

Micro-Meteoroid and Orbital Debris (MMOD) Protection Overview

NASA Hypervelocity Impact Technology (HVIT) Group

Eric Christiansen/JSC-XI4

Dana Lear/JSC-XI4

Jim Hyde/JSC-XI4 (JETS)



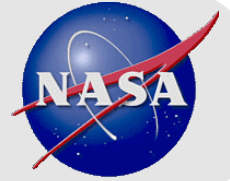
MMOD 101 Topics

- MM and OD environments
- Observed MMOD impact damage
- MMOD risk assessment process
- MMOD protection
- Hypervelocity Impact Technology (HVIT) group at NASA Johnson Space Center



MMOD Environment Models

- **Orbital Debris environment definition model is provided by Johnson Space Center (Orbital Debris Program Office)**
 - OD is the predominate threat in low Earth orbit
 - Man-made objects in orbit about Earth impacting up to 16 km/s
 - average 9-10 km/s for ISS orbit
 - High-density (steel), medium-density (aluminum) and low-density (plastic) are major constituents of the debris population
 - ORDEM 3.0 is latest model: <http://orbitaldebris.jsc.nasa.gov/>
- **Meteoroid model provided by Marshall Space Flight Center**
 - Natural particles in orbit about sun
 - Mg-silicates, Ni-Fe, others (porous, average density = 1.0g/cm^3)
 - Meteoroid impact speeds: 11-72 km/s
 - Average in Earth orbit 22-23 km/s
 - MEM-R2 is latest release:
<http://www.nasa.gov/offices/meo/home/index.html>

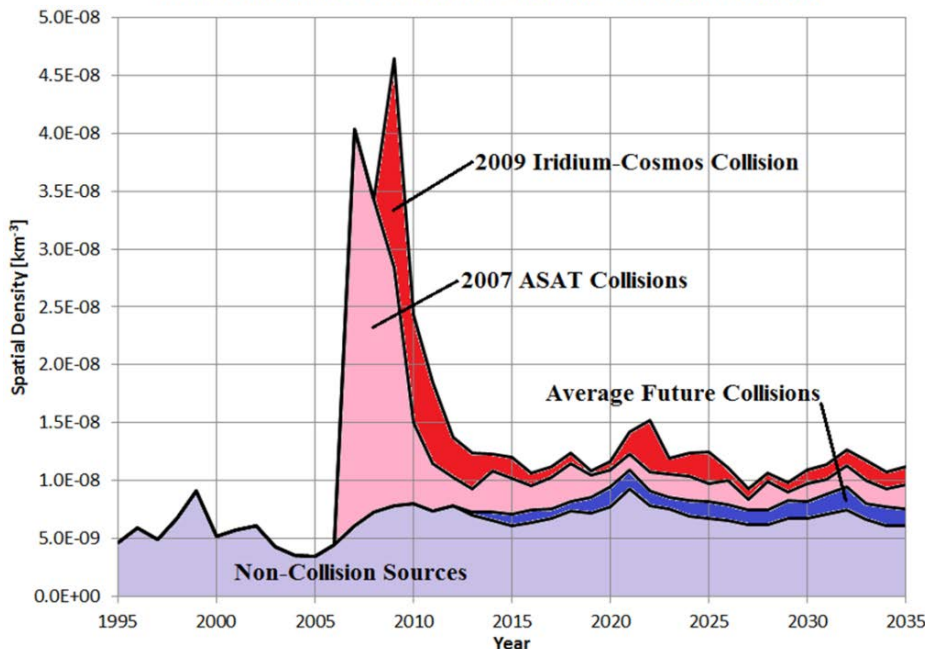


MMOD Environment Models

- **Meteoroids consist of background sporadic flux (static), and streams from meteor showers (variable)**
 - Occasionally, showers can turn into storms
- **Orbital Debris is dynamic, changing as function of the rate of on-orbit explosions & collisions, launch rate and atmospheric drag/solar activity**

400km altitude

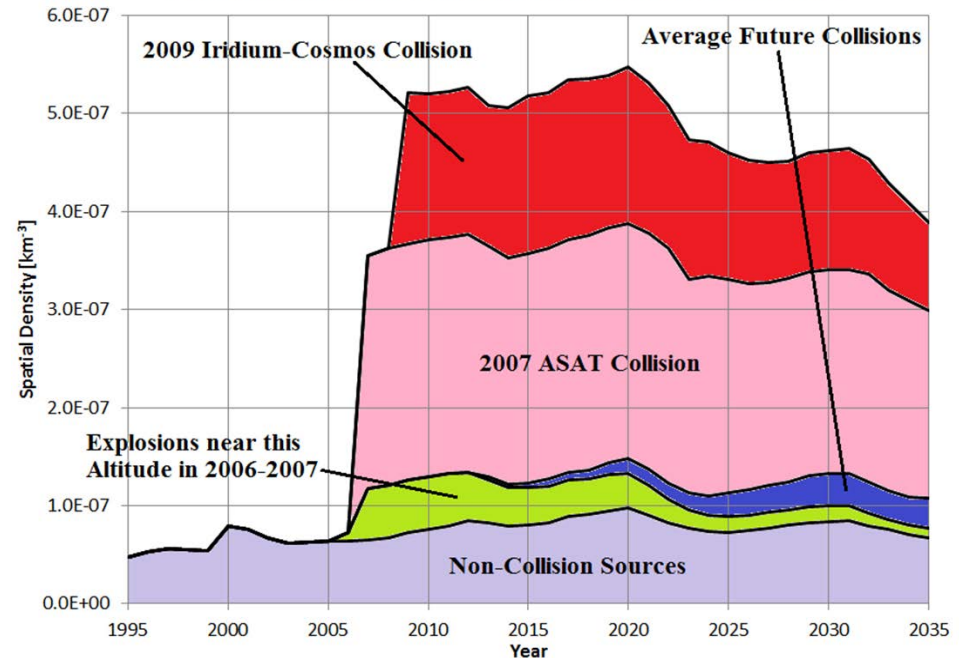
Time Evolution of >1 cm ORDEM 3.0 Debris at 400 km Altitude

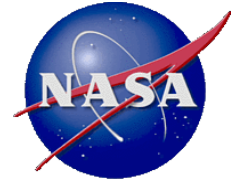


Note, Spatial Density is proportional to impact risk

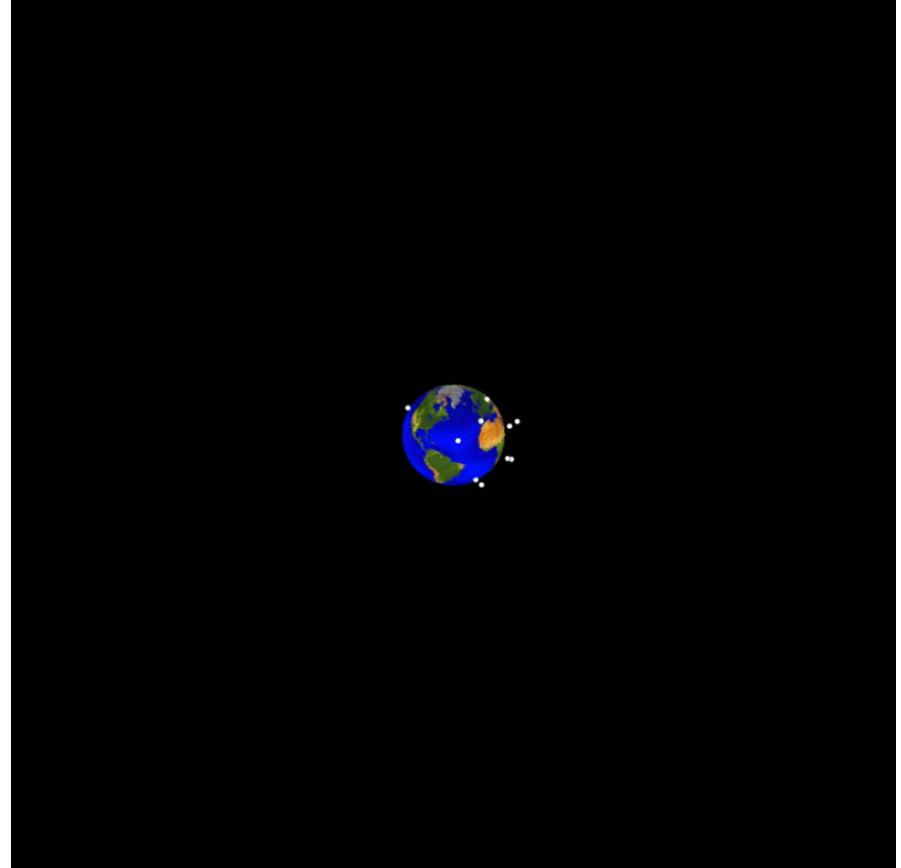
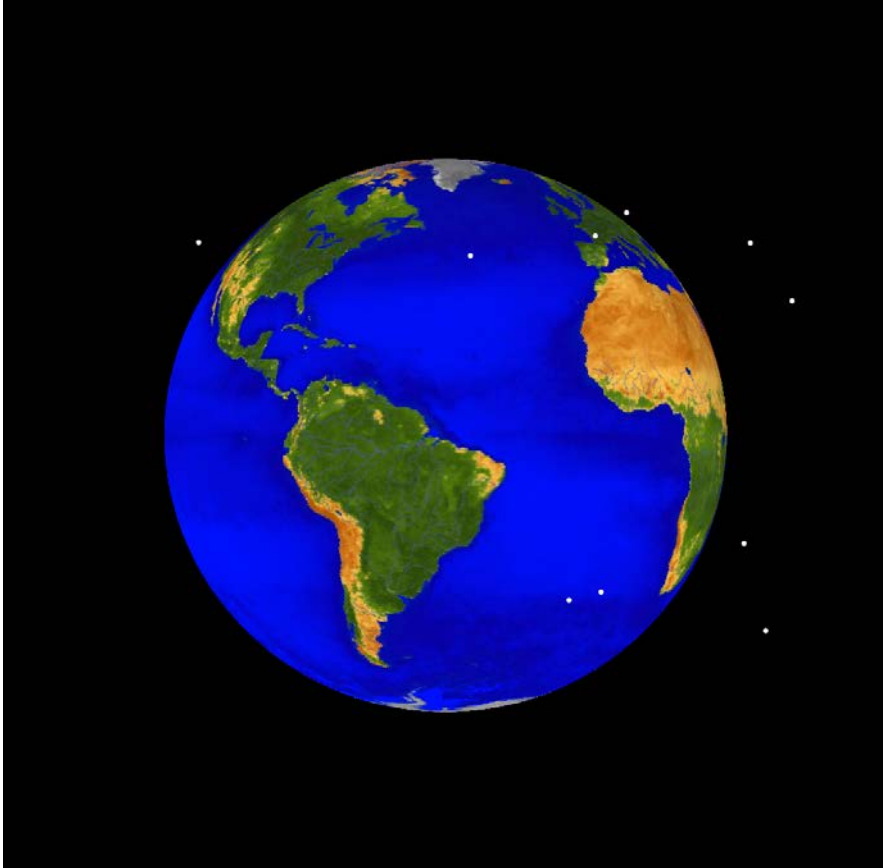
705km altitude

Time Evolution of >1 cm ORDEM 3.0 Debris at 705 km Altitude

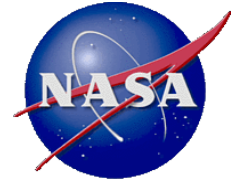




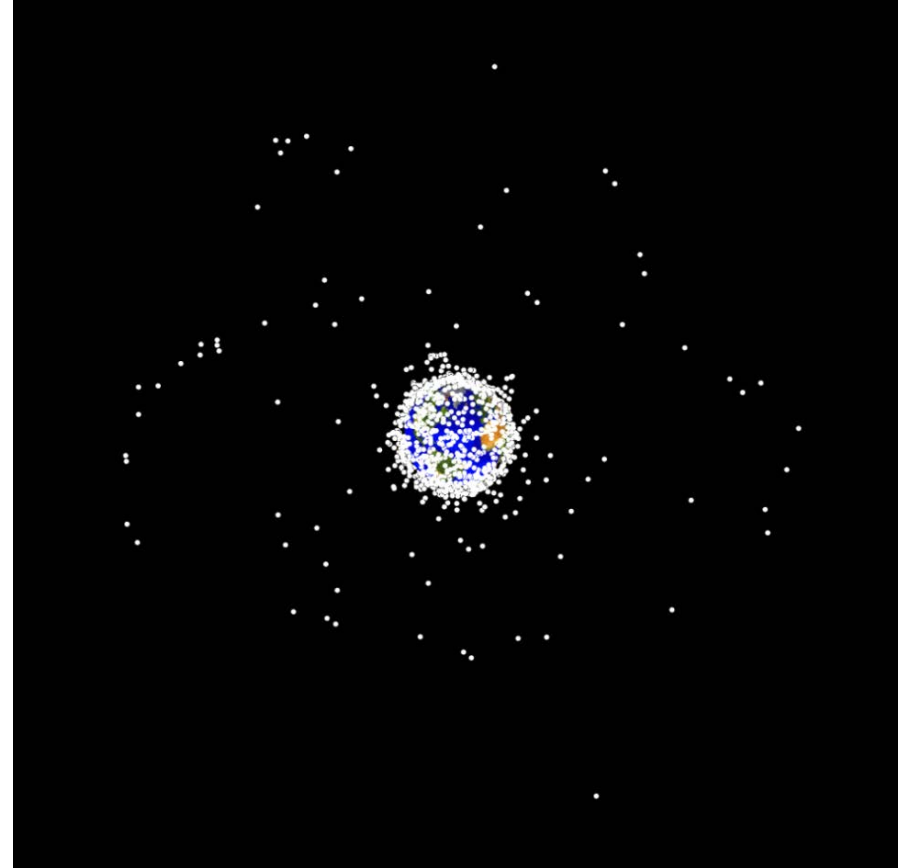
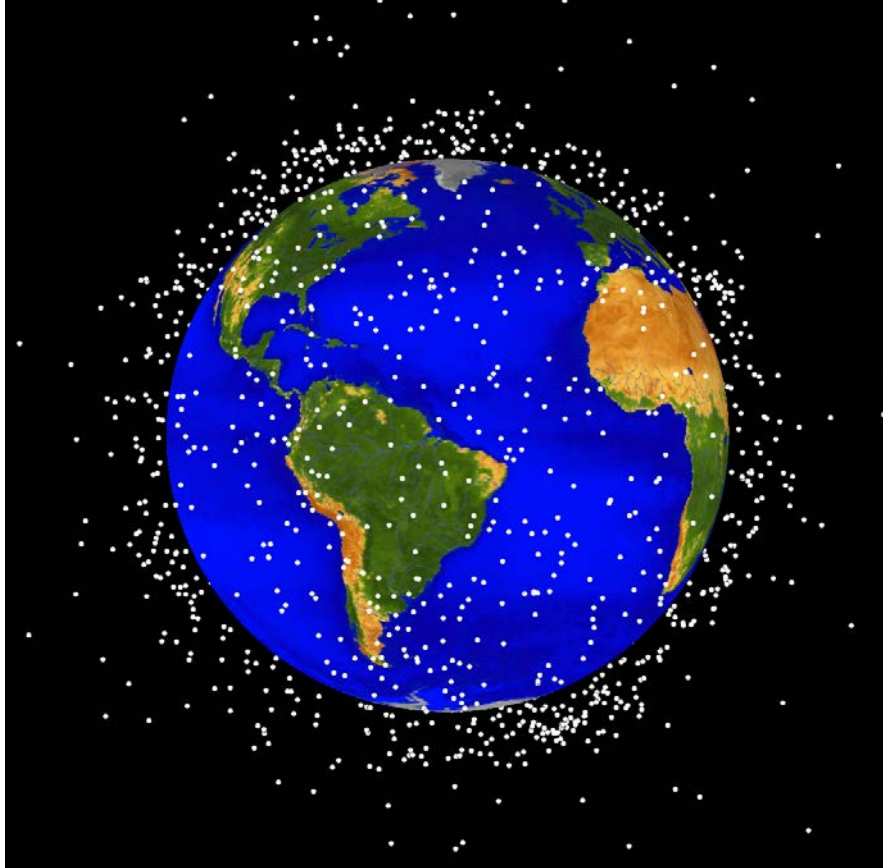
1960



