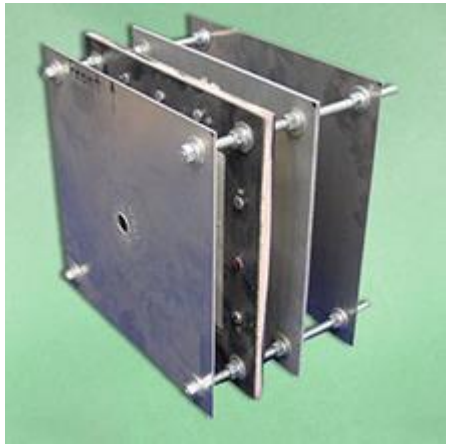






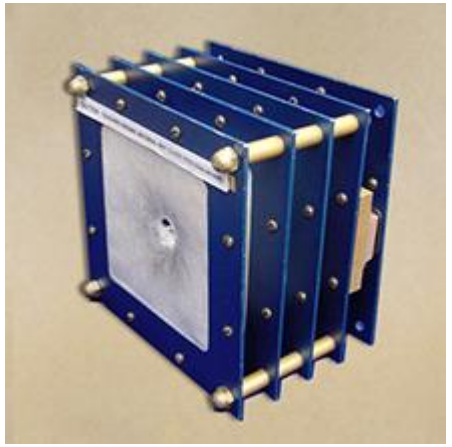
Variations on Whipple Shield

Add additional shock layers and different materials



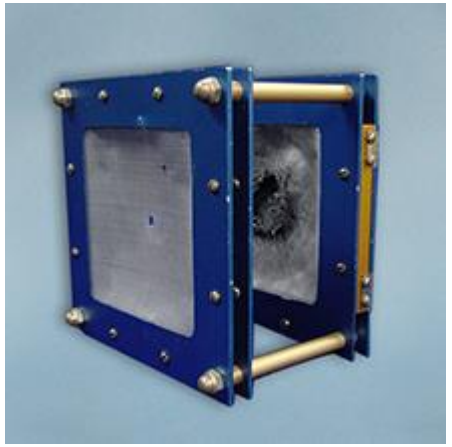
Stuffed Whipple

Layers of Nextel and Kevlar inserted between the bumper and the rear wall.



Multi-Shock Shield

Multiple layers of Nextel inserted to further shock the particle.



