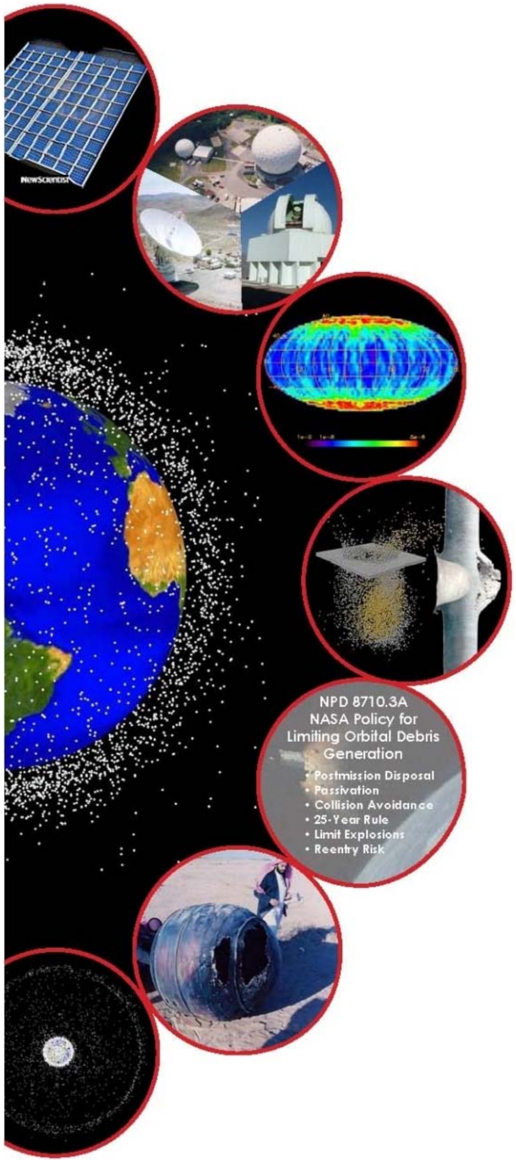
NASA Orbital Debris Program

Orbital Debris Program Office
NASA Johnson Space Center

Primary Program Responsibilities



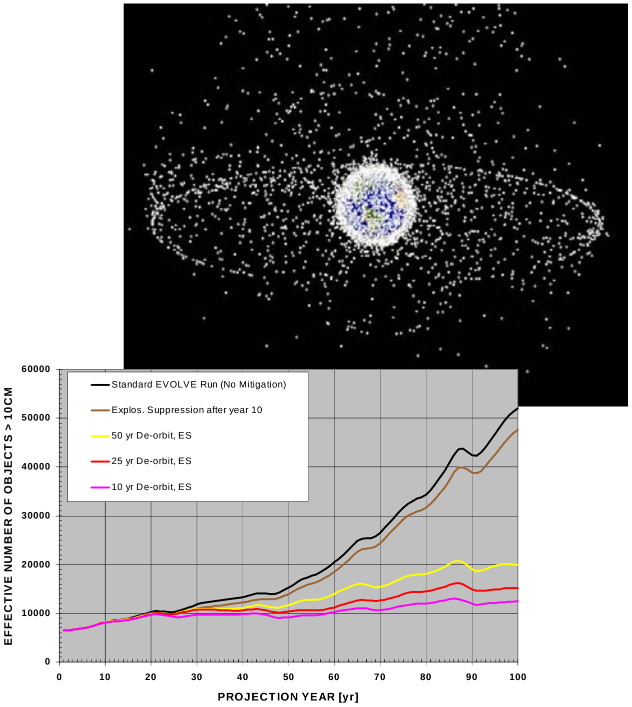
- **Characterize the orbital debris environment to support risk assessments for all NASA projects and programs.**
  - Ground-based and space-based measurements
  - Breakup and population modeling
  - Hypervelocity impact phenomenology and effects

- **Provide technical and policy level assistance to NASA HQ, other US Government agencies and the commercial sector.**

- **Represent the US in international fora, including the United Nations and the Inter-Agency Space Debris Coordination Committee (IADC).**

- **Evaluate risk of human casualties from satellite reentries.**

Orbital Debris Program Overview



Debris Assessment Software

Normal Operations
Accidental Explosions
Intenational Breakups
On-Orbit Collisions
Postmission Disposal
Reentry Survival

Satellite Breakup Risk Assessment Model

Measurements

Ground-based and in-situ measurements of debris smaller than 10-cm diameter

Modeling

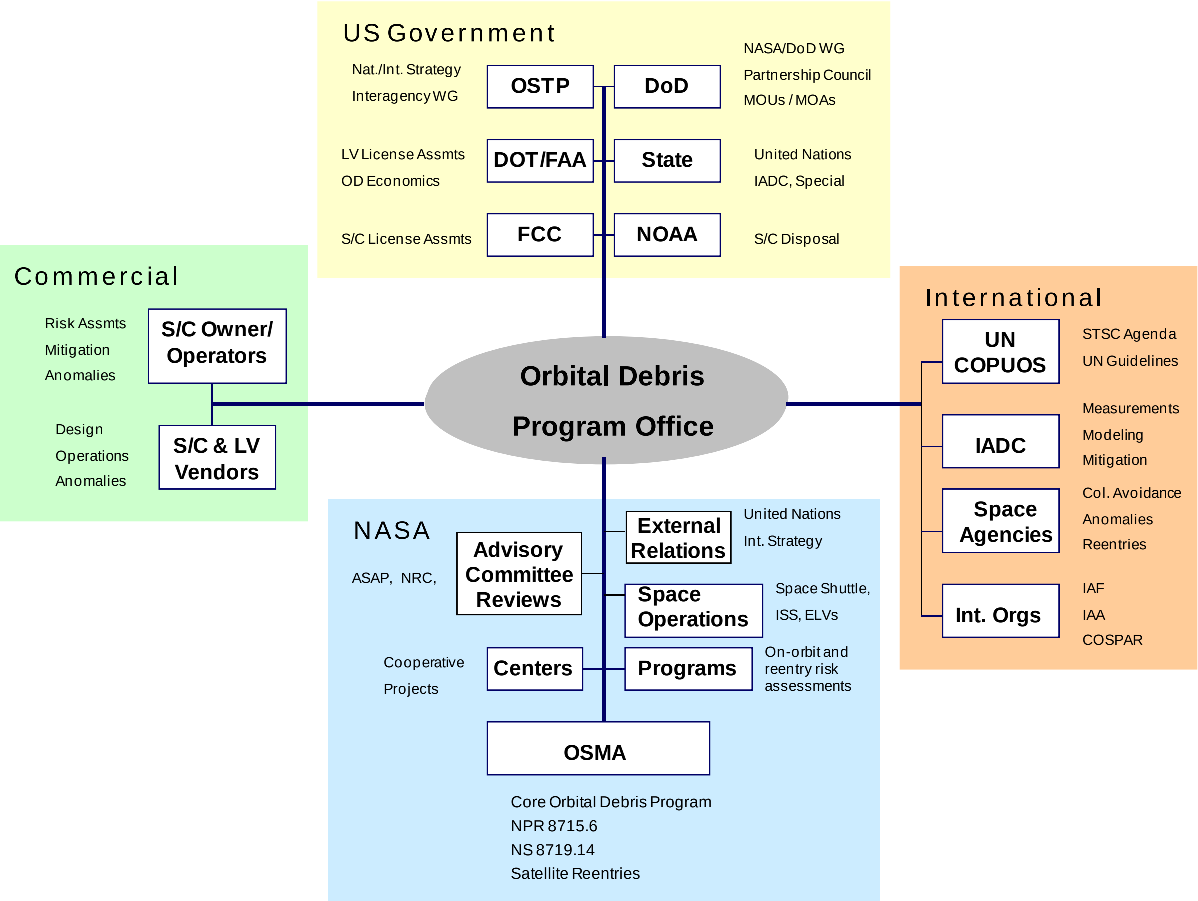
Develop near-term engineering, long-term evolutionary, and special purpose models

Risk Assessment

Develop software tools to permit risk assessments for all NASA space projects: human space flight and robotic

Orbital Debris Program Interfaces

- **NASA Orbital Debris Program established at JSC in 1979.**
- **Currently funded directly from HQ OSMA.**
- **Recognized as world leader in environment definition and modeling and in mitigation policy development.**
- **Close cooperation with DoD in a variety of space situational awareness areas.**



Orbital Debris Program Office

US Government

Nat./Int. Strategy
Interagency WG
OSTP
DoD
NASA/DoD WG
Partnership Council
MOUs / MOAs

LV License Assmts
OD Economics
DOT/FAA
State
United Nations
IADC, Special

S/C License Assmts
FCC
NOAA
S/C Disposal

Commercial

Risk Assmts
Mitigation
Anomalies
S/C Owner/ Operators

Design
Operations
Anomalies
S/C & LV Vendors

International

UN COPUOS
STSC Agenda
UN Guidelines

IADC
Measurements
Modeling
Mitigation

Space Agencies
Col. Avoidance
Anomalies
Reentries

Int. Orgs
IAF
IAA
COSPAR

NASA

ASAP, NRC,
Advisory Committee Reviews

External Relations
United Nations
Int. Strategy

Space Operations
Space Shuttle,
ISS, ELVs

Cooperative
Projects
Centers

Programs
On-orbit and reentry risk assessments

OSMA
Core Orbital Debris Program
NPR 8715.6
NS 8719.14
Satellite Reentries

For more information – see our website at: http://orbitaldebris.jsc.nasa.gov/

NASA Orbital Debris Program Office

The NASA Orbital Debris Program Office, located at the Johnson Space Center, is the lead NASA center for orbital debris research. It is recognized world-wide for its initiative in addressing orbital debris issues. The NASA Orbital Debris Program Office has taken the international lead in conducting measurements of the environment and in developing the technical consensus for adopting mitigation measures to protect users of the orbital environment. Work at the Center continues with developing an improved understanding of the orbital debris environment and measures that can be taken to control debris growth.

Orbital Debris Research at NASA

Orbital Debris research is divided into the following broad research efforts:

- Modeling
- Measurements
- Protection
- Mitigation
- Reentry

Get the Latest Orbital Debris News

The *Orbital Debris Quarterly News* (ODQN) contains the latest breaking news in orbital debris research.

Why Orbital Debris Mitigation?

- **U.S. has endorsed the United Nations' *Orbital Debris Mitigation Guidelines*.**
- **President's National Space Policy directs agencies and departments to implement *U.S. Government Orbital Debris Mitigation Standard Practices*.**
- **In compliance with above, NASA has established NPR 8715.6A, *NASA Procedural Requirements for Limiting Orbital Debris*, and NS 8719.14A, *Process for Limiting Orbital Debris*.**
  - Formal Orbital Debris Assessment Reports (ODARs) are due to NASA HQ in conjunction with the PDR, CDR, and SMSR milestones.

To preserve near-Earth space for future generations

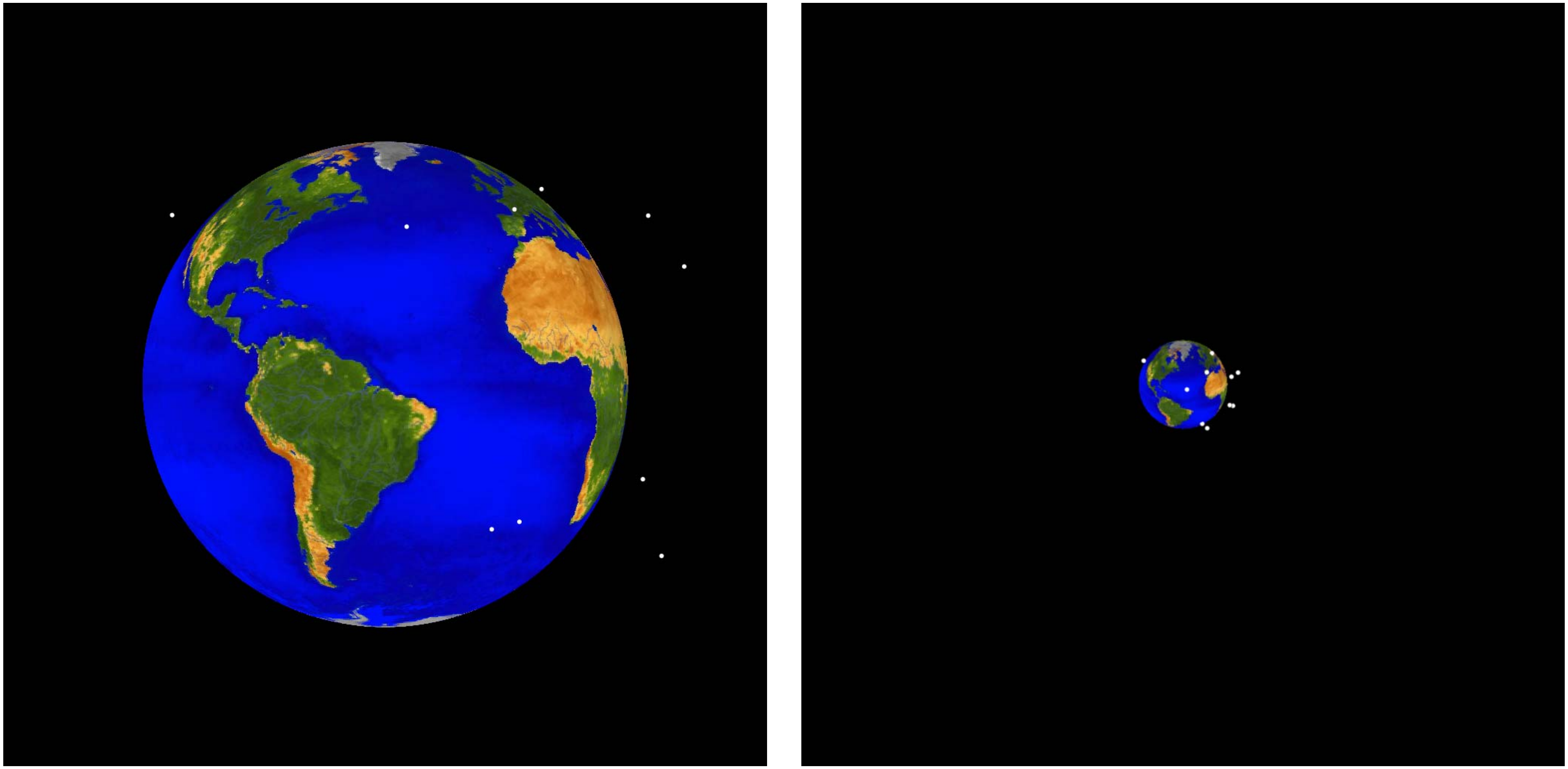
National Aeronautics and Space Administration