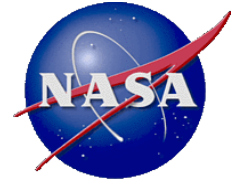
Cataloged objects >10 cm diameter



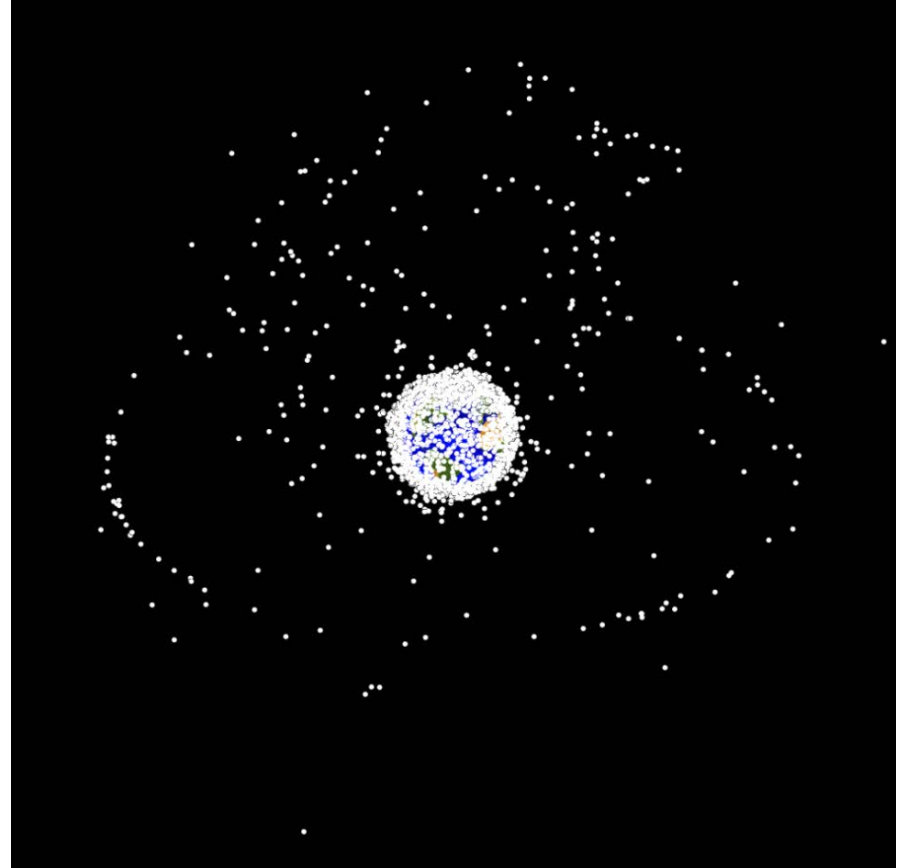
1970



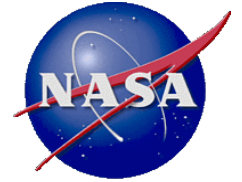
Cataloged objects >10 cm diameter



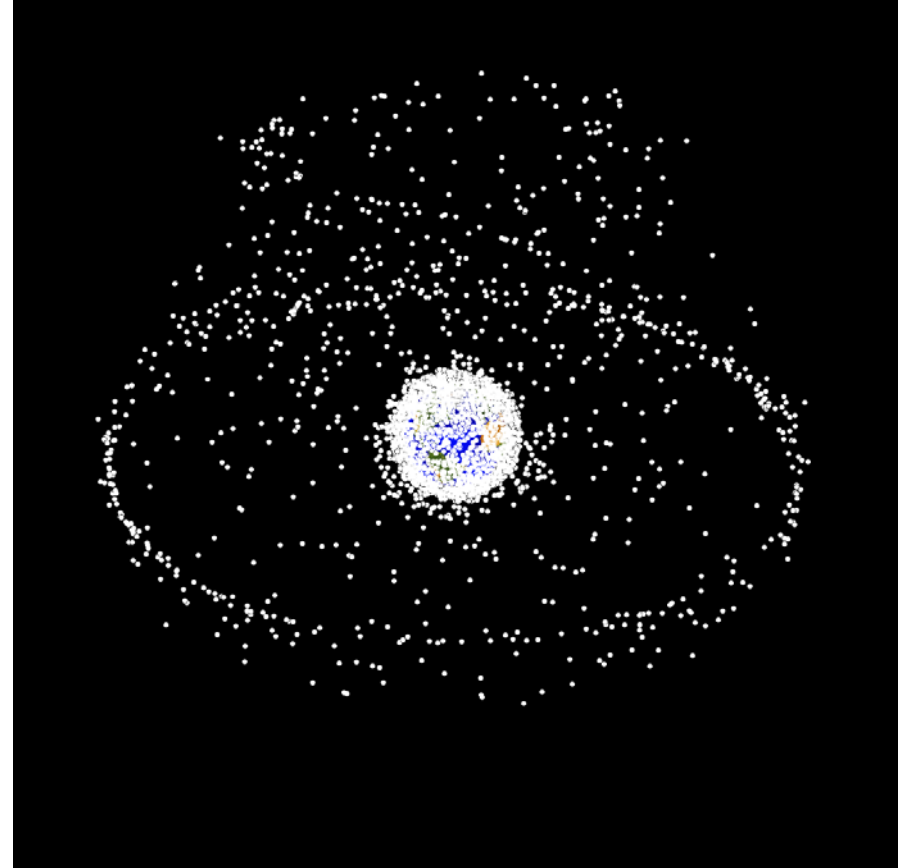
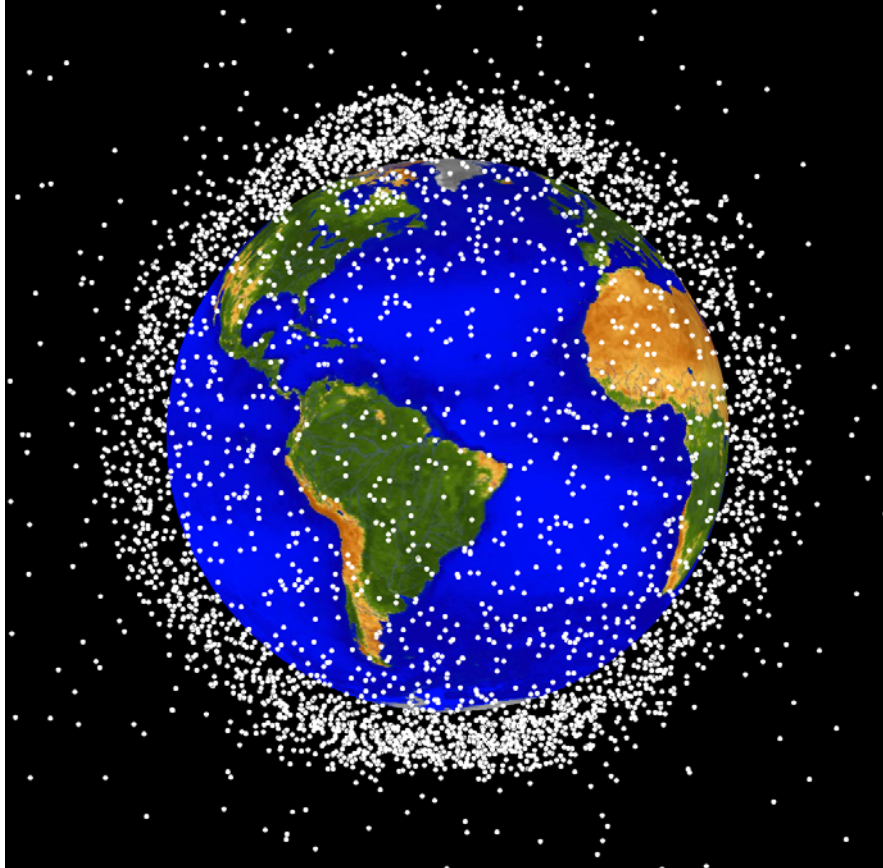
1980



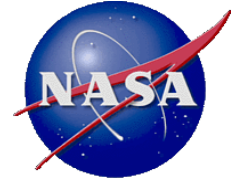
Cataloged objects >10 cm diameter



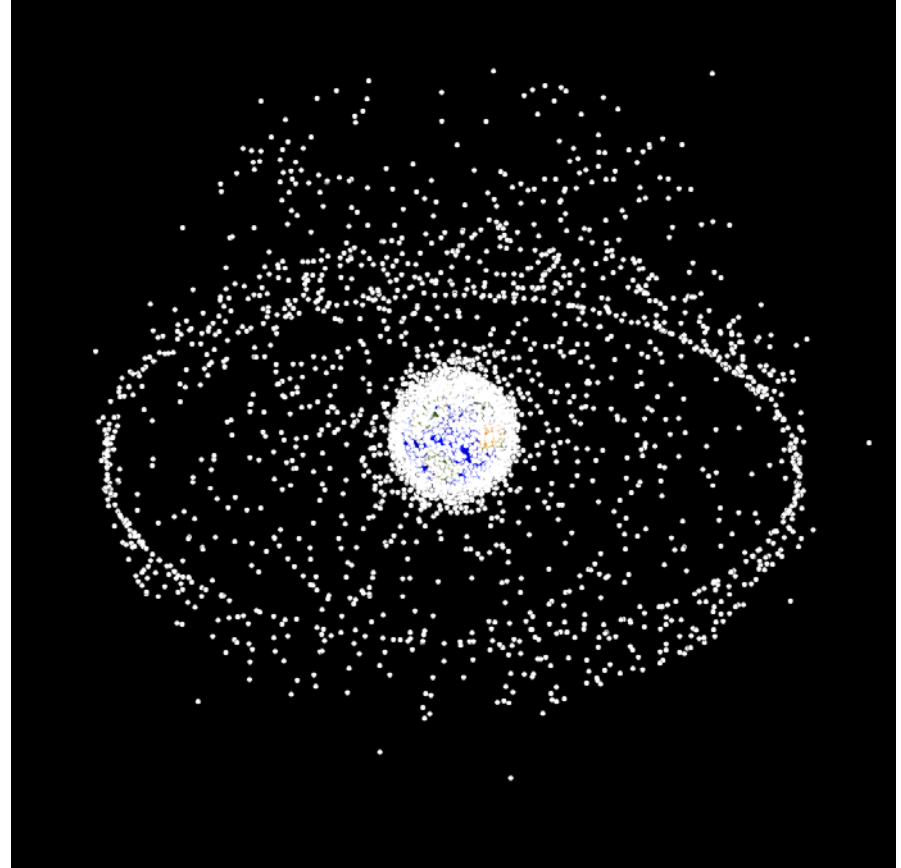
1990



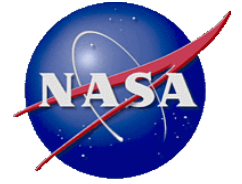
Cataloged objects >10 cm diameter



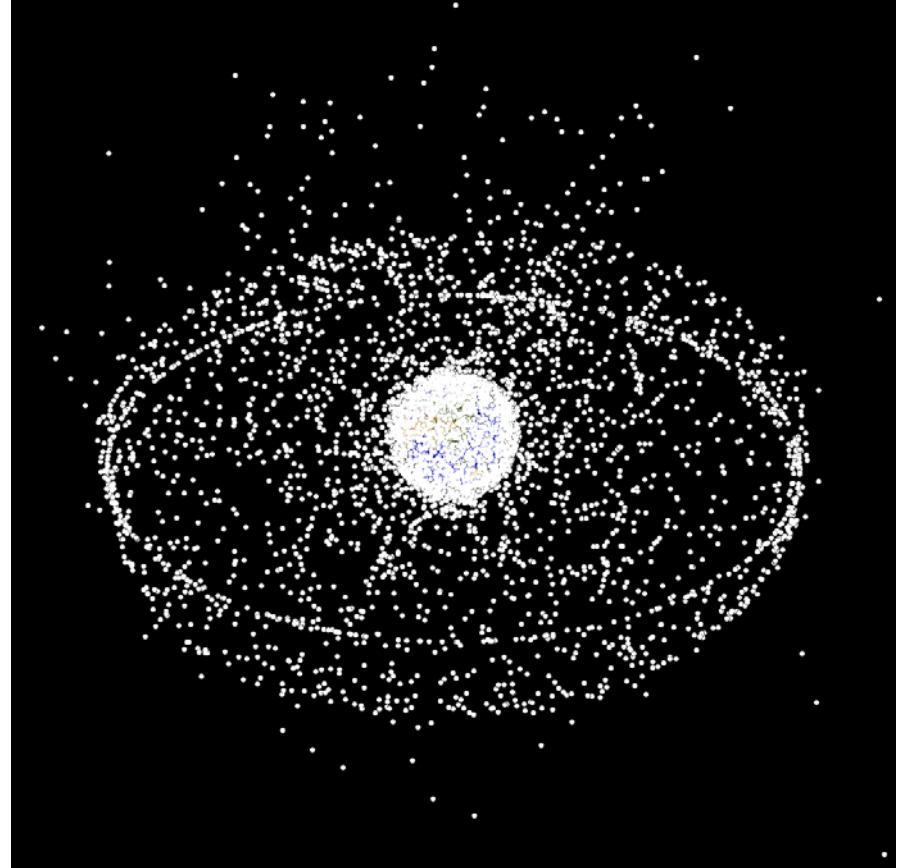
2000



Cataloged objects >10 cm diameter



2010

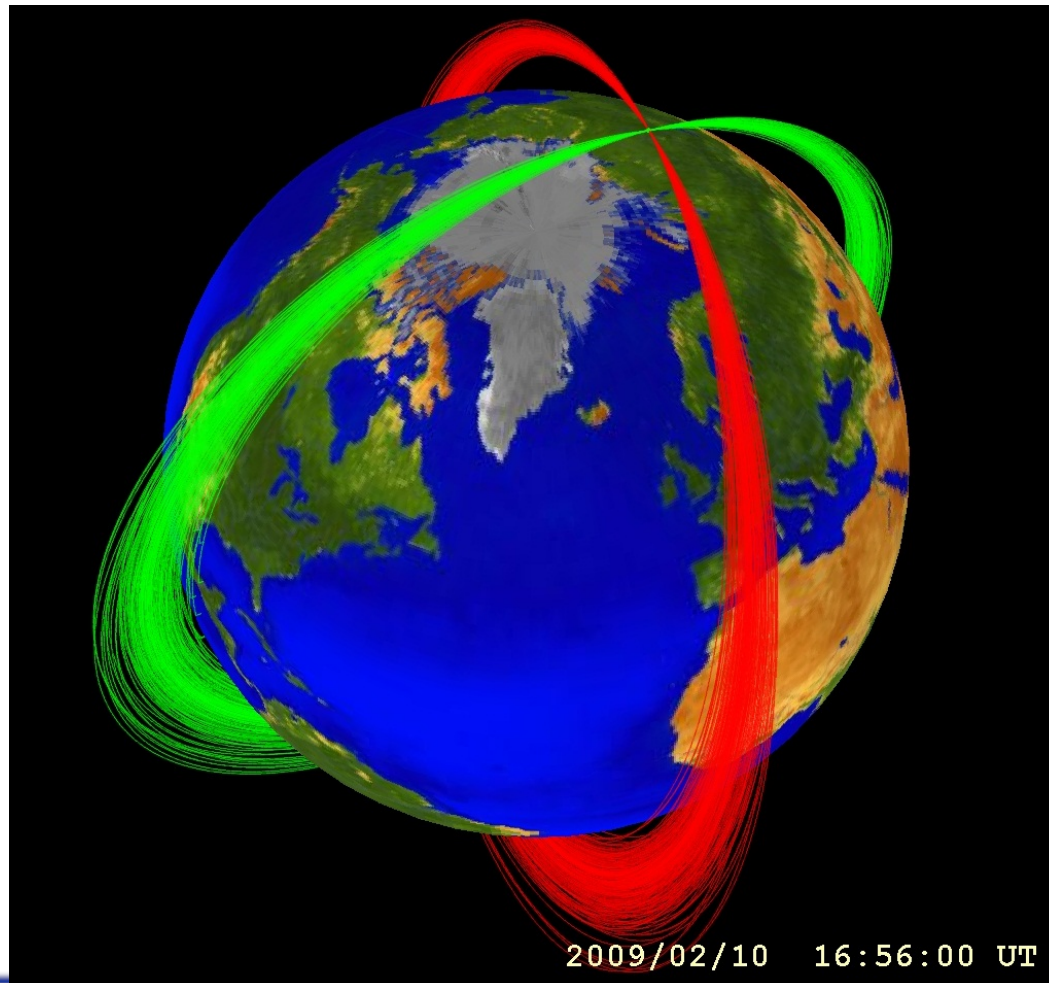


Cataloged objects > 10 cm diameter



Debris movies

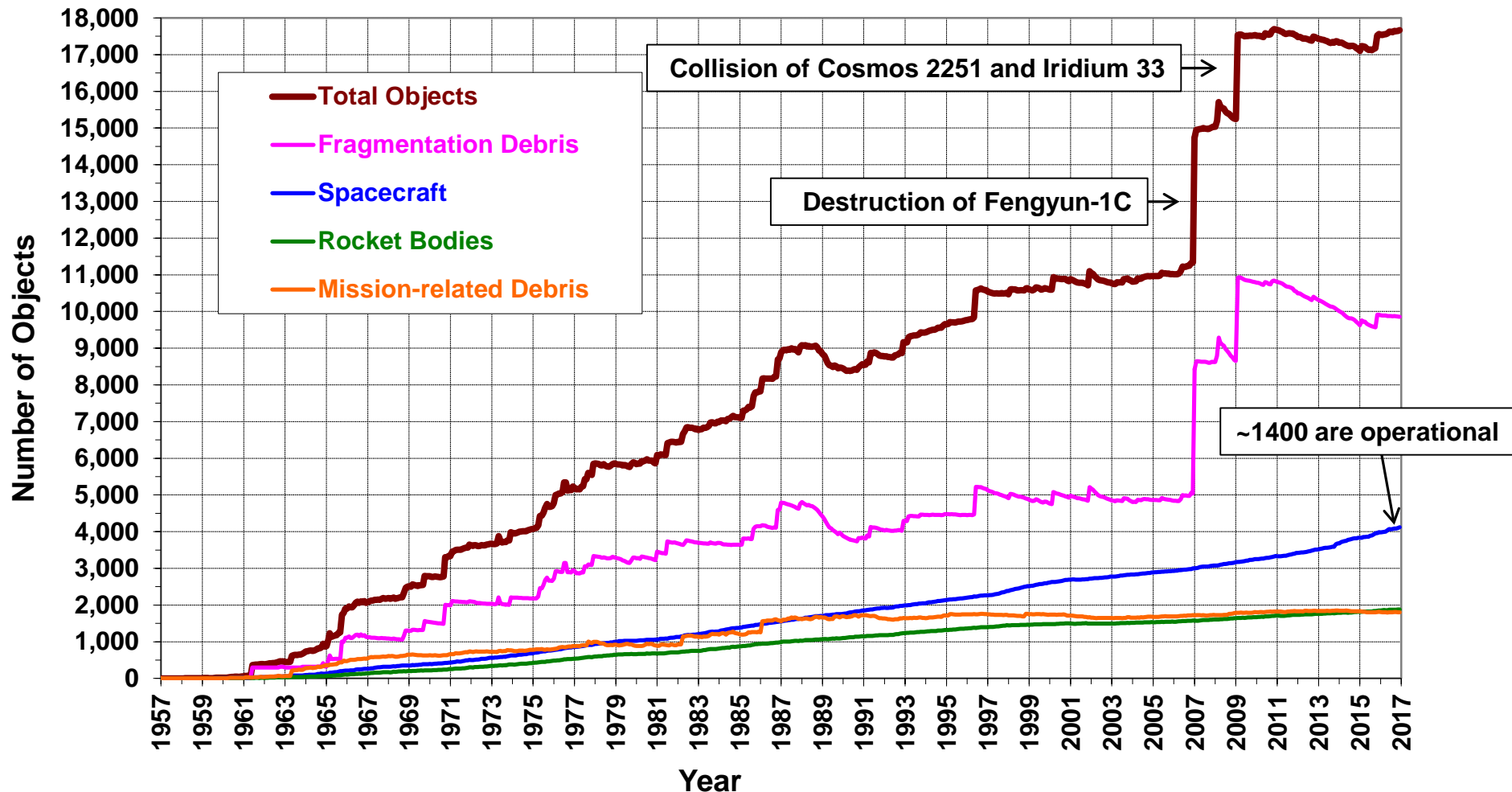
- **Iridium-Cosmos collision**
- **Debris fly-through**