Mesh Double Bumper

Bumper consists of a double layer of aluminum mesh



Metallic Foam Panel

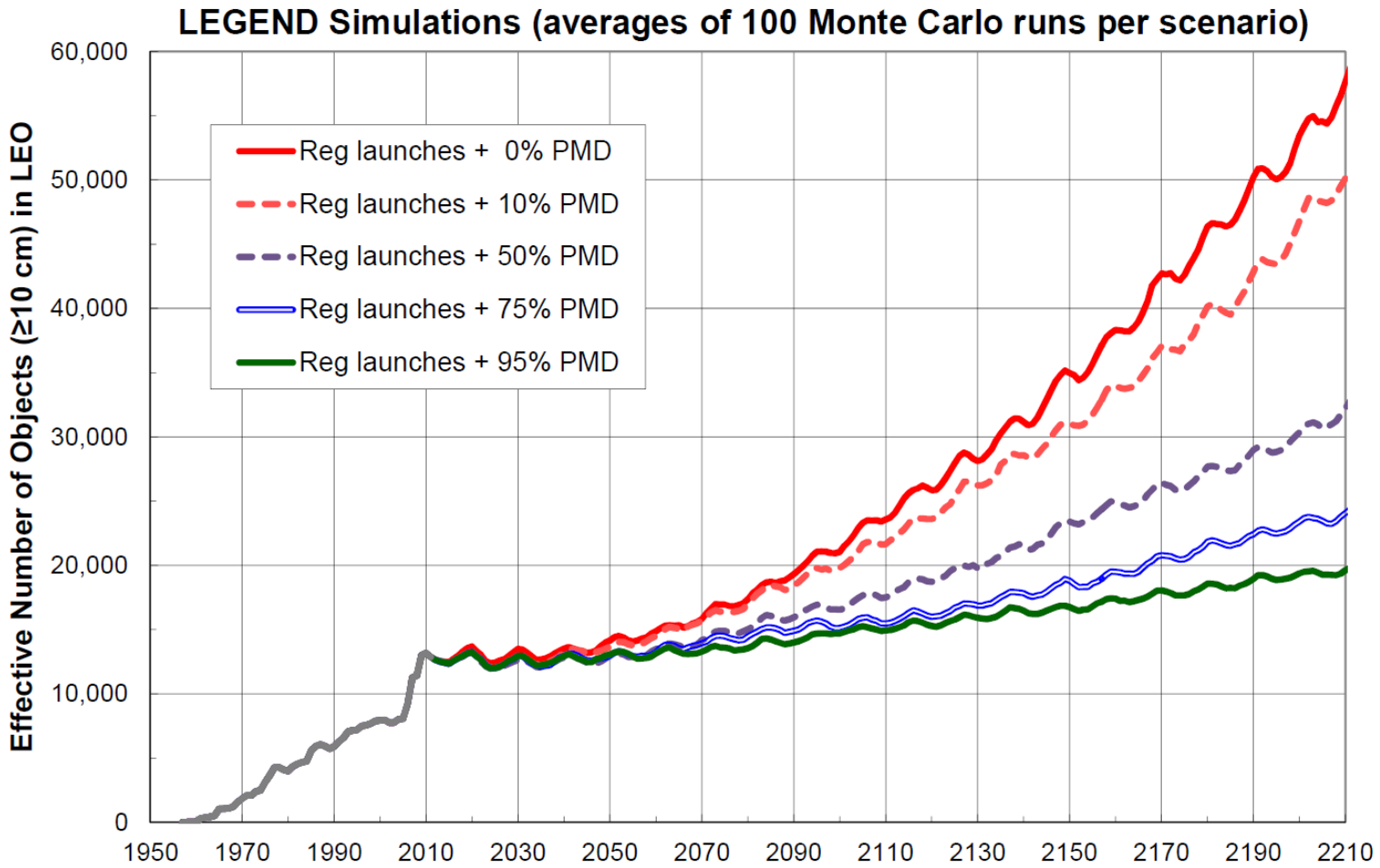
The stand-off volume can be filled with foam to further attenuate particle energy.

Limiting Debris Production

Guidelines to prevent additional debris

- Limit debris release during normal operation
- Minimize potential breakups during operational phases
- Limit the probability of accidental collision
- Avoid intentional destruction
- Minimize potential for post-mission breakups
  - Passivate spacecraft by removing stored energy (e.g., depressurize tanks, discharge batteries)
- Limit long-term presence of spacecrafts after end of mission
  - 25-year/5-year rules
  - Deorbit or dispose of launch vehicle stages after use