Characterizing the Earth’s Satellite Population: Sources of Orbital Debris

Orbital Debris Program Office
NASA Johnson Space Center

Growth of the Earth Satellite Population

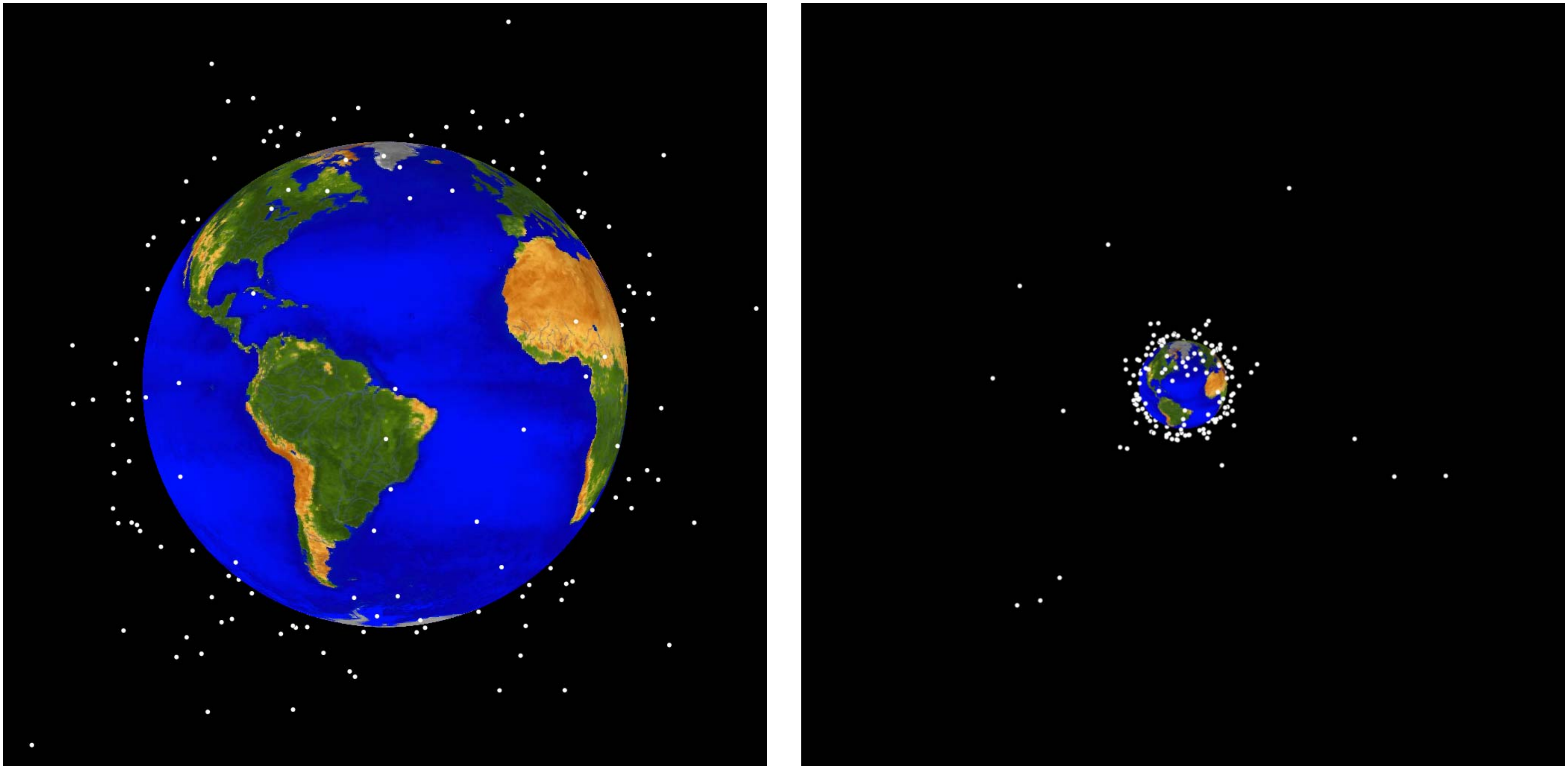
1960



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

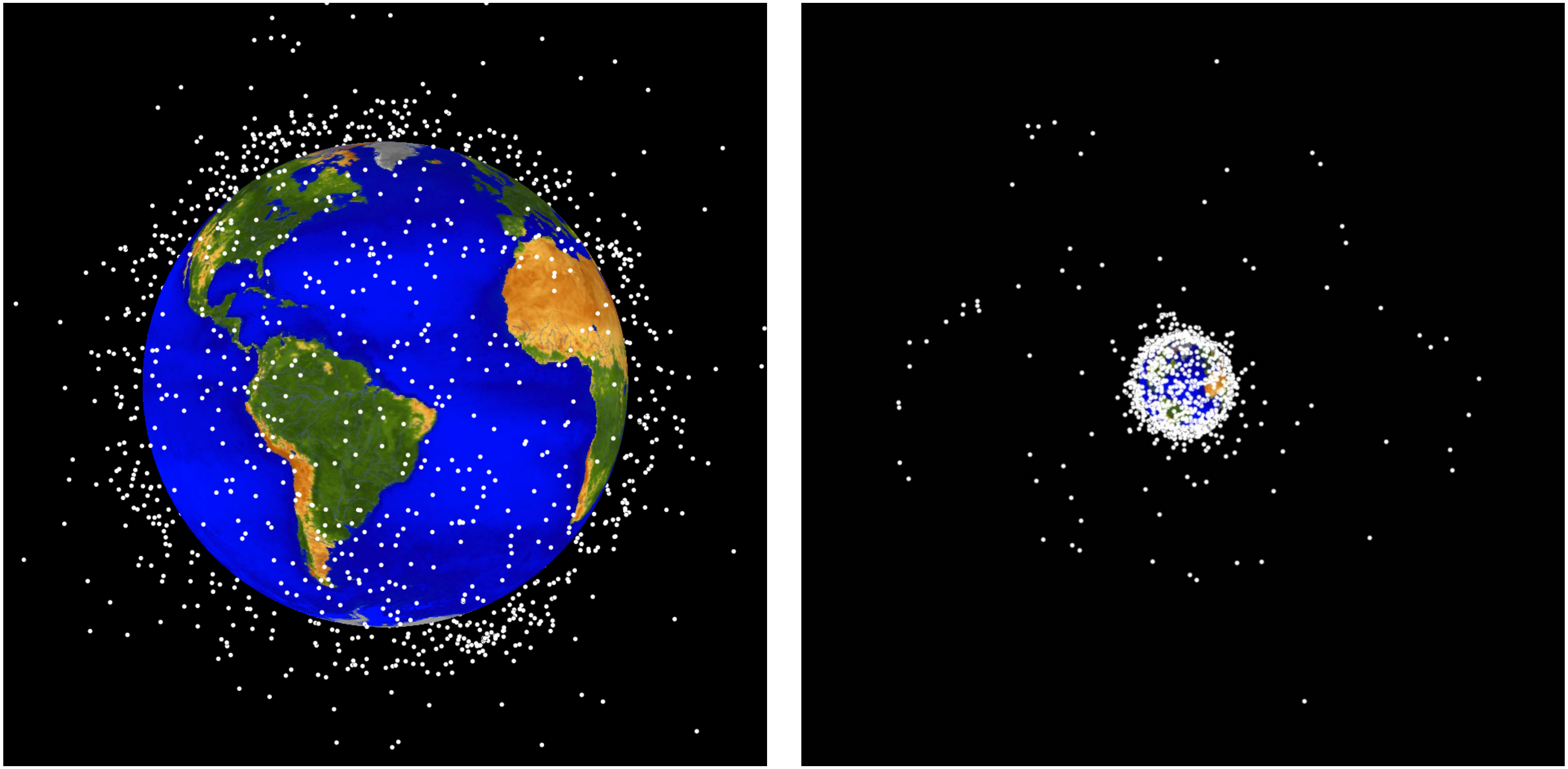
1965



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

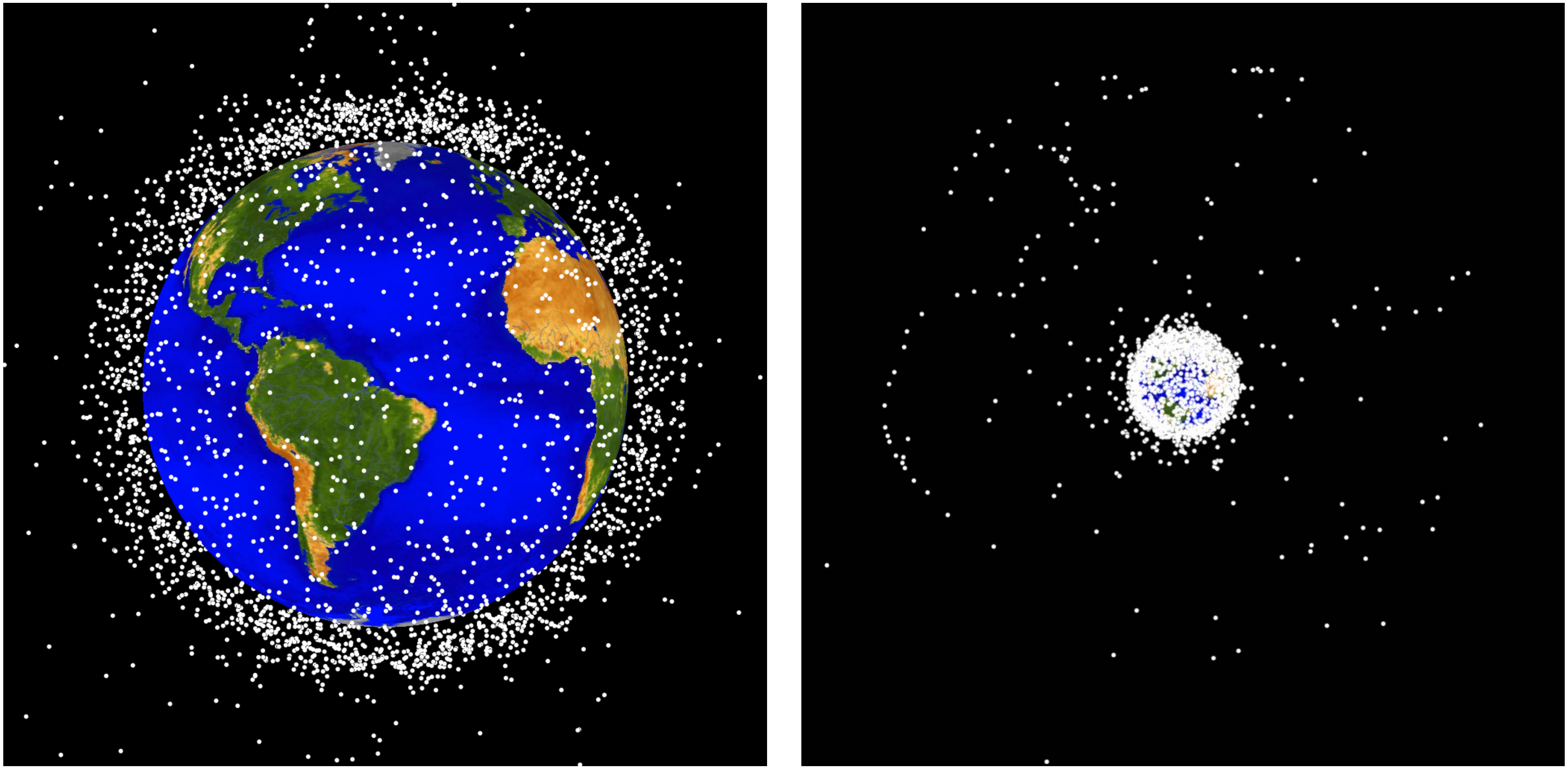
1970



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

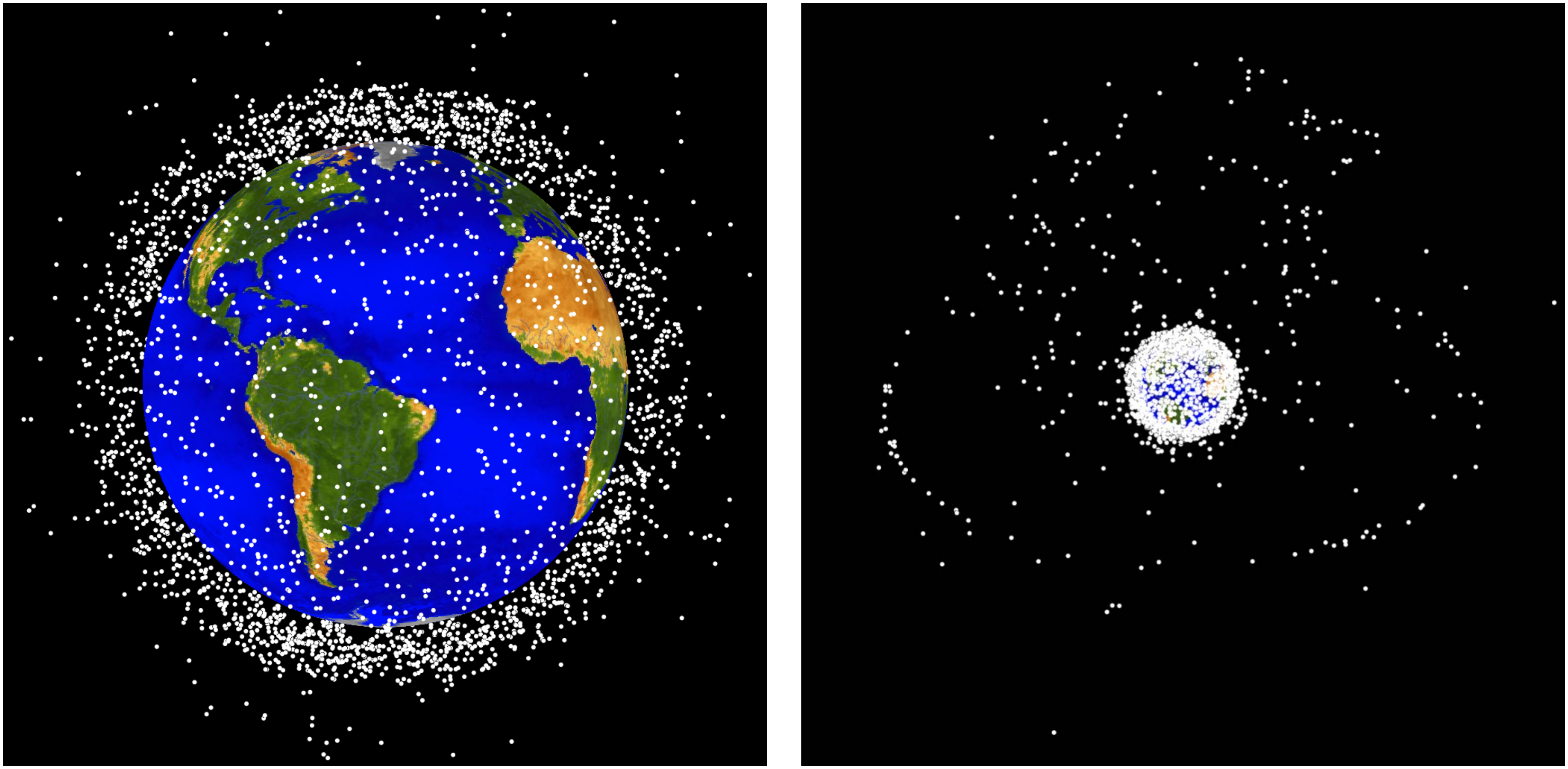
1975



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

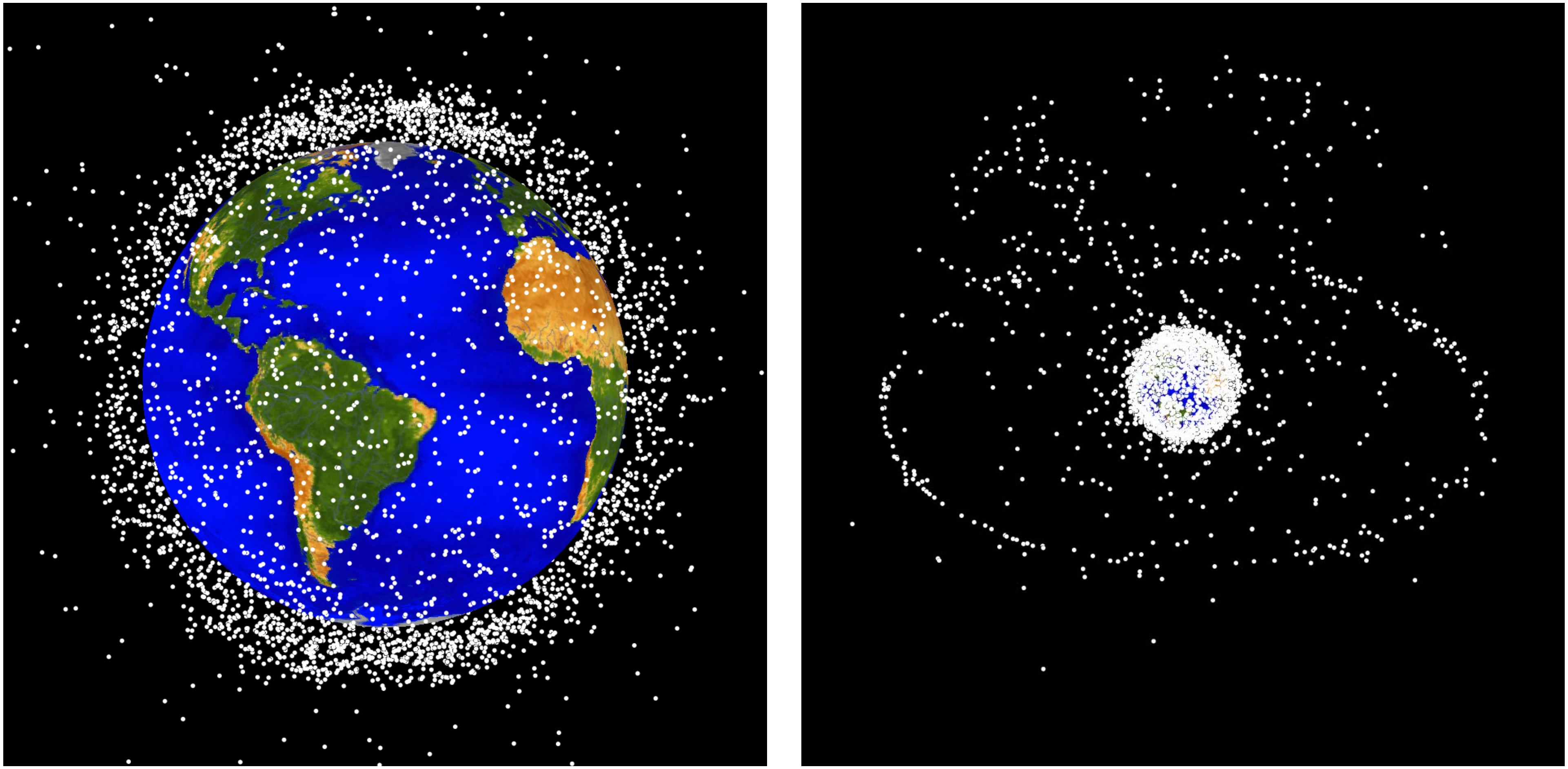
1980



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

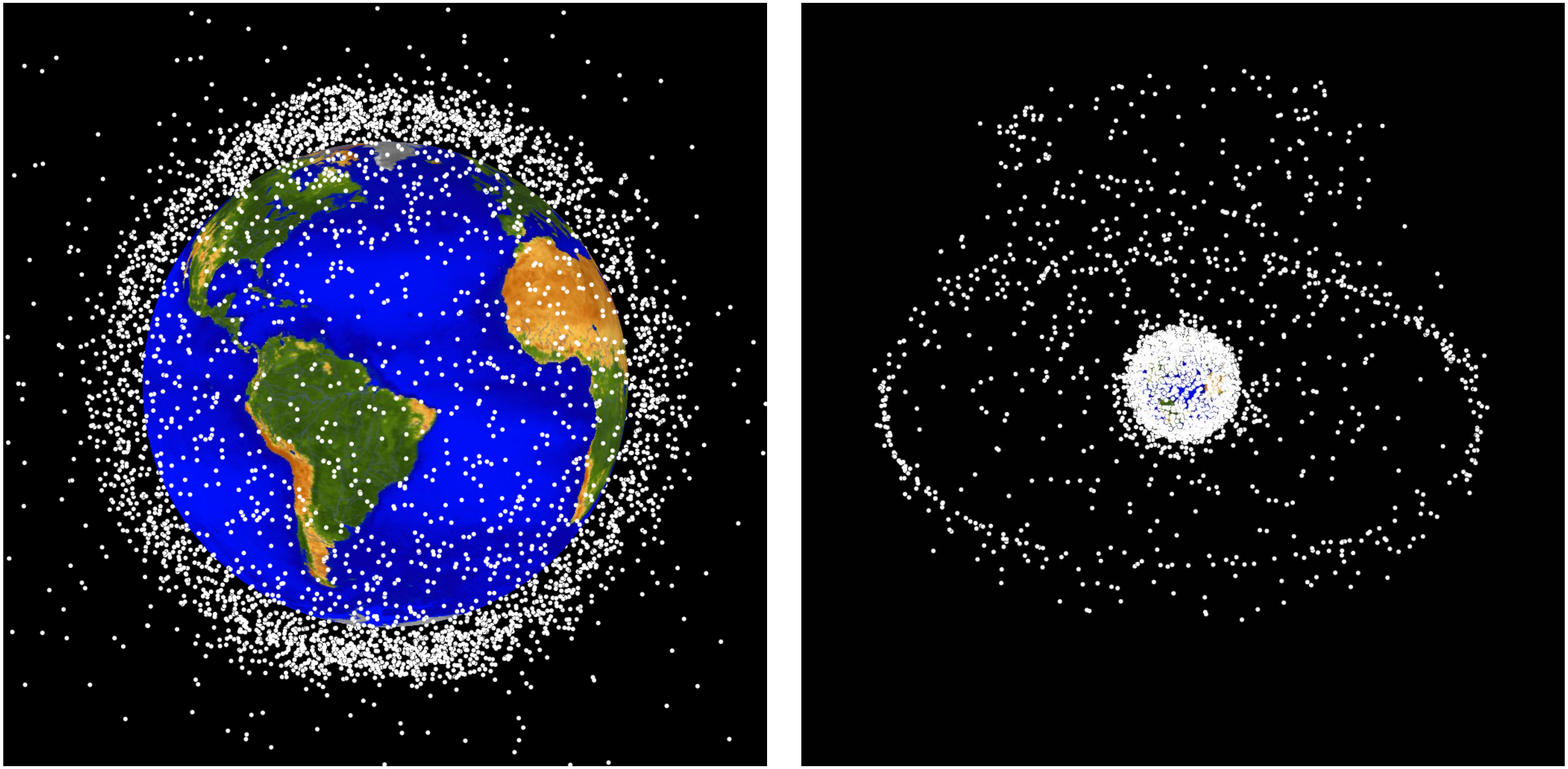
1985



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

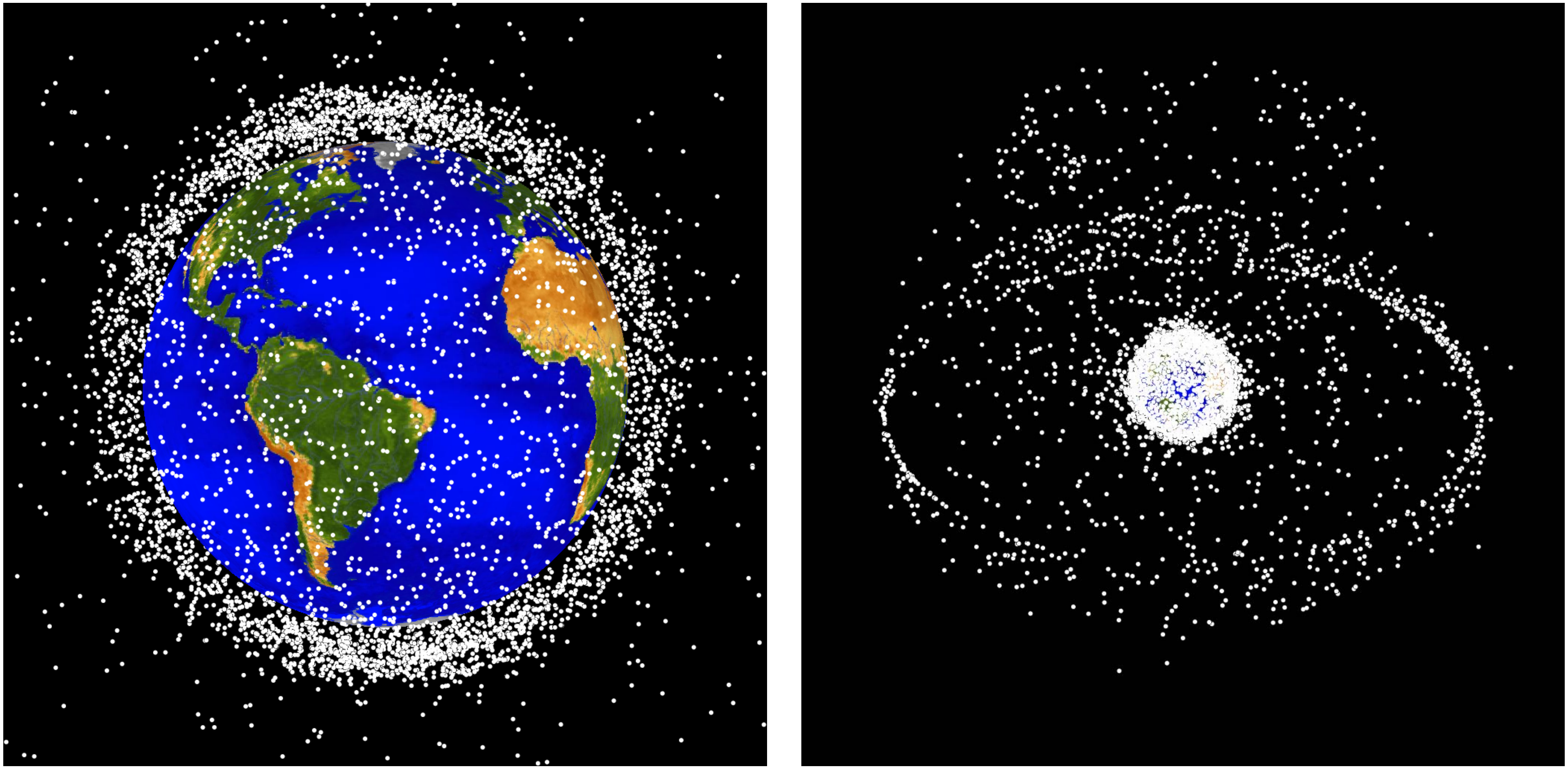
1990



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

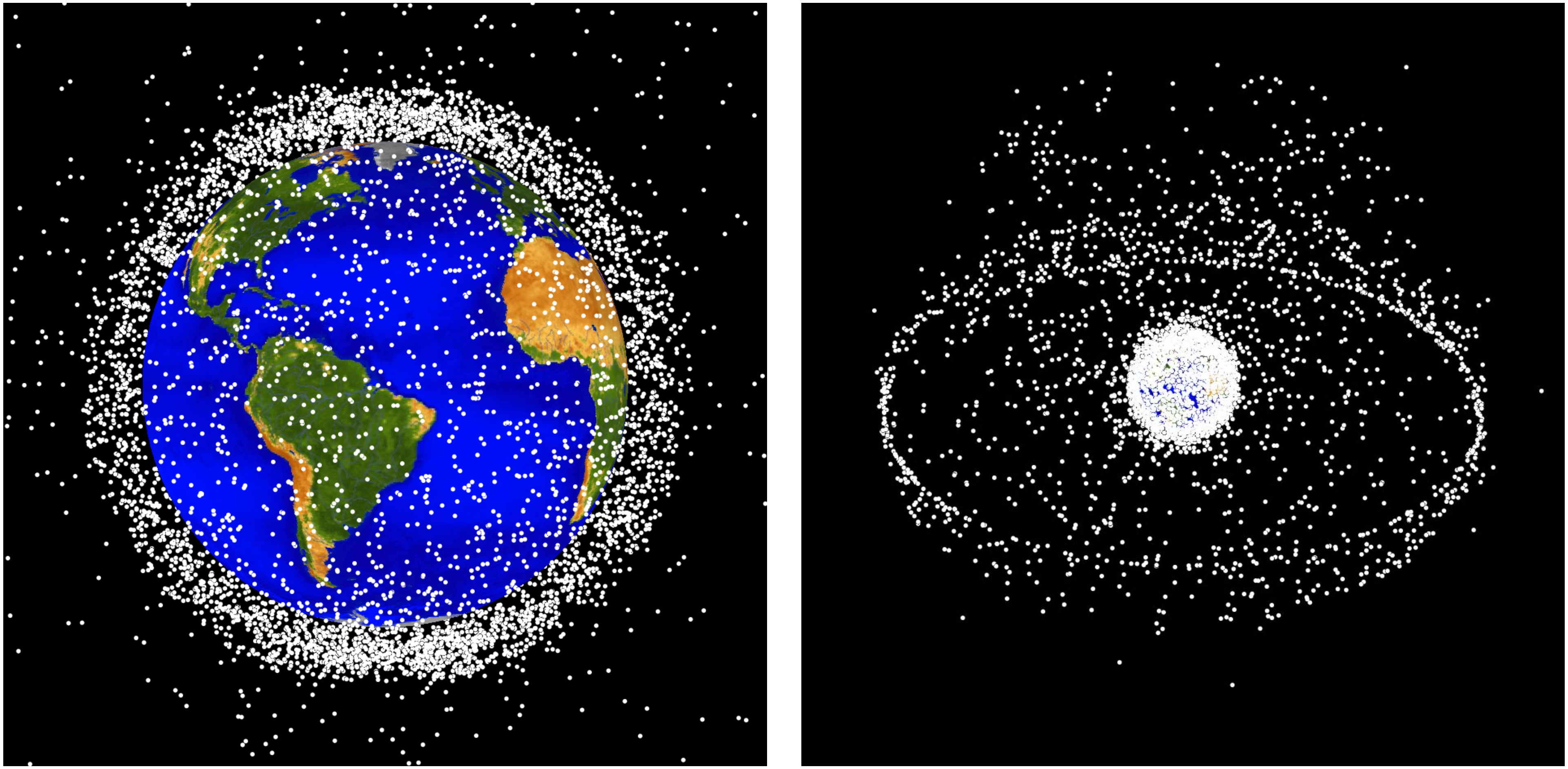
1995



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

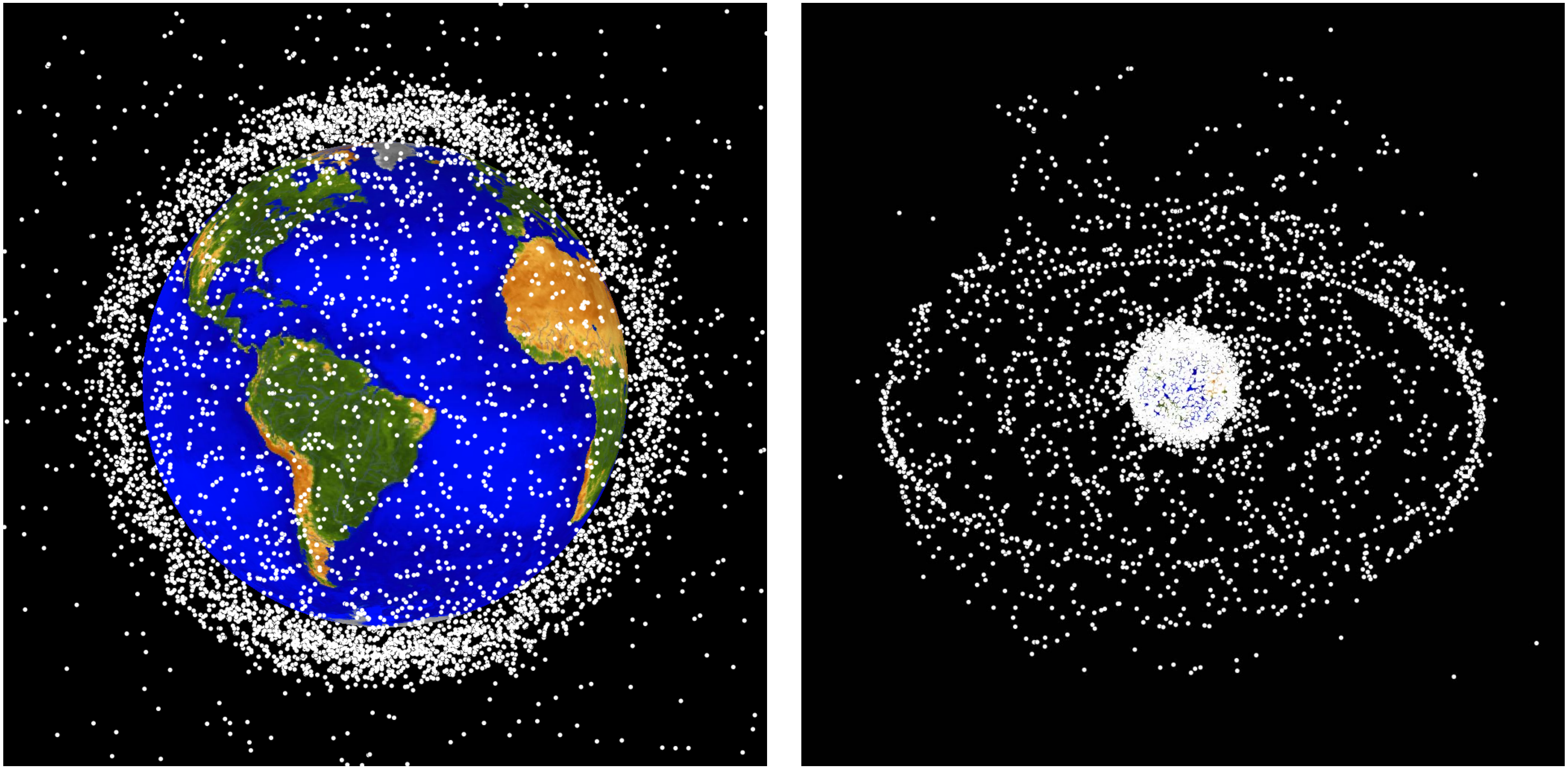
2000



Cataloged objects >10 cm diameter

Growth of the Earth Satellite Population

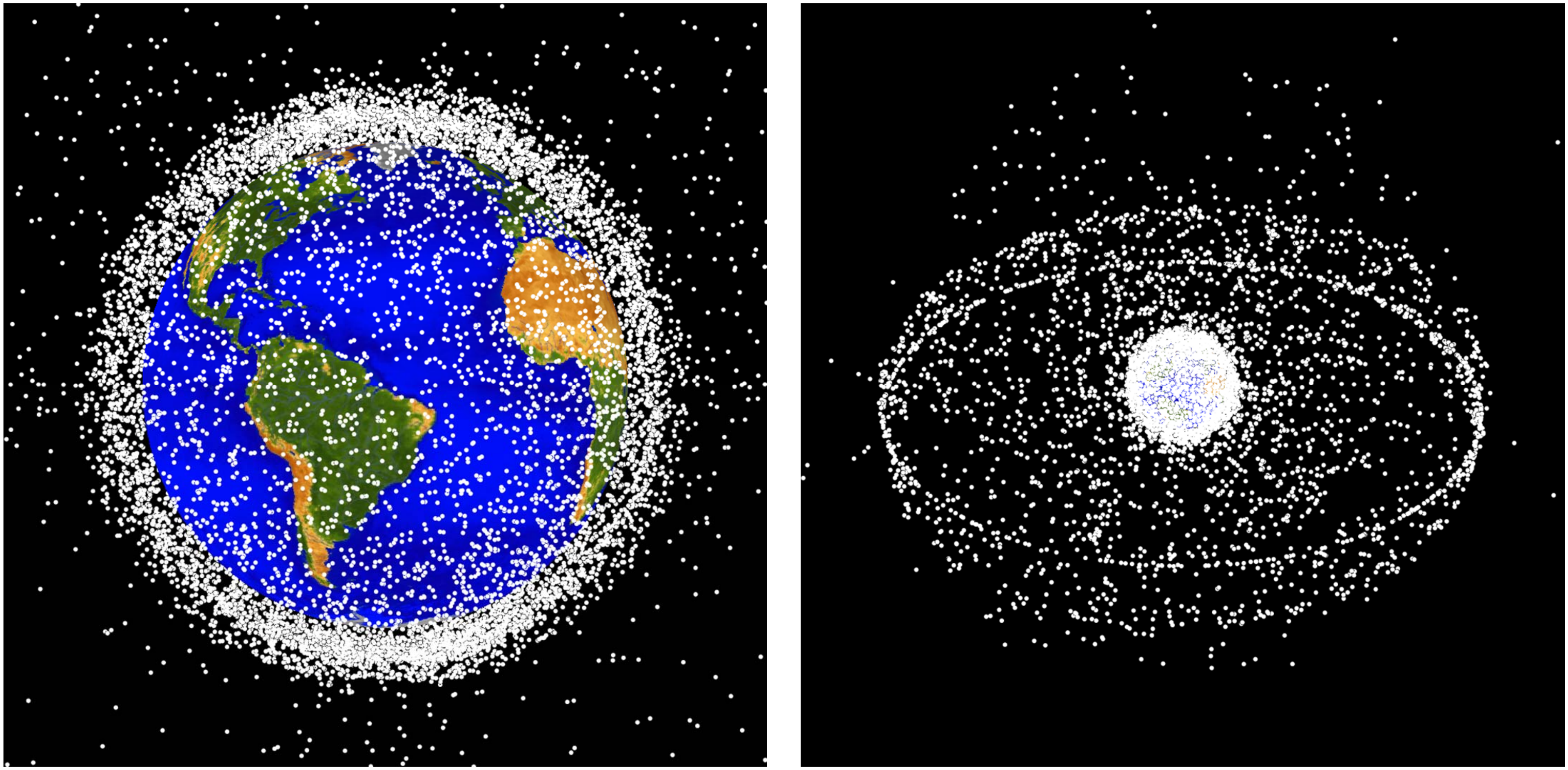
2005



Cataloged objects >10 cm diameter

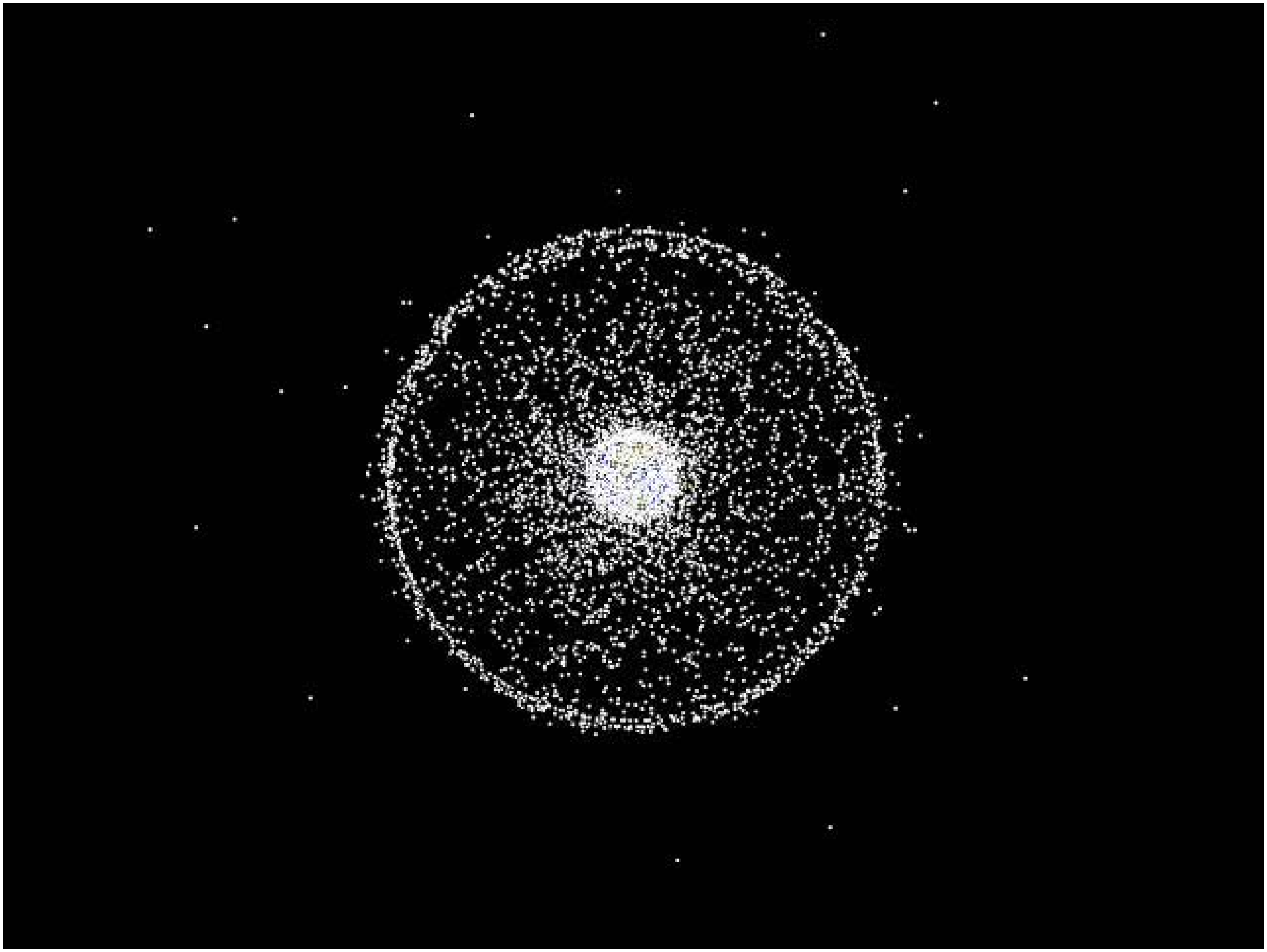
Growth of the Earth Satellite Population

2010

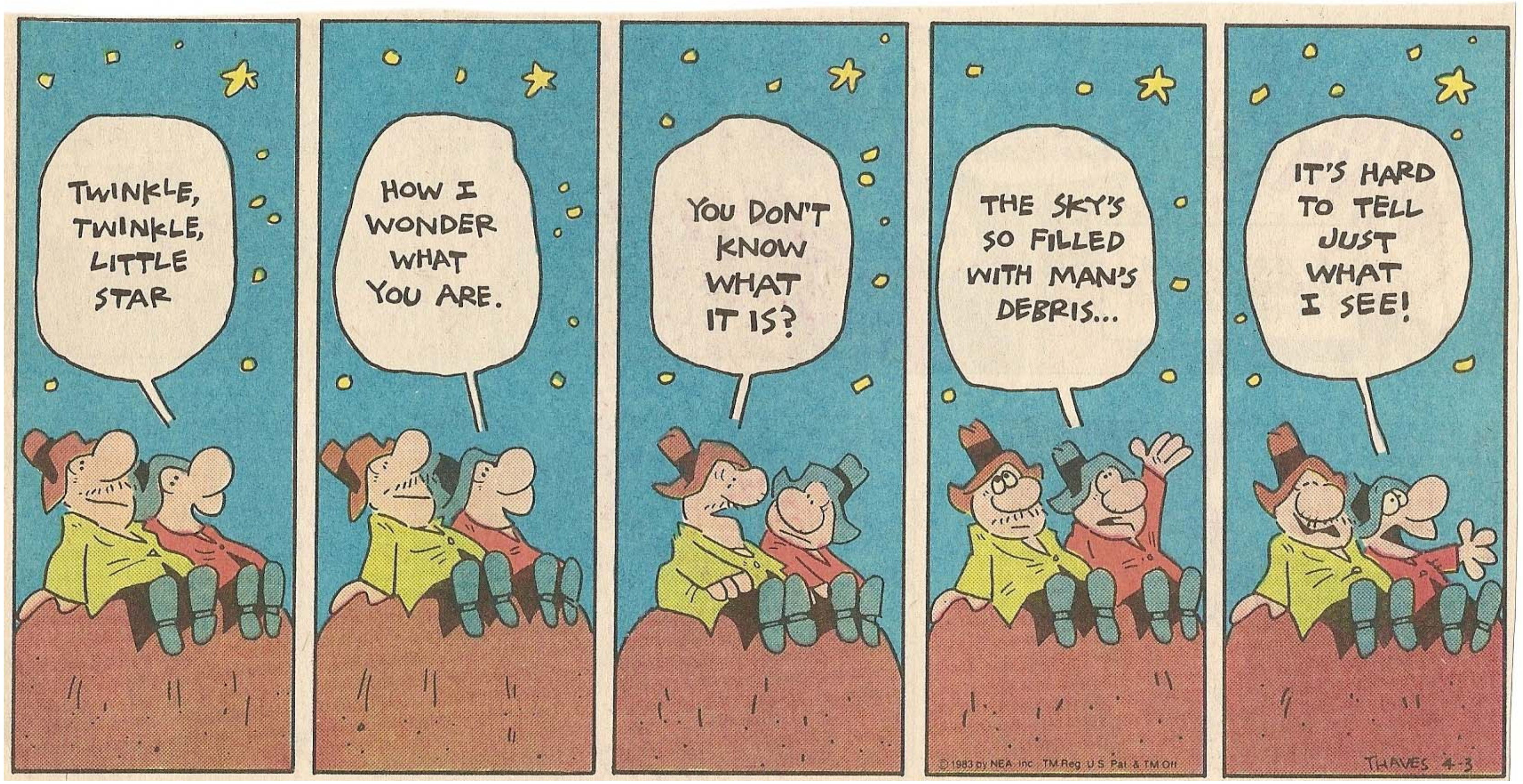


Cataloged objects >10 cm diameter

Orbital Debris in Motion

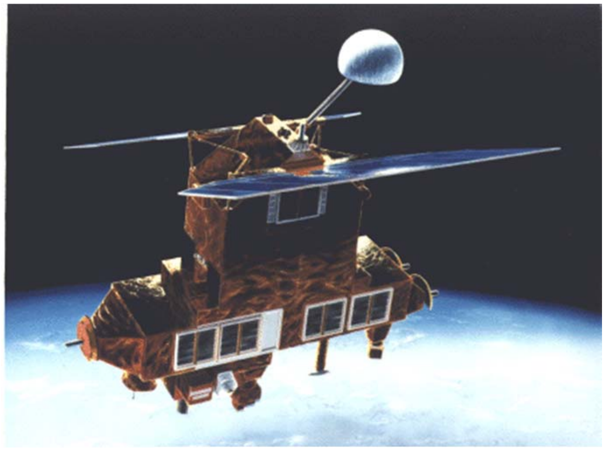


Orbital Debris: A Perspective by Frank and Ernest



What is Orbital Debris?