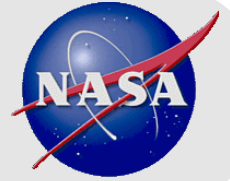
Evolution of the Cataloged Satellite Population



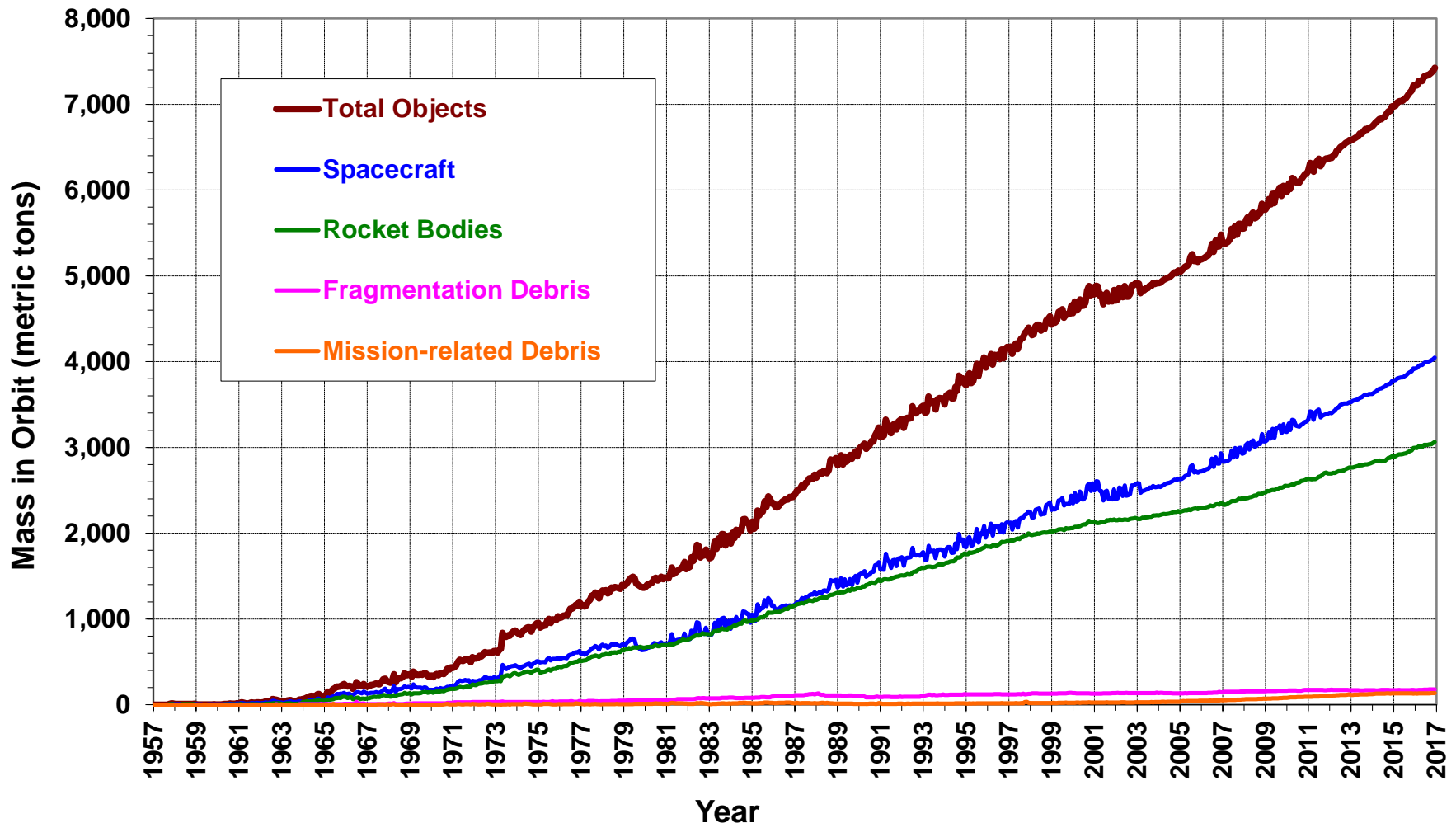
- According to the U.S. Satellite Catalog, the number of 10 cm and larger objects in Earth orbit increased slightly in 2016.



Mass in Near-Earth Space Continues to Increase



- The material mass in Earth orbit continues to increase and exceeded 7400 metric tons in 2016.

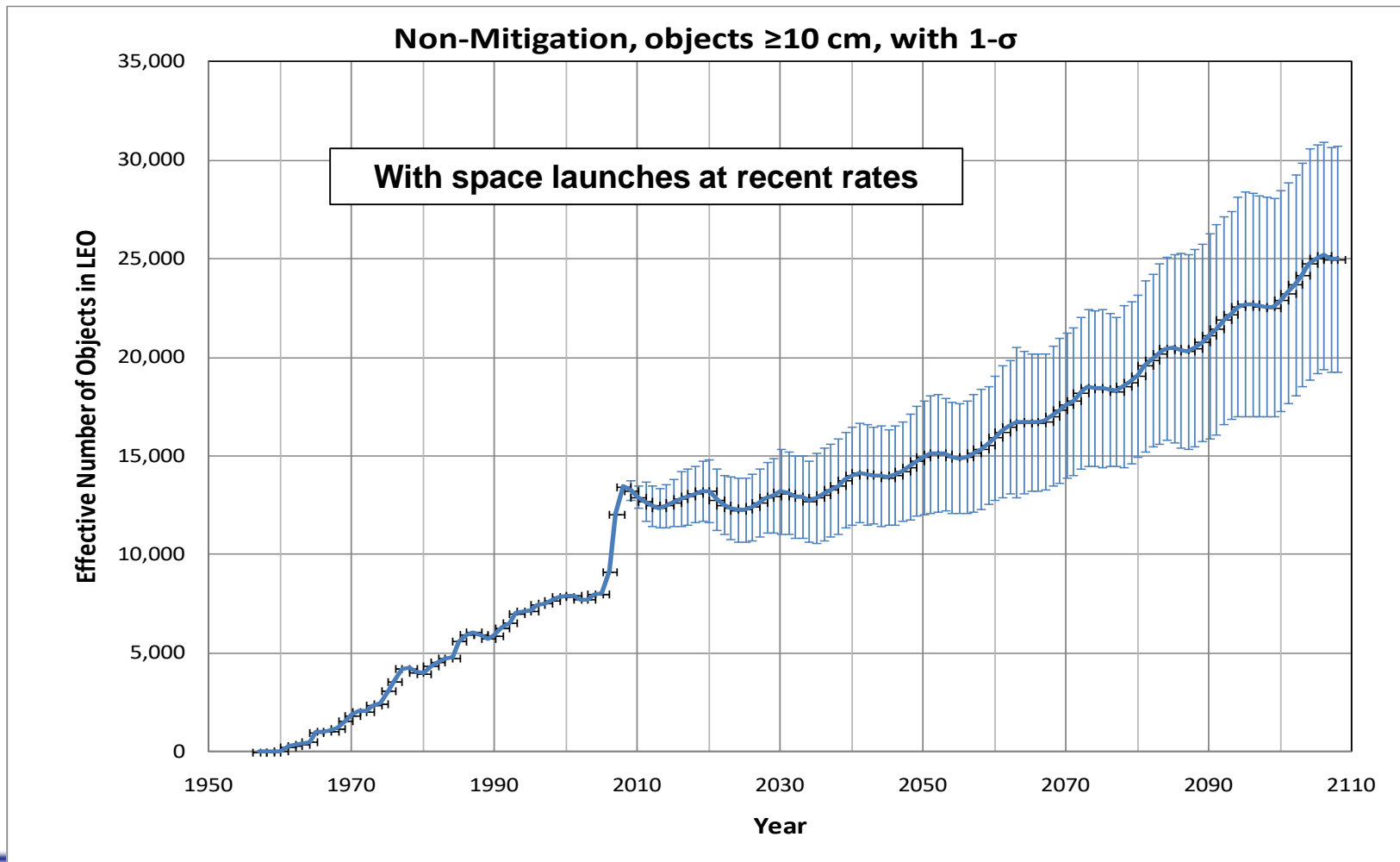




Long-Term Projection & the Kessler Syndrome

“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”

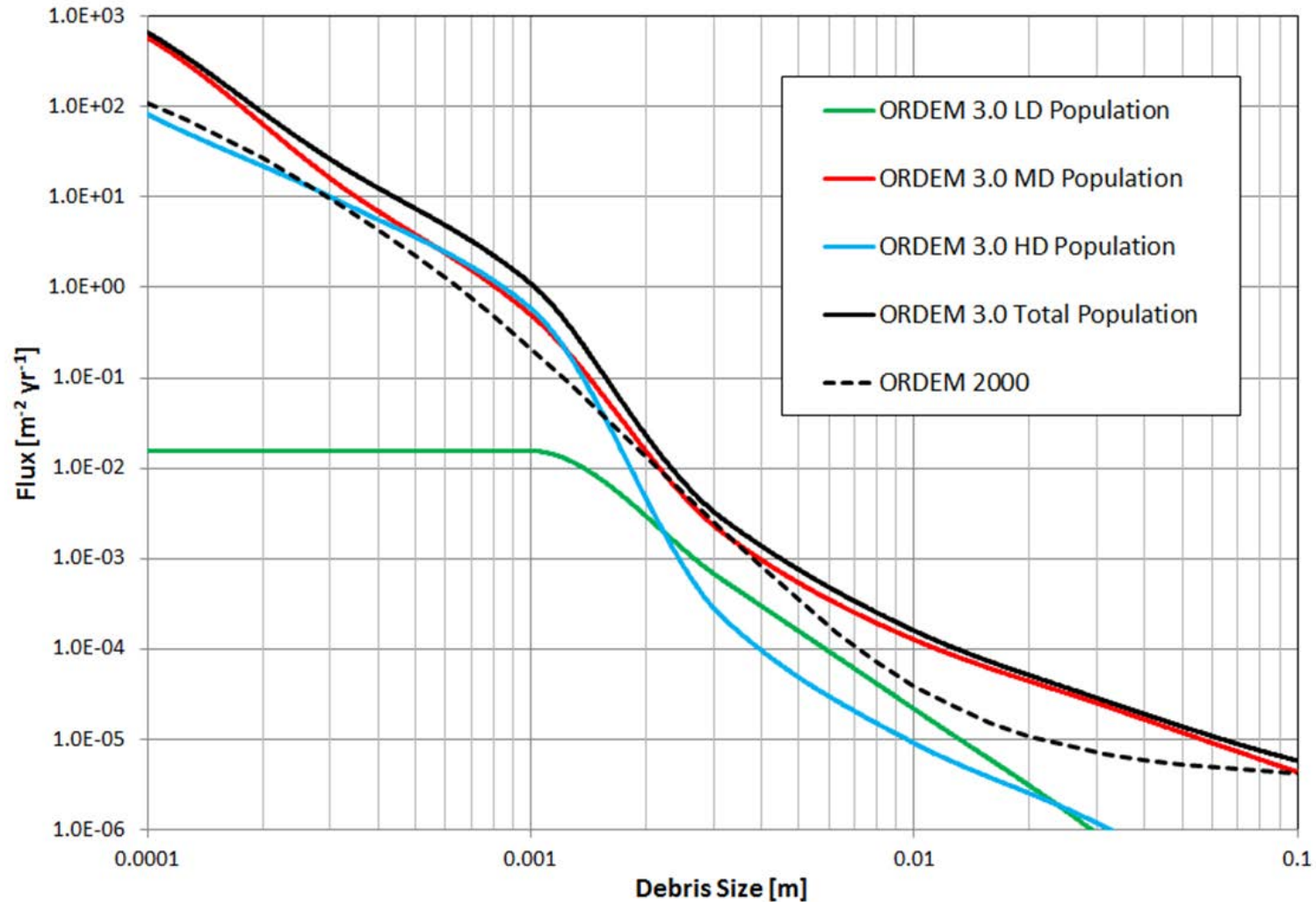
– Liou and Johnson, Science, 20 January 2006



Orbital Debris Material Distributions – A-Train



ORDEM Populations for 2013 98° 705 km Orbit Flux as a Function of Debris Size

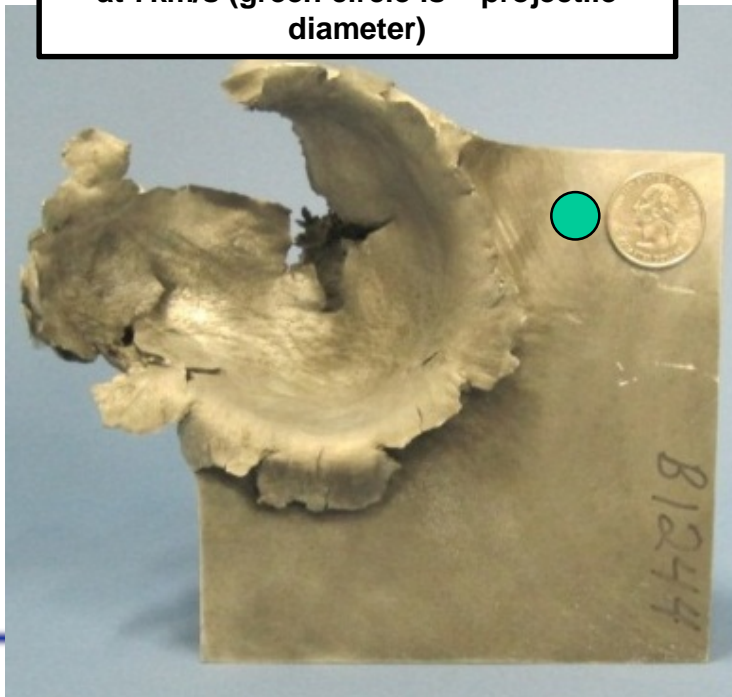




Effects of Micrometeoroid and Orbital Debris (MMOD) Impacts

- **Even small MMOD impacts can cause considerable damage**
 - Hypervelocity MMOD impacts represent a substantial threat to spacecraft
 - Rule of thumb: at 7km/s, aluminum sphere can penetrate completely through an aluminum plate 4x the sphere's diameter

Damage from a 1.3cm diameter sphere at 7km/s (green circle is = projectile diameter)