Post-mission Disposal (PMD) Effectiveness

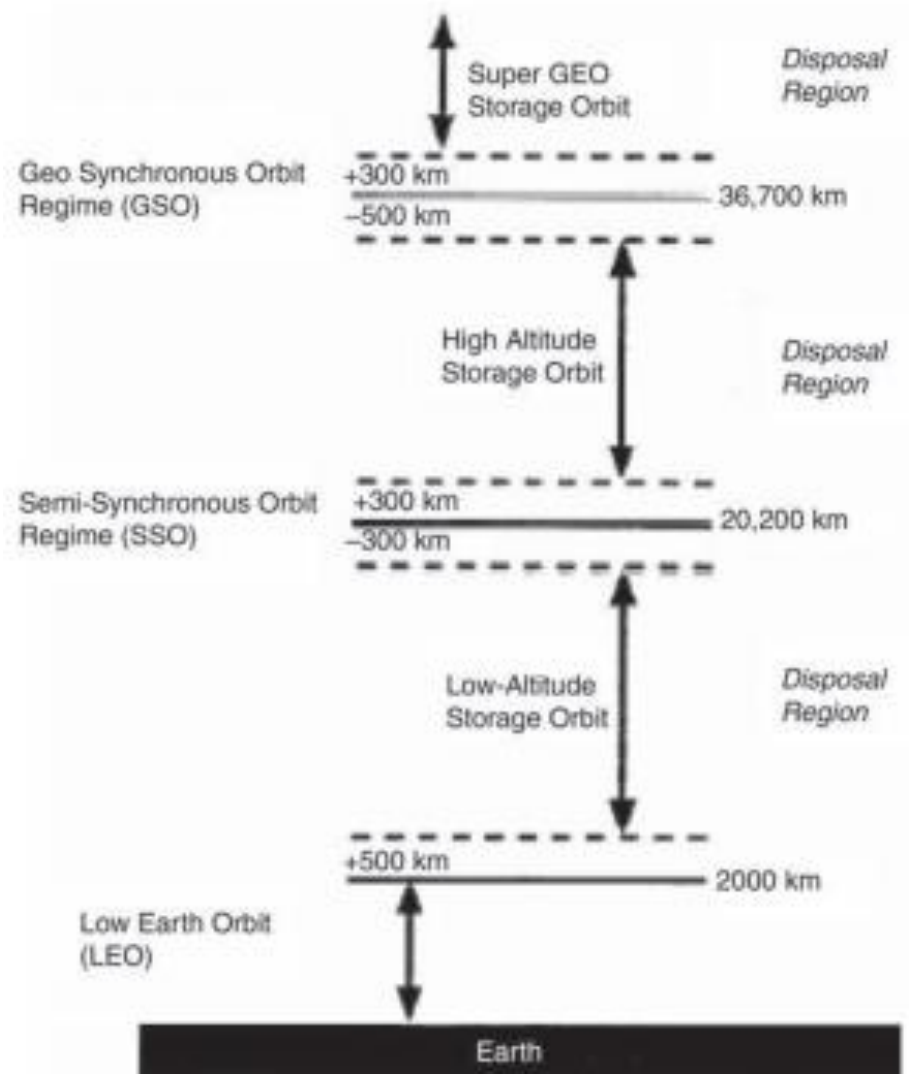


Effect of deorbiting within 25 years post-mission

Post-mission Disposal

Spacecraft in LEO ⟶ deorbit

Spacecraft >LEO ⟶ graveyard orbit