- **Orbital debris is any object in Earth orbit which no longer serves a useful function.**



Non-operational Spacecraft

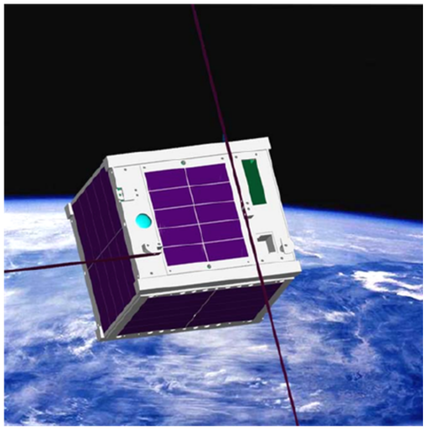
Derelict Launch Vehicle Stages

Fragmentation and

Mission-related Debris

Non-operational Spacecraft

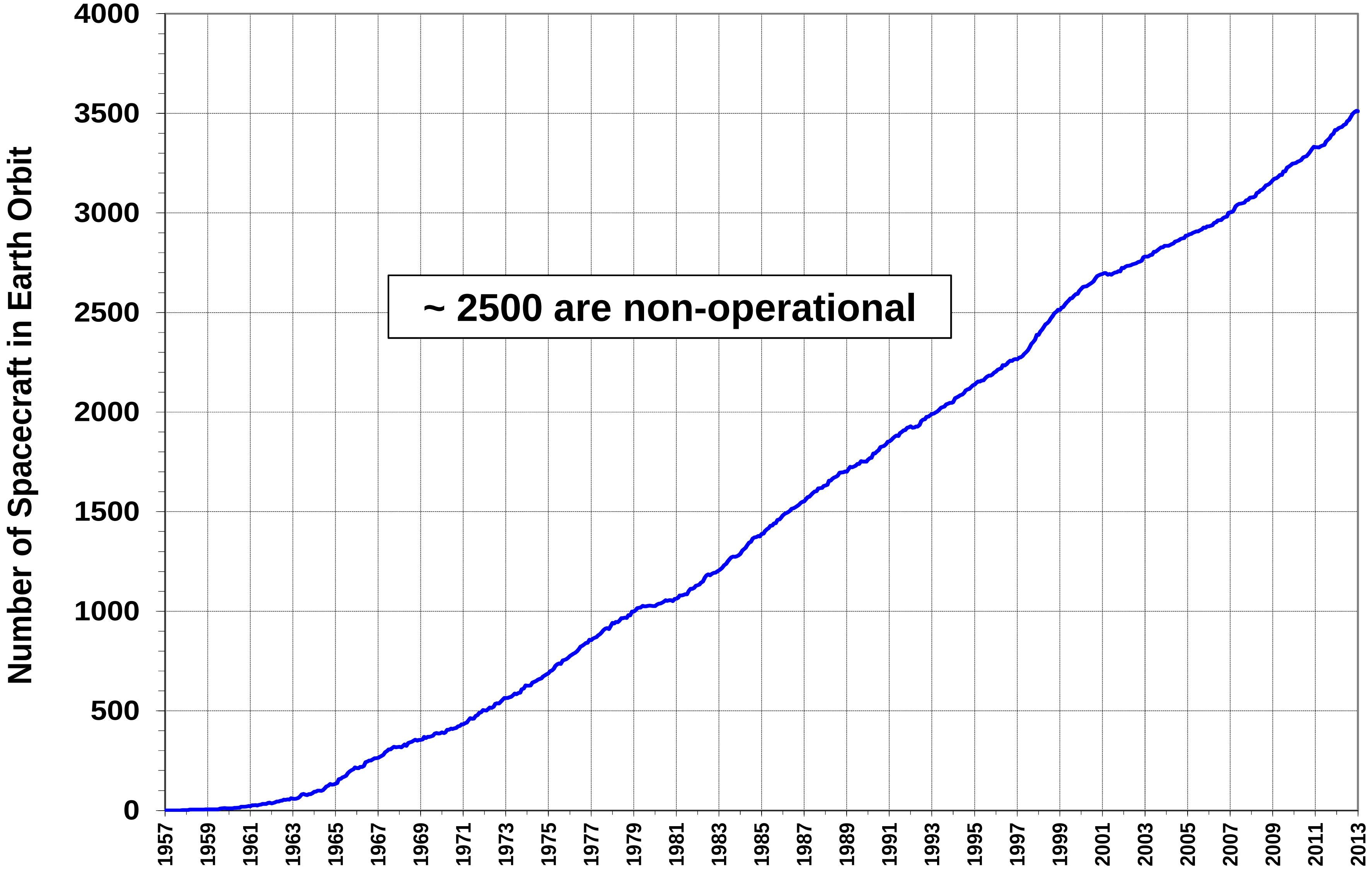
- **More than 7000 spacecraft have been placed into Earth orbit since Sputnik 1 in 1957.**
- **Currently, >3500 spacecraft remain in Earth orbit.**
  - ~1000 are operational; the rest are orbital debris
- **Small: Picosats and Microsats**
  - Operational lifetimes typically months to a few years
- **Large: Geosynchronous spacecraft**
  - Operational lifetimes typically a decade or more



Cubesats: 1 kg

TDRS 1: 2 metric tons

Growth of Spacecraft in Earth Orbit

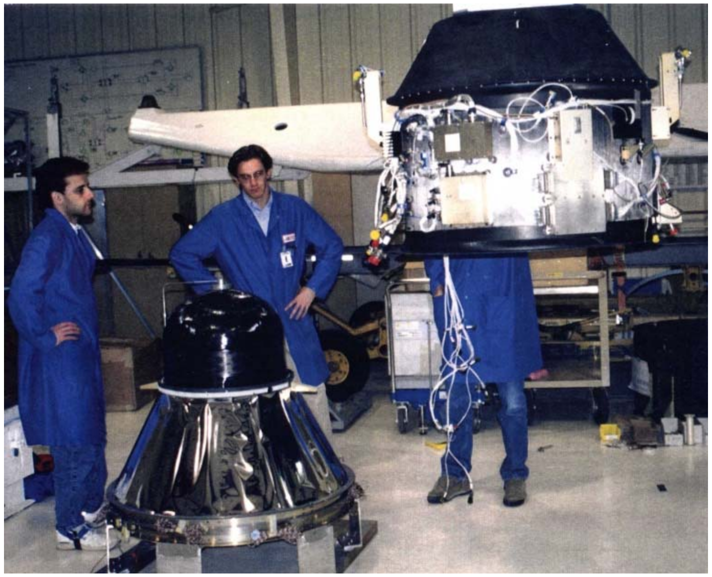


~ 2500 are non-operational

Launch Vehicle Stages

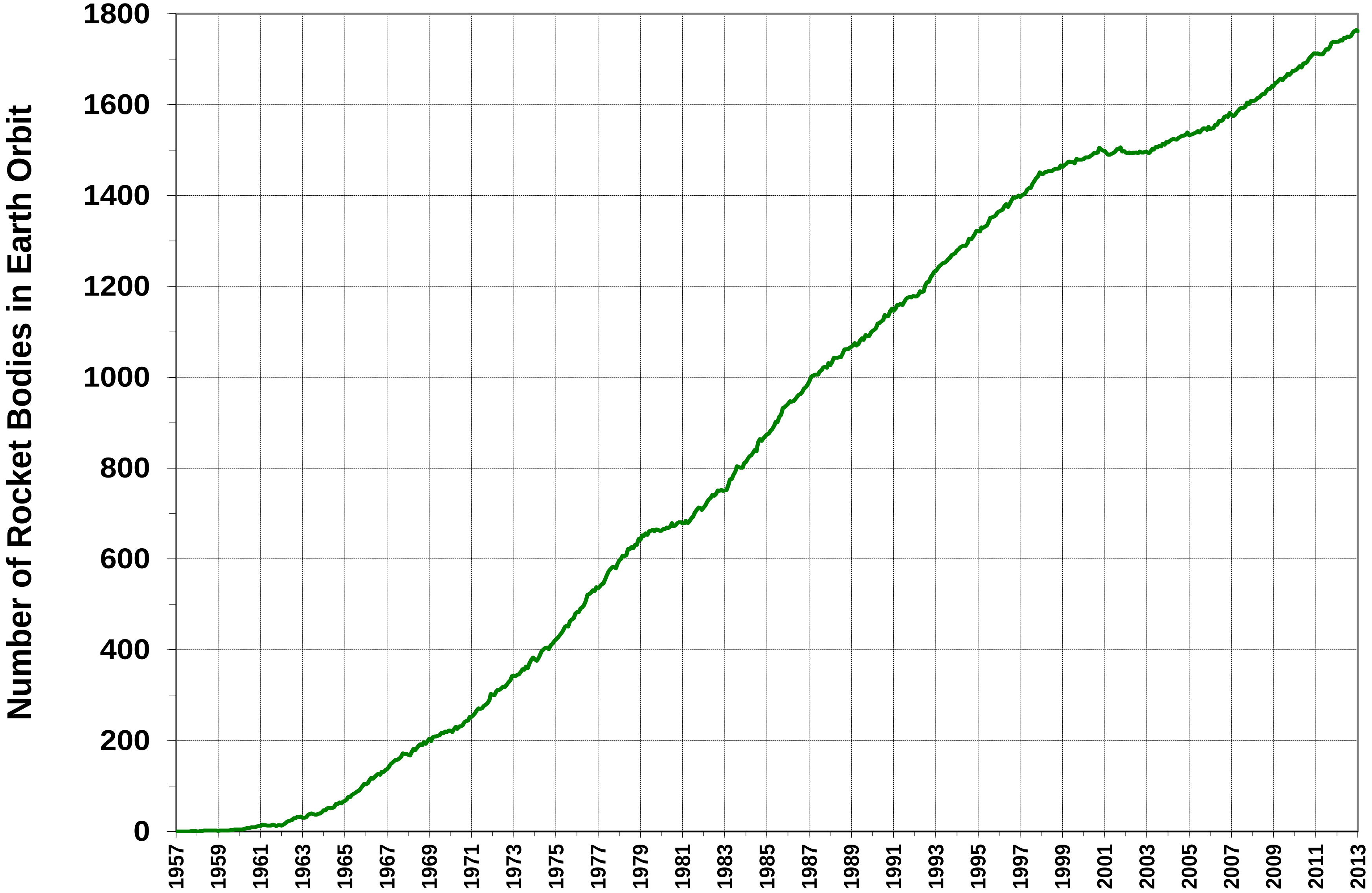
- More than 5500 launch vehicle stages have been placed into Earth orbit since Sputnik 1 in 1957.
- Currently, >1750 launch vehicle stages remain in Earth orbit.
- Sizes range from <100 kg to 9 metric tons

Atlas V Centaur stage



Pegasus upper stage

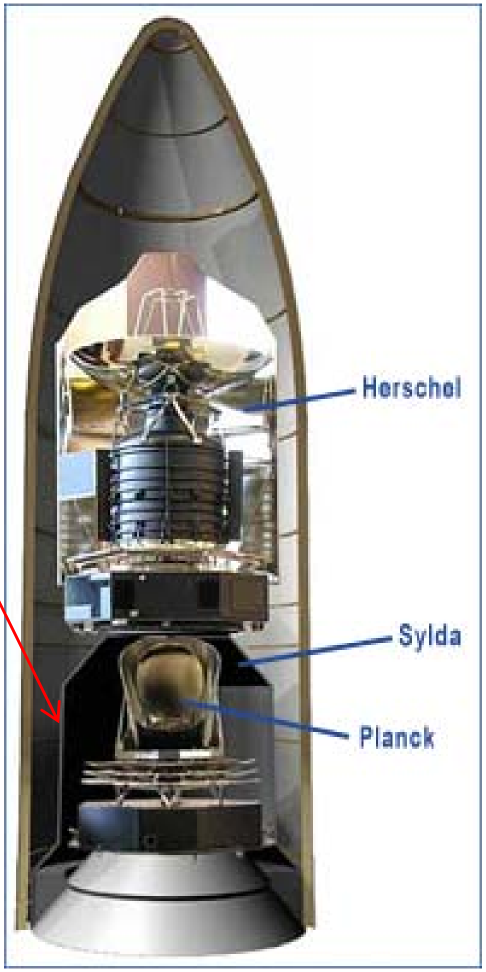
Growth of Launch Vehicle Stages in Earth Orbit

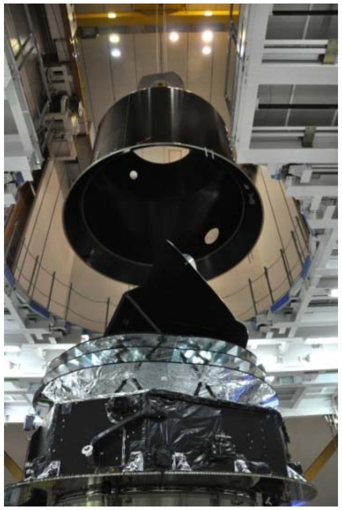


Mission-related Debris

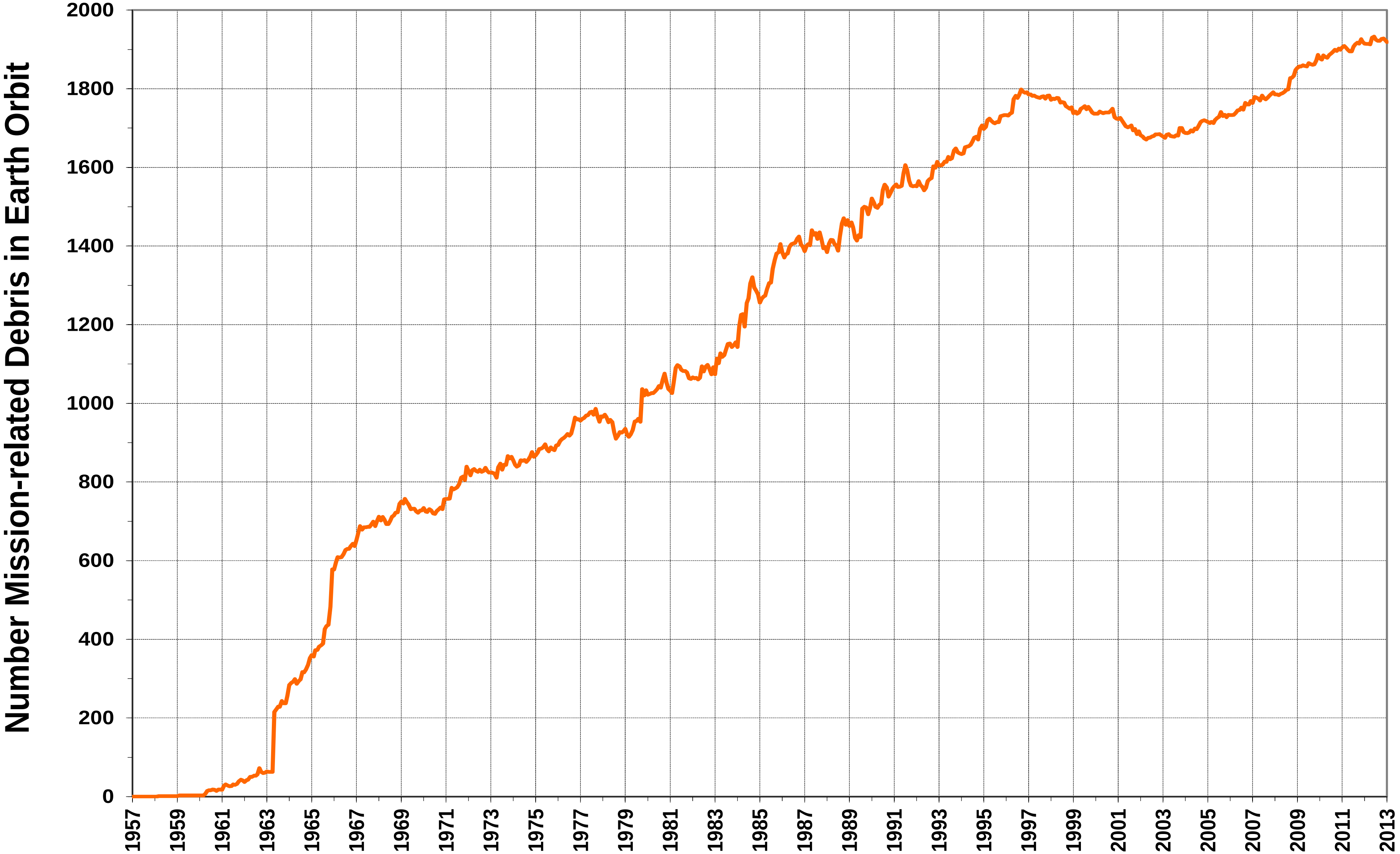
- **During the launch and satellite deployment processes, some debris can be generated, e.g., sensor and engine covers, straps, springs, and yo-yo despin weights.**
- **Most spacecraft and launch vehicles are now designed to eliminate or limit the generation of mission-related debris.**
  - One exception is for multiple payload launches, *e.g.*, Ariane and Delta 2

Ariane 5 SYLDA Payload Dispenser





Growth of Mission-related Debris



Fragmentation Debris

- **The majority of debris in Earth orbit has originated from the fragmentation of spacecraft and rocket bodies.**

- **Fragmentation events can generally be classified in one of three categories:**
  - Anomalous events: Typically one or a few debris released at low velocities, often possessing higher than normal area-to-mass ratios. Many of these debris have short orbital lifetimes. More than 100 events identified with spacecraft and upper stages.
  - Explosions: Intentional or accidental, resulting in only a few to several hundreds of large debris and many more smaller debris. Ejection velocities range from very low to very high for a single event. 200 events identified.
  - Collisions: Also can be intentional or accidental. Debris distributions similar to explosions. Two major events since 2007.

NASA, U.S., and international guidelines and standards seek to eliminate or limit the occurrence of satellite fragmentations of all kinds.

Top Ten Worst Satellite Breakups (based on cataloged debris)

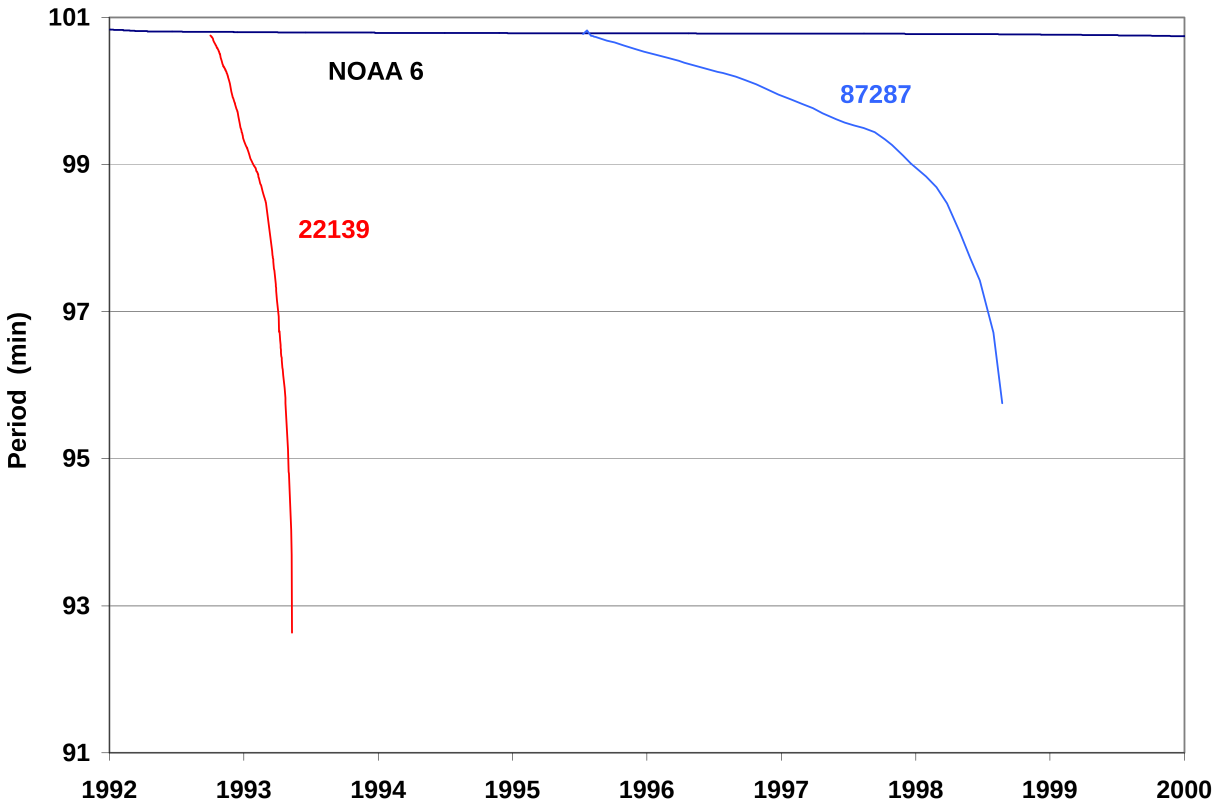
COMMON NAME	CATALOGED DEBRIS*	DEBRIS IN ORBIT*	YEAR OF BREAKUP	ALTITUDE OF BREAKUP	CAUSE OF BREAKUP
Fengyun-1C	3378	3070	2007	850 km	Intentional Collision
Cosmos 2251	1603	1339	2009	790 km	Accidental Collision
STEP 2 Rocket Body	710	55	1996	625 km	Accidental Explosion
Iridium 33	598	473	2009	790 km	Accidental Collision
Cosmos 2421	509	0	2008	410 km	Unknown
SPOT 1 Rocket Body	492	31	1986	805 km	Accidental Explosion
OV 2-1 / LCS 2 Rocket Body	473	35	1965	740 km	Accidental Explosion
Nimbus 4 Rocket Body	375	243	1970	1075 km	Accidental Explosion
TES Rocket Body	371	106	2001	670 km	Accidental Explosion
CBERS 1 Rocket Body	344	173	2000	740 km	Accidental Explosion

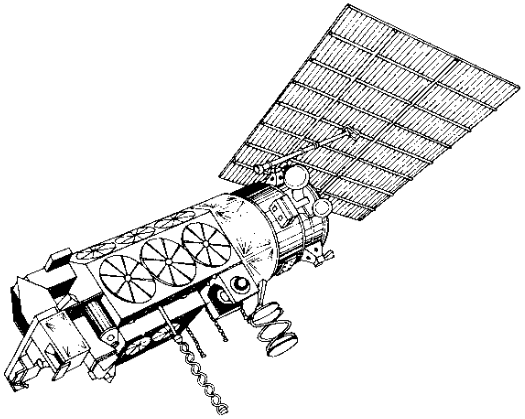
Total: 8853 **Total: 5525**

* As of 5 February 2013

NOAA 6 Anomalous Events

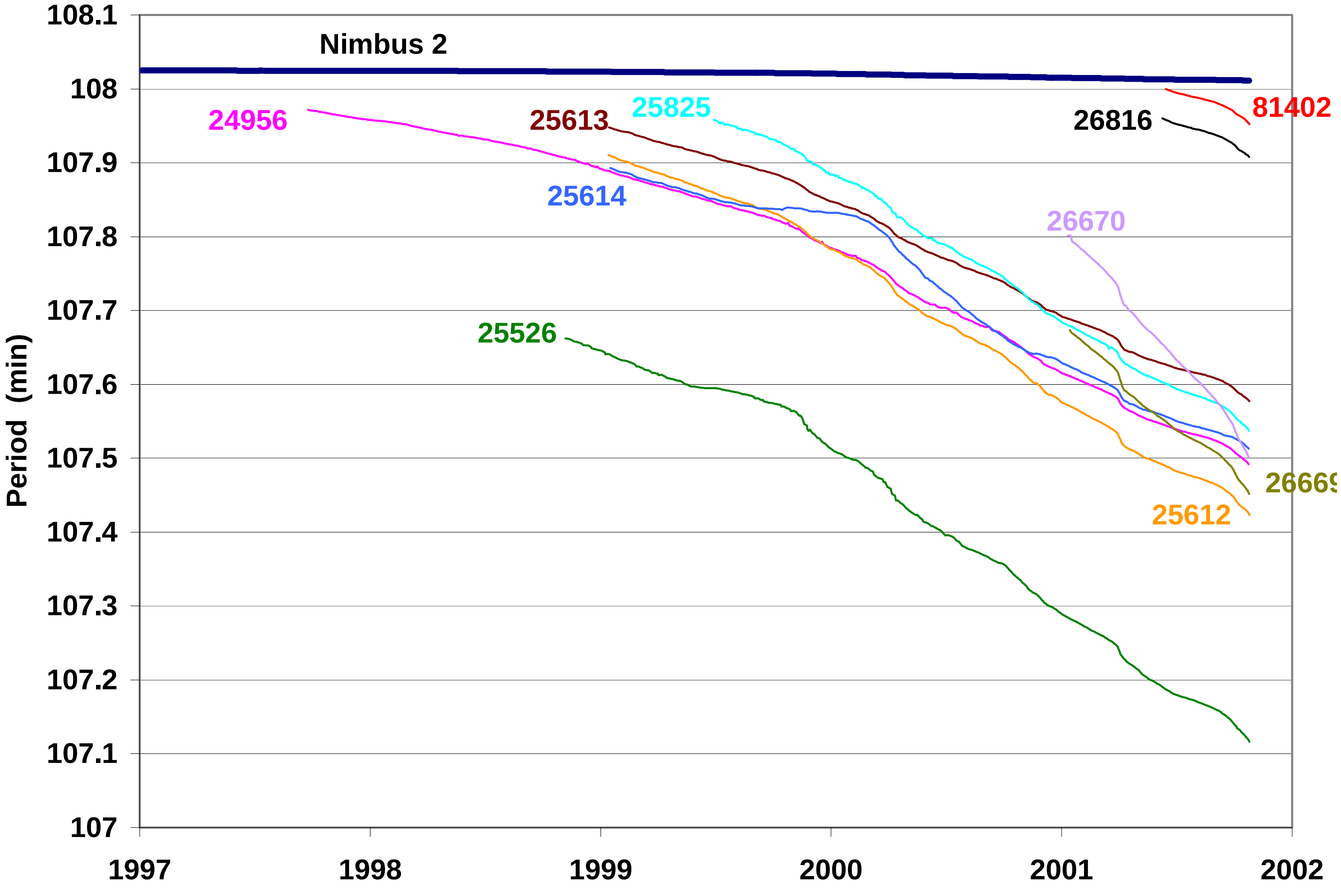
- NOAA 6 (launched 27 June 1979) has experienced at least two anomalous events, 13 and 16 years after launch, respectively

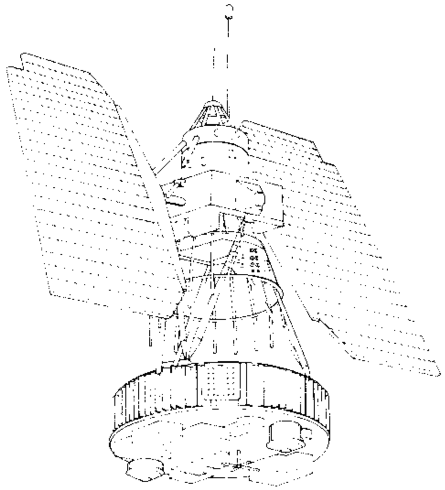




Nimbus 2 Debris Releases

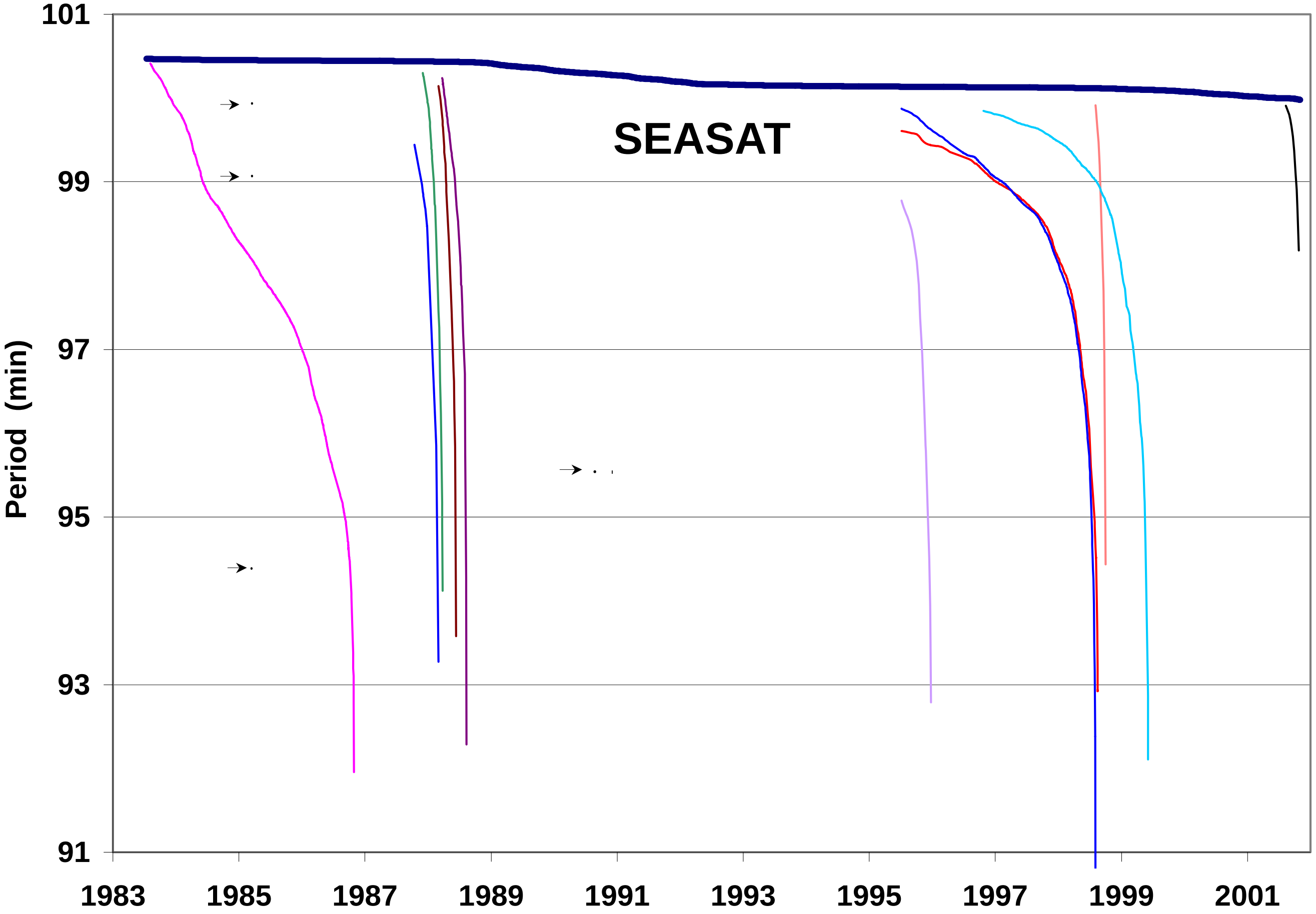
- **Debris releases began ~30 years after launch**