Comparison of size of projectile to size of impact crater

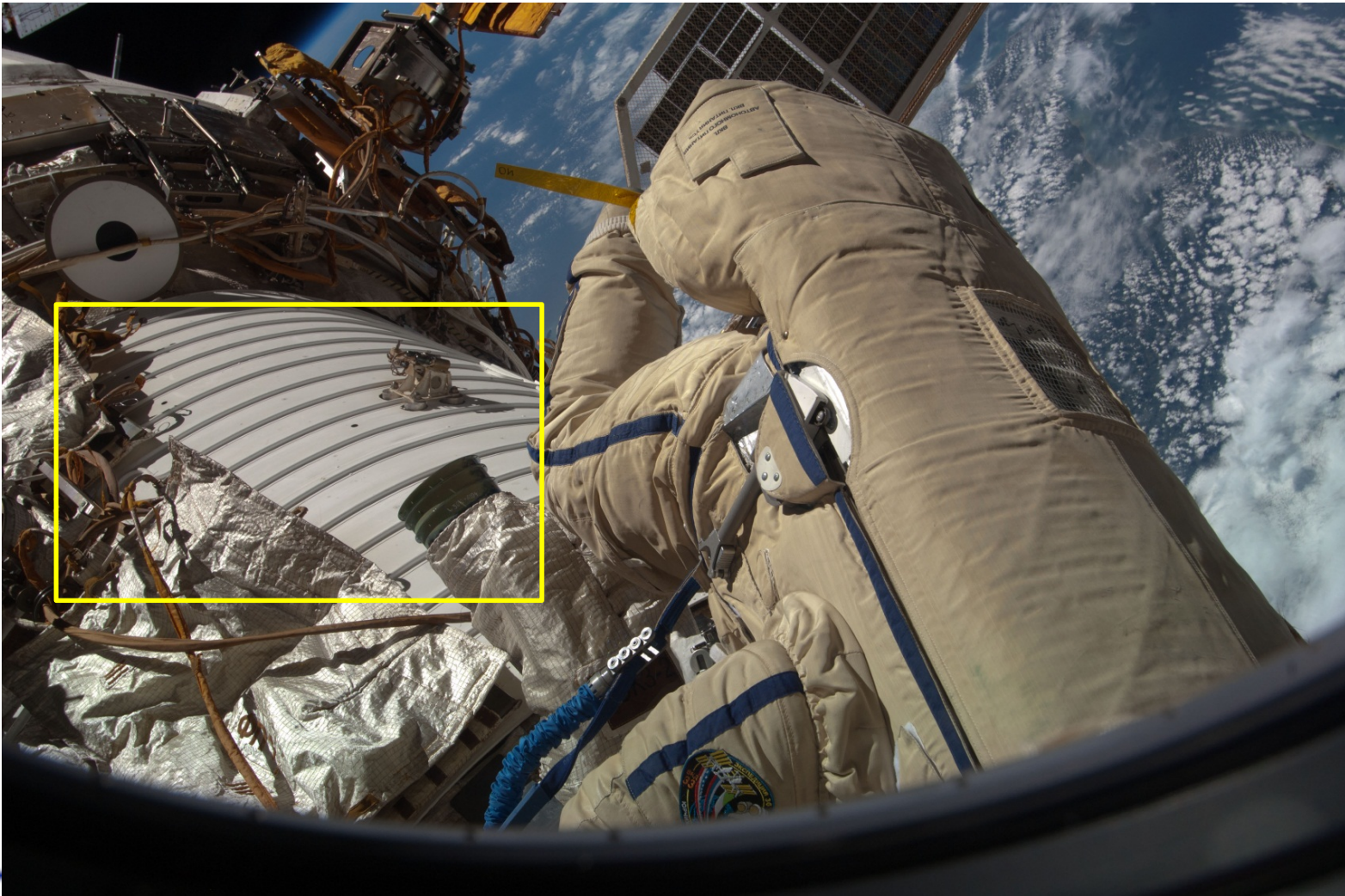


Attached spall



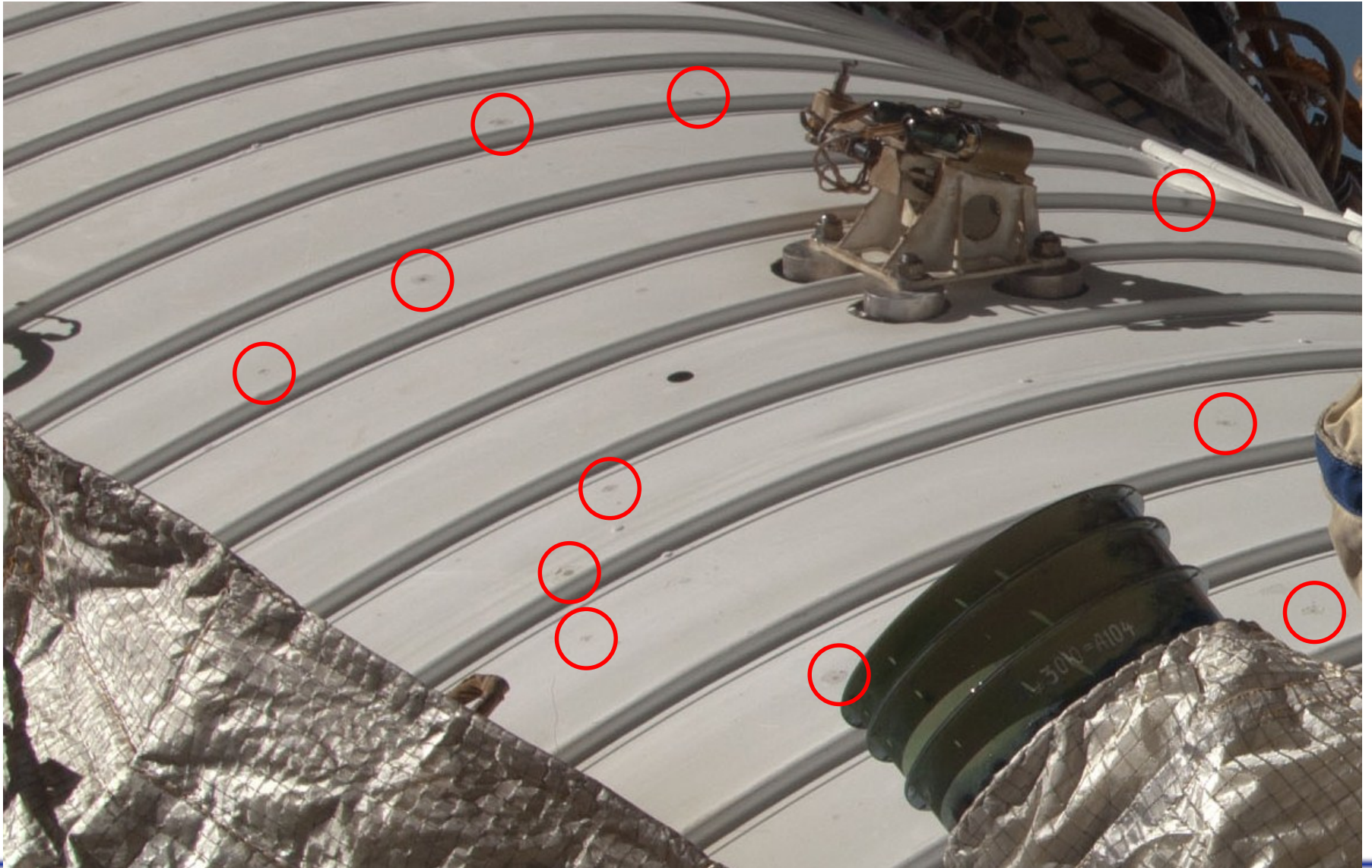
MMOD Damage to ISS Radiators

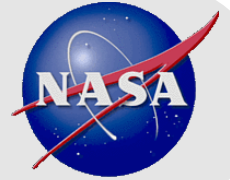
- **MMOD impact damages observed to ISS radiator panels during Russian EVA (June 2013)**





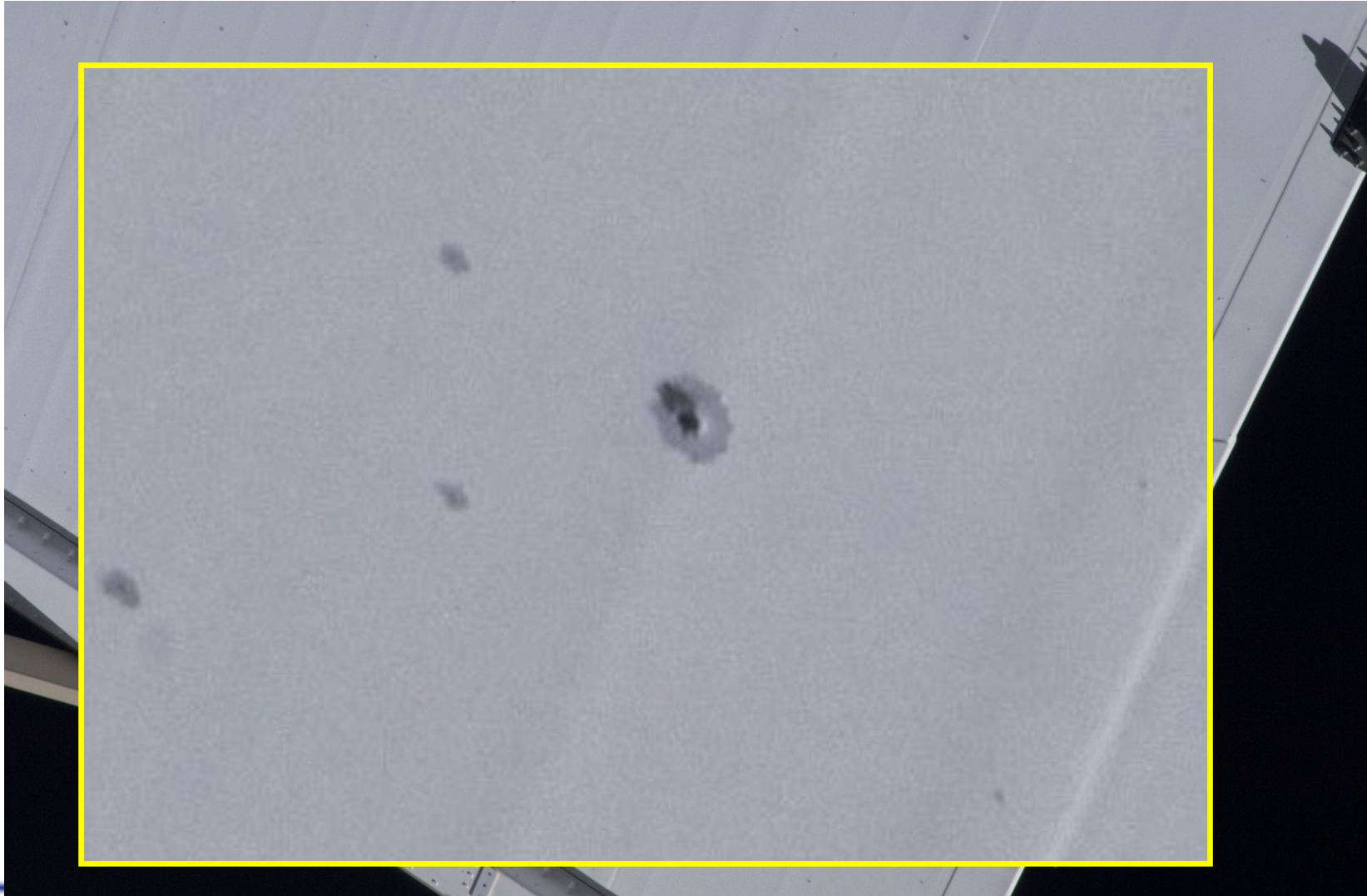
MMOD Damage to ISS Radiators

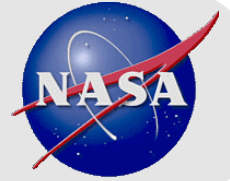




MMOD Damage to ISS Radiators (US)

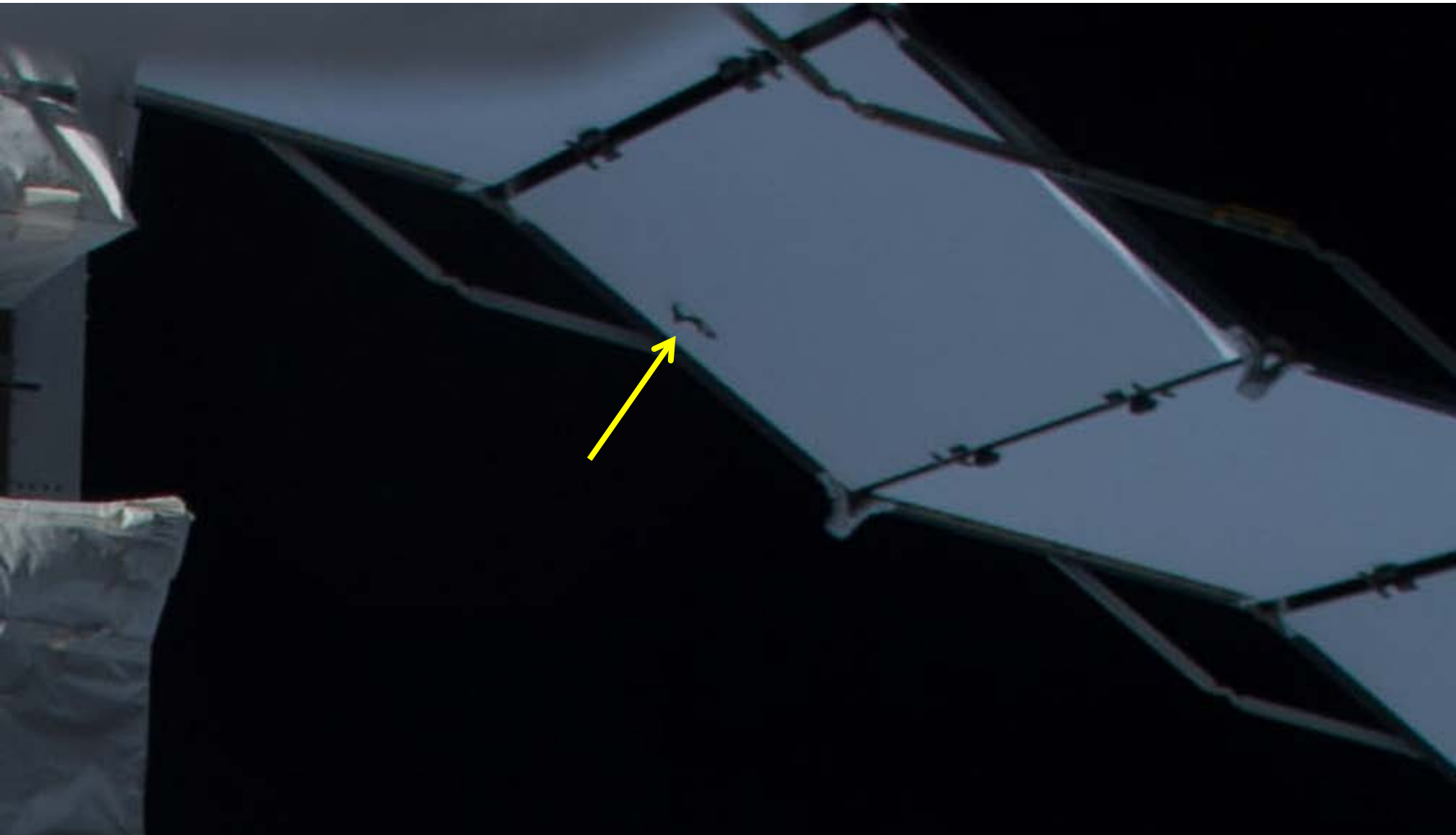
- **MMOD impact damages observed to ISS radiator panels (Aug. 2013)**



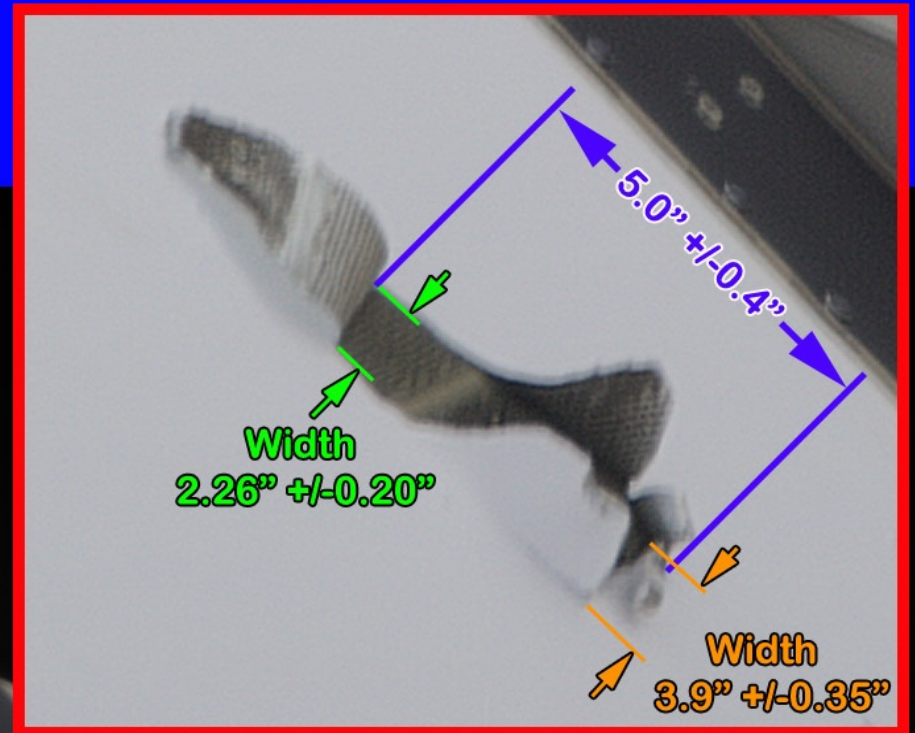


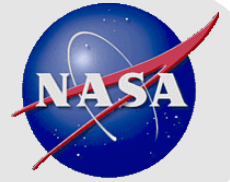
ISS Photovoltaic Radiator (P4) MMOD damage