Geostationary Satellite Disposal

Increase in perigee altitude (km) given by:

$$\Delta h_p = 235 + 1000 C_r (A/m)$$

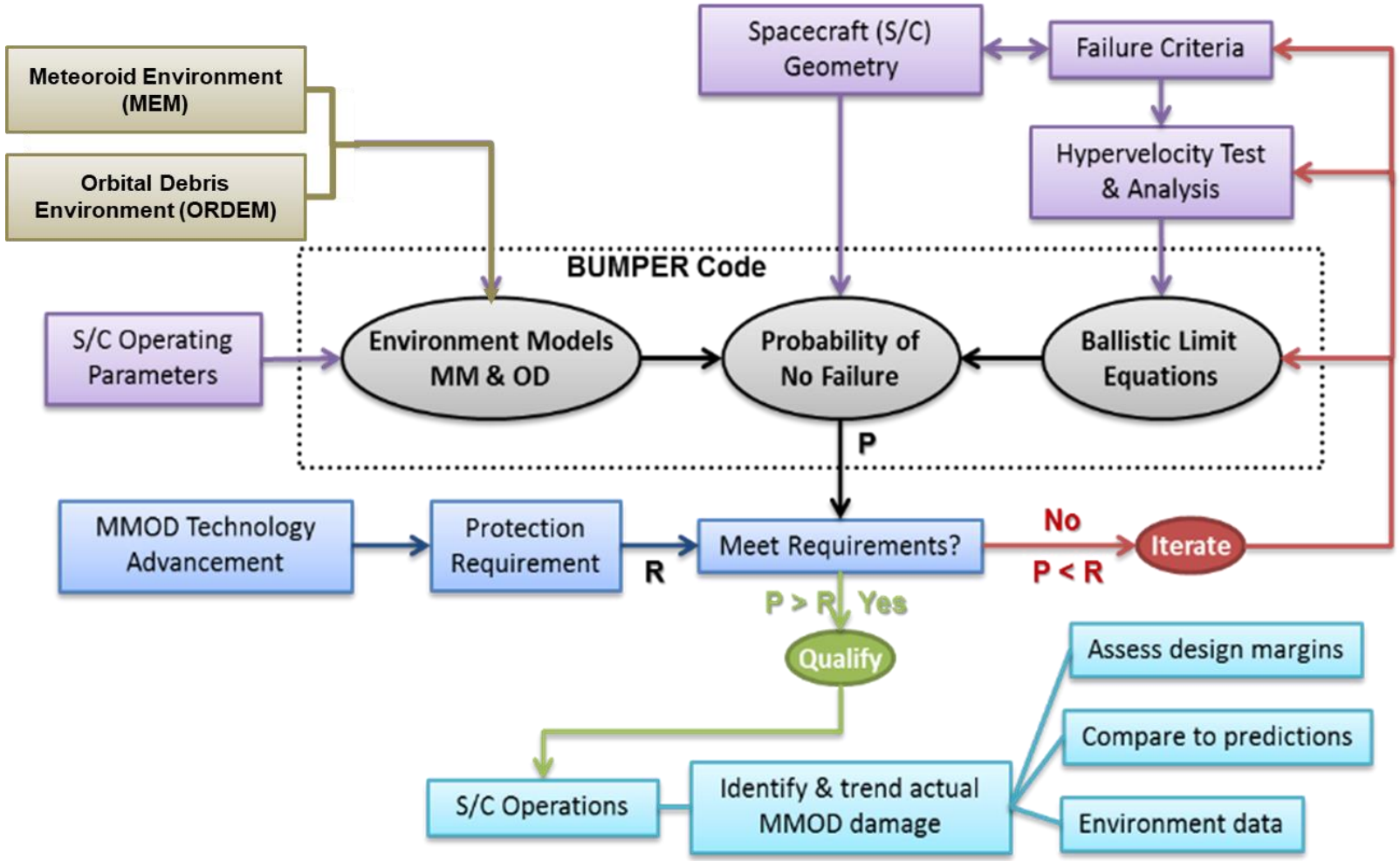
A/m = area to mass ratio (m^2/kg)