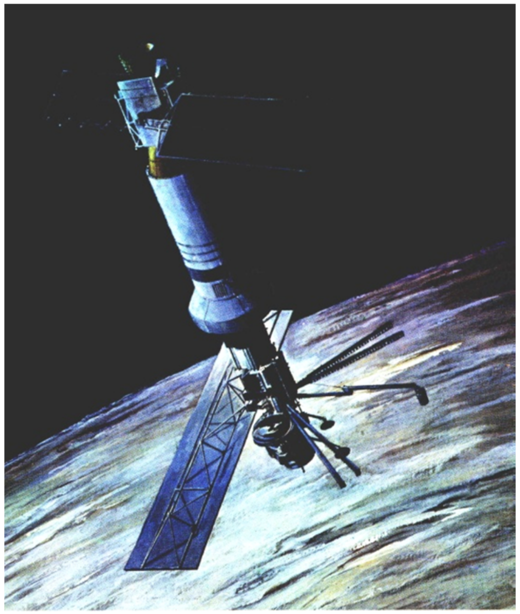




SEASAT Debris Events

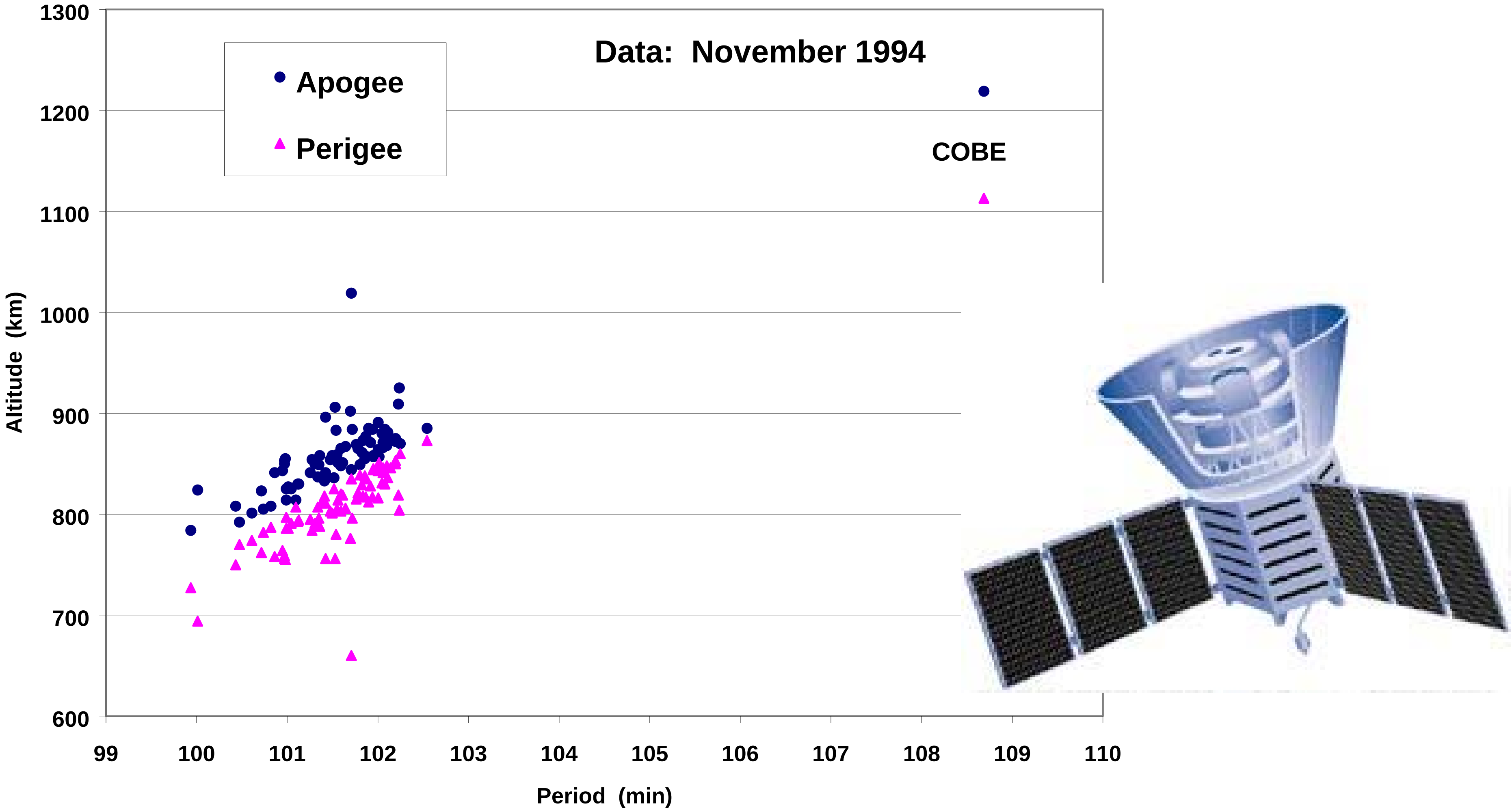
- Debris releases began 5 years after launch; debris exhibited different average area-to-mass ratios





COBE Debris Cloud

- **COBE released 76 debris 3-4 years after launch in 1989 while still operational; most debris decayed within 4-5 years of release; all have now reentered.**

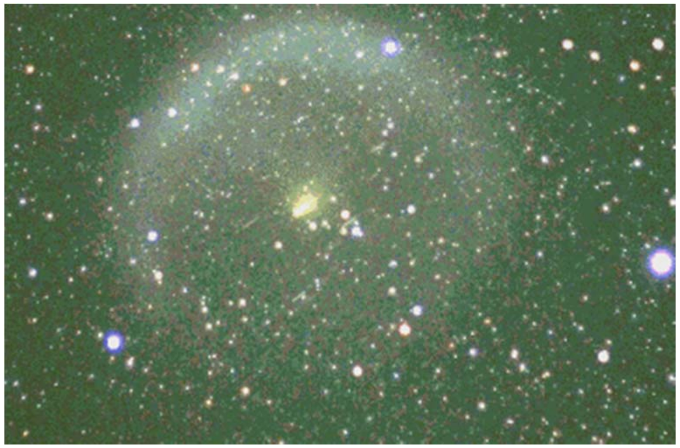


Launch Vehicle Upper Stage Explosions

- **Until 2007 launch vehicle upper stage explosions were the single greatest contributor to the hazardous debris environment.**

- **Nearly all these explosions occurred after successful satellite deployment missions. The time of the event varied from 24 hours after launch to more than two decades after launch.**
  - Passivation of the upper stages after mission completion (removal of residual propellants and pressurants) has been highly successful in preventing such explosions.

- **In Feb 2006, a Proton Briz M malfunctioned, leaving a large amount of propellants on board. One year later it exploded into an estimated 1000+ large fragments.**



Worst Launch Vehicle Upper Stage Explosions

Stage Type	Breakup Year	Time in Orbit	Debris Cataloged*	Assessed Cause
Pegasus HAPS	1996	24 months	710	Pressurant induced
Ariane 1 3rd stage	1986	9 months	492	Propellant induced
Titan Transtage	1965	0 months	473	Propulsion failure
Agena D	1970	6 months	375	Unknown; Propellant induced?
PSLV 4th stage	2001	2 months	371	Propellant induced
Long March 4 3rd stage	2000	5 months	344	Propellant induced

* As of February 2013

- **All missions except Titan Transtage performed their satellite delivery missions successfully.**
- **A Proton Briz M might have produced 1000 or more debris in February 2007, but cataloging the debris has been difficult.**

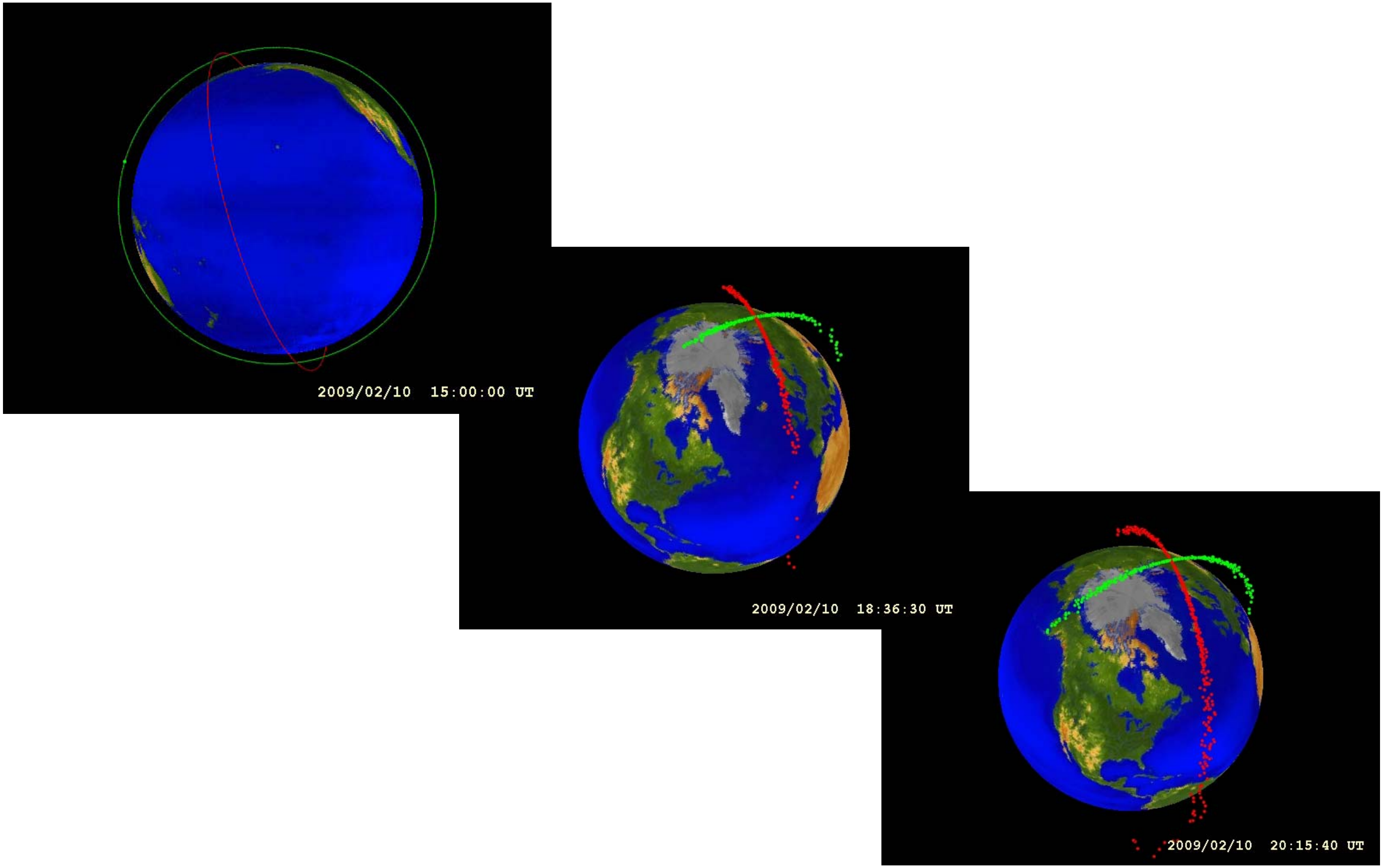
Spacecraft Fragmentations

- **As of 1 January 2013, Russia (including the former USSR) was responsible for 51 deliberate spacecraft detonations.**
  - Anti-satellite tests
  - Loss of controlled reentry capability
  - Loss of attitude
- **Battery failures account for 8 spacecraft breakups (1 U.S.).**
- **At least three U.S. spacecraft suffered fragmentations during propulsion operations: USA 68, Mars Observer, and CONTOUR.**
- **34 events from unknown causes (including 22 of a single Russian satellite type).**

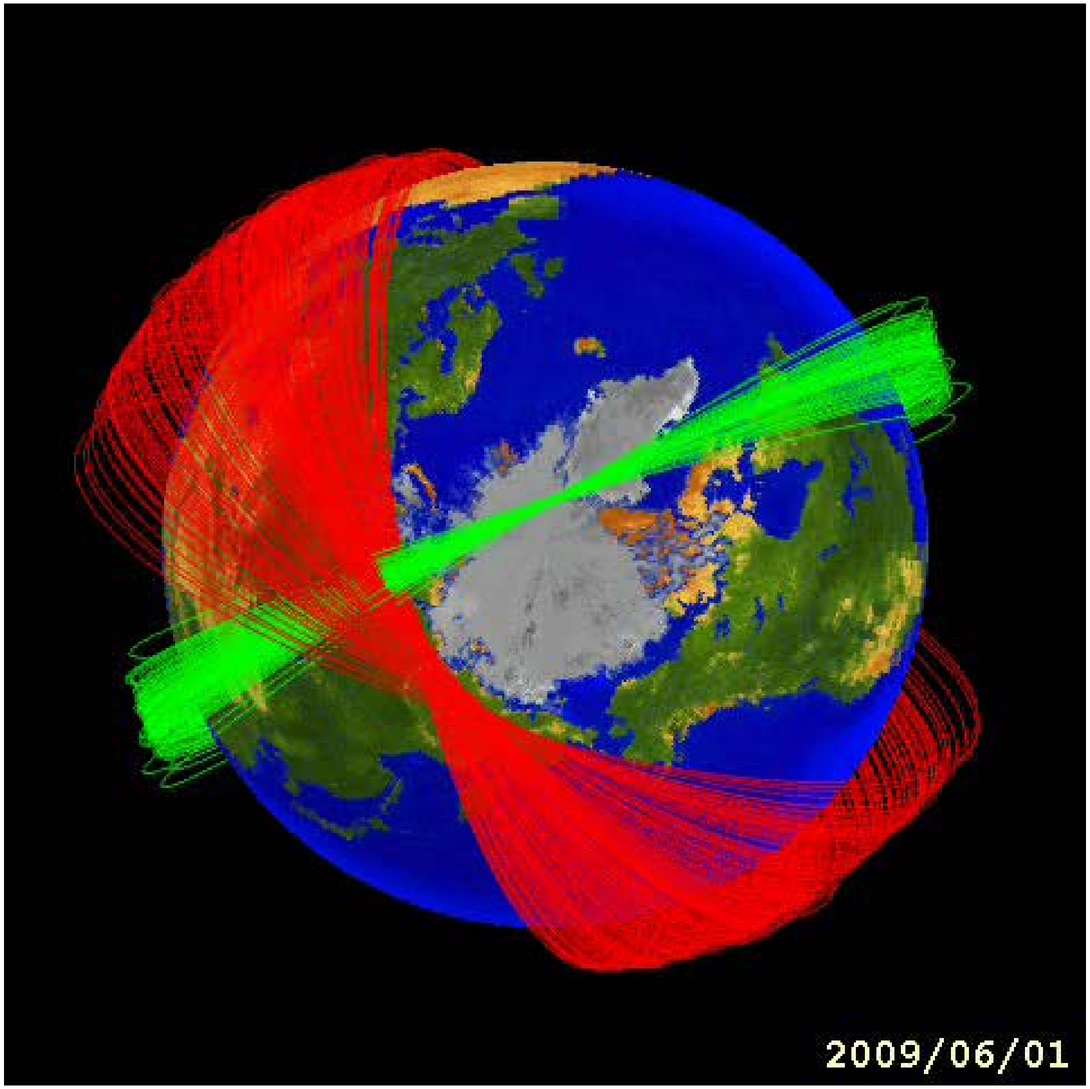
Accidental Satellite Collisions

- **Four known accidental hypervelocity collisions between cataloged objects.**
  - 1991: Cosmos 1934 struck by piece of mission-related debris
  - 1996: CERISE struck by piece of Ariane 1 fragmentation debris
  - 2005: U.S. upper stage struck by piece of Chinese upper stage fragmentation debris
  - 2009: Collision of Iridium 33 and Cosmos 2251 spacecraft
- **The first three events created very few debris. The collision of Iridium 33 and Cosmos 2251 resulted in more than 2200 large (trackable) debris and many more smaller debris.**
- **A few low velocity collisions have also occurred during operations but have resulted in no or few debris, *e.g.*, Progress-M 34 and the Mir Space Station.**

Iridium-Cosmos Collision: Initial Debris Spread

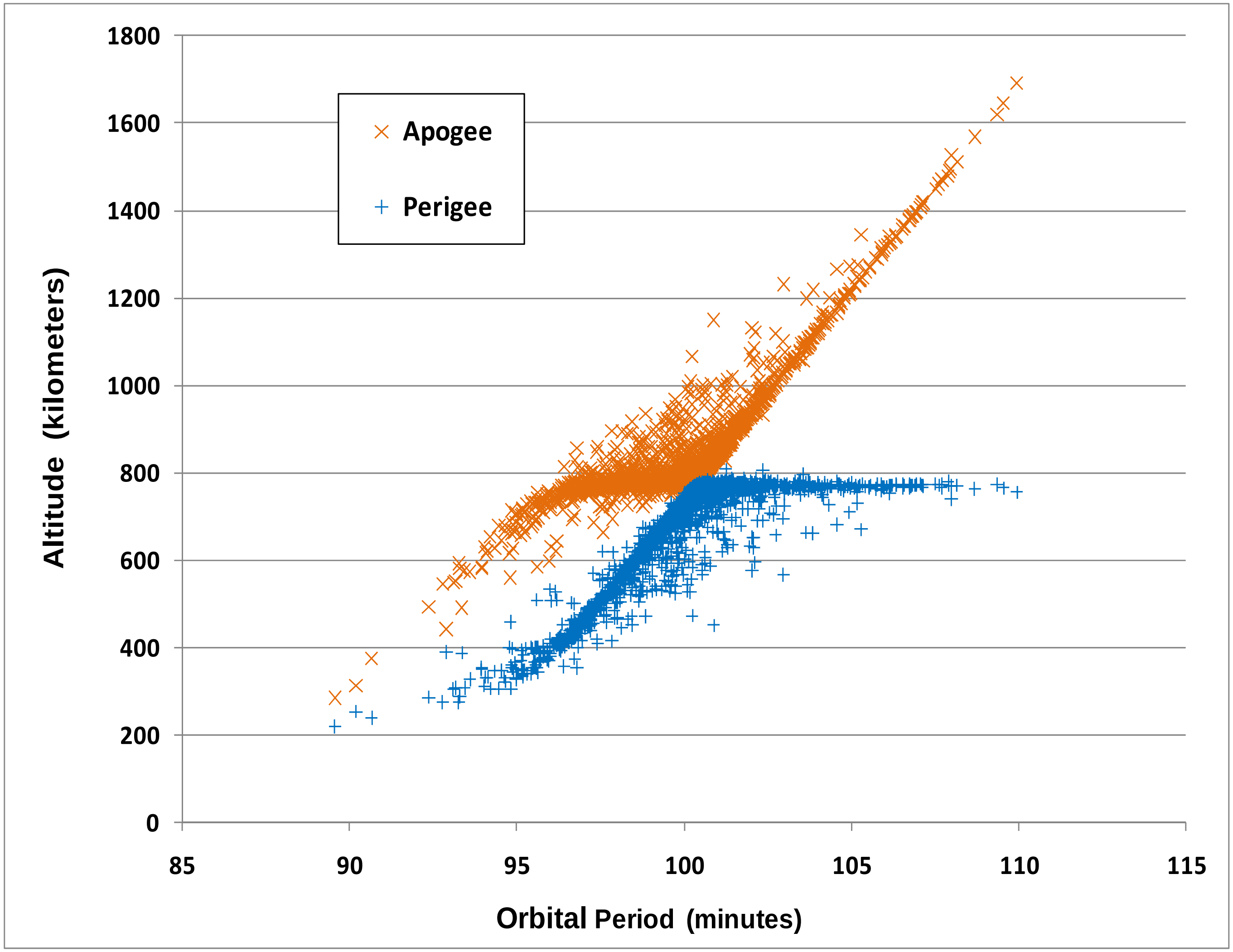


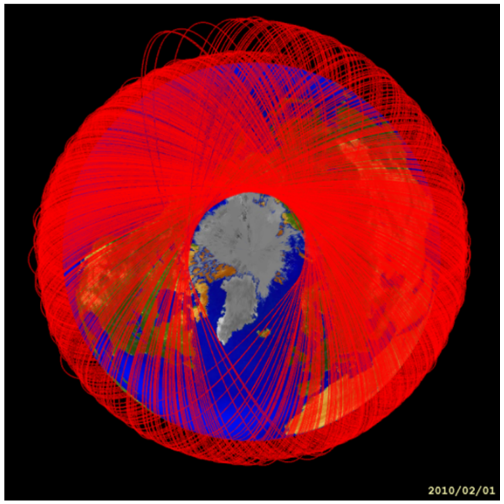
Iridium-Cosmos Collision: Orbital Planes



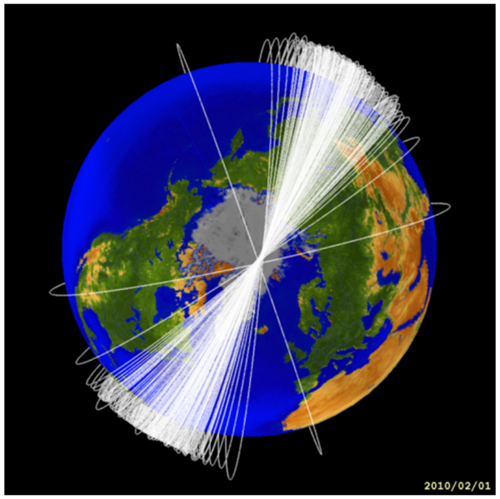
Iridium-Cosmos Collision

- **One year after the accidental collision of Iridium 33 and Cosmos 2251, more than 2000 large debris had been identified.**





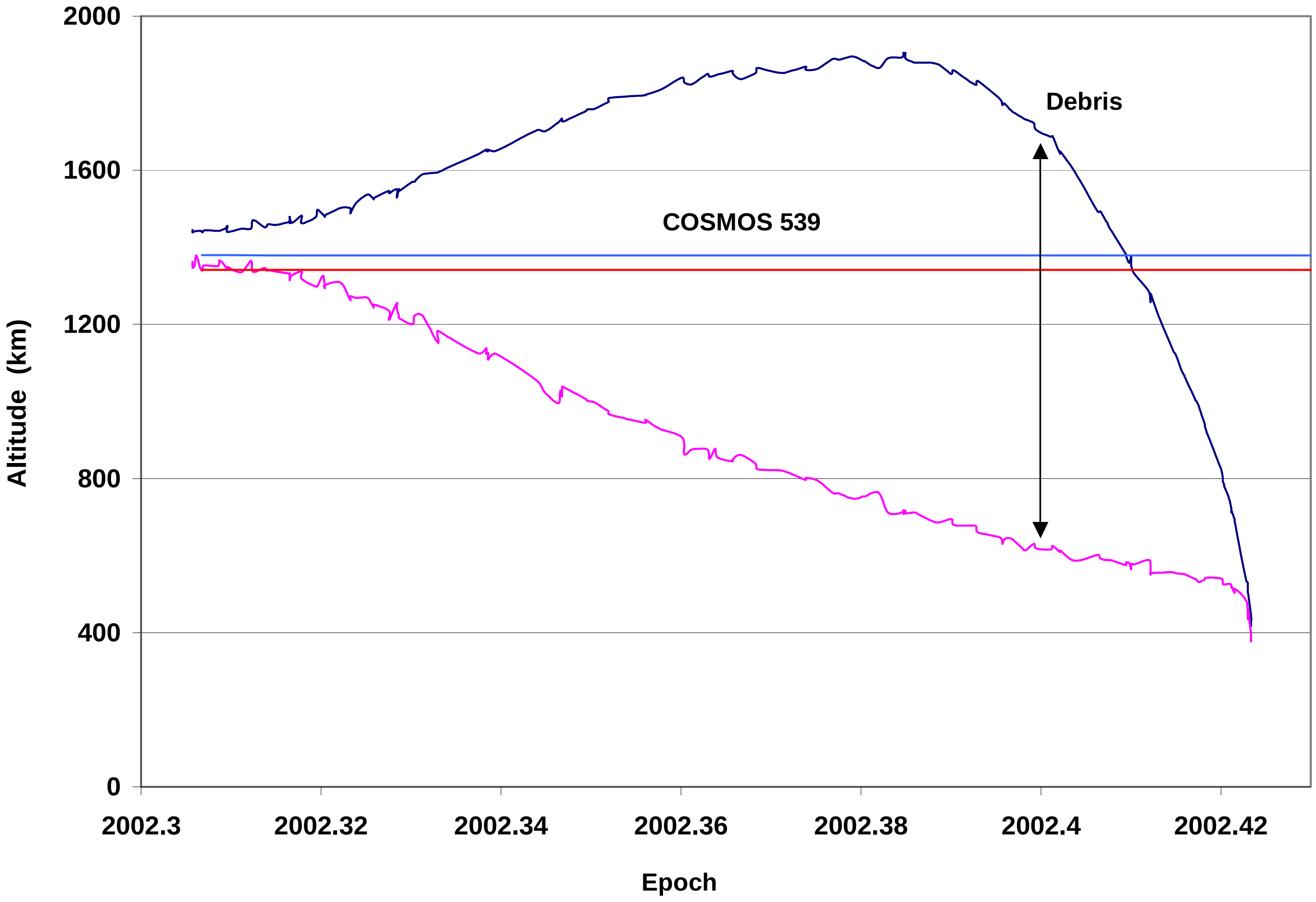
Cosmos 2251 Debris



Iridium 33 Debris

Cosmos 539 Potential Accidental Collision

- Cosmos 539 was nearly 30 years old in 2002 when its orbit was perturbed and a new debris piece was generated with high A/M

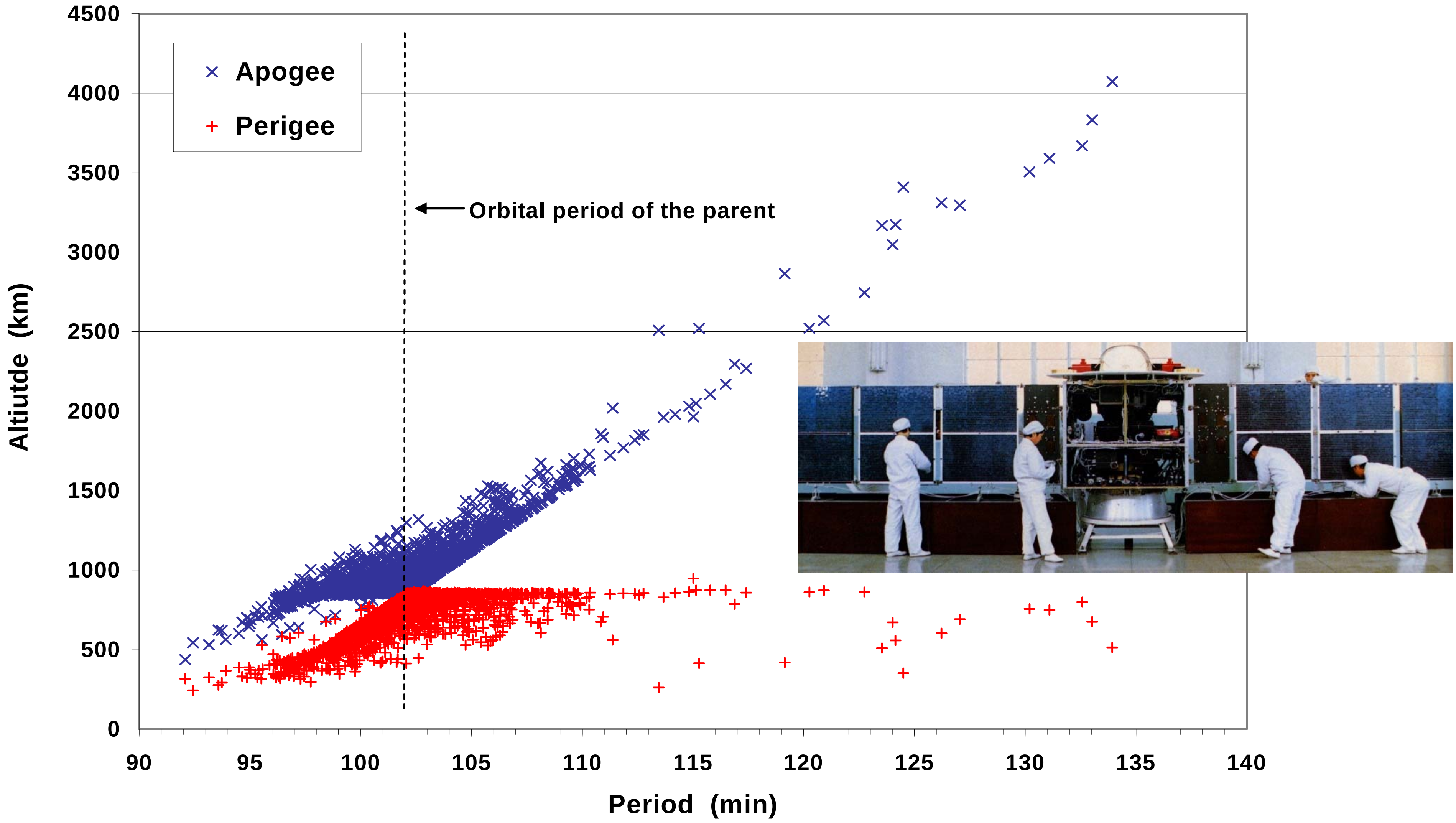


Deliberate Satellite Collisions

- **Four deliberate hypervelocity satellite collisions have occurred.**
  - Solwind satellite destroyed in 1985 during test of U.S. anti-satellite device; all debris reentered within 19 years.
  - USA-19 intentionally collided with orbital stage a few hours after launch in 1986 under an experiment by DoD (SDIO); all cataloged debris reentered in less than one year.
  - USA-193 destroyed in 2008 shortly before reentry to prevent risk of human casualty from on-board hazardous material; all but one cataloged debris reentered within eight months.
  - Fengyun-1C destroyed in 2007 during test of Chinese anti-satellite device; nearly 3400 large debris created; many will be long-lived.

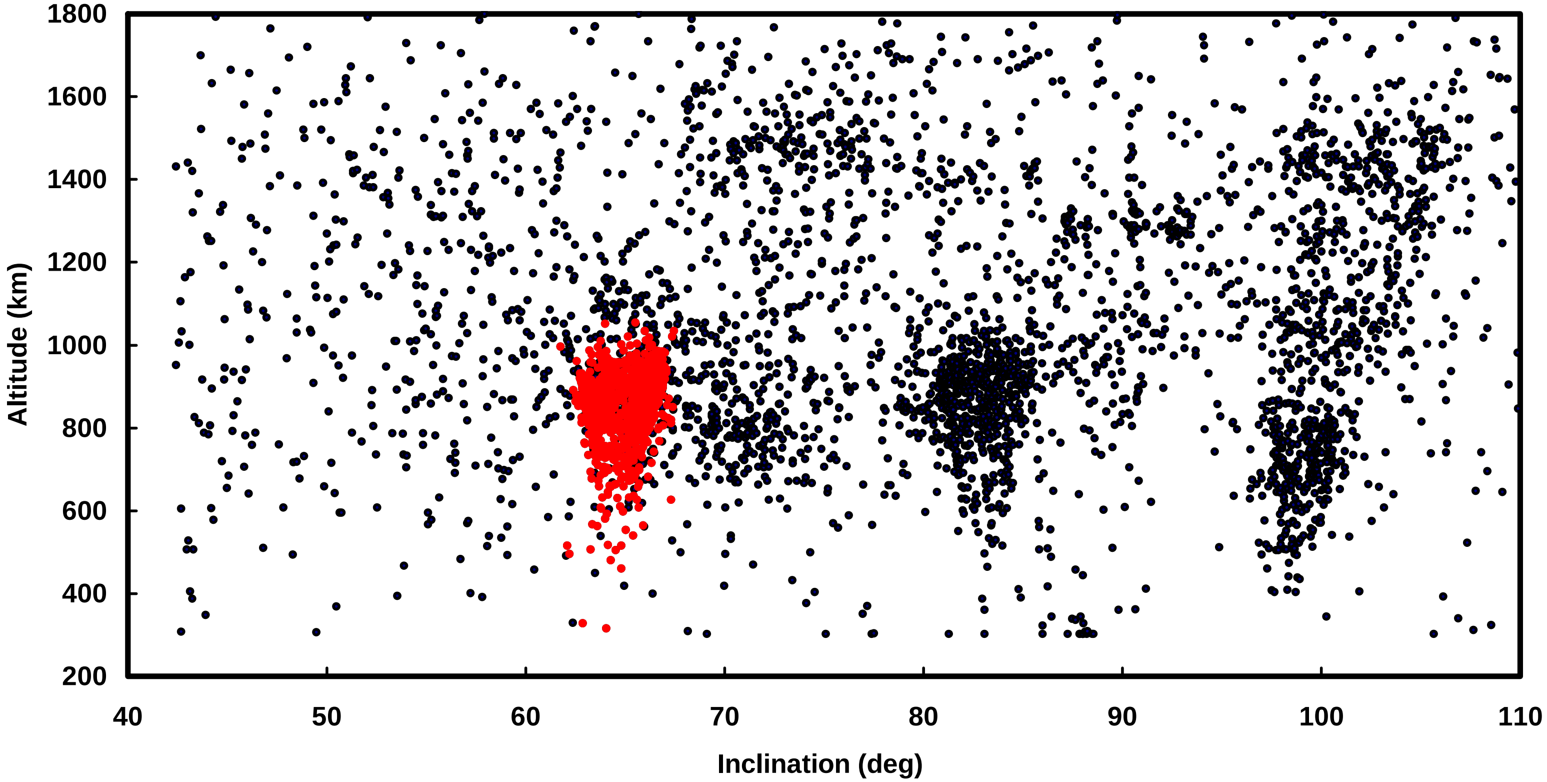
Debris Distribution from Fengyun-1C

- Fengyun-1C debris is spread across the entire LEO region and beyond.