- **Initial indication found on 6/30/2014**



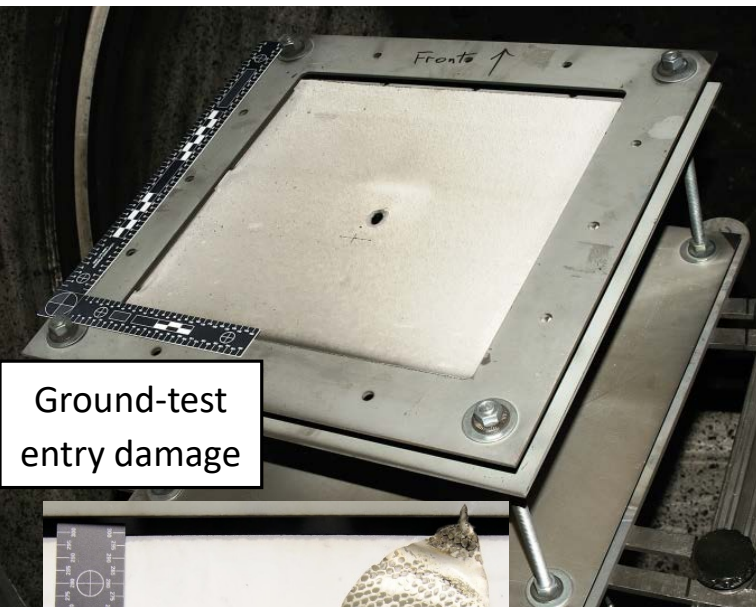
Measurement of P4-PVR Radiator Damage "2A" Side of Panel 3



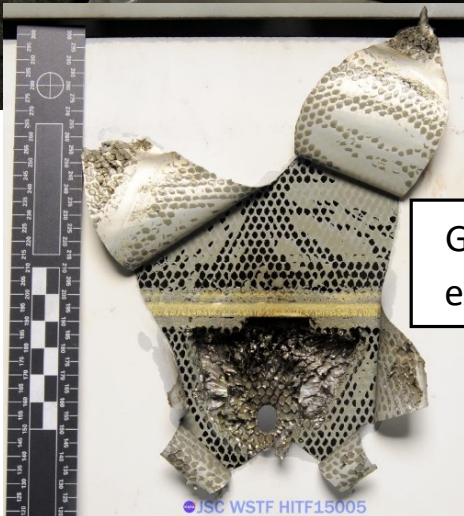


Ground hypervelocity impact test MMOD damage compared to P4 photovoltaic radiator damage

- Good comparison between on-orbit damage and ground-based hypervelocity impact test from 4.5 mm diameter aluminum spherical projectile at 7.08 km/s and 50 deg impact angle (angle from target normal) compares well with actual damage

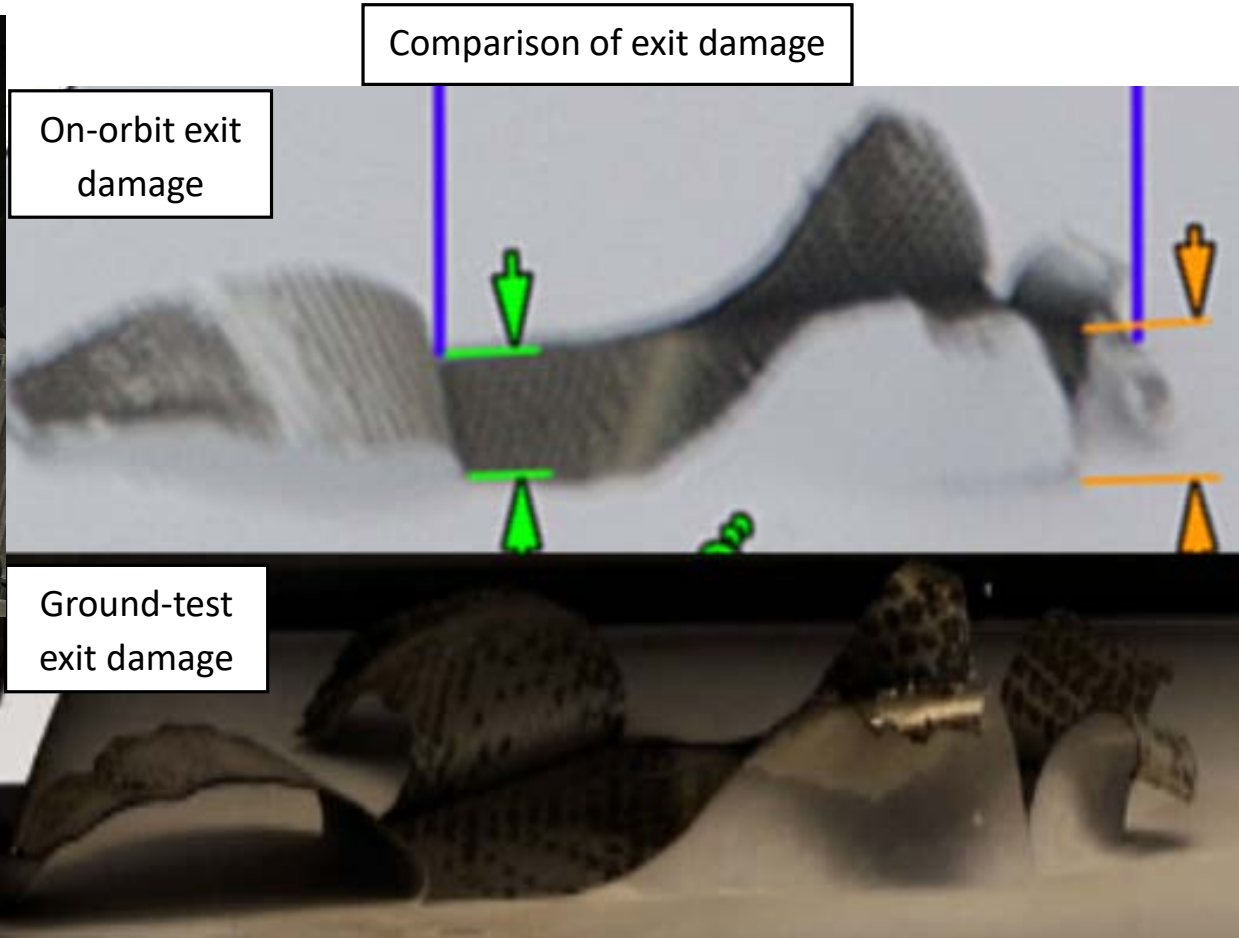


Ground-test entry damage



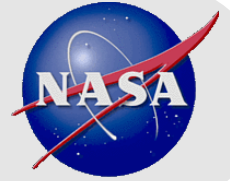
Ground-test exit damage

JSC WSTF HITF15005



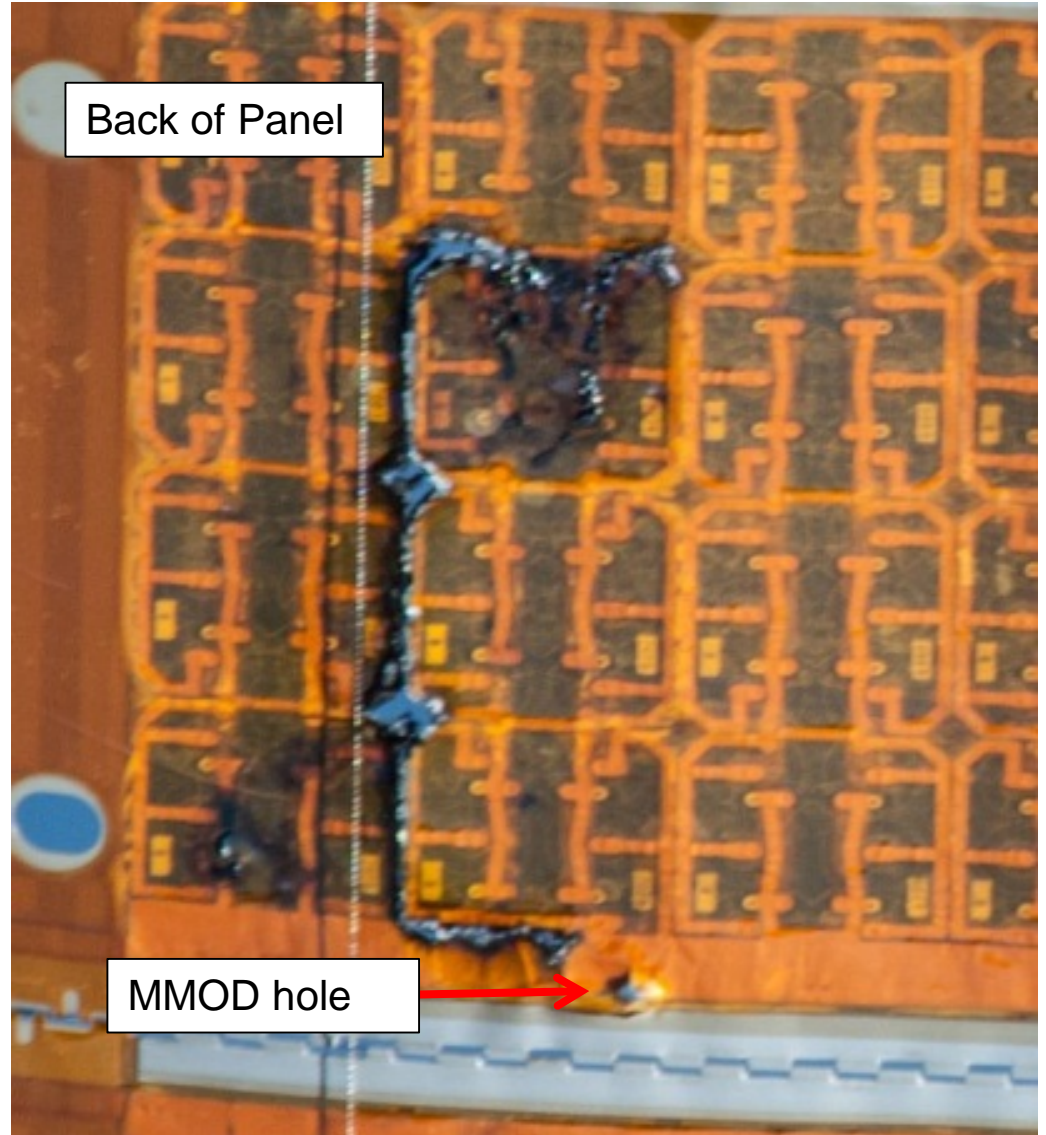
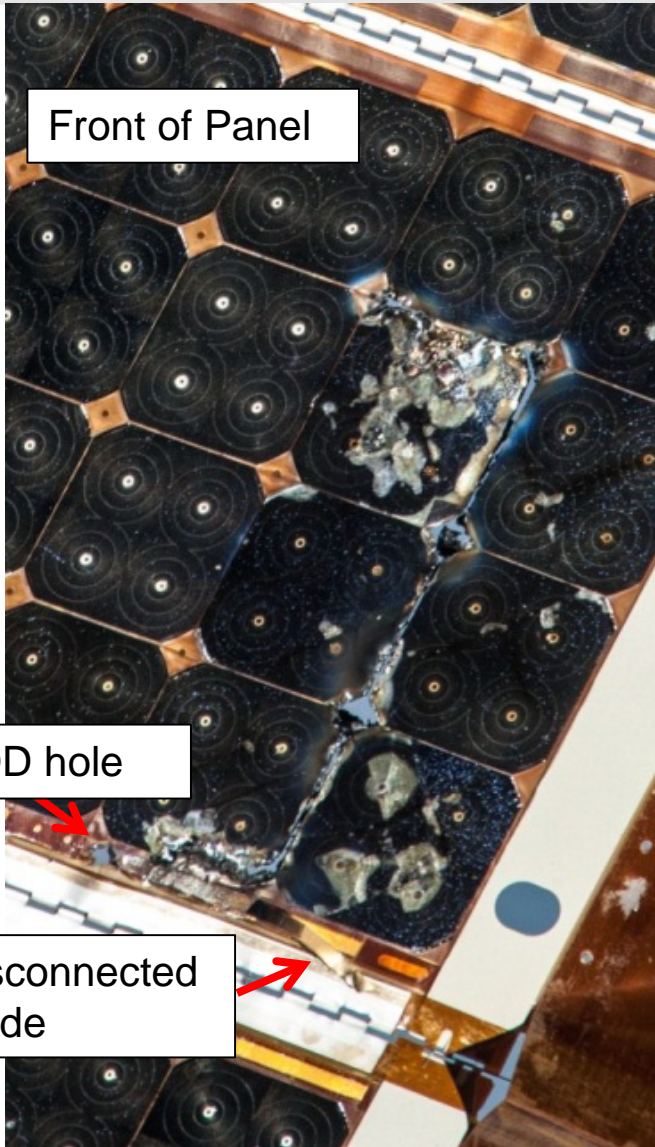
On-orbit exit damage