C_r = radiation pressure coefficient ($1 \leq C_r \leq 2$)

235 = 200 km + lunisolar perturbation that lowers perigee by 35 km

Risk Assessment and Prediction

Bumper Risk Assessment Process



Ballistic Limit Equations (BLEs)

Predicts how a system or structural element will sustain a penetration or critical failure following a hypervelocity impact

Equation expressing the M/OD critical diameter as a function of velocity for a given particle type/density, impact angle, shape, etc.

Failure criteria=damage threshold beyond which is unacceptable

- Examples:
  - Through-penetration of a shield
  - Spallation of material from the interior of a module
  - Crater depth X% of a heat shield

BLEs are defined based on failure criteria

Single Wall BLE

$$d_c = \left[\frac{t_t}{K_f K_1 \rho_p^{\beta} \rho_t^{k} V^{\gamma} \cos(\theta)^{\xi}}\right]^{1/\gamma}$$

d_c= critical diameter

K_f=factor to specify failure mode

K_1=factor that includes yield strength, Mach

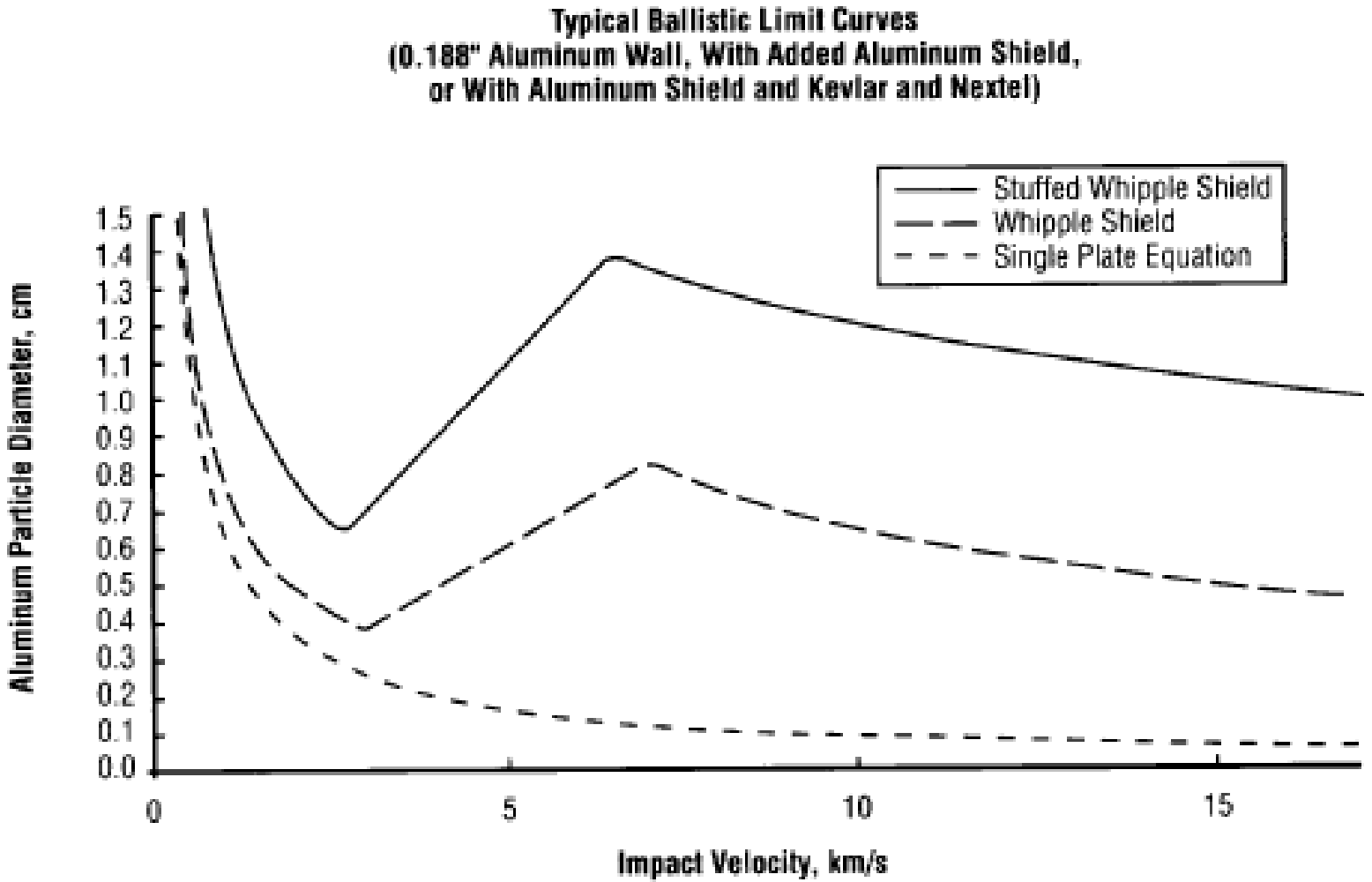
t_t=target plate thickness

V^{γ}=projectile velocity

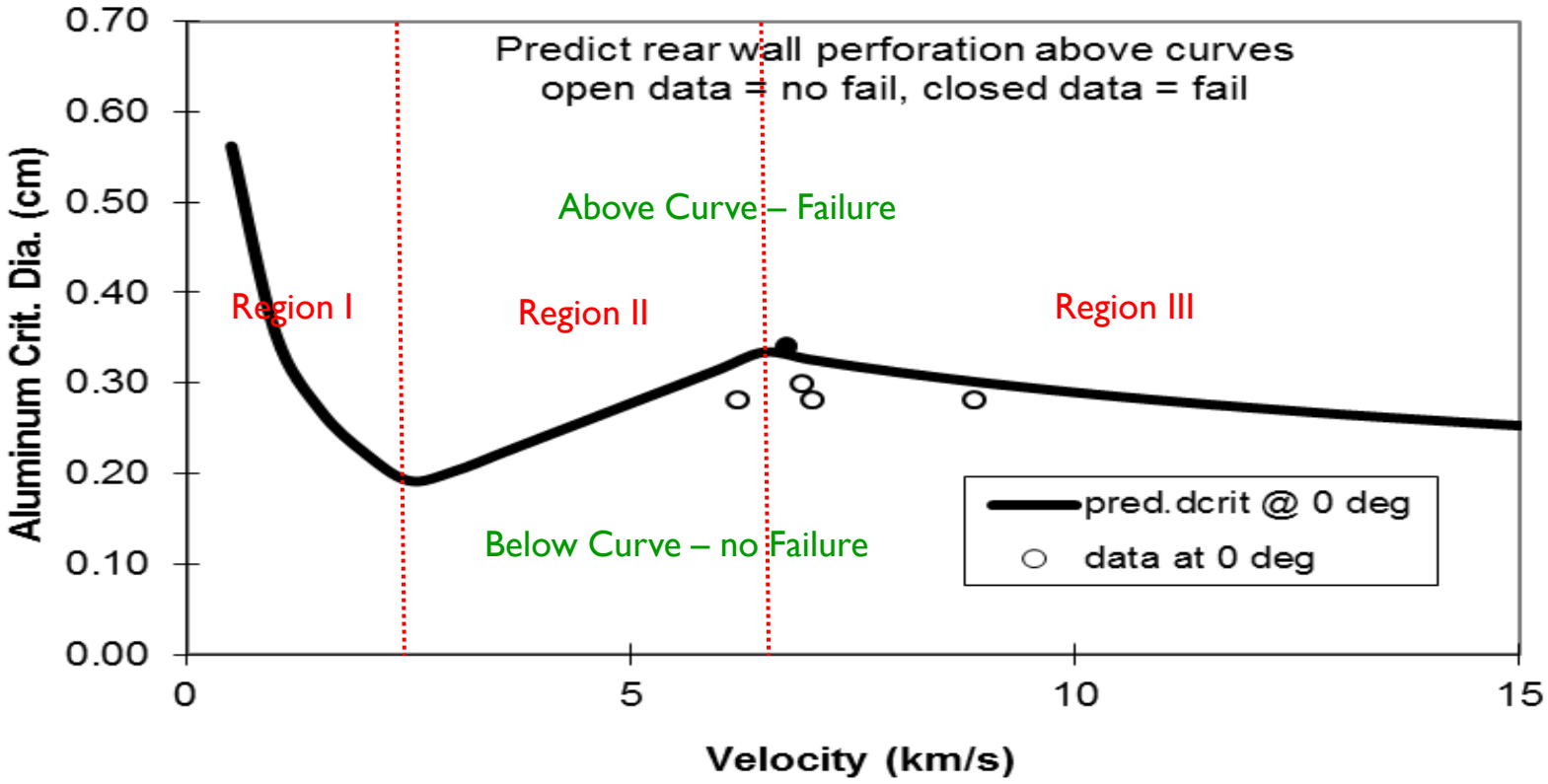
θ=impact angle from normal

β, γ, k, ξ=superscripts

Ballistic Limit Curve (BLC)