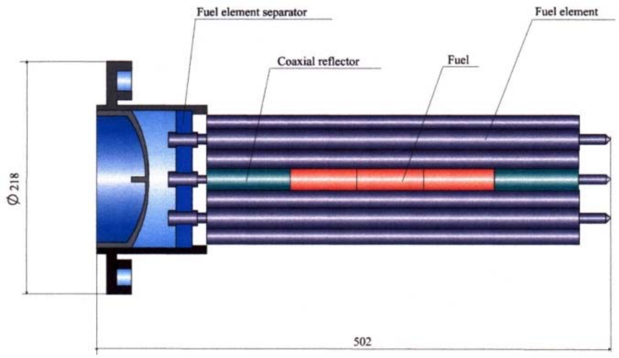
New Debris Source Discovered

- **During observations of the orbital debris environment in the 1990’s, NASA discovered an unexpectedly dense population of small particles in orbits near 900-1000 km with 65 degree inclinations.**
  - 55 objects larger than 5 cm had been officially cataloged by February 2013
  - More than 100,000 particles between 5 mm and 5 cm are estimated

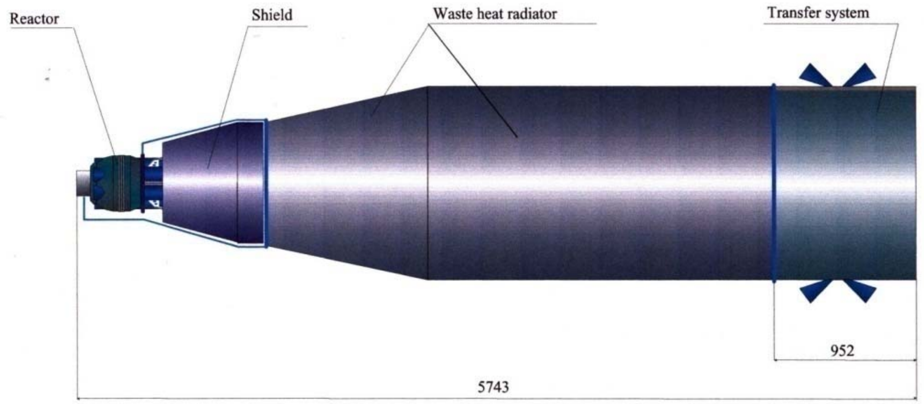


Coolant Release from Nuclear Reactors

- **The source of these particles is assessed to be sodium potassium coolant from the primary coolant loop of Bouk reactors which ejected their fuel rod assemblies, following a redesign after the uncontrolled reentry of Cosmos 954 in 1978. At least 14 vehicles have ejected their reactor cores.**



Reactor Core (enlarged)

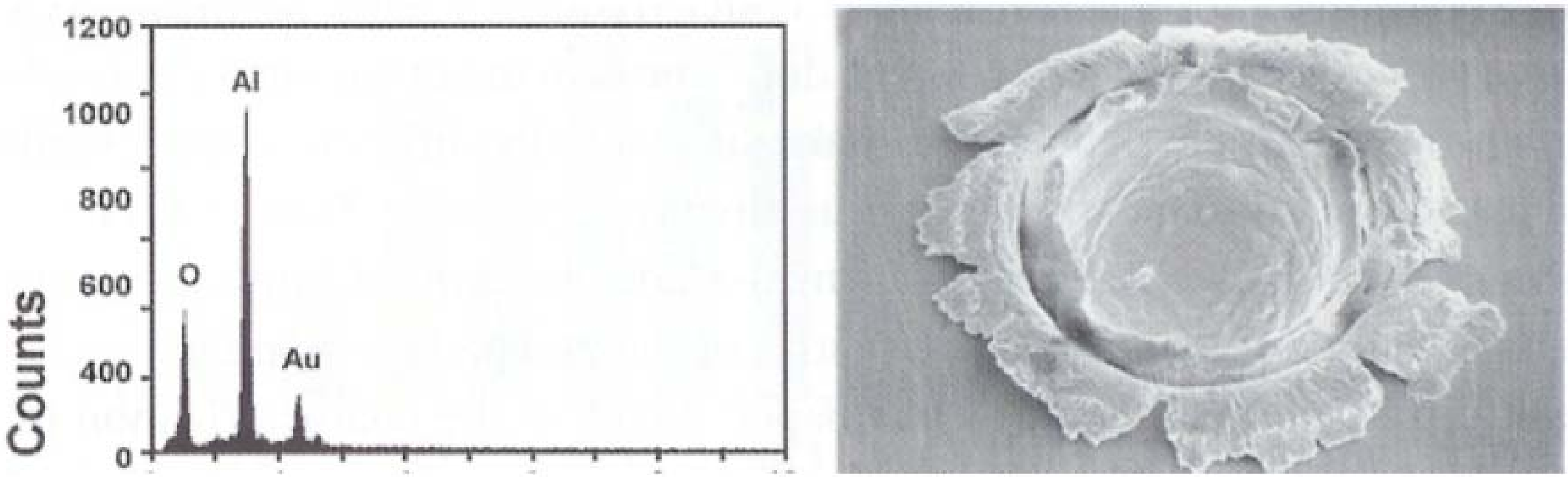


- **Bouk and Topaz secondary coolant loops are possible future sources of sodium potassium droplets from space debris impacts on radiators.**

- **No coolant particles have yet been observed in the orbital regime of the U.S. SNAP-10A reactor (launched in 1965).**

Solid Rocket Motor Effluents

- **Solid rocket motors eject large quantities of small particles, during burn and after shut-down.**
- **Two size categories: 5-35 microns and 0.1 mm to 5 cm**
- **The largest, most hazardous particles are released after SRM shut-down.**



LDEF gold surface impacted by aluminum oxide SRM particle.

Sample SRM Debris Photos

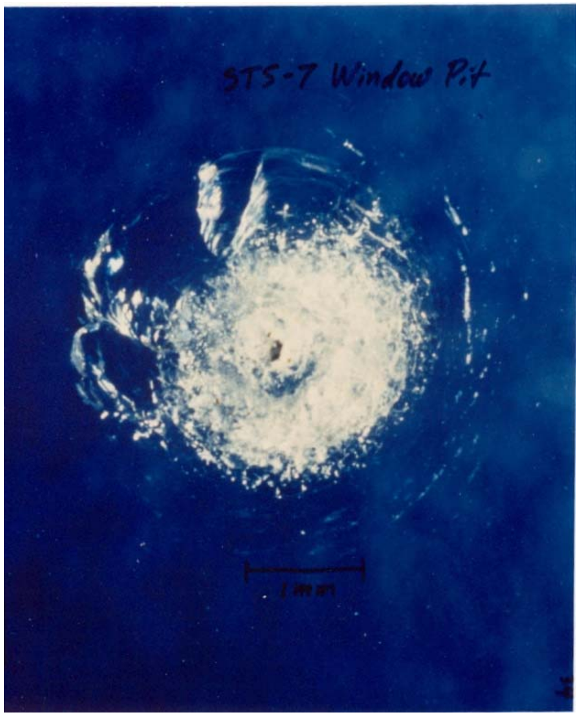
Space Shuttle SRBs 20.5 seconds after separation

Pegasus SRM 15.5 sec after shutdown

Paint Particles

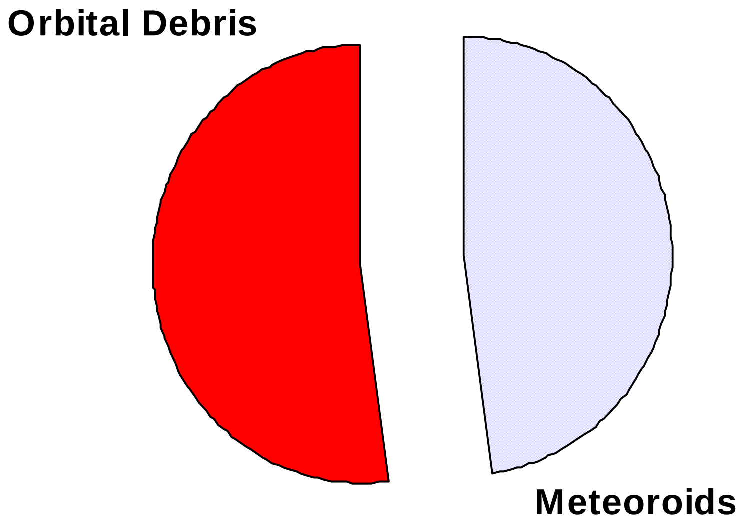
- **During inspection of the windows of the Challenger Space Shuttle following its STS-7 mission in 1983, a 3-mm-diameter, 0.4-mm-deep crater was discovered. The window pane had to be replaced.**

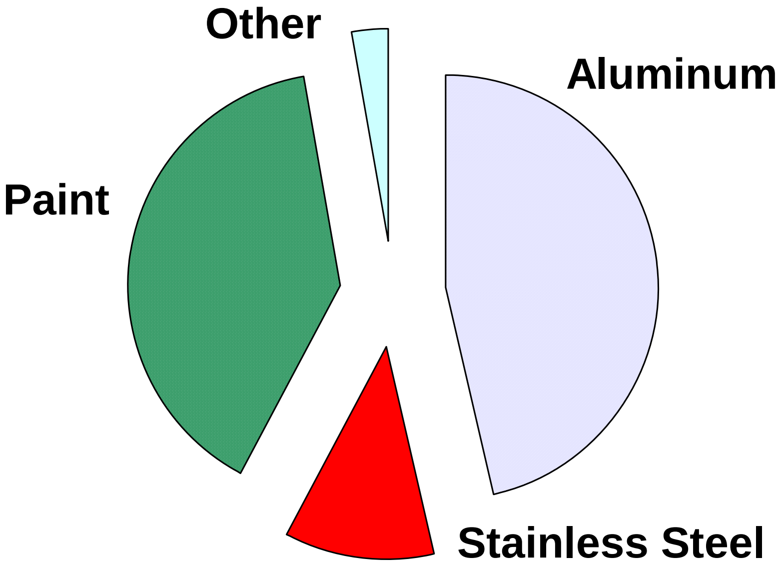
- **Examination of residue in the crater indicated that the particle had been a fleck of paint. Hypervelocity paint impacts have commonly been found on subsequent Space Shuttle missions.**



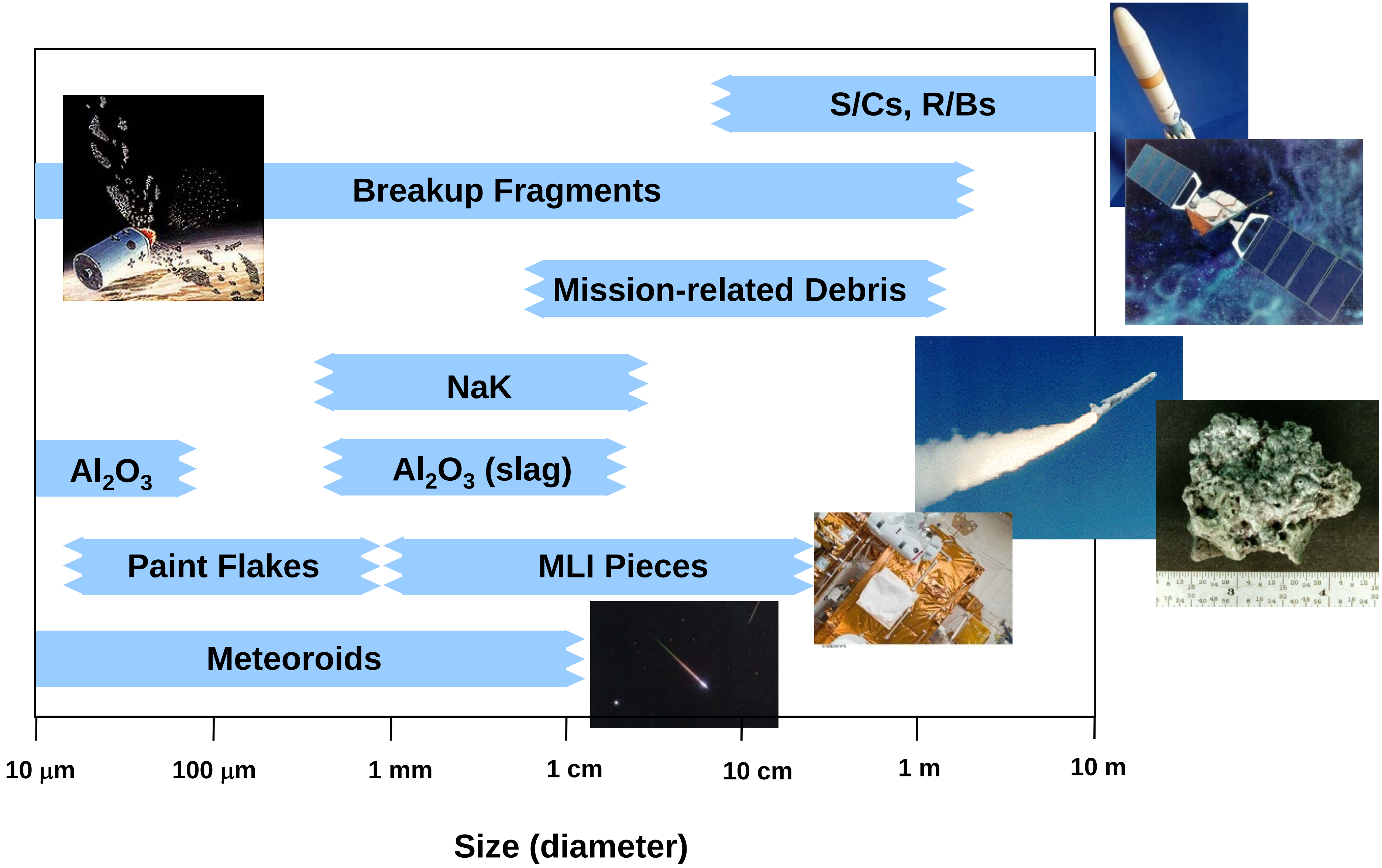
Types of Space Shuttle Windows Impactors

- During 1992-2001 a total of 463 Shuttle window impactors were characterized by type.
- Impactors were typically 0.01-0.06 mm in diameter, but some were as large as 0.2 mm in diameter.





Summary (1)


S/Cs, R/Bs
Breakup Fragments
Mission-related Debris
NaK
Al_2O_3
Al_2O_3 (slag)
Paint Flakes
MLI Pieces
Meteoroids
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
Size (diameter)

Summary (2)

- **Many millions of debris are currently in Earth orbit.**

- **They range in size from a few microns to tens of meters in length and come from a variety of sources.**

- **They pose a risk to all space operations, both human space flight and robotic.**

- **In general:**

  - Objects larger than ~5 mm pose mission termination risks.

  - Objects smaller than 1 mm pose mission degradation risks.

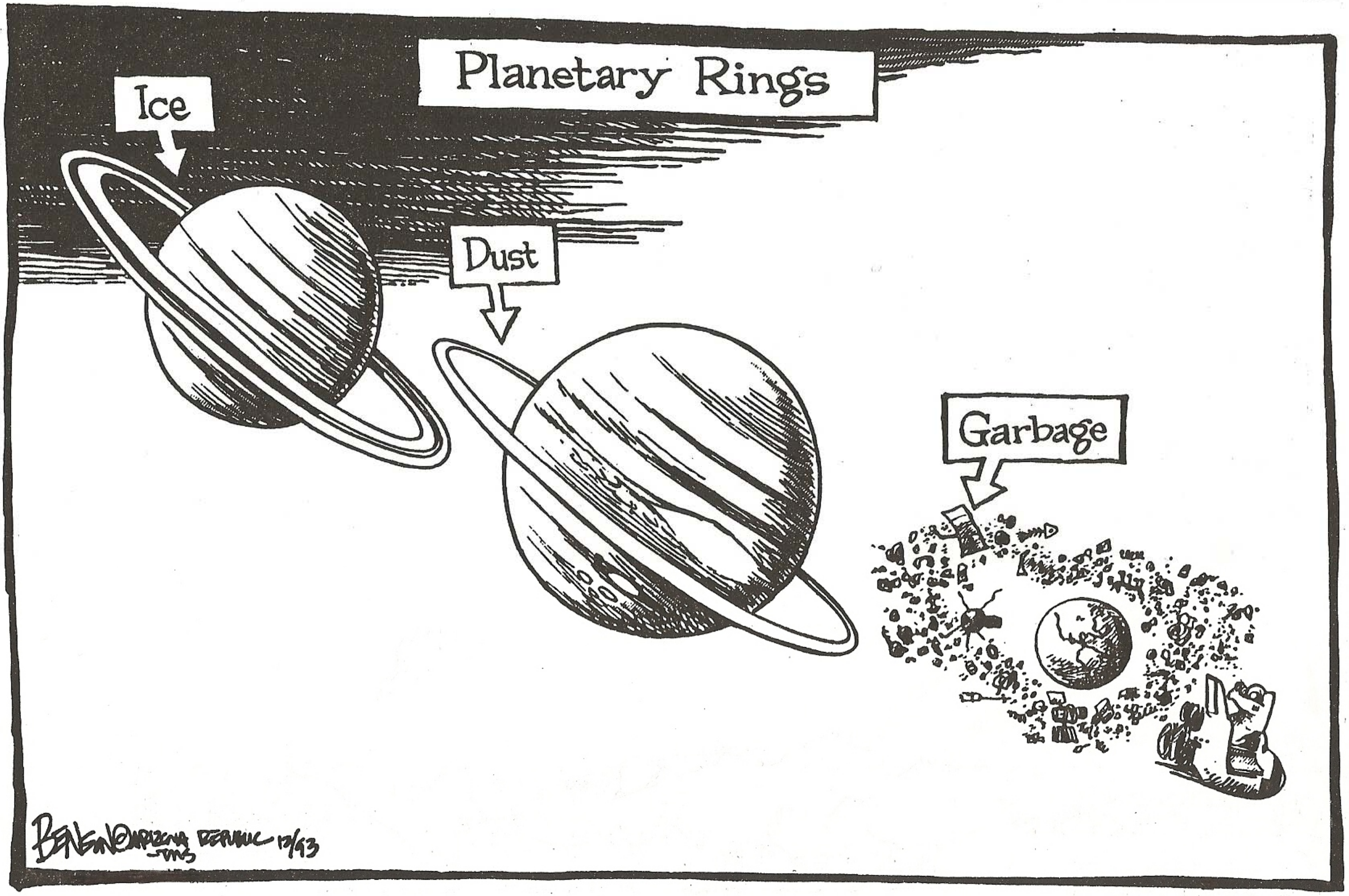

ACCORDING TO NASA, SPACE JUNK HAS BECOME A PROBLEM. YEARS OF DEBRIS FROM SPACE MISSIONS...
Richard
04/06
©2009 Tribune Media Services, Inc. All rights reserved
... IS ACCUMULATING AROUND EARTH. THINGS SUCH AS NUTS, BOLTS, GLOVES ...
www.gocomics.com/brewsterrockit brewrockit@yahoo.com
... AND FORGOTTEN SPACE WALKERS.
HELLO? COULD SOMEONE LET ME BACK IN?

National Aeronautics and Space Administration

Characterizing the Earth’s Satellite Population: Counting Debris

Orbital Debris Program Office
NASA Johnson Space Center

OPINIONS/STEVE BENSON



How Much Debris Is There?

Softball or larger (> 10 cm): 20,000+

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

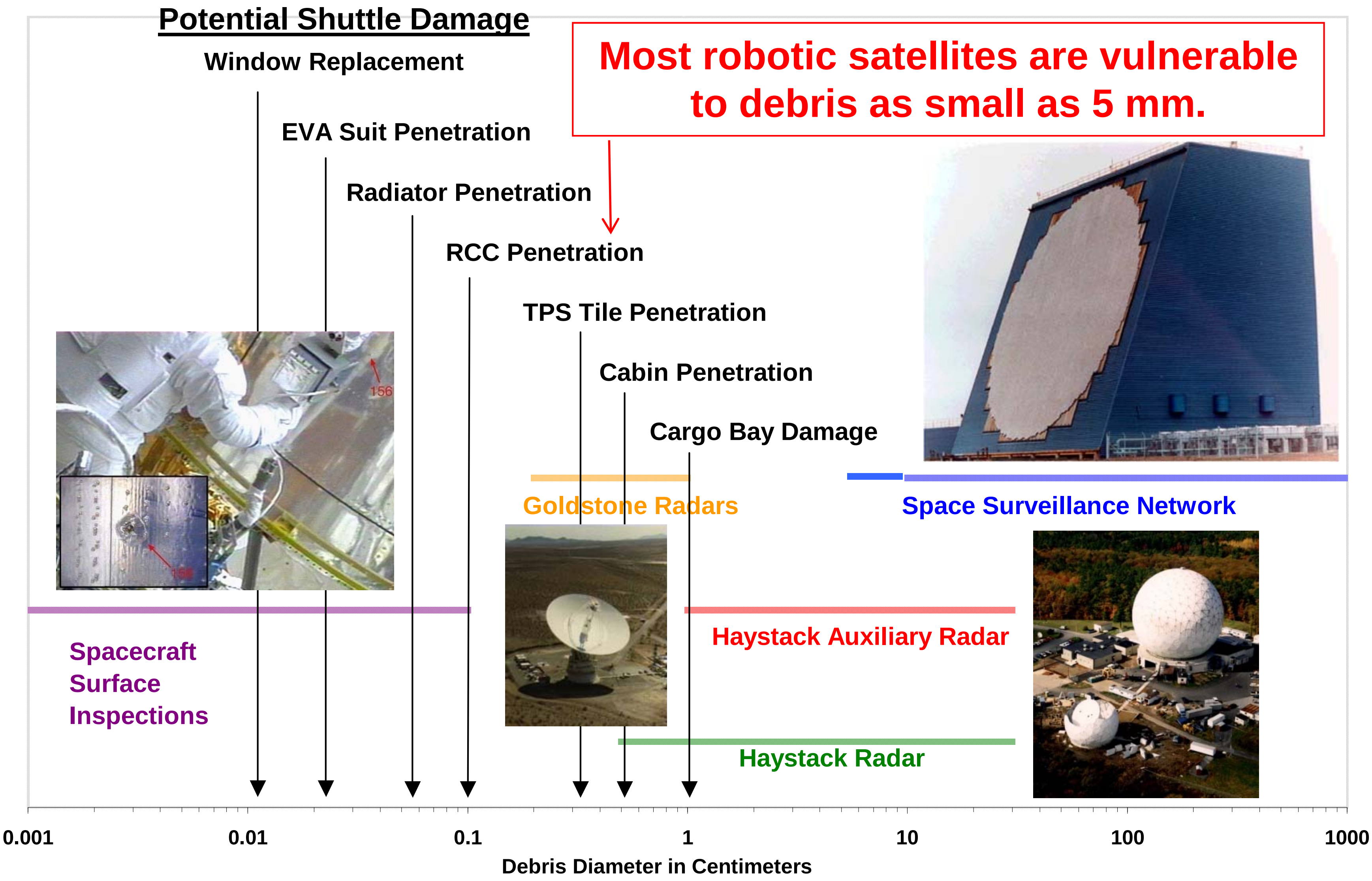
Dot or larger (> 1 mm): ~135,000,000
(1/4 the size of a BB)

How do we know this?

Orbital Debris Detection Responsibilities and Capabilities

- **NASA and DoD share responsibility for determining the Earth satellite population at various sizes and altitudes.**
  - DoD is the lead for objects $\geq$ 10 cm in LEO and $\geq$ 1 m in GEO
  - NASA is the lead for objects < 10 cm in LEO and < 1 m in GEO
- **DoD assessments are deterministic, while NASA assessments are primarily statistical.**
- **A wide variety of radars and electro-optical sensors are employed.**
- **DoD databases are also used for conjunction assessments and collision avoidance, while NASA models support probabilistic risk assessments for the small debris population.**
- **NASA also has the lead for predicting the future Earth satellite population.**

Orbital Debris Detectors and Damage Potential



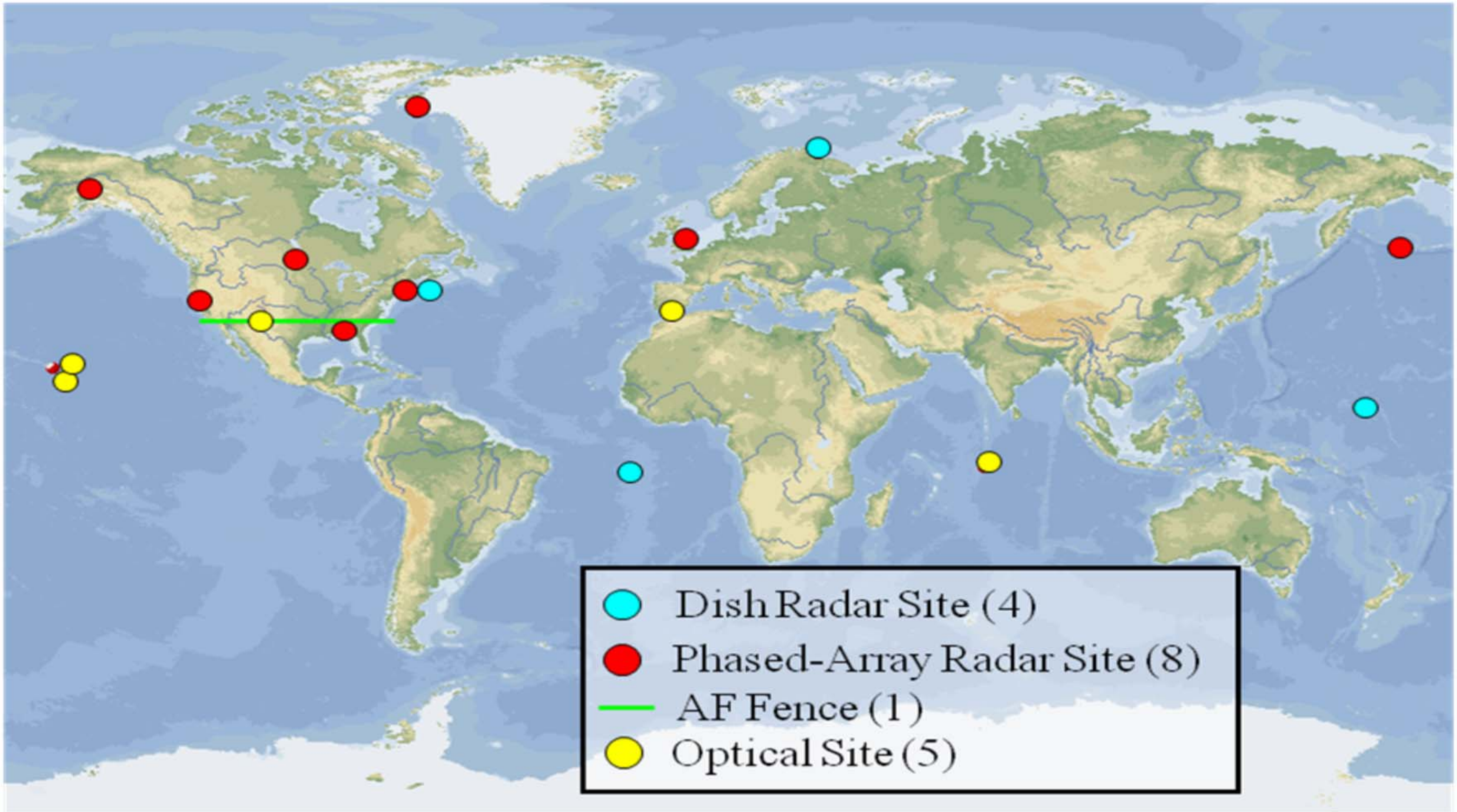
Most robotic satellites are vulnerable to debris as small as 5 mm.