Ground-test exit damage



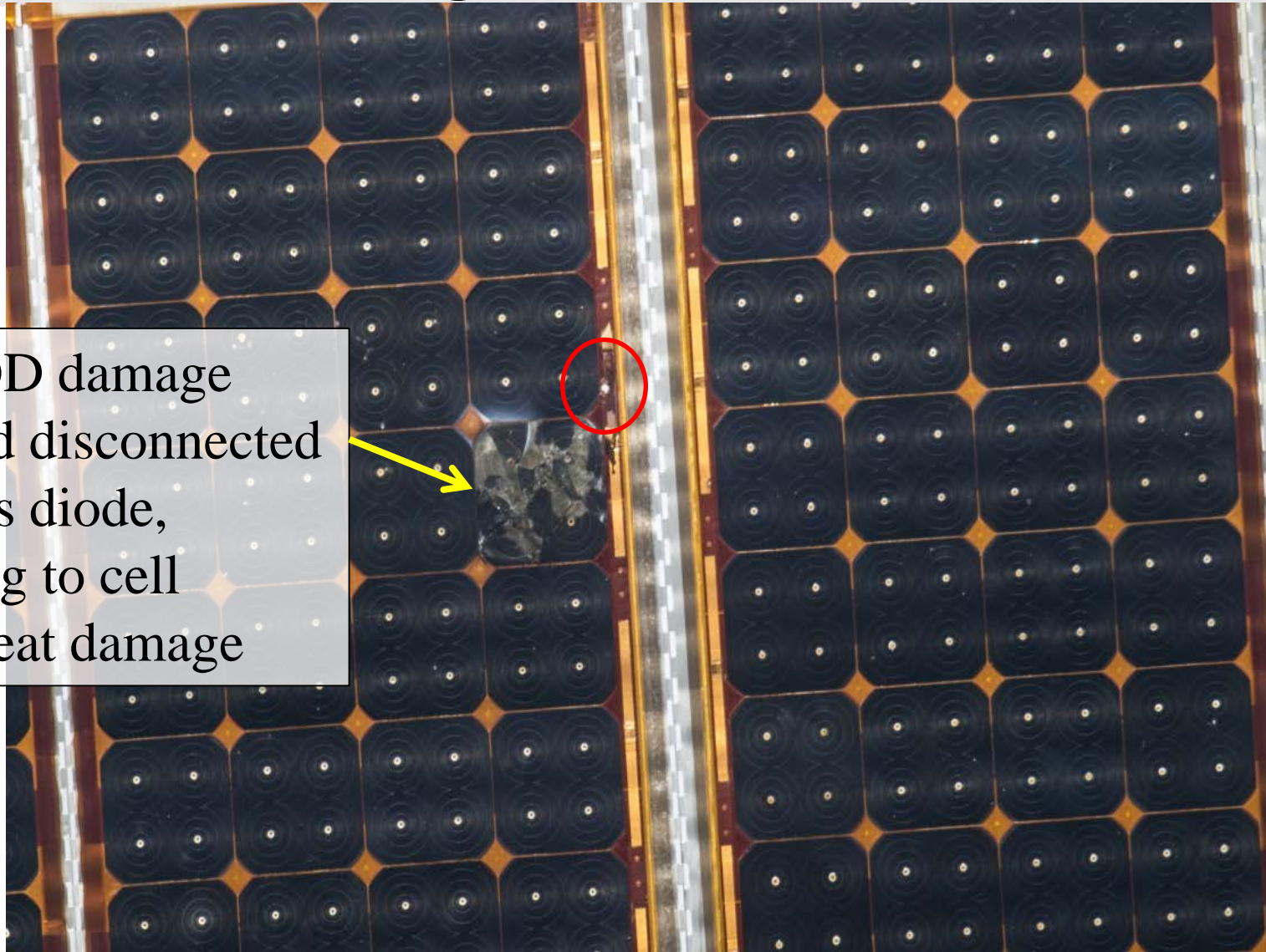
Solar Array Damage

MMOD impact breaks bypass diode causing overheating





Another example of ISS Solar Array Damage from MMOD

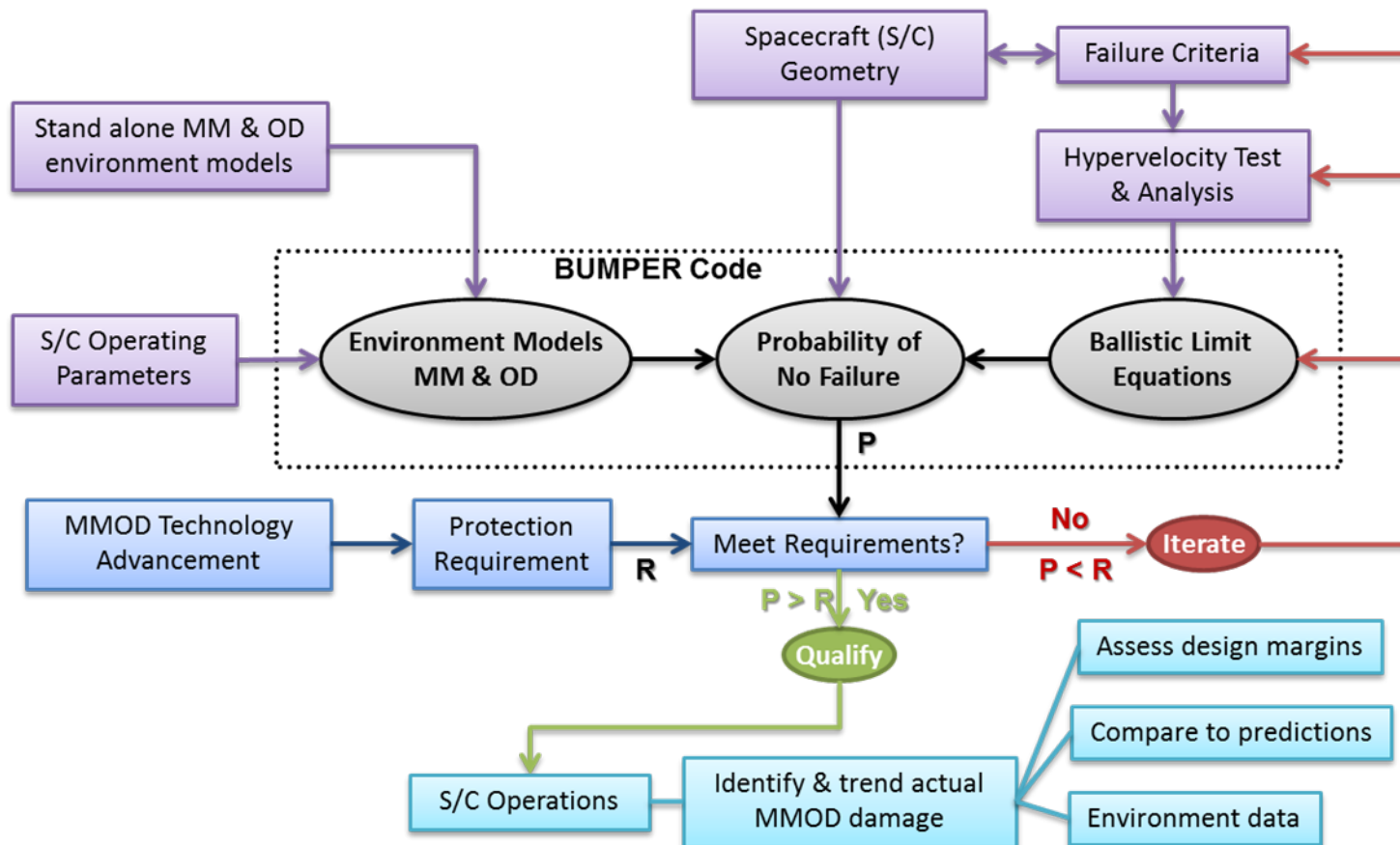


MMOD damage
caused disconnected
bypass diode,
leading to cell
overheat damage



MMOD Risk Assessment Process

- Process used by HVIT to identify MMOD risk drivers, evaluate risk mitigation options, optimize MMOD shielding, verify compliance with protection requirements





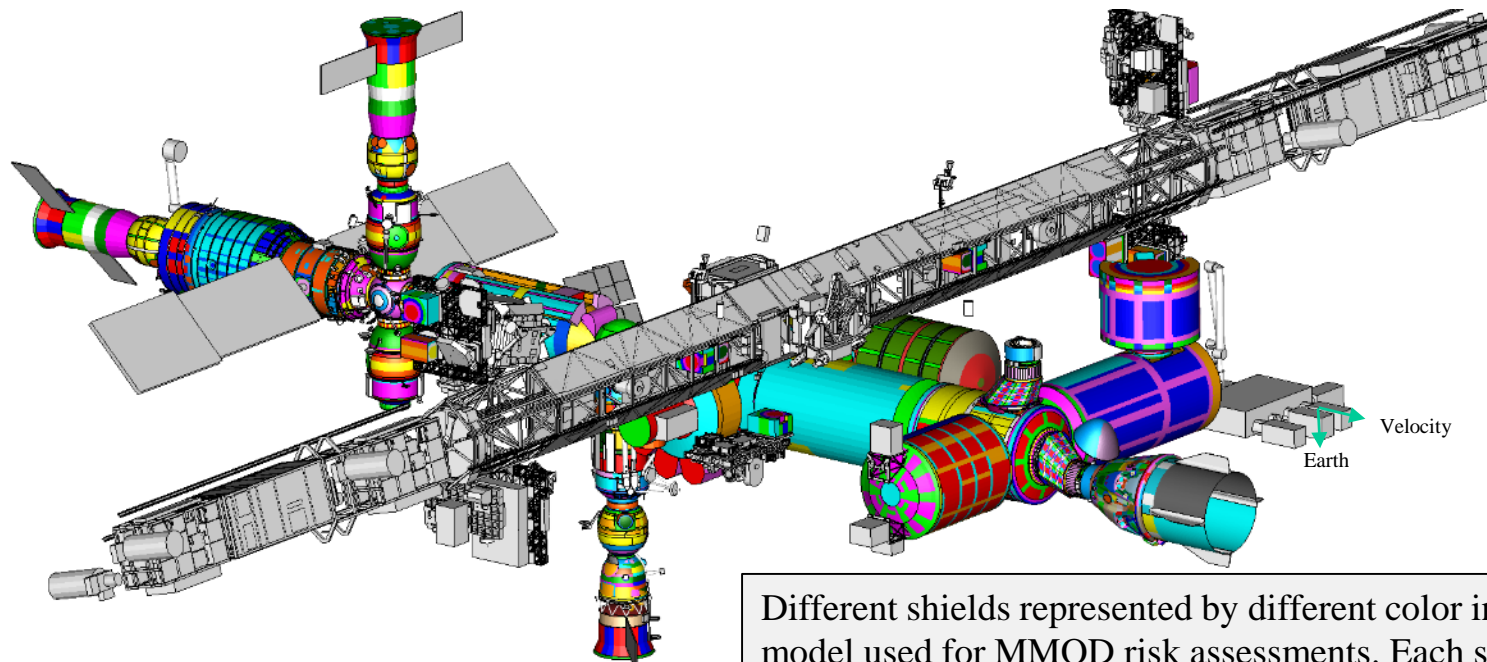
Risk Relationships

- **Poisson Statistics used to determine failure risk**
 - Probability of No Failure = $\exp(-N)$
 - N = mean number of failures
 - N = flux of MMOD particles at/above ballistic limit particle size (number per $\text{m}^2\text{-year}$) * surface area (m^2) * time (years)
 - PNF expressed in fraction
 - **Note: as spacecraft size increases, or mission duration increases, PNF decreases**
 - **Note 2: as ballistic limit particle size increases (i.e., by using tougher materials or better shielding), flux decreases and PNF increases (improves)**
 - Risk of Failure = $1 - \text{PNF}$
 - Risk expressed in terms of % or Odds of failure
- **Option: can determine an average MMOD particle size that spacecraft shield needs to stop in order to meet a given reliability level, knowing the area and mission duration**

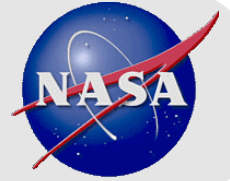


ISS shielding overview

- Several hundred MMOD shields protect ISS, differing by materials, standoff distance, and capability
- Heavier shields on front & sides (where we expect most MMOD impacts), less capable shielding on aft, nadir and visiting vehicles

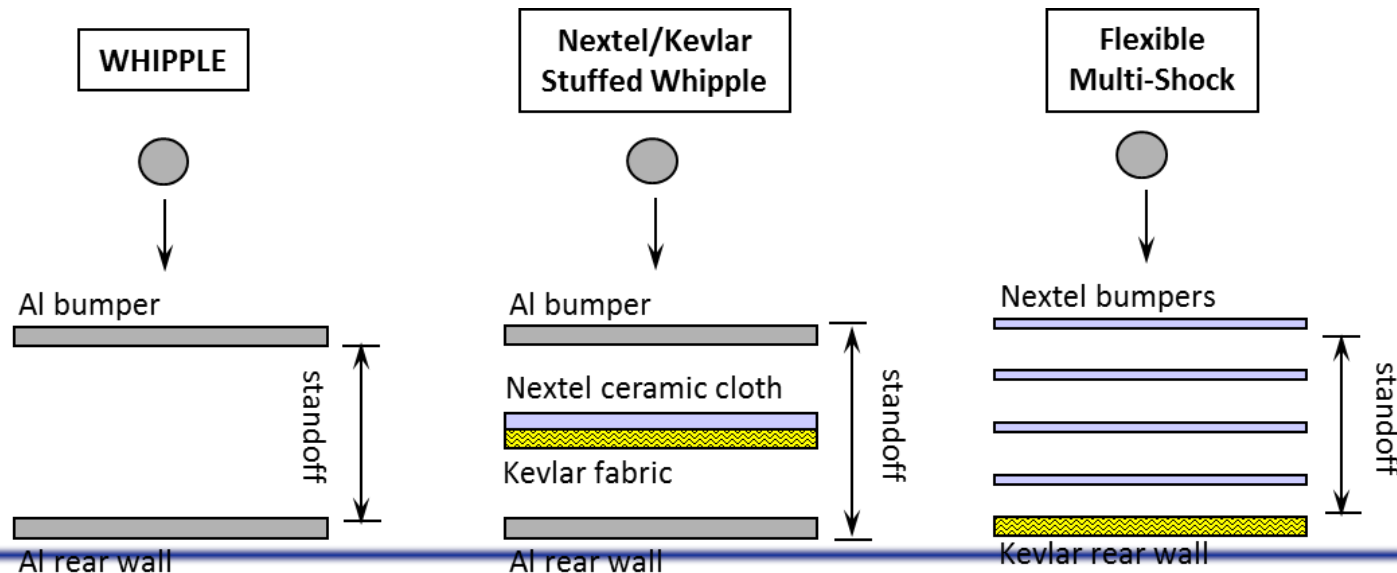


Different shields represented by different color in geometry model used for MMOD risk assessments. Each shield varies in performance, i.e., the MMOD particle size that shield protects is a function of impact speed, angle, particle density, and projectile shape/orientation.



MMOD Shielding

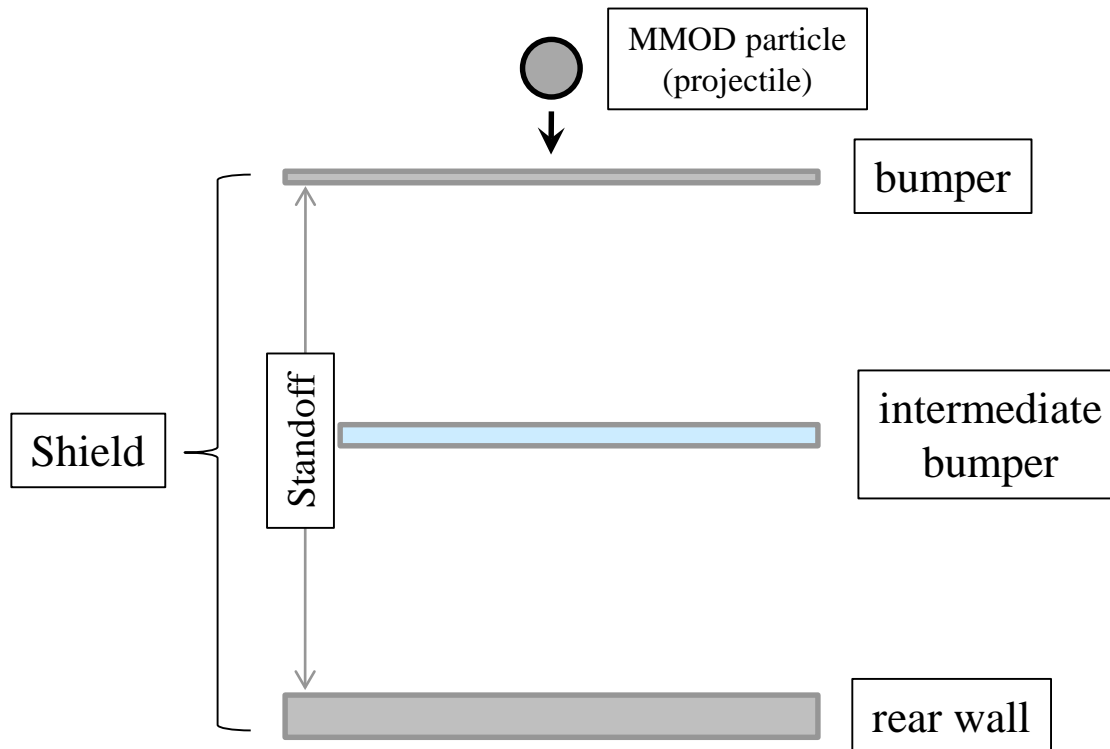
- A multi-layer spaced shield provides more effective protection from hypervelocity impact than single layer
- **Several types of shielding applied to spacecraft MMOD protection**
 - Whipple shields
 - Nextel/Kevlar “Stuffed Whipple” shields
 - Multi-Shock shields
- **Protection performance characterized by impact tests & simulations**
 - Defined by “ballistic limit” equations (BLEs)





MMOD shielding background

- **MMOD shields typical composed of bumper(s), standoff, and rear wall (final protection layer)**
 - Exclude multi-layer insulation (MLI) thermal blanket