Whipple Shield Ballistic Limit Curve



Region I: Deformed but intact projectile

Region II: Fragmented projectile, dispersed energy

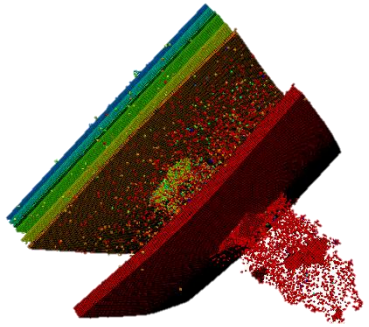
Region III: Melted projectile

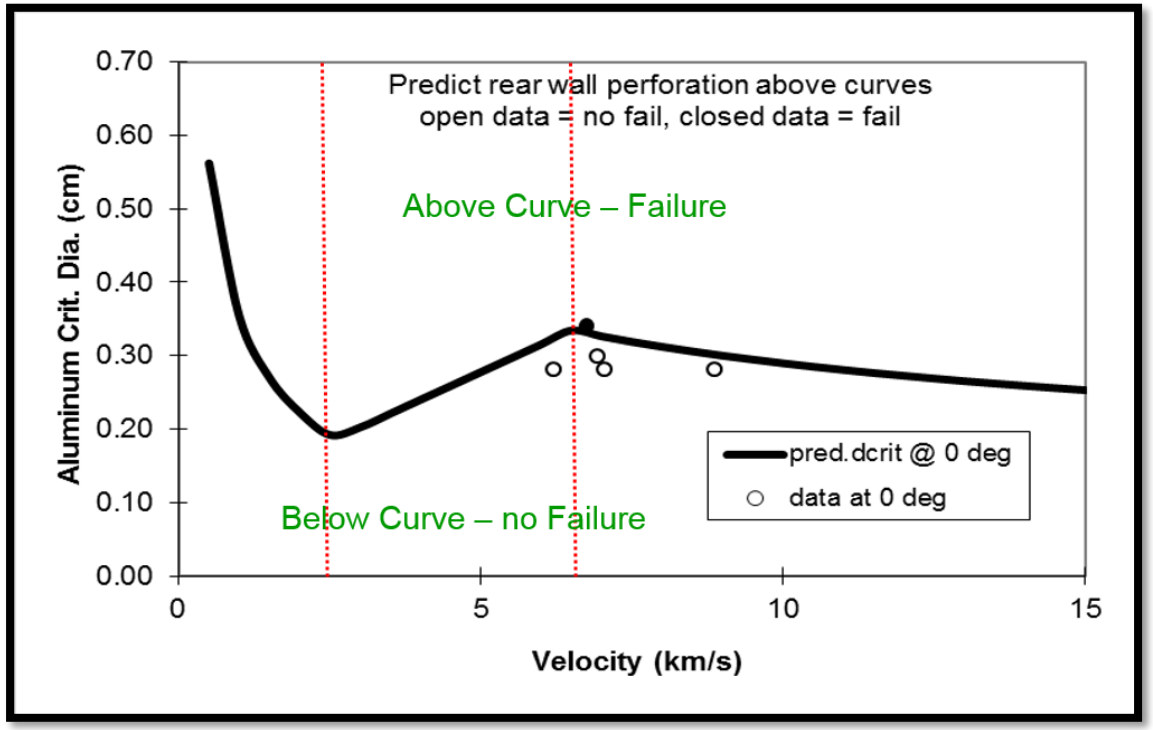
Developing BLEs/BLCs



Testing

Simulations





Dual-wall Ballistic Limit Curve

Hypervelocity Impact Testing

Two stage light-gas guns

- Ignited propellant in first stage expands and propels piston
- Piston compresses hydrogen/helium volume until rupture disk bursts
- Release of light gas into barrel propels projectile within a sabot to test velocity
- Scored sabot separates upon barrel exit and is caught by sabot catcher while projectile proceeds to target