Potential Shuttle Damage

- Window Replacement
- EVA Suit Penetration
- Radiator Penetration
- RCC Penetration
- TPS Tile Penetration
- Cabin Penetration
- Cargo Bay Damage

U.S. Space Surveillance Network

- **The Department of Defense operates the U.S. Space Surveillance Network (SSN), which is comprised of radars and electro-optical sensors around the world, and maintains the official U.S. Satellite Catalog.**
  - Objects as small as 5-10 cm in low Earth orbit
  - Objects as small as ~1 m in geosynchronous orbit



Phased-Array Radars

- **SSN phased-array radars operate in UHF (sensitivity to ~ 10 cm and L-band (sensitivity to ~ 5 cm) and can easily detect/track multiple objects simultaneously. They primarily observe LEO and near-LEO.**

Cobra Dane radar, L-band, LEO

Eglin radar, UHF, LEO and Deep Space

PAVE PAWS radar, UHF, LEO

Dish Radars

- **SSN dish radar operate at a variety of frequencies from UHF to Ka-band and most are capable of detecting objects up to GEO, although sensitivity decreases with range.**

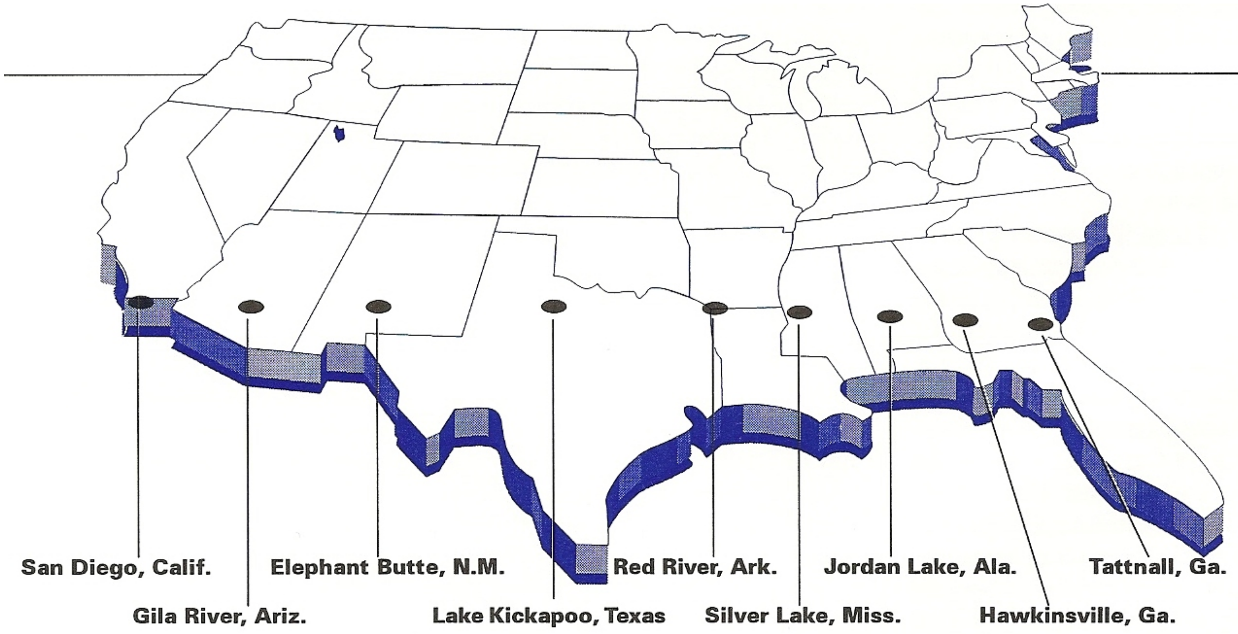
- **Dish radars normally are tasked to track only one object at any time.**

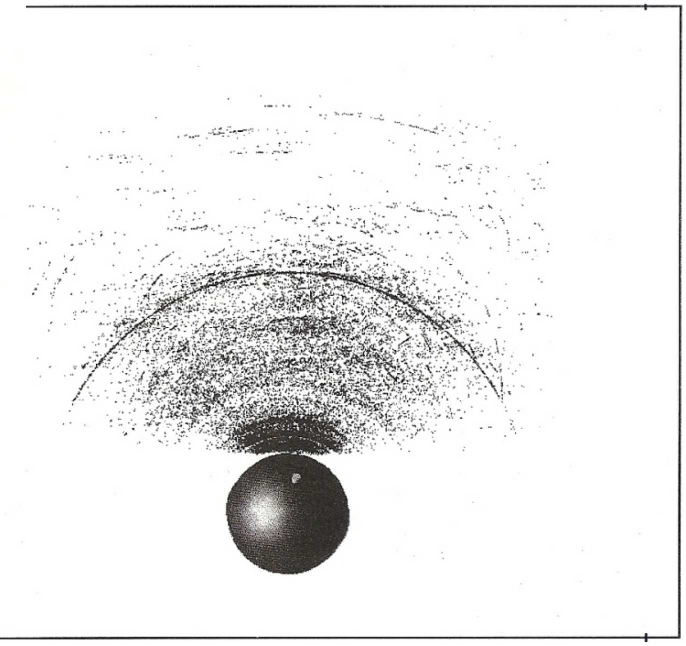
ALTAIR radar in the Pacific Ocean

Globus II radar in Norway

VHF Fence Radar (1)

- **Three VHF transmitters and six receivers located at approximately 33 N latitude across the U.S. constitute a interferometric fence which can detect objects ~30 cm and larger passing through.**



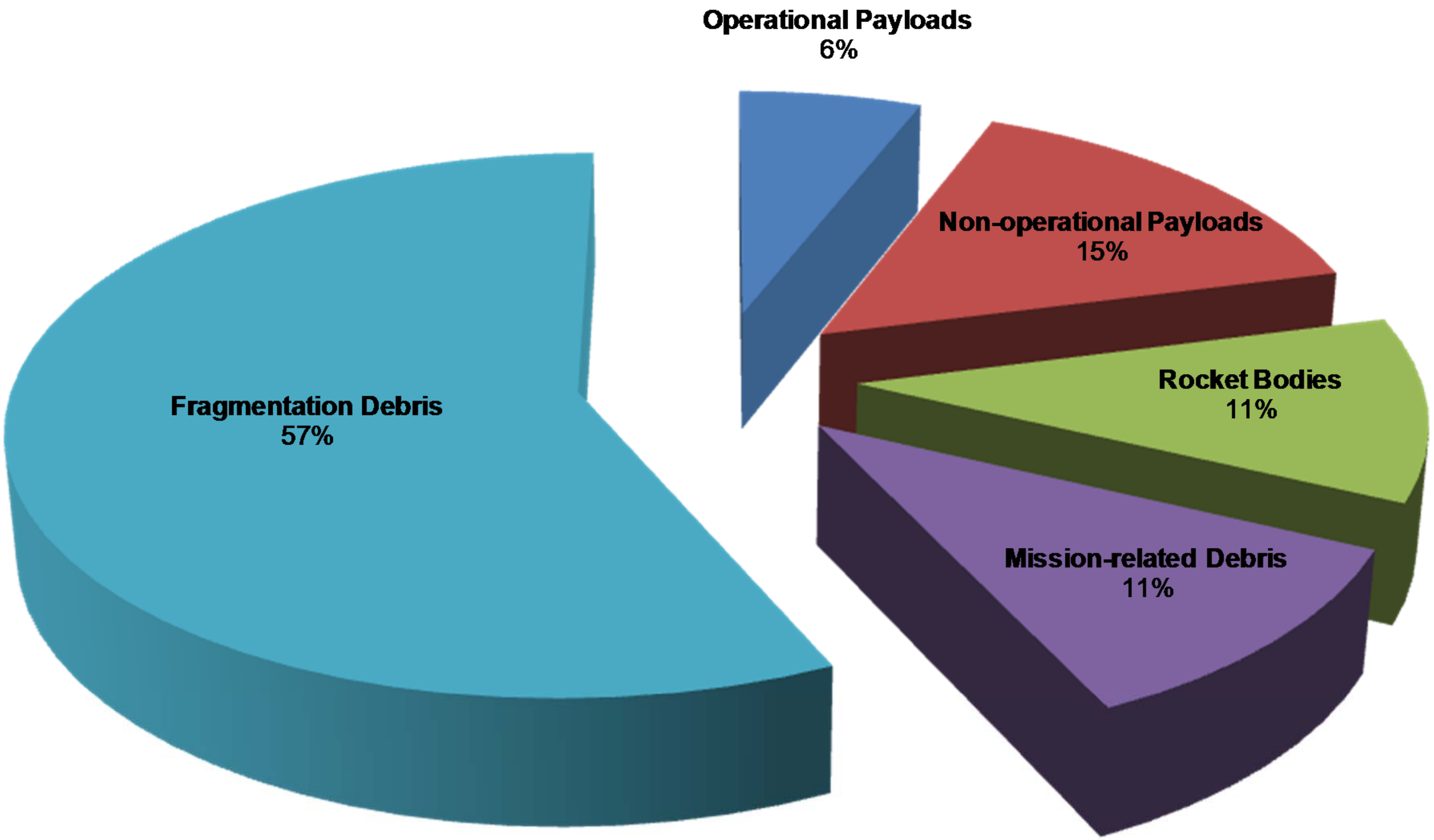


VHF Fence Radar (2)

Jordan Lake Transmitter

Red River Receiver

Breakdown of Current U.S. Satellite Catalog



Orbital debris constitutes 94% of all officially cataloged objects in Earth orbit.

As of February 2013

Orbital Debris in the 5 mm – 10 cm Range

- **NASA and DoD jointly fund observations by the Haystack and Haystack Auxiliary (HAX) radars to detect objects as small as 5 mm in LEO.**
  - NASA analyses the data to develop an environmental model.

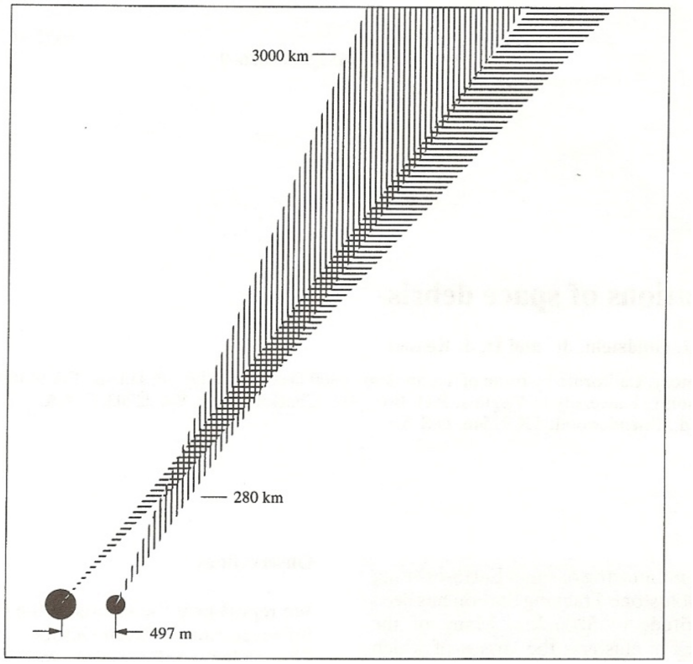
Haystack radar, X-band; narrow field of view; can detect debris as small as 5 mm in LEO

HAX radar, Ka-band; wider field of view; can detect debris as small as 2 cm in LEO

JPL Goldstone Radars

- **NASA utilizes 70-m dish and 34-m dish radars at JPL Goldstone to detect objects as small as 2-3 mm in LEO.**

- **The two radars operate in a bi-static mode, *i.e.*, the larger dish (DSS-14) transmits in X-band and the smaller dish (DSS-15) receives.**

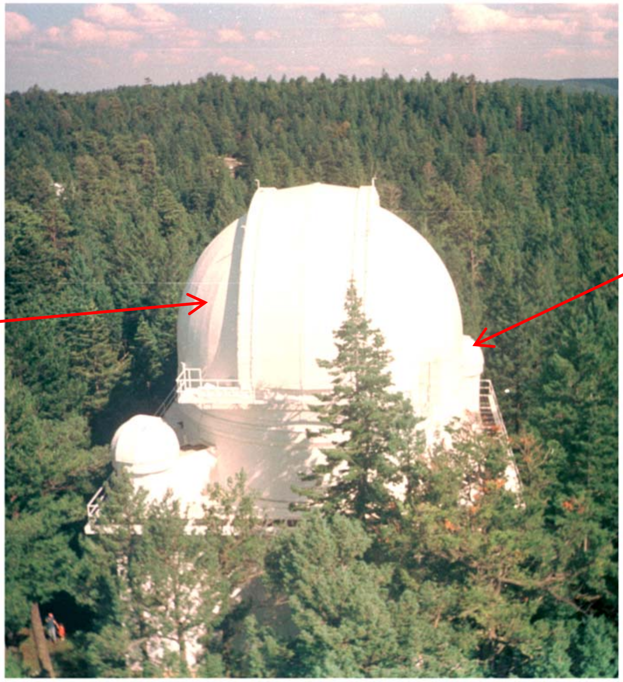


Optical Detection of Debris in LEO

- **From 1994 to 2002 NASA operated CCD Debris Telescope (CDT) and the Liquid Mirror Telescope (LMT) to detect cm-class objects in low Earth orbit.**

- **One objective was to compare debris radar visibility with optical visibility.**

- **During the last several years, both telescopes were operated at an observatory at Cloudcroft, NM.**



CCD Debris Telescope

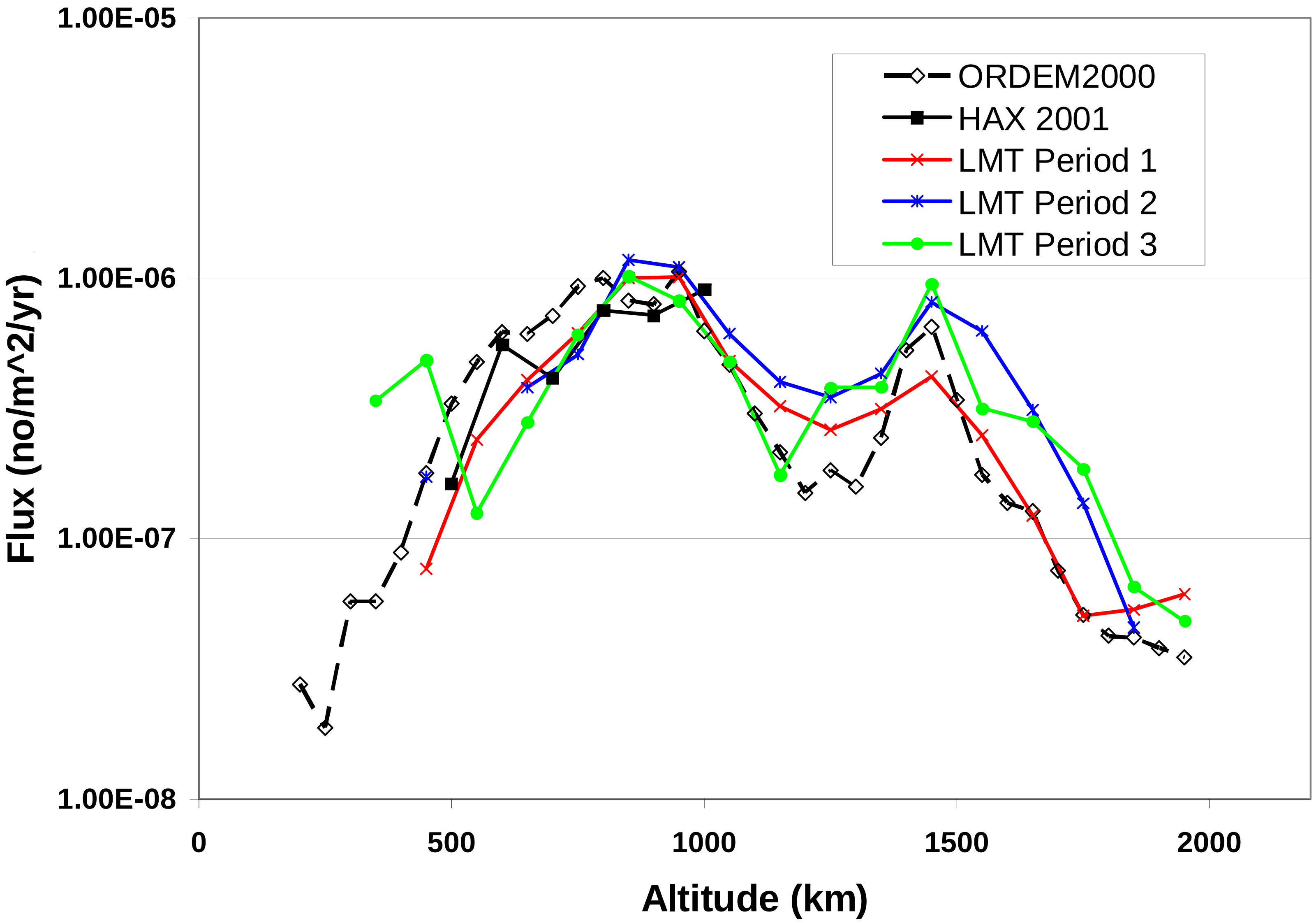
Liquid Mirror Telescope

Former Cloudcroft Telescopes

CCD Debris Telescope

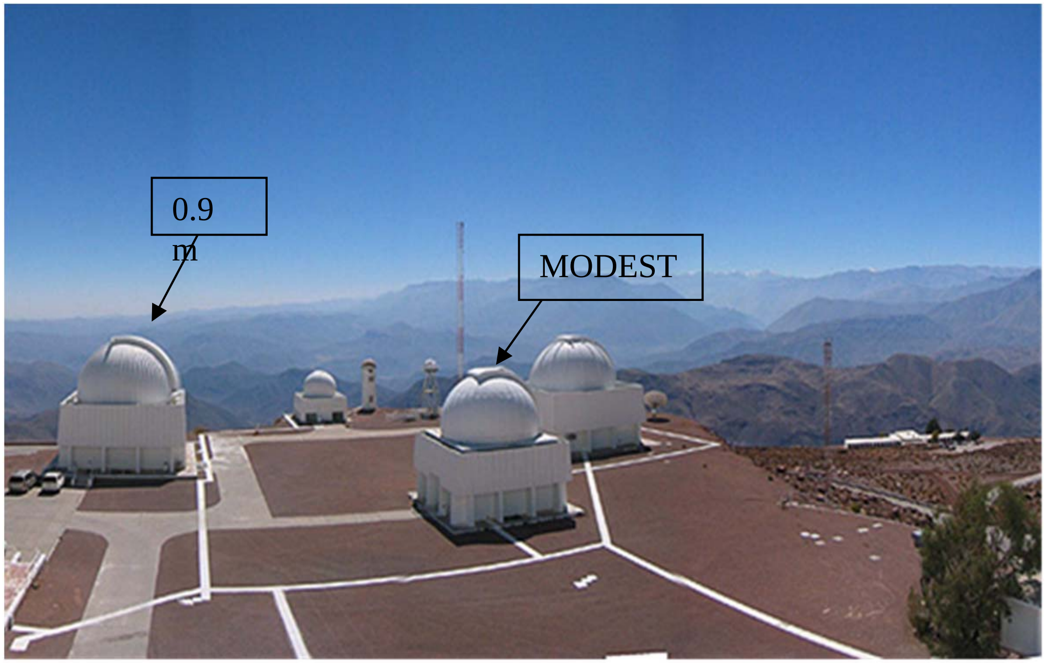
Liquid Mirror Telescope,
3-meter diameter

Radar-Optical Model Agreement



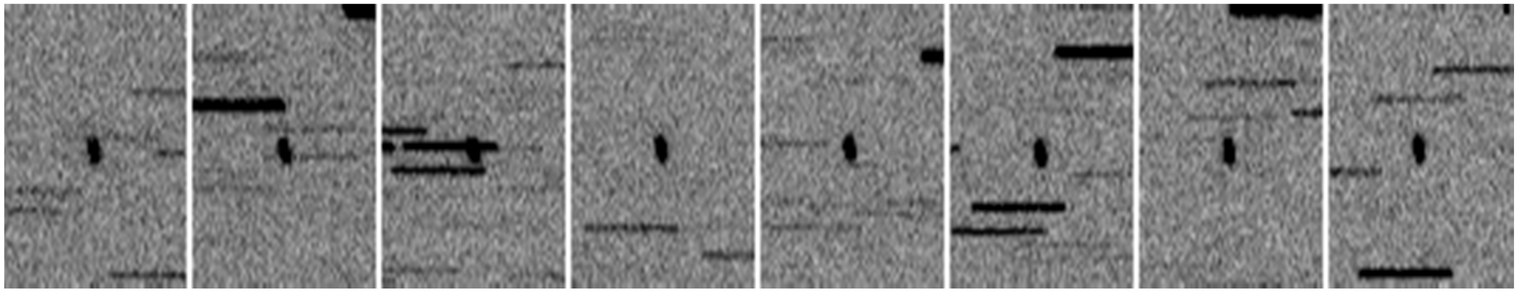
Debris in Geosynchronous Orbits

- For observations of geosynchronous debris (>30 cm), NASA works with a University of Michigan telescope in Chile: the Michigan Orbital Debris Survey Telescope (MODEST).



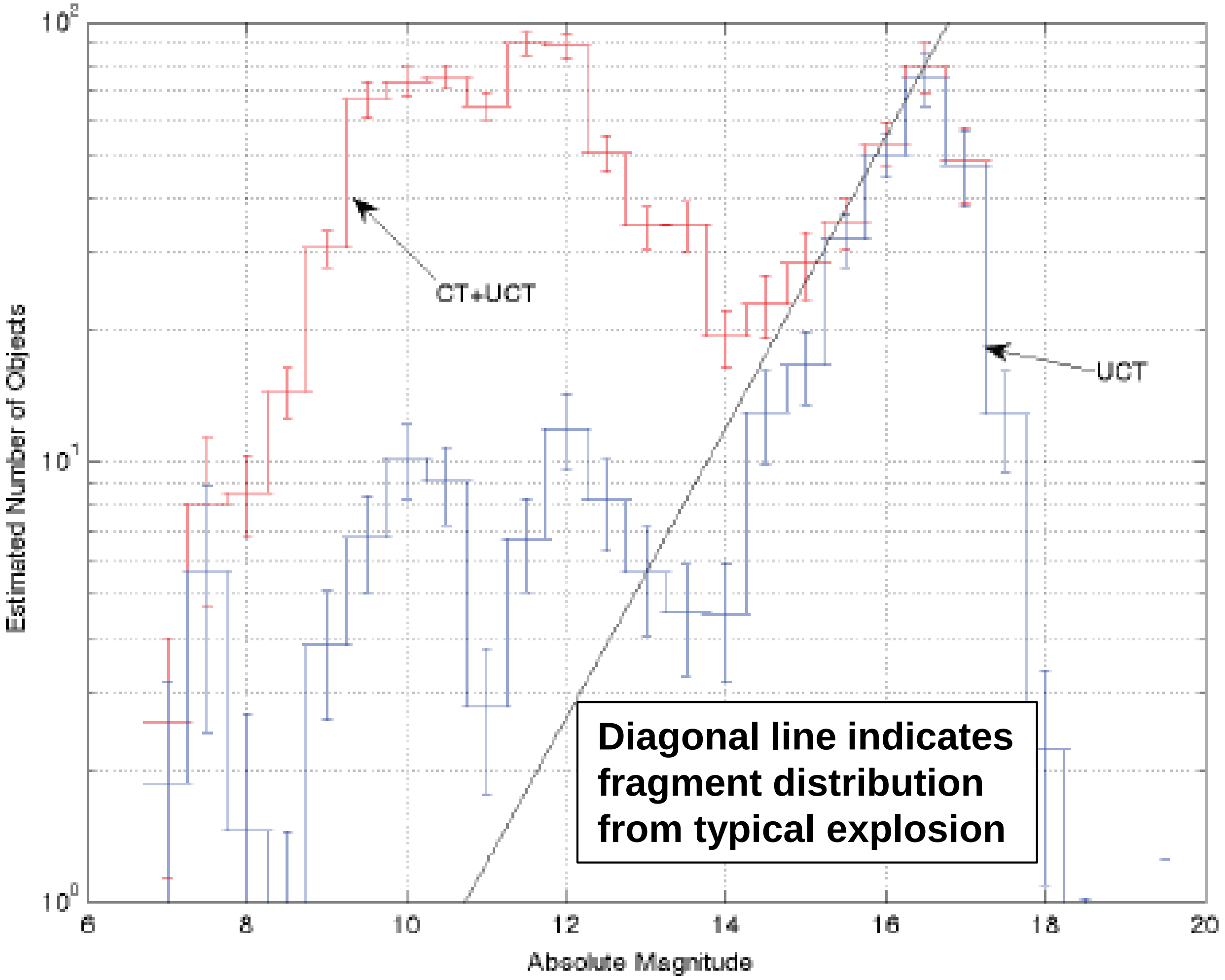
- A nearby telescope is sometimes used to obtain additional track data.

Stars are streaks;
satellites are dots or ovals



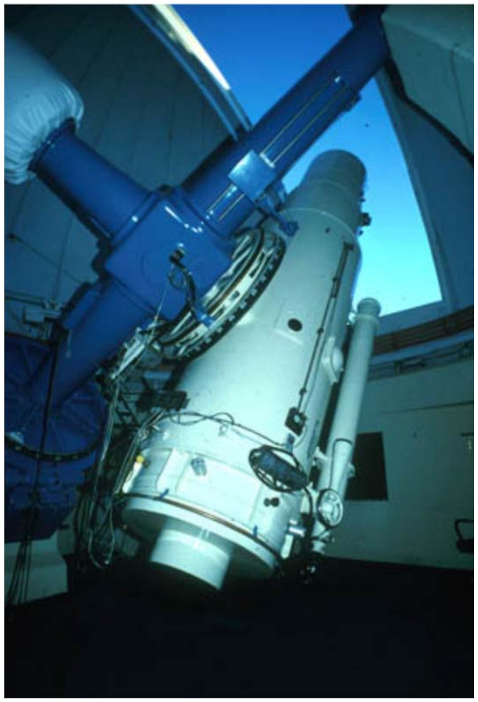
Uncataloged Debris near GEO

- **MODEST has detected a significant population of uncataloged debris near GEO.**



Diagonal line indicates fragment distribution from typical explosion

CT = Cataloged
UCT = Uncataloged



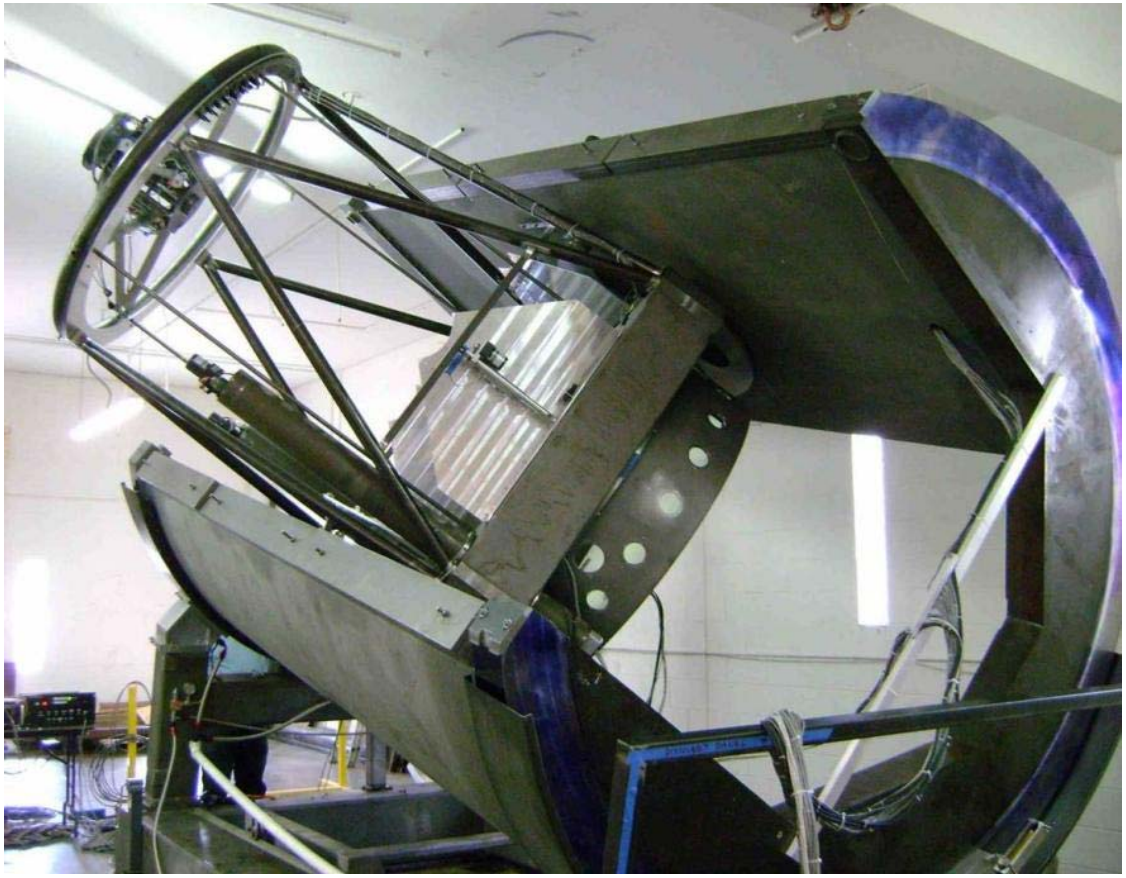
Meter-Class Autonomous Telescope (MCAT)

- **NASA is currently working with the Department of Defense to deploy a new 1.3-m telescope on Ascension Island in the Atlantic Ocean.**

- **The low latitude of the site will permit observations of low inclination debris at all altitudes.**
  - Debris as small as 10 cm in GEO should be detectable.

- **The telescope will be operated remotely from JSC.**

- **Operations will start in 2014.**

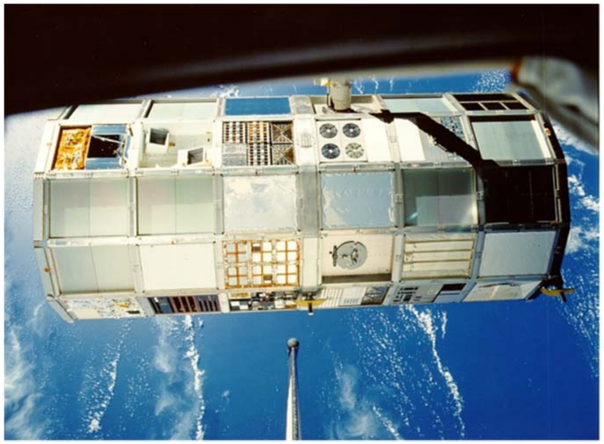


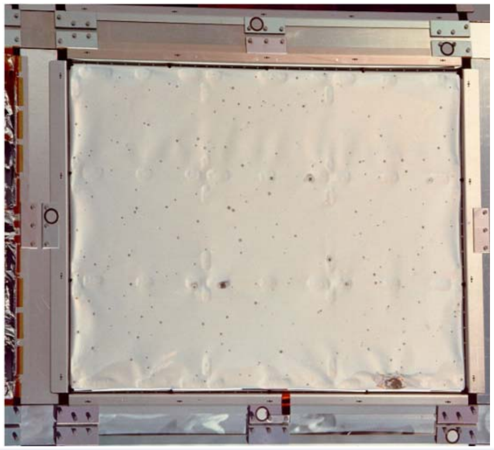
The MCAT telescope and mount will be non-traditional.

Sub-Millimeter Orbital Debris

- **Sub-millimeter debris cannot be easily detected with terrestrial sensors.**
- **NASA examines the surfaces of objects returned from space to discern the population of sub-millimeter debris.**
  - Examination of the Space Shuttle after every flight.
  - Examination of materials returned from the International Space Station, the Hubble Space Telescope and other robotic spacecraft.
- **The Long-Duration Exposure Facility (LDEF) [1984-1990] provided the first detailed assessment of small particle debris in low Earth orbit.**

LDEF





Panel from LDEF

The Hubble Space Telescope as a Witness Plate

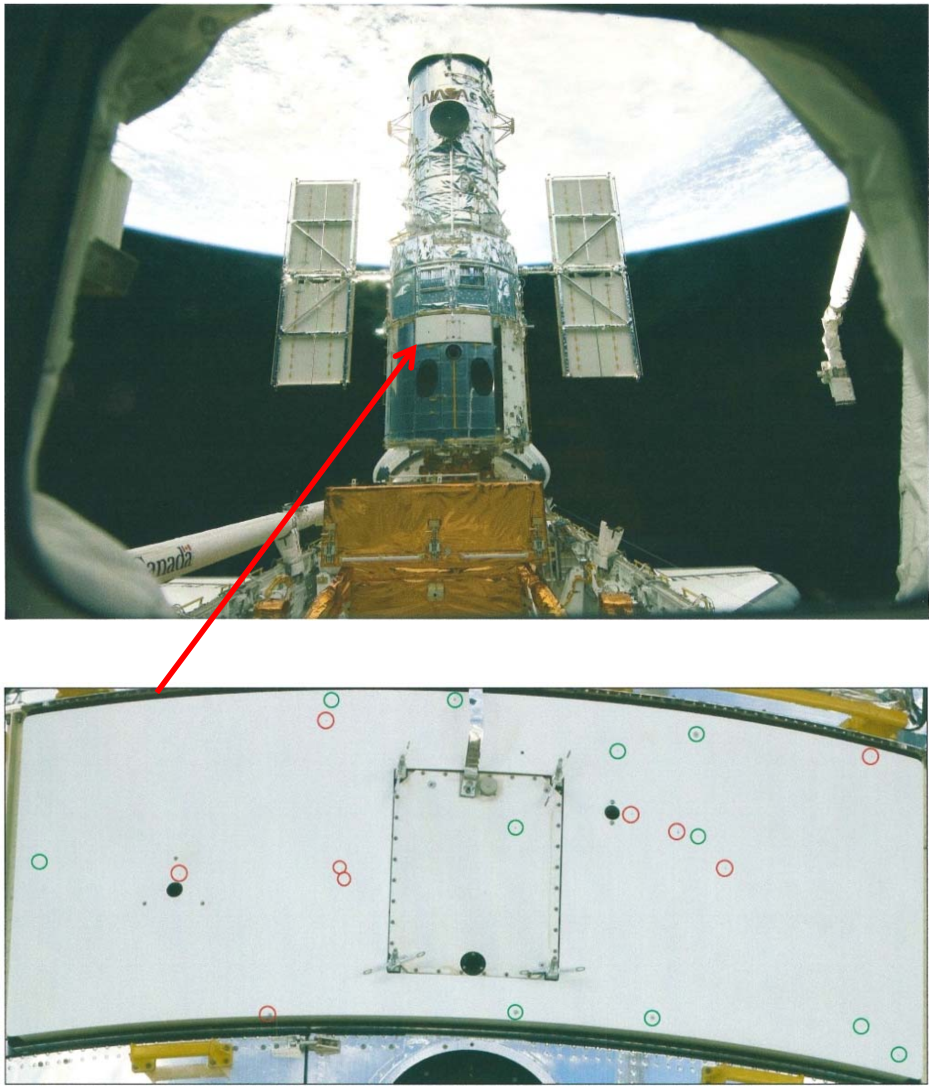
- **During each HST servicing mission a photographic survey is conducted to detect the effects of small particle impacts.**

- **Solar arrays have also been returned to Earth for careful examination of impact features.**

Photo from HST Servicing Mission 3A (Dec 1999).