Purpose: Breakup MMOD particle, laterally disperse resulting debris

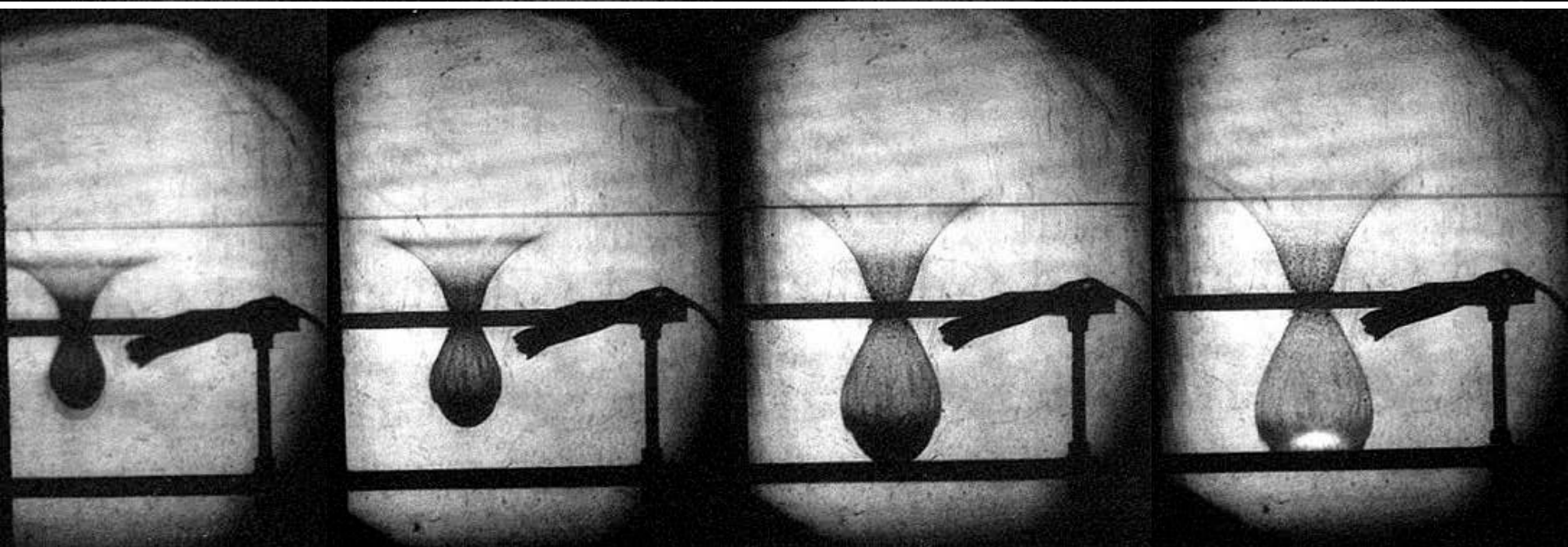
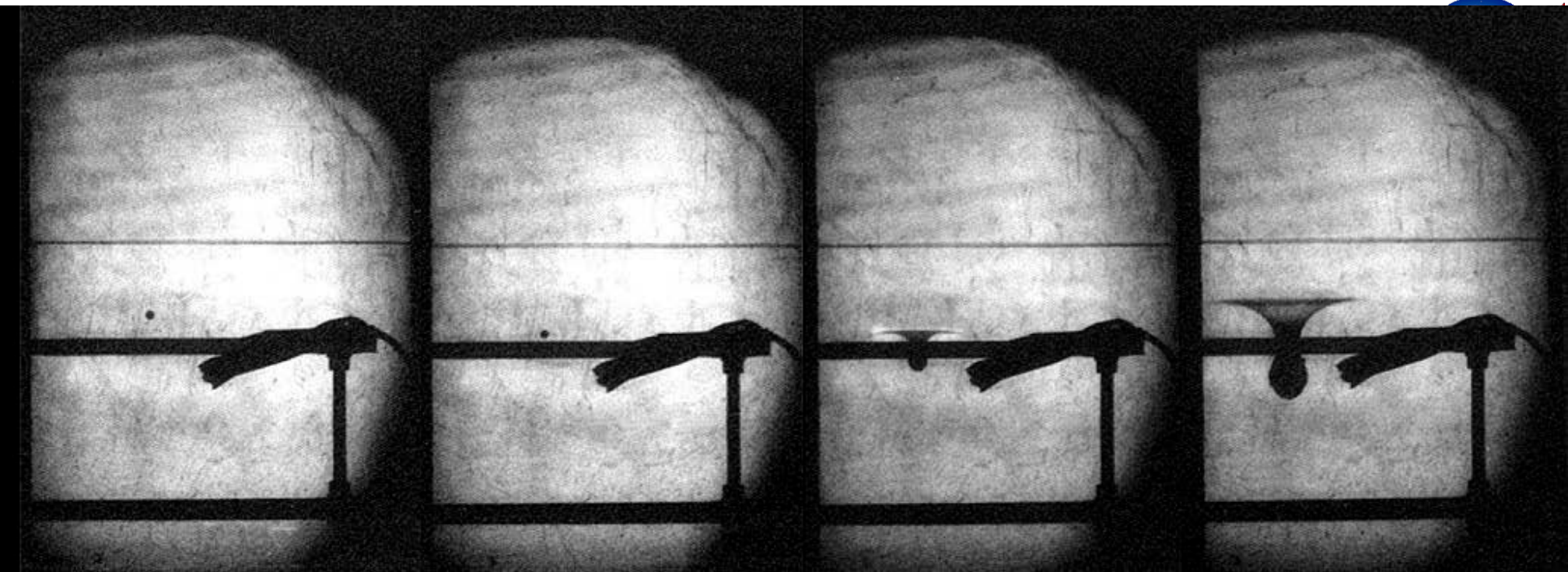
Key material & physical parameters ($V \geq 7$ km/s): density, thickness to projectile diameter ratio, thermal properties

Purpose: Further breakup debris from first impact, slow expansion of debris cloud

Key material & physical parameters ($V \geq 7$ km/s): combination of first bumper and rear wall properties

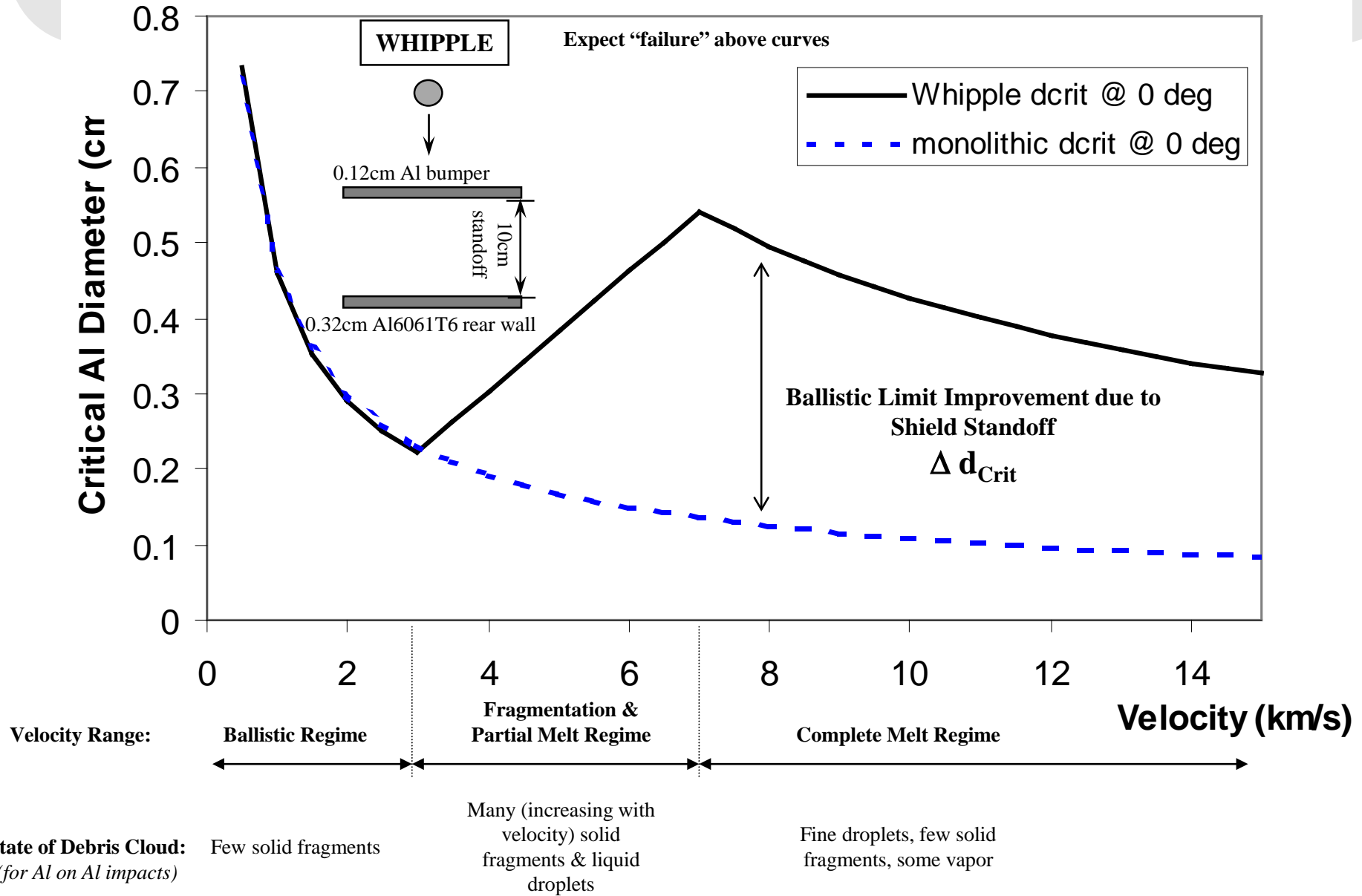
Purpose: Stop debris from MMOD & bumper(s)

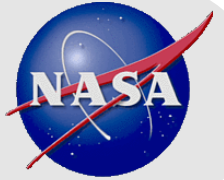
Key material & physical parameters ($V \geq 7$ km/s): strength, toughness, thickness





Ballistic Limits for Whipple Shield & equal mass Monolithic





Hypervelocity Impact Technology (HVIT) Group

- **Background**

- The HVIT group has been in existence for over 30 years at JSC developing and evaluating spacecraft micrometeoroid and orbital debris (MMOD) shielding for crewed and non-crewed spacecraft, and designing operational techniques to reduce MMOD risk
- Small cadre of skilled and accomplished technical & engineering staff
- HVIT works closely with the spacecraft engineering/design groups to develop MMOD protection solutions to meet MMOD requirements with minimum mass, cost and schedule
- Products are based on a combination of hypervelocity impact test and analysis

- **Goal**

- Improve MMOD protection of NASA spacecraft to meet/exceed crew safety and mission success requirements

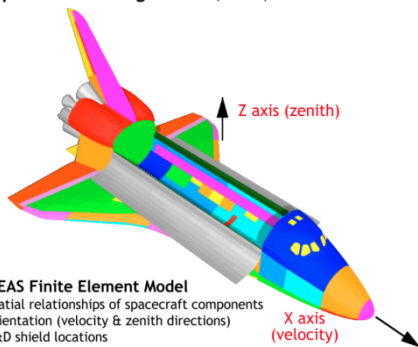


MMOD Risk Assessment Tools

- Bumper Code – Perform penetration & damage risk assessments
- MSC-Surv – Assess consequences of penetration for ISS: loss-of-crew, evacuation risk
- Hydrocodes (CTH, Autodyn, Exos, others) – Numerical simulation of hypervelocity impact

Bumper Code

Spacecraft Configuration (I-DEAS)

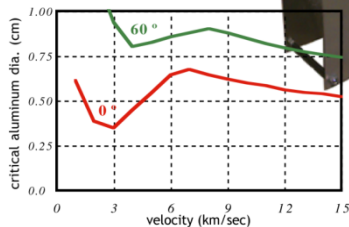


I-DEAS Finite Element Model

- Spatial relationships of spacecraft components
- Orientation (velocity & zenith directions)
- M&D shield locations

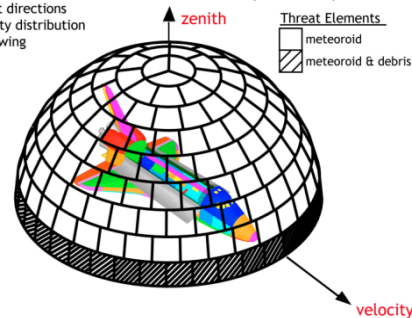
Critical Particle Diameter Calculation (RESPONSE)

Whipple Shield Ballistic Limit
(failure above lines)



Meteoroid & Debris Environments (GEOMETRY)

- Threat directions
- Velocity distribution
- Shadowing

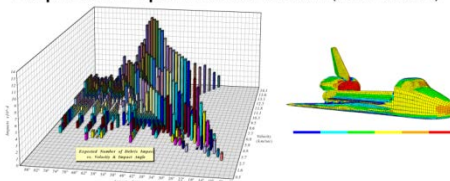


Compute Penetrating Flux & PNP statistics (SHIELD)

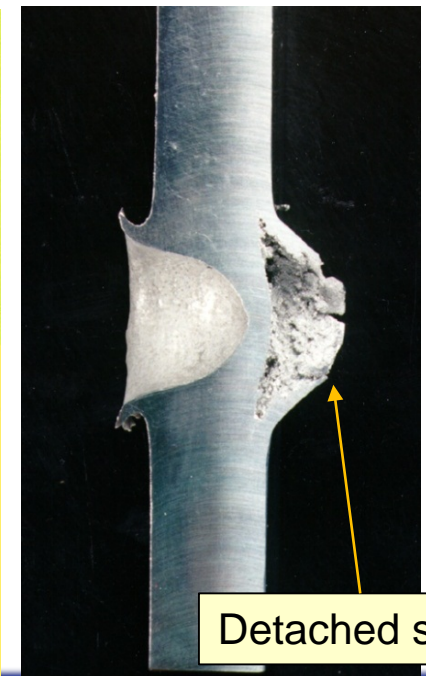
Space Shuttle Orbital Debris Threat Assessment

Orbiter Region	Impact Risk From Lmm. D. Debris		Debris Penetration Risk	
	Probability per Impact	Risk of Impact	Probability per Penetration	Risk of Penetration
RCC	0.995338	1/214	0.995411	1/224
windows	0.999335	1/1505	0.999796	1/4912
pb door radiators	0.999465	1/105	0.999908	1/82500
wing & fuselage TPS	0.963074	1/29	0.968923	1/928
fwd fuselage TPS	0.985322	1/69	0.990022	1/1023
payload bay & bulkheads	0.997431	1/291	0.998939	1/8223
TOTALS	0.934622	1/15	0.993132	1/146

Graphical Interpretation of Results (I-DEAS & EXCEL)



CTH Code

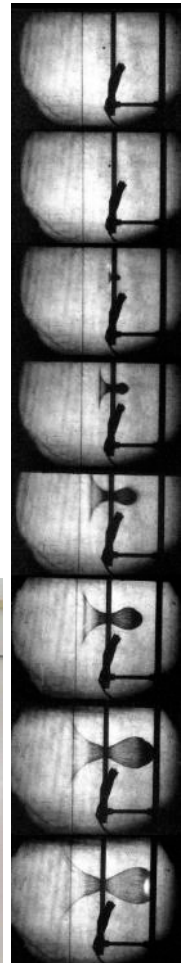
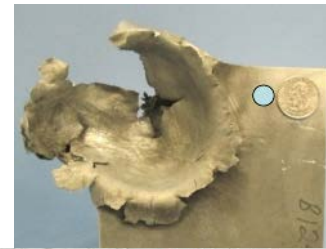
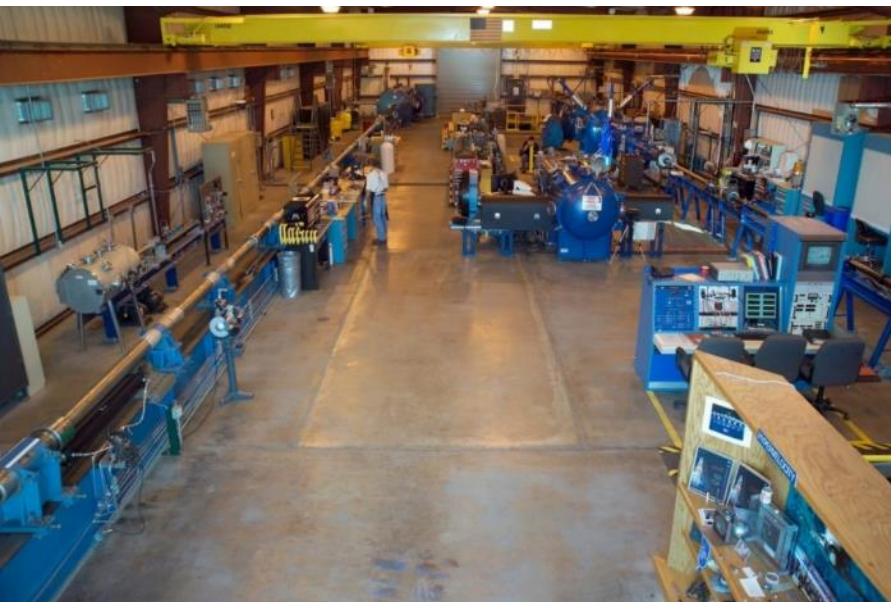


Detached spall

HVIT analysis anchored in hypervelocity impact test results



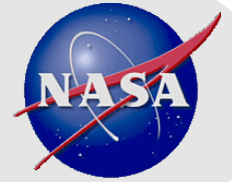
- JSC-XI HVIT plans and performs over 400 impact tests per year
 - White Sands Test Facility (WSTF) two-stage light gas-guns up to 8 km/s
 - University of Dayton Research Institute (UDRI) 3-stage launcher to 10 km/s
 - Southwest Research Institute (SwRI) shaped-charge launcher to 11 km/s
- Data used to develop and verify ballistic limit equations used in Bumper code on range of different spacecraft components and subsystems