WSTF 17-caliber barrel and test chamber

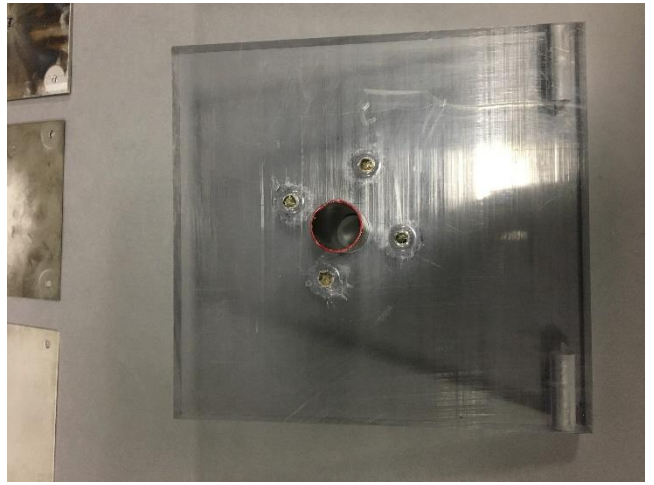


Two-stage light gas guns can achieve ~7 km/s

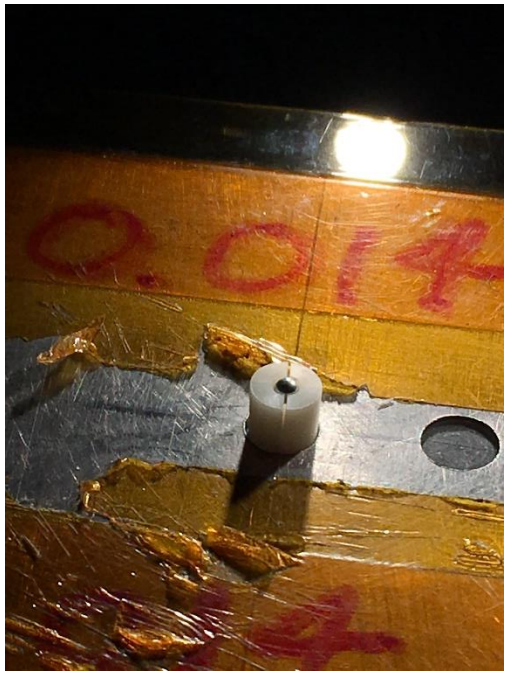
- Three-stage LGG ~10 km/s

ISS shield impacted by 10 mm Al projectile at 5.67 km/s





Sabot Catcher

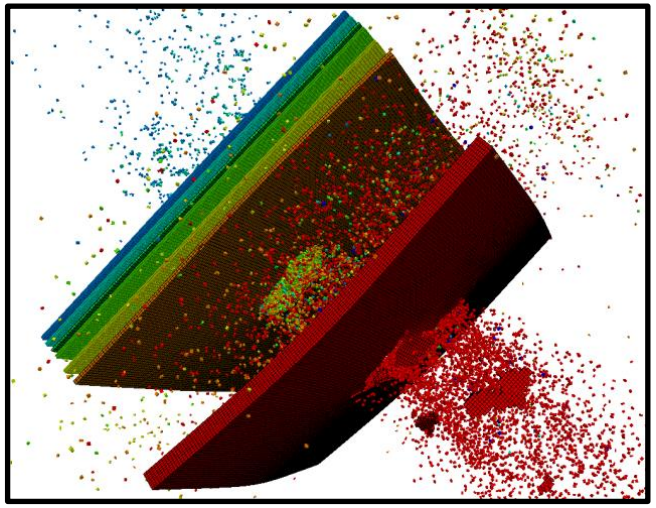


Sabot with projectile

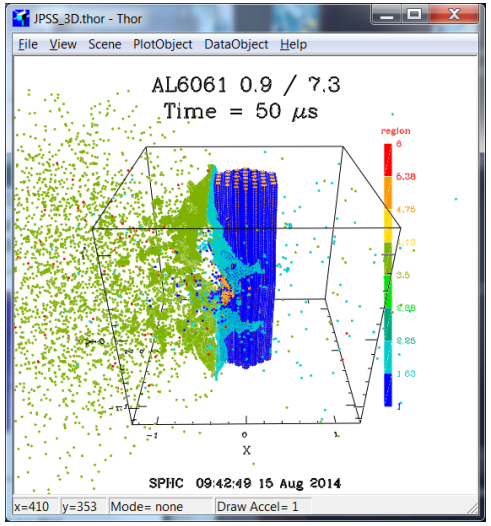
Hydrocode Simulation

Modeling and simulation required to predict hypervelocity impact at conditions not possible to test (e.g., velocities >10 km/s)

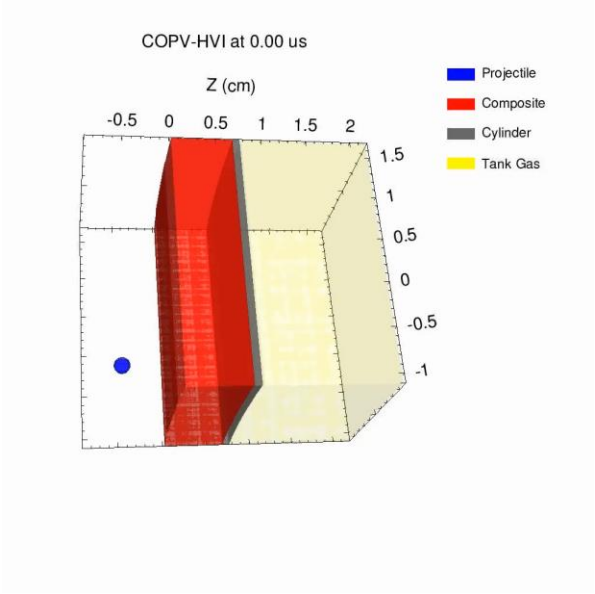
Hydrocodes used to model highly dynamic shock response to hypervelocity impacts



Impact on ISS Shield



Impact on Wire Bundle



Impact on Composite Overwrapped Pressure Vessel

Conclusion/Resources

Summary

M/OD is a primary risk to people and assets—especially in Earth orbit

Large uncertainties are present when calculating risk due to difficulties in testing in the M/OD regime and characterizing the M/OD environments

With the end of the Space Shuttle Program, new in situ data sources are needed.

SSN catalog characterizes only the large debris—debris particles below observational threshold can still cause catastrophic damage

- Need accurate modeling and robust shielding

International cooperation needed to:

- Remove decommissioned satellites
- Passivate post-mission assets still in orbit
- Reduce accidental and intentional (eliminate these) explosions and collisions in space

Websites

NASA Orbital Debris Program Office: https://orbitaldebris.jsc.nasa.gov/

NASA Meteoroid Environment Office: https://sma.nasa.gov/sma-disciplines/meteoroid-environments

NASA Hypervelocity Impact Technology: https://hvit.jsc.nasa.gov/shield-development/