Latest Inspection of the HST Components

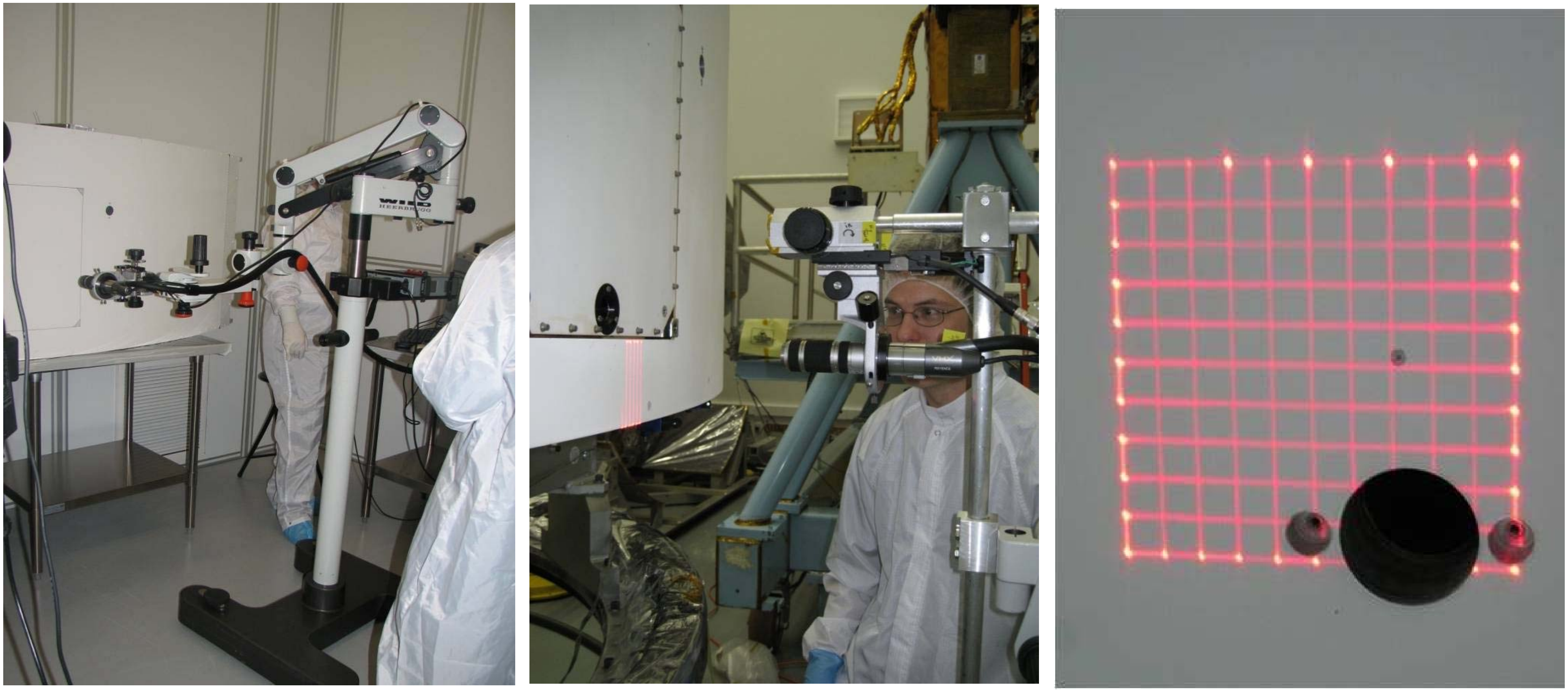
- In May 2009, Space Shuttle Atlantis visited and successfully refurbished the Hubble Space Telescope.
- The Wide Field Planetary Camera 2 was removed and returned to Earth after 16 years in space.
- Numerous large impact features (green circles) had occurred since the last servicing mission in 2002 (red circles).
- Microscopic examinations have revealed nearly 700 hypervelocity impact features greater than 0.3 mm in diameter.



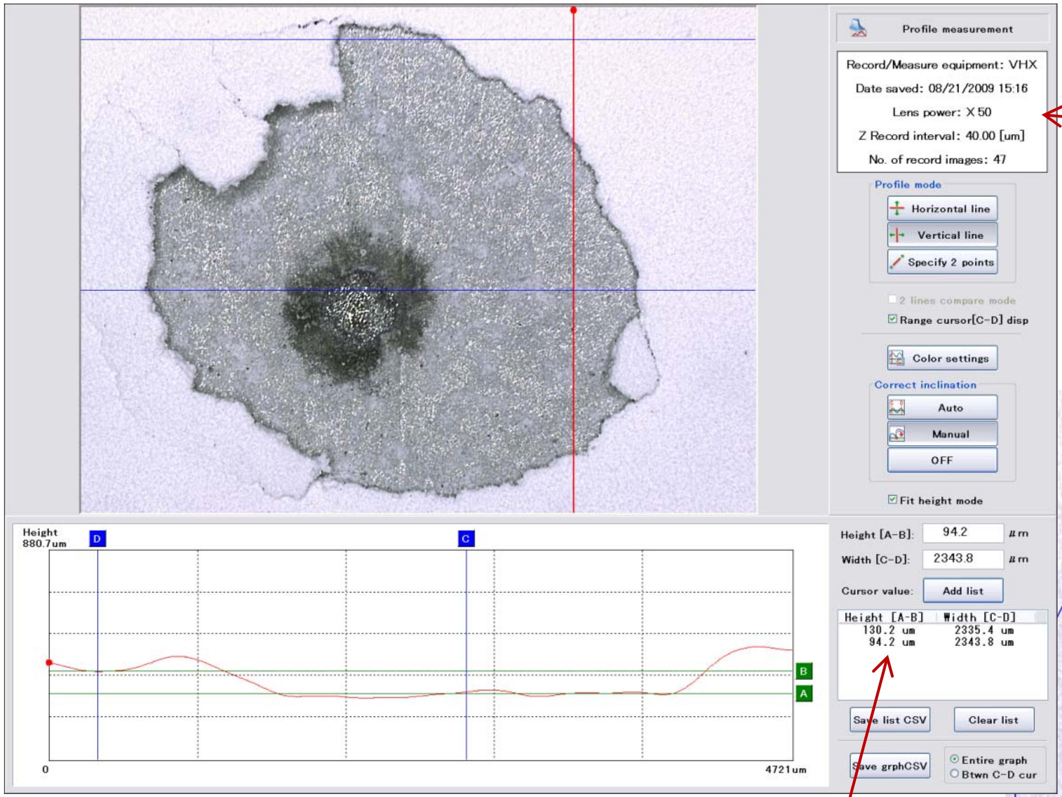
WFPC2 Radiator (2.2 m long, 0.8 m tall)

Inspection Instruments

- **Keyence VHX-600 digital microscope (up to 5000x optical, 2D and 3D)**
  - Records each impact feature’s shape, size, depth, and volume
- **LAP CAD-Pro laser template projector**



Measuring Large Craters



Record/Measure equipment: VHX
Date saved: 08/21/2009 15:16
Lens power: X 50
Z Record interval: 40.00 [um]
No. of record images: 47

☐ 2 lines compare mode
☑ Range cursor[C-D] disp
☑ Fit height mode

Height [A-B]: 94.2 µm
Width [C-D]: 2343.8 µm
Cursor value:

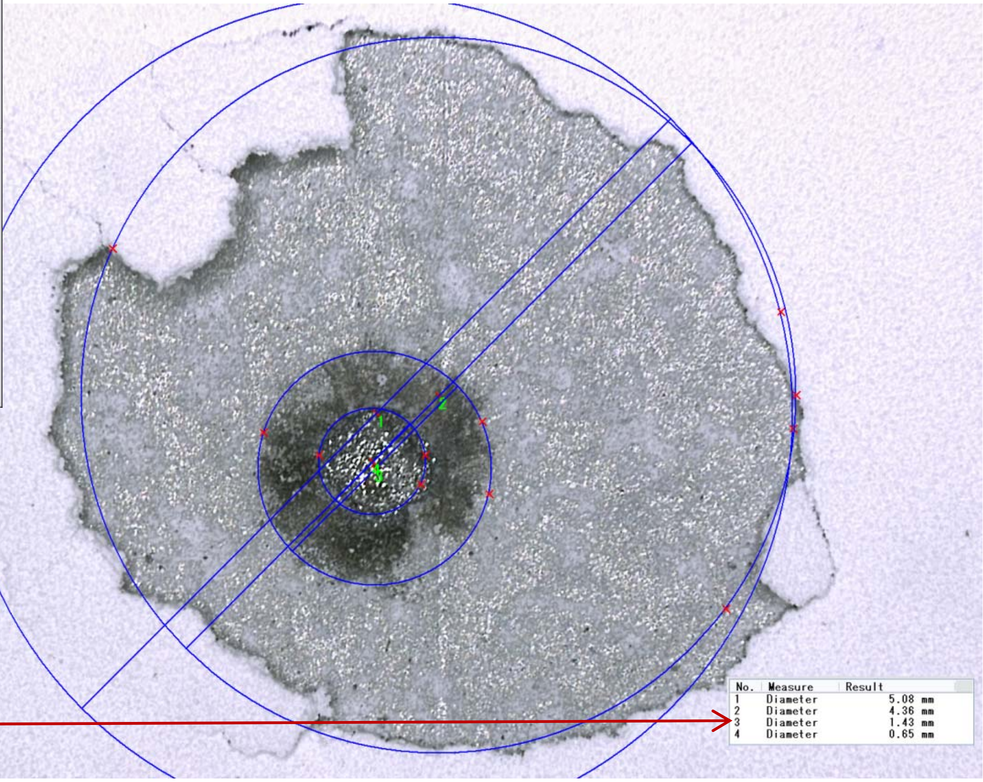
Height [A-B]	Width [C-D]
130.2 um	2335.4 um
94.2 um	2343.8 um

◉ Entire graph
○ Btwn C-D cur

Inputs

Four Diameters:

- Spallation
- Bare metal
- “Burned” metal
- Lips or center



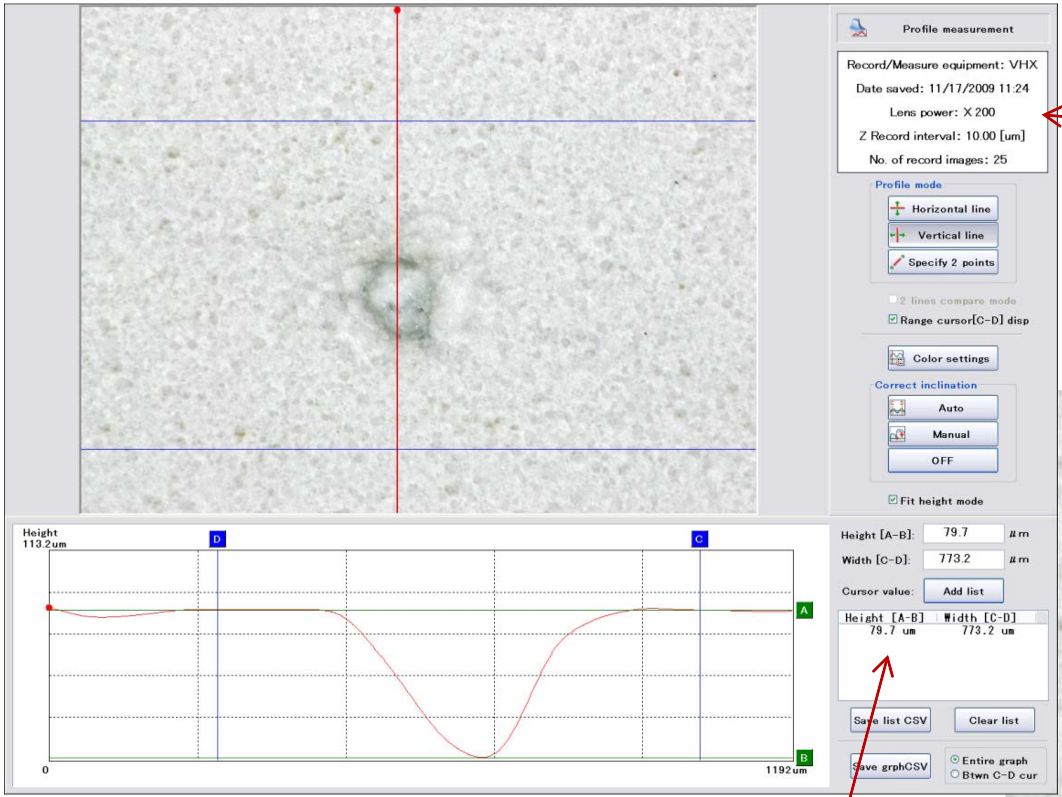
No.	Measure	Result
1	Diameter	5.08 mm
2	Diameter	4.36 mm
3	Diameter	1.43 mm
4	Diameter	0.65 mm

Two Depths:

- Central crater depth
- Paint thickness

Results

Measuring Small Craters



Record/Measure equipment: VHX
Date saved: 11/17/2009 11:24
Lens power: X 200
Z Record interval: 10.00 [um]
No. of record images: 25

☑ Range cursor[C-D] disp

☑ Fit height mode

Height [A-B]: 79.7 µm
Width [C-D]: 773.2 µm
Cursor value:

Height [A-B]	Width [C-D]
79.7 um	773.2 um

◉ Entire graph
○ Btwn C-D cur

Inputs

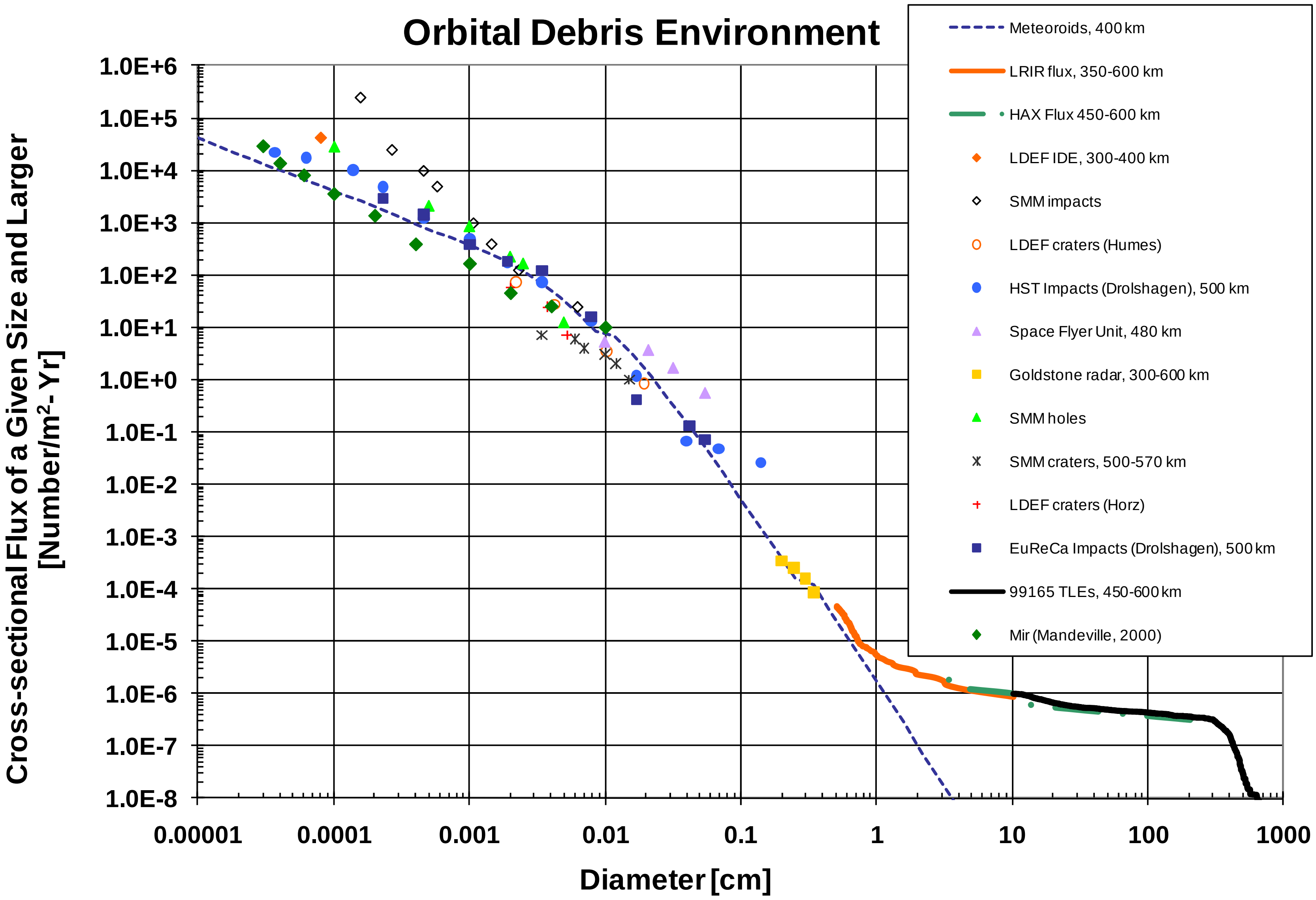
Two Diameters:
- **Spallation**
- **Center**

No.	Measure	Result
1	Diameter	436.76 um
2	Diameter	213.70 um

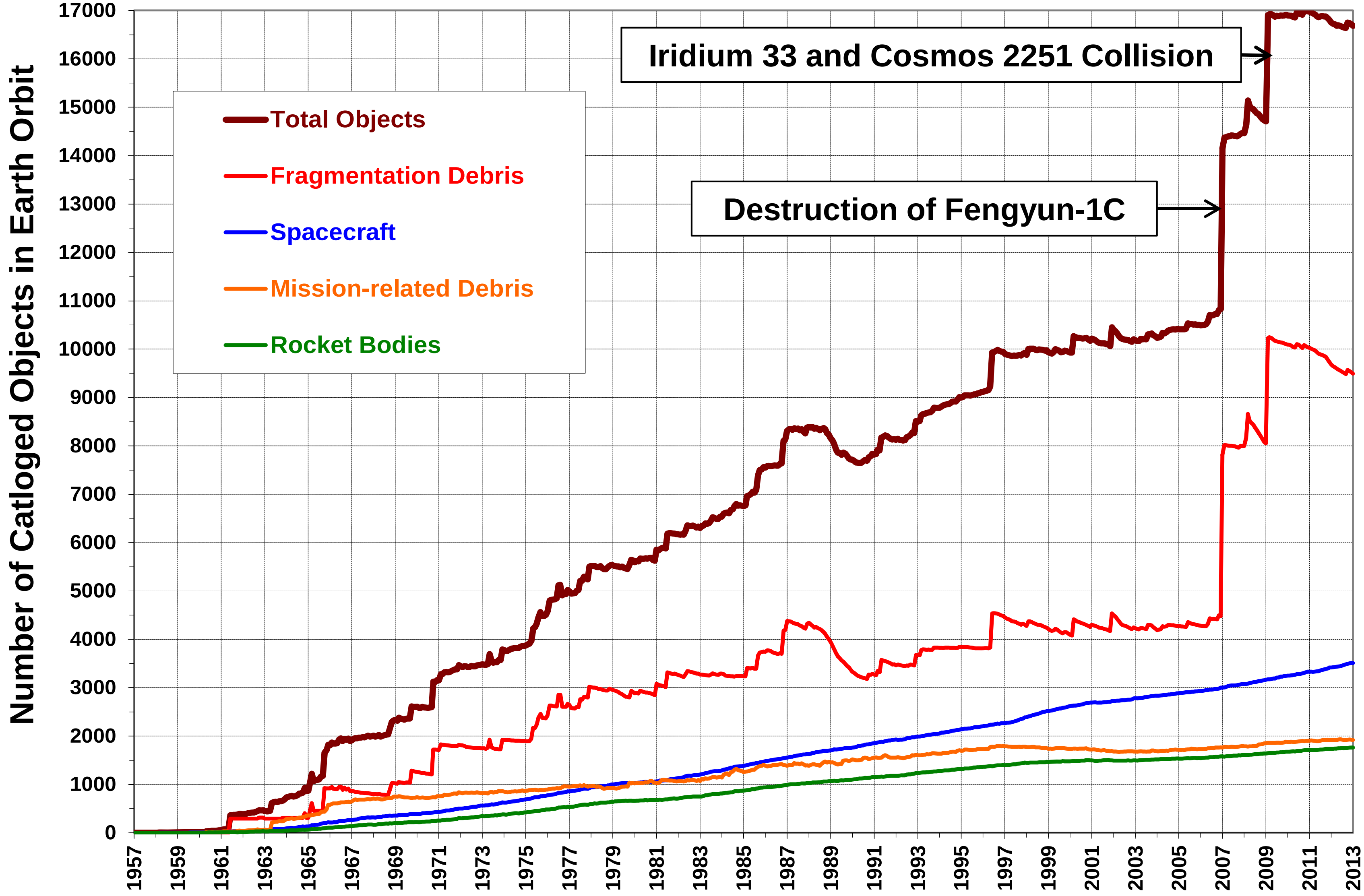
One Depth:
- **Central crater depth**

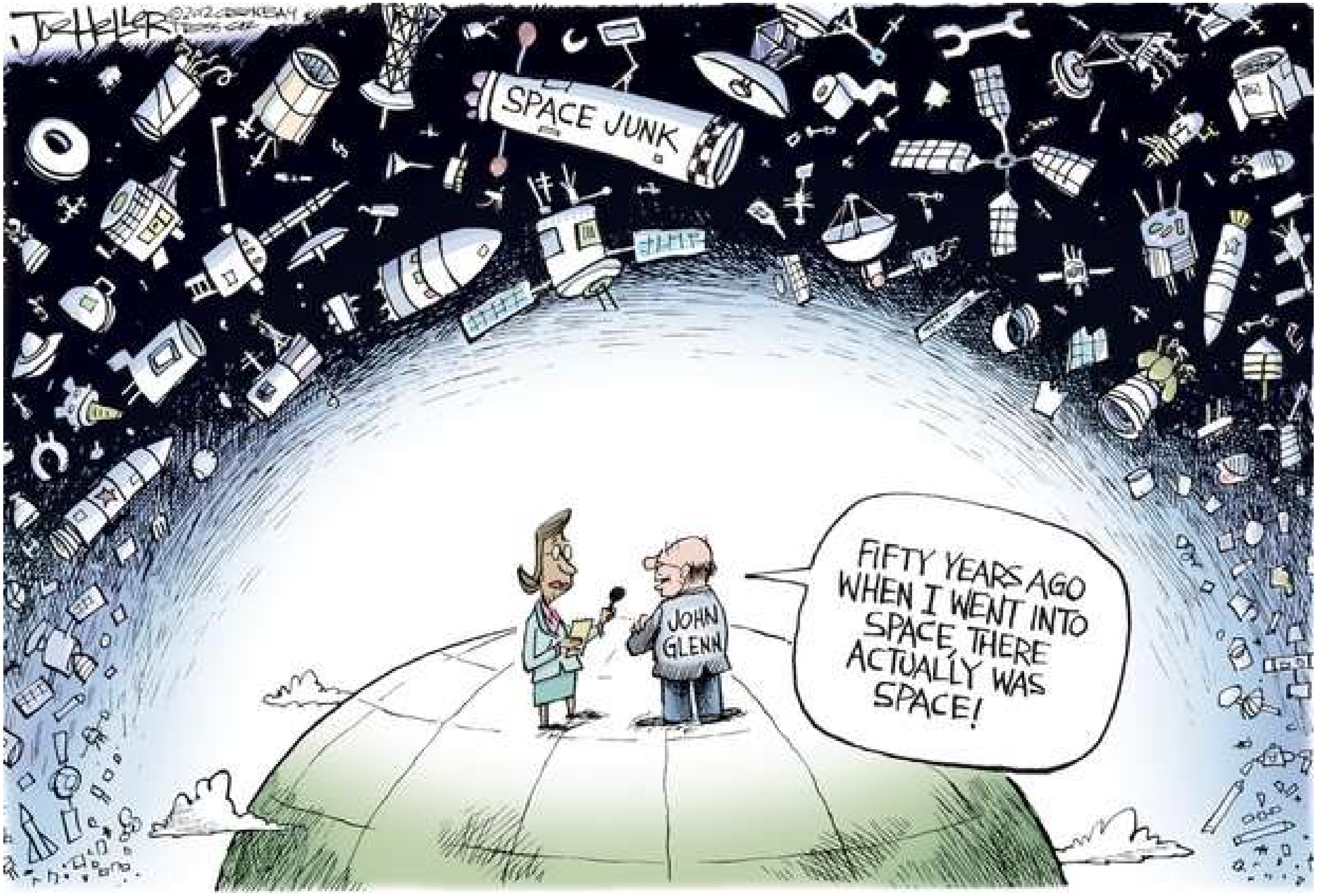
Results

Human Space Flight Regime Flux



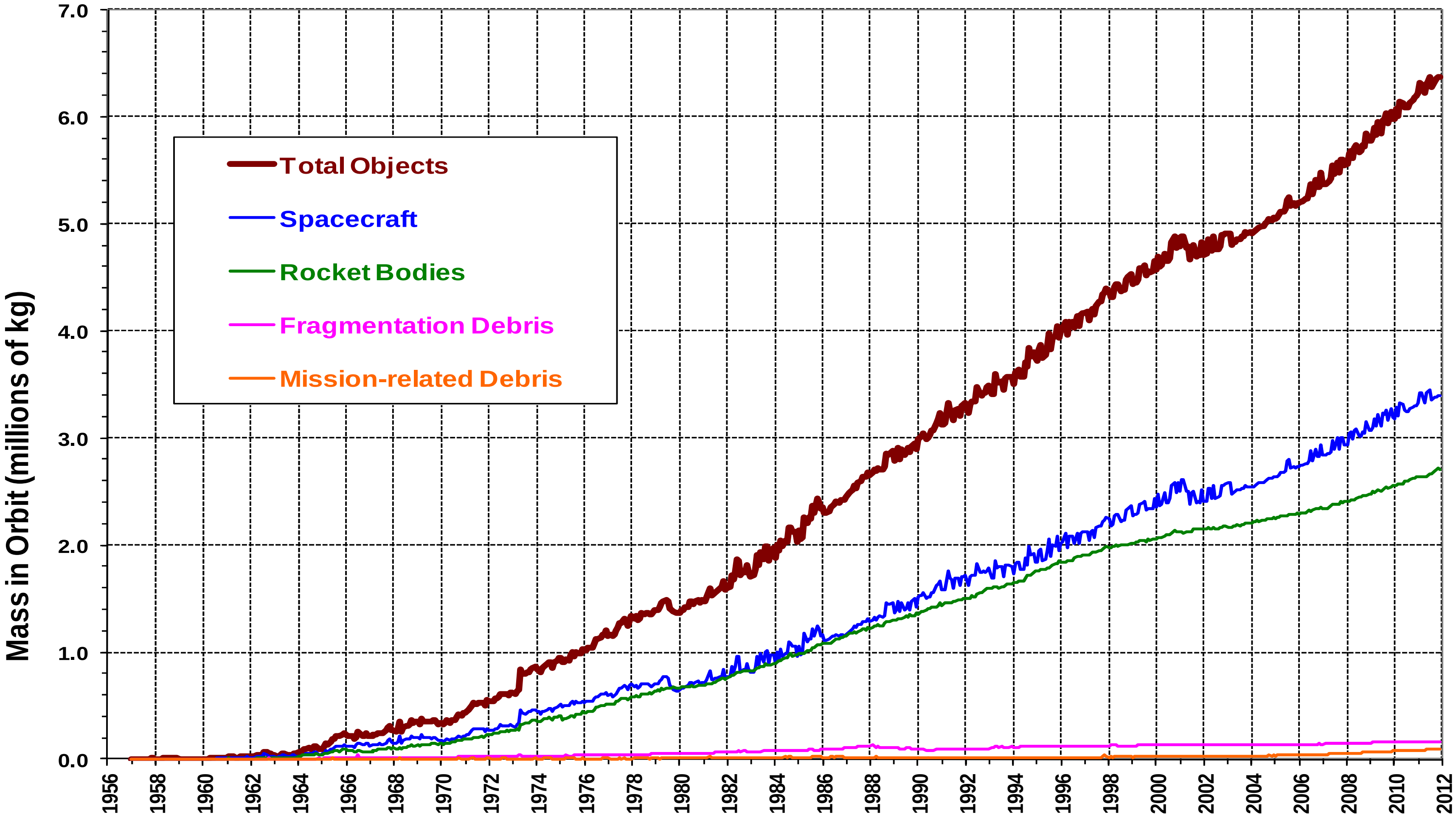
Growth of the Cataloged Satellite Population in Earth Orbit: Numbers of Objects



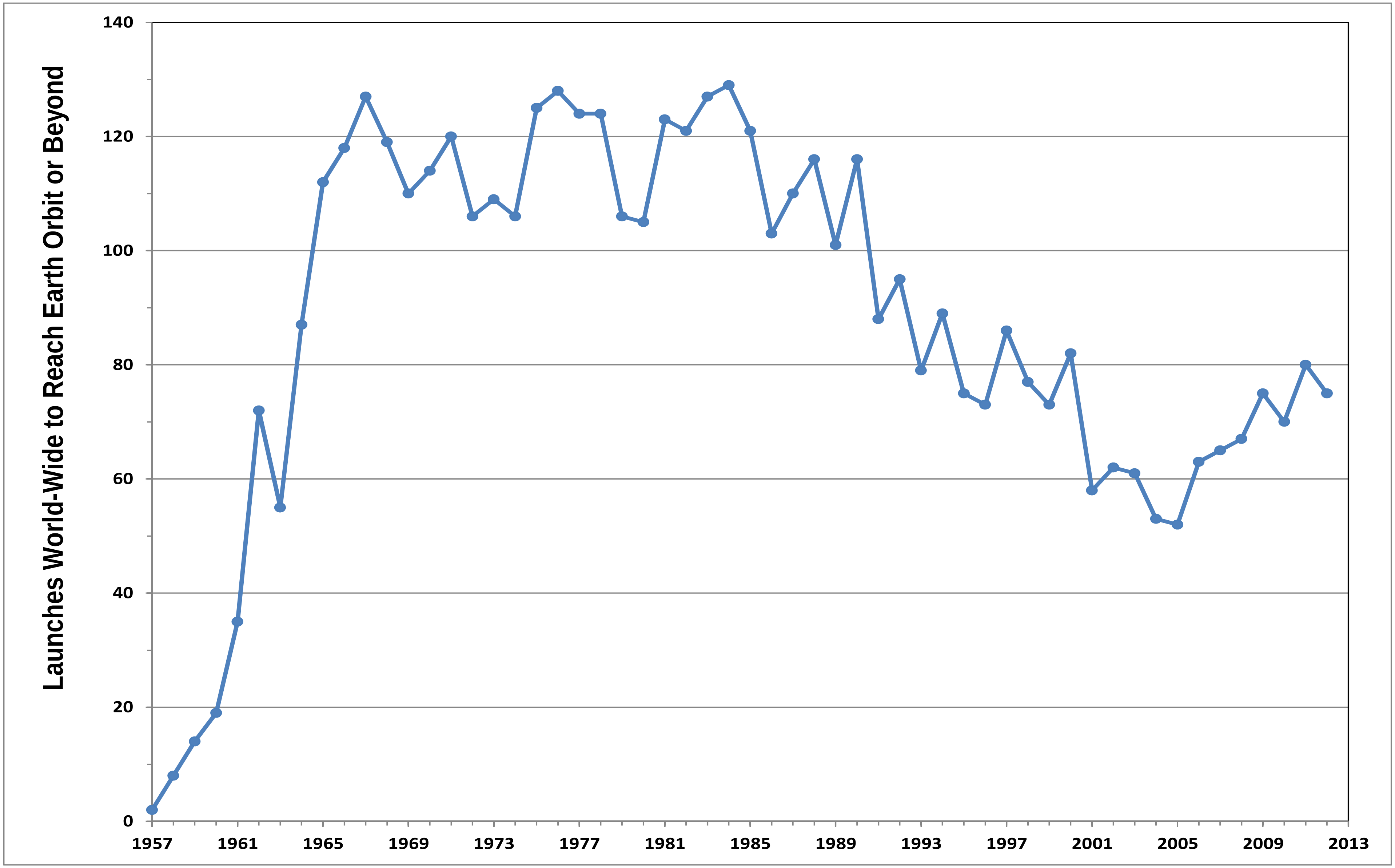

JoeHeller
SPACE JUNK
JOHN GLENN
FIFTY YEARS AGO WHEN I WENT INTO SPACE, THERE ACTUALLY WAS SPACE!