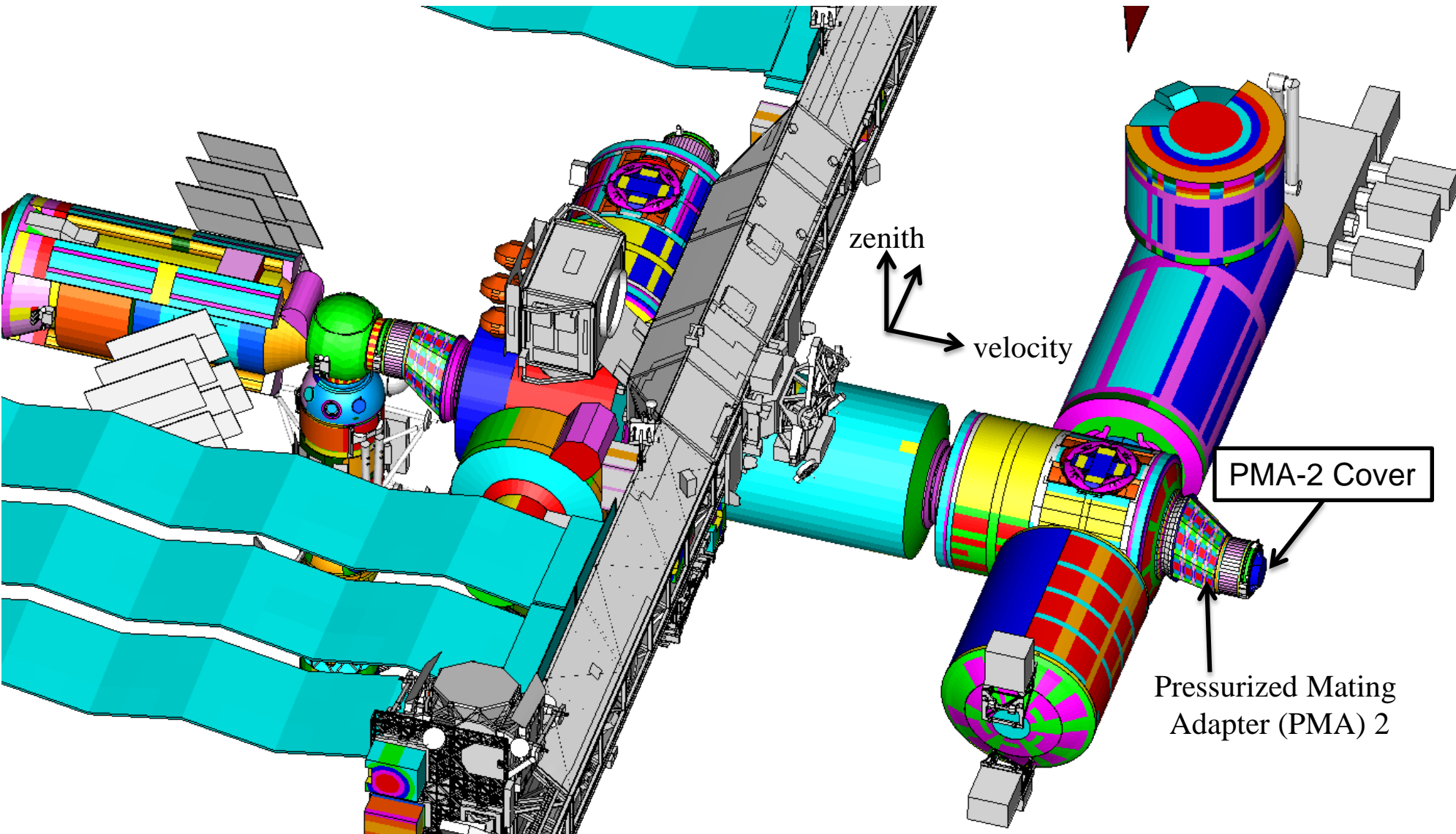
Post-flight Inspection Results for the ISS PMA-2 Cover



- HVIT and Boeing personnel inspected the PMA-2 cover for MMOD impacts after it was returned on the SpaceX CRS-6 mission
 - The cover was exposed to MMOD impacts for 1.63 years (from July 2013 to February 2015)
 - Located on the forward port of the ISS pressurized mating adapter 2 (PMA-2)
 - Cover is 2m diameter multilayer blanket with a beta-cloth exterior surface (Teflon coated glass fabric)
- Twenty-six (26) micrometeoroid and orbital debris (MMOD) impact features were found
- Observed hypervelocity impact features were compared with Bumper 3 predictions using ORDEM 3.0 and MEM-R2



PMA-2 cover location on ISS



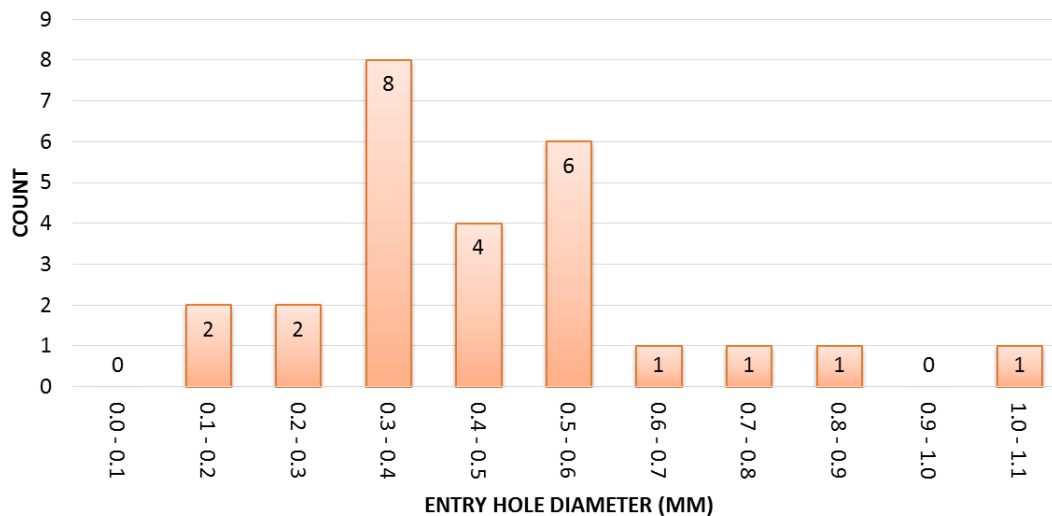


Post Flight Inspection Results

- 26 impact features indicated by colored markers in image on right
- Max hole diameter = 1.01 mm
- Average crater diam. = 0.45 mm



Entry Hole Diameter Distribution, PMA-2 Cover

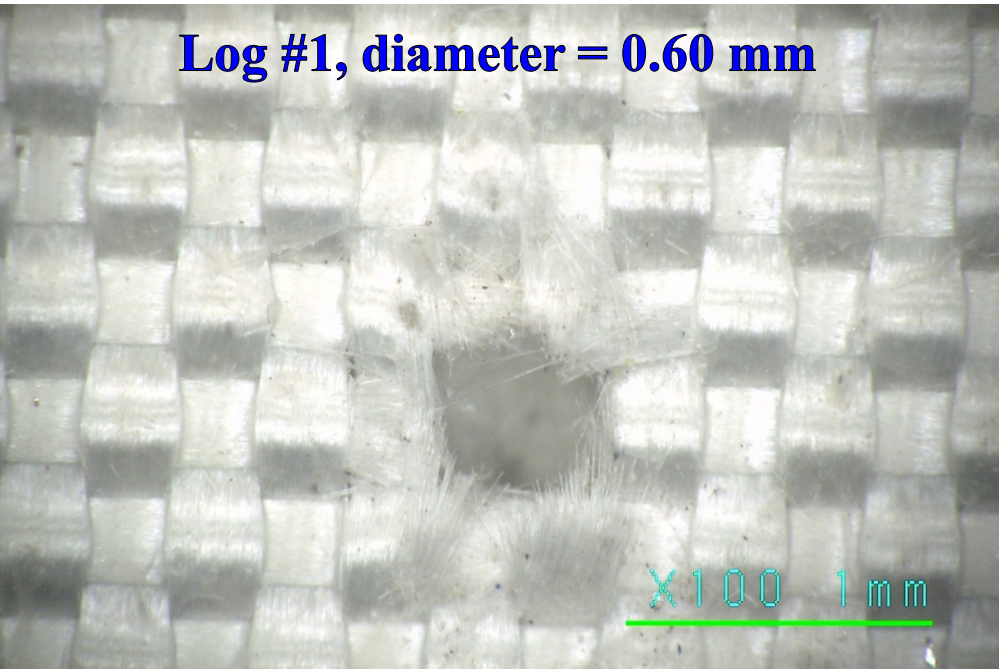




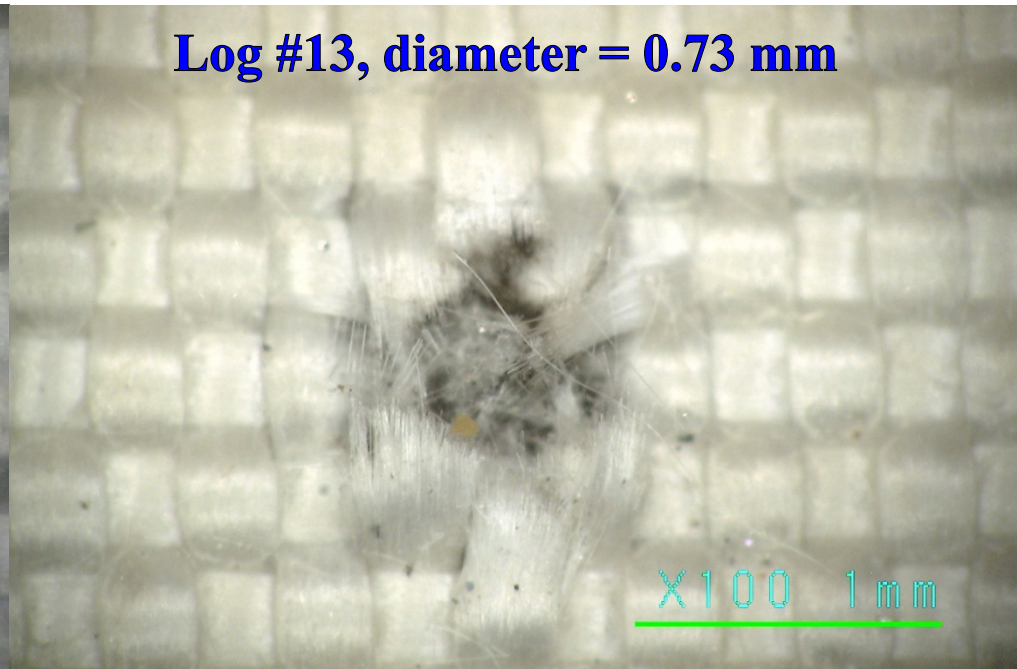
Sampling at Impact Sites

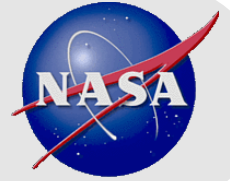
- Six samples were extracted intact using a “hole punch” technique
- Relative orientation of internal layers was preserved
- Samples were examined by Scanning Electron Microscope (SEM) equipped with energy dispersive X-ray (EDX) spectrometers to locate and determine elemental composition of impact residues

Log #1, diameter = 0.60 mm



Log #13, diameter = 0.73 mm





SEM/EDS Results

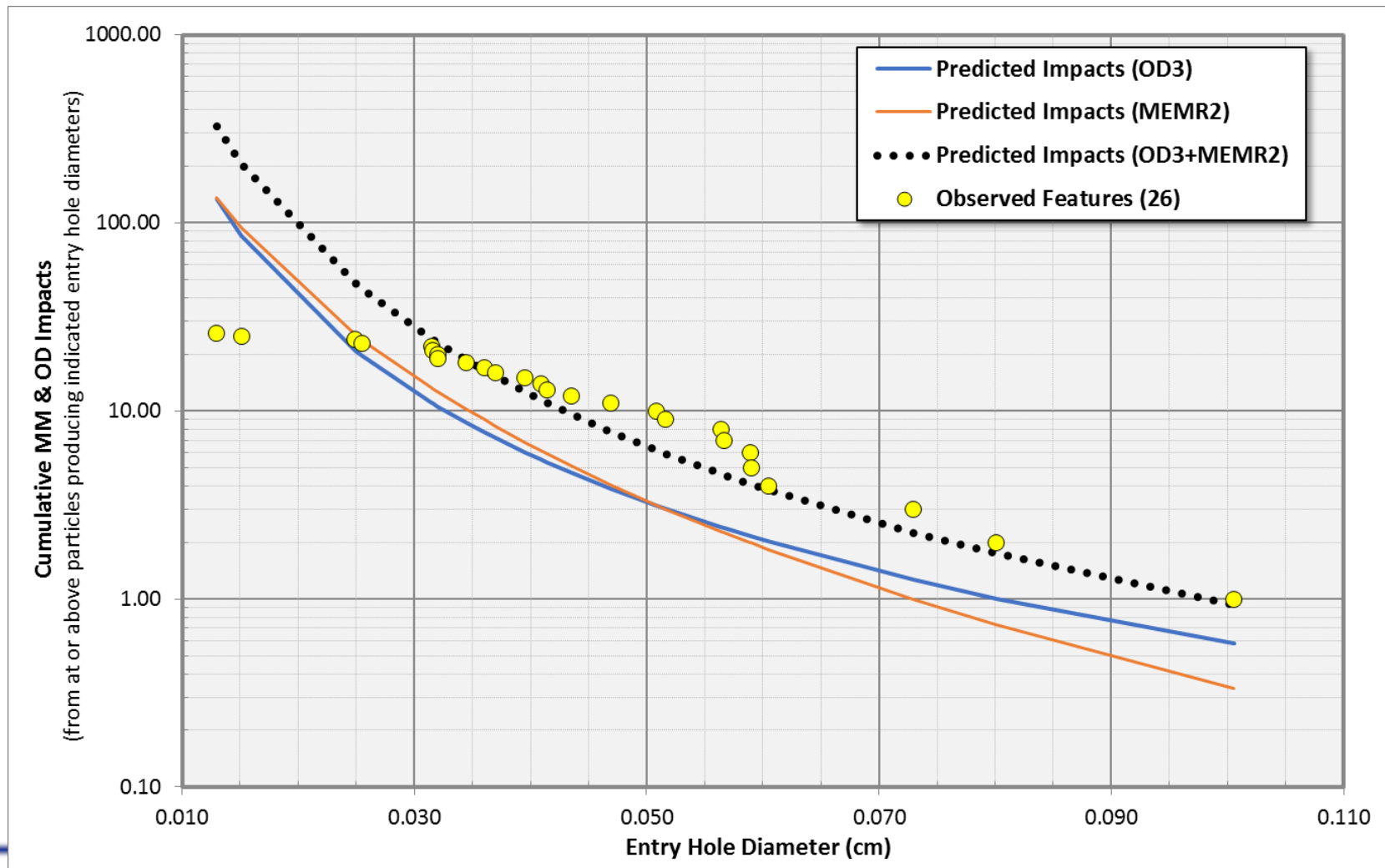
- SEM-EDXA compositional indication of high density orbital debris (OD) as the source in 4 of 6 samples, and micrometeoroid (MM) in 2 samples

Impact Site	Hole Size (mm)	Impactor Type: Major Constituents	Possible Impactor
1	0.60	OD: Steel, ZnS, FeO, Ti	Steel
2	1.01	OD: Steel, Nickel-Oxide	Steel
10	0.80	OD: Steel, Iron-oxide	Steel
12	0.57	MM: Ca, Mg, Fe, S, O	Chondrite
13	0.73	MM: Fe, Ni, S	metal/sulfide-rich
24	0.36	OD: Steel, Iron-oxide, Ti	Steel



Comparison between observed holes and Bumper 3 predictions

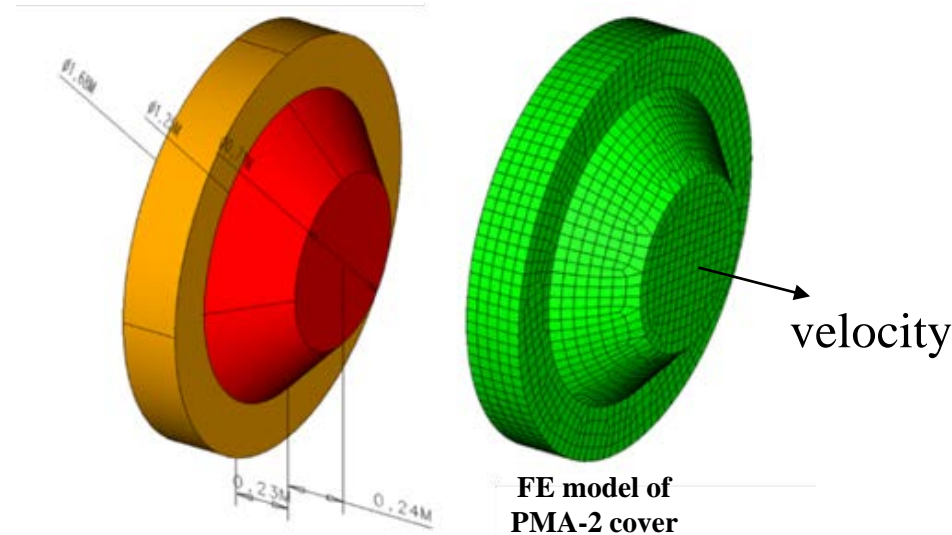
- Bumper predictions for MM and OD are consistent with observations for holes sizes $> 0.3\text{mm}$ (counts for hole sizes $< 0.3\text{mm}$ suffer from observer/eye limits)





Bumper Code Assessment

- Bumper 3 was used to calculate the expected number of holes in the beta cloth of a stand alone model of the PMA-2 cover (see table below)
- Years = 2013 through 2015
- Time averaged altitudes
- Damage equation = beta cloth hole size



Hole Diameter (cm)	MEM R2	ORDEM 3.0	MMOD TOTAL
0.0288	16.89	14.60	31.49
0.0460	4.40	3.87	8.27
0.0920	0.46	0.68	1.14
0.1380	0.11	0.30	0.40
0.1840	0.04	0.15	0.19
0.2300	0.02	0.08	0.10

Start Date	End Date	Days	Years	Altitude (km)
7/9/13	1/1/14	176	0.482	413.6
1/1/14	1/1/15	365	1.000	414.5
1/1/15	2/25/15	55	0.151	402.1
Total		596	1.633	



References

- **More information available:**
 - NASA TP-2003-210788, Meteoroid/Debris Shielding
 - NASA TM-2009-214785, Handbook for Designing MMOD Protection
 - NASA TM-2003-212065, Integration of MMOD Impact Protection Strategies into Conceptual Spacecraft Design
 - NASA TM-2009-214789, MMOD Shield Ballistic Limit Analysis Program
 - NASA TM-2015-218214, NASA Meteoroid Engineering Model Release 2.0
 - NASA TP-2015-218592, NASA Orbital Debris Engineering Model ORDEM 3.0 – Verification and Validation