Growth of the Cataloged Satellite Population: Mass of Objects

- Recently, the rate of mass growth in low Earth orbit has averaged nearly 200 metric tons per year. Only ~40% of the mass is in LEO.



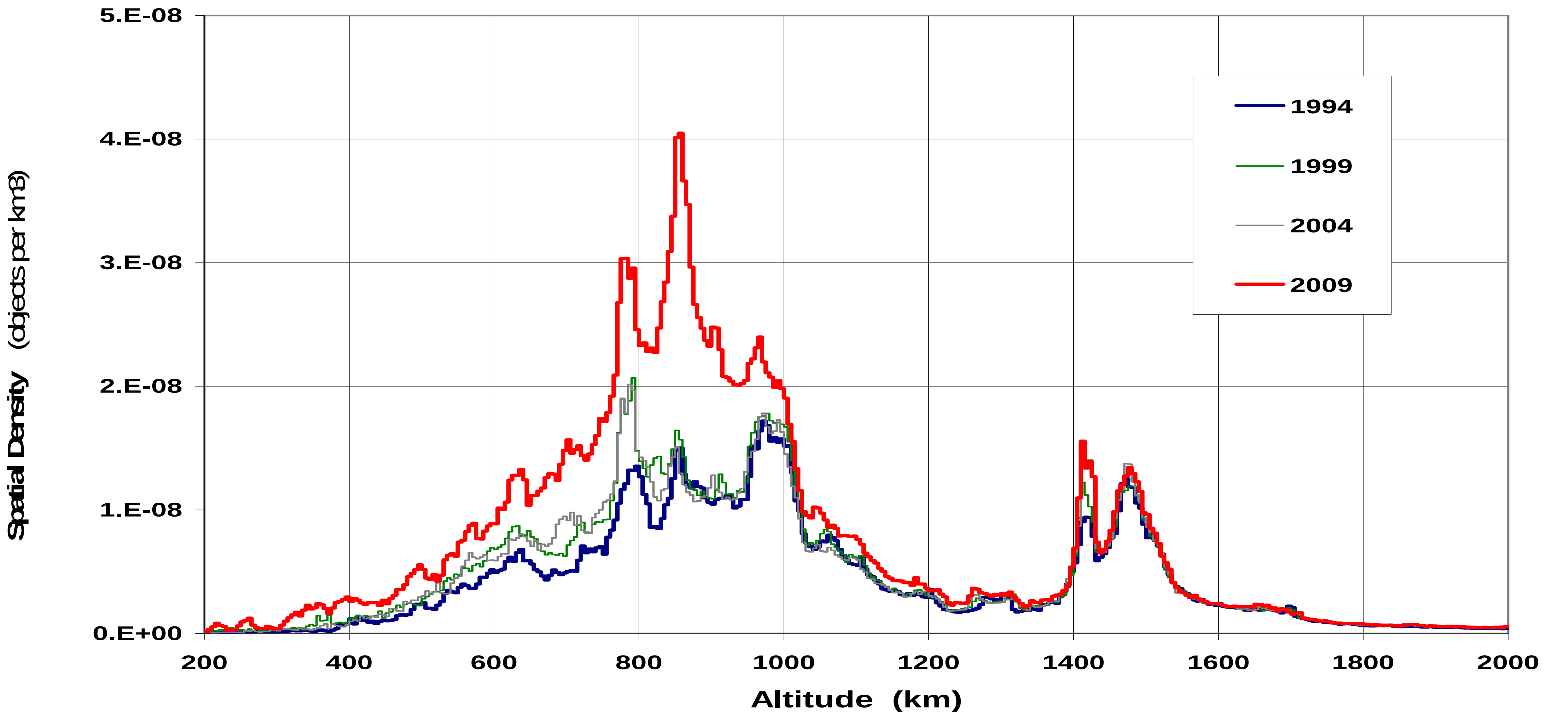
Launch Rate is Not a Useful Parameter for Judging Growth of the Satellite Population



LEO Spatial Density

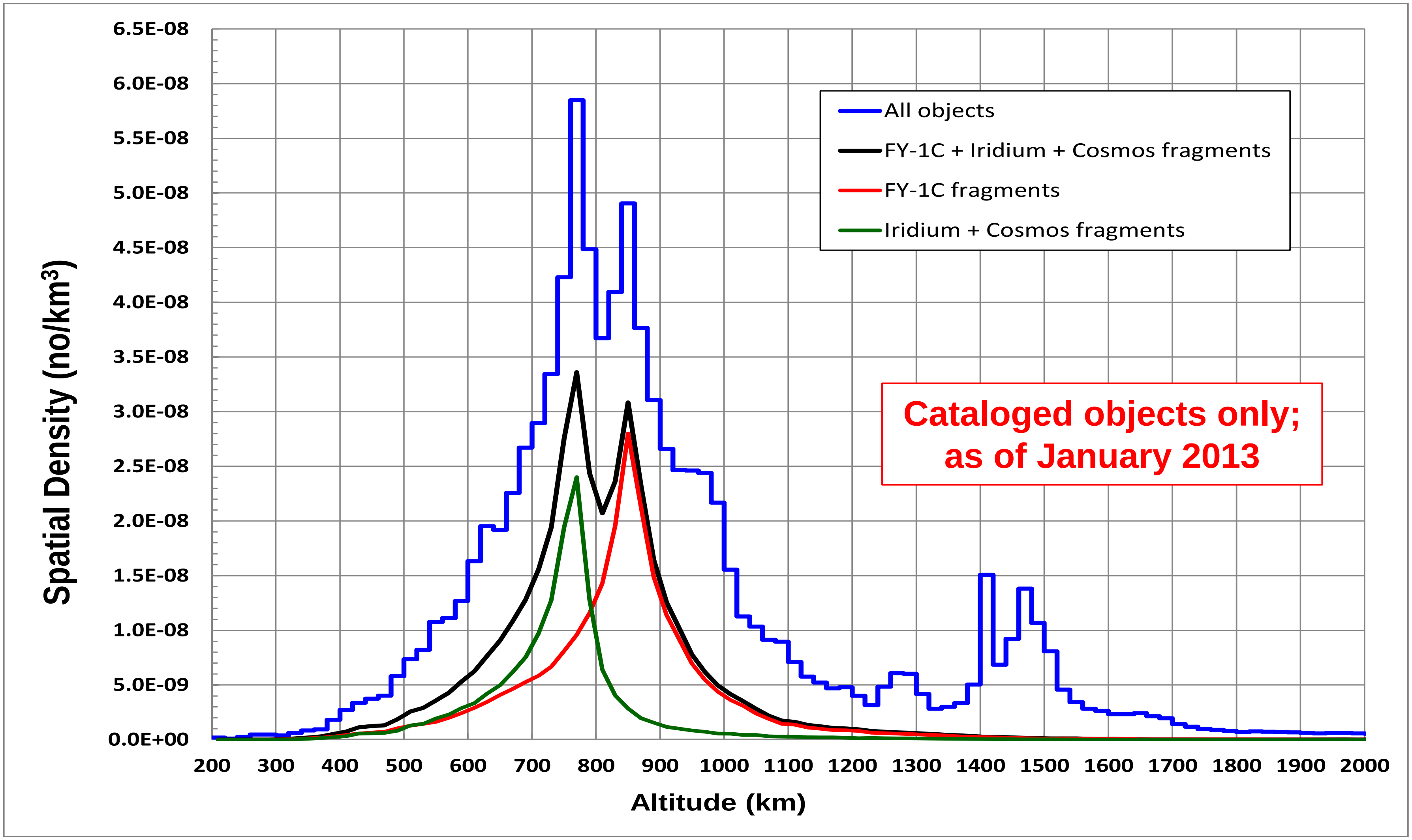
- One of the primary parameters of interest is spatial density, i.e., the number of objects per unit volume (typically per km^3).

- The graphic below indicated the serious effect of the Chinese ASAT test in January 2007 on the cataloged satellite population. It does not reflect the US-Russian satellite collision in Feb 2009 (next page).



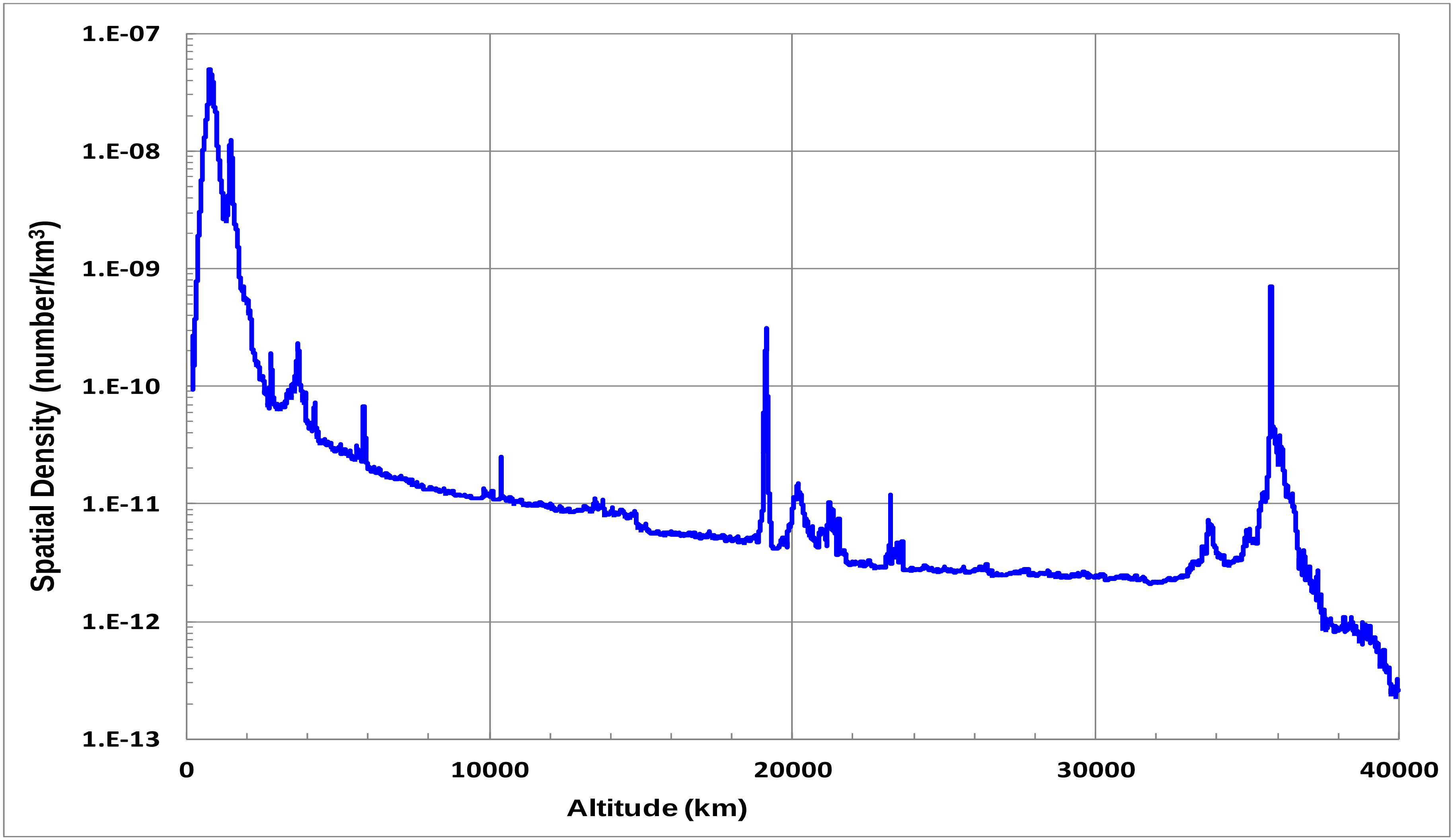
More Current LEO Spatial Density

- **The collision of the Iridium 33 and Cosmos 2251 satellites significantly altered the amount and distribution of orbital debris in LEO.**

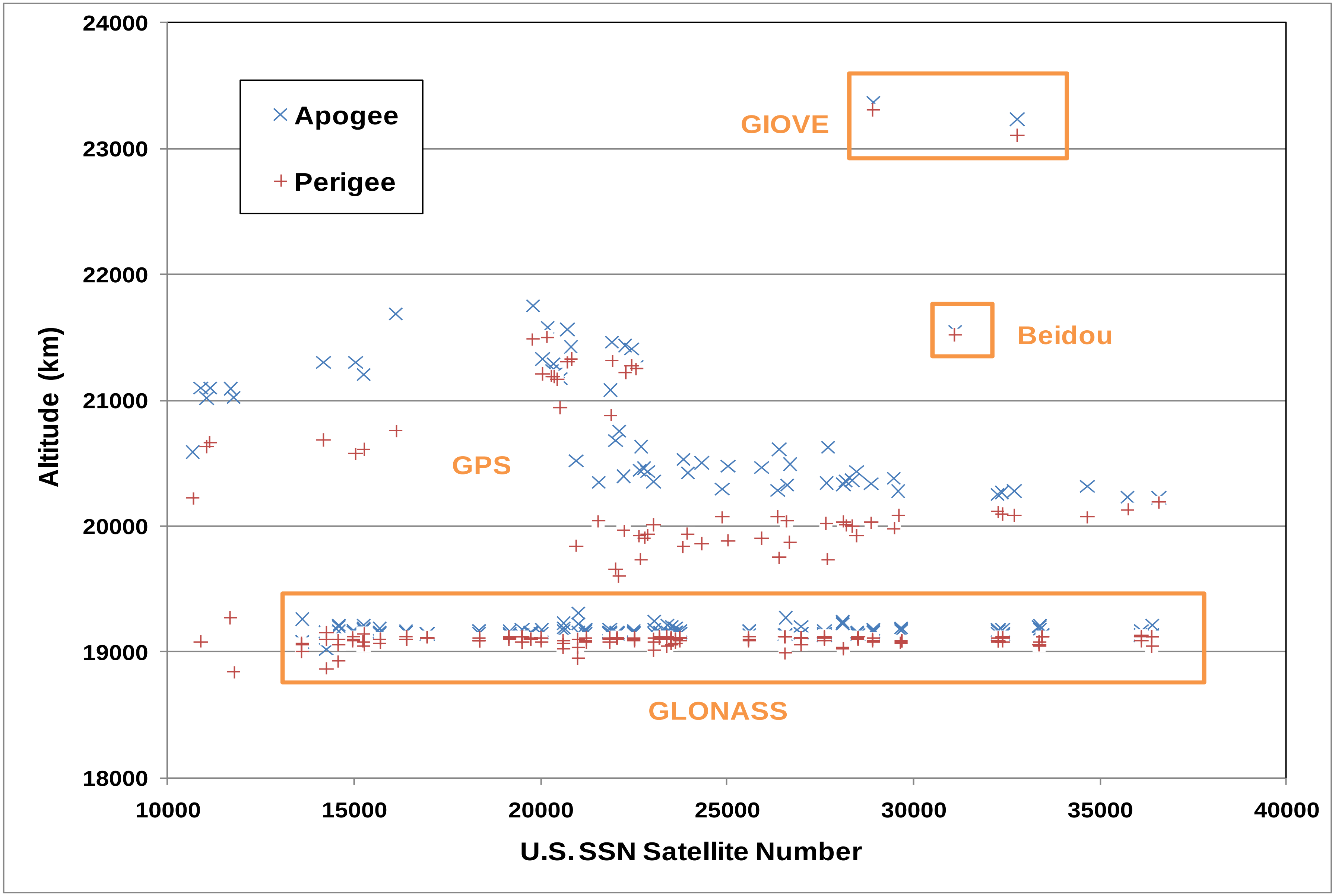


Spatial Densities Through GEO

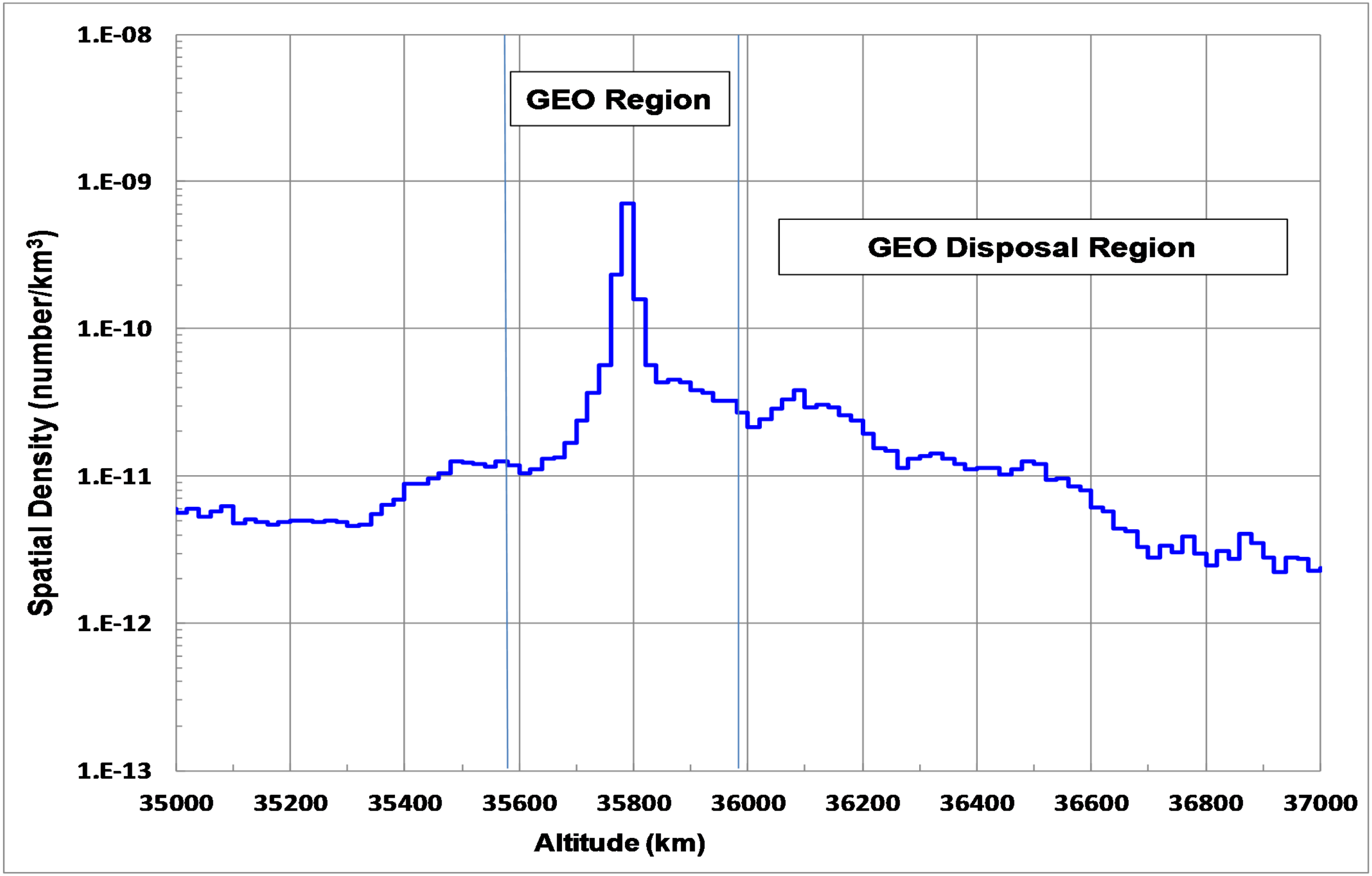
- Spatial densities in general decrease above LEO with higher concentrations near semi-synchronous and geosynchronous altitudes.



Orbits of MEO Navigation Spacecraft (July 2010)



GEO Spatial Densities

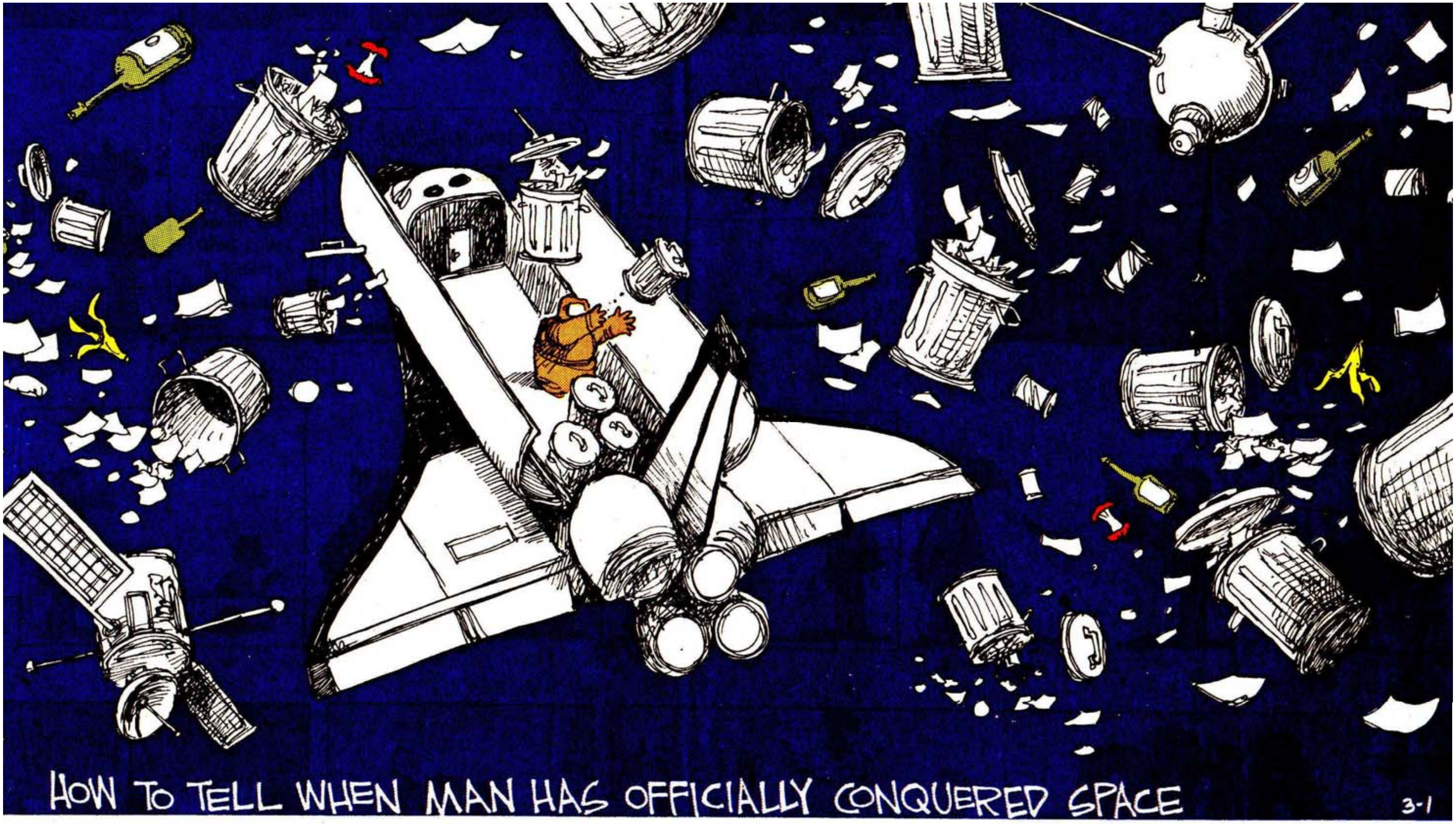


Summary

- **Using a wide variety of sensors and techniques, NASA has characterized the orbital debris environment for sizes from tens of microns to tens of meters.**

- **The orbital debris environment is highly dynamic due to space activity, satellite fragmentations and degradations, and solar effects.**

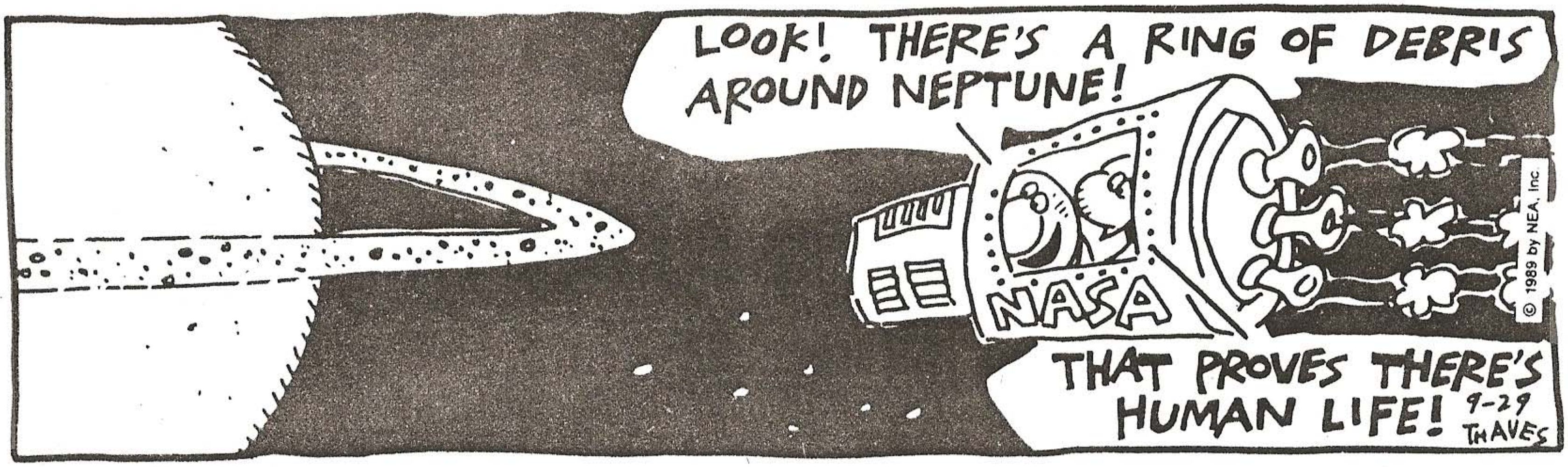
- **Consequently, the environment must be monitored on a continuing basis and models of the environment must be periodically revised.**


HOW TO TELL WHEN MAN HAS OFFICIALLY CONQUERED SPACE
3-1

National Aeronautics and Space Administration

Characterizing the Earth’s Satellite Population: An Overview of NASA’s Orbital Debris Engineering Model

Orbital Debris Program Office
NASA Johnson Space Center


LOOK! THERE'S A RING OF DEBRIS AROUND NEPTUNE!
NASA
THAT PROVES THERE'S HUMAN LIFE!
9-29
THAVES
© 1989 by NEA, Inc.

Orbital Debris Engineering Models

- **Orbital debris engineering models are mathematical tools to assess orbital debris flux**
  - Created primarily for spacecraft designers to accurately assess spacecraft risk
  - Also have been used historically to estimate sensor flux (e.g., predicted counts in a radar beam)

- **Need to be updated periodically**
  - Changes in the environment
  - New data
  - New techniques
  - Need for expanded capabilities

- **For vehicle design and operational requirements, orbital debris engineering models must also predict the environment a decade or two into the future.**

NASA Orbital Debris Engineering Model History

- **Prior to 1994 the NASA orbital debris engineering model (ORDEM) consisted of a simple flux curve based mostly on analytical model results.**
- **The 1994 ORDEM for Space Station Freedom and ORDEM96 used new Haystack data to describe 1 cm – 10 cm regime accurately for the first time.**
  - Finite inclination and eccentricity bands still described by analytic formulae.
- **ORDEM2000 used new techniques and computer improvements to describe complicated orbit distributions.**
  - ORDEM now primarily empirical.
  - Populations saved as digital ensembles rather than analytic functions.
- **All ORDEM versions through ORDEM2000 were applicable only for low Earth orbits.**

ORDEM 3.0 New Features

- **Environment is expanded past LEO.**
  - Includes data for objects in MEO and GEO
  - Elliptical spacecraft orbits handled explicitly
- **Orbital debris flux uncertainties provided for the first time.**
  - Primarily uncertainties in population estimates
  - Need to propagate to final flux values
- **Material density types have been introduced.**
  - Material densities influence damage equations
- **Debris shape was analyzed carefully but is not explicitly included in the model. At critical sizes, shape variation is normally limited.**

ORDEM 3.0 Supporting Data

- **The ORDEM series derived environments are based on analysis of existing data available at the time of development of each version.**

- **The Chinese ASAT test (2007) and Iridium-Cosmos collision (2009) cloud populations have been explicitly added based on empirical radar data analysis and modeling of future cloud evolution.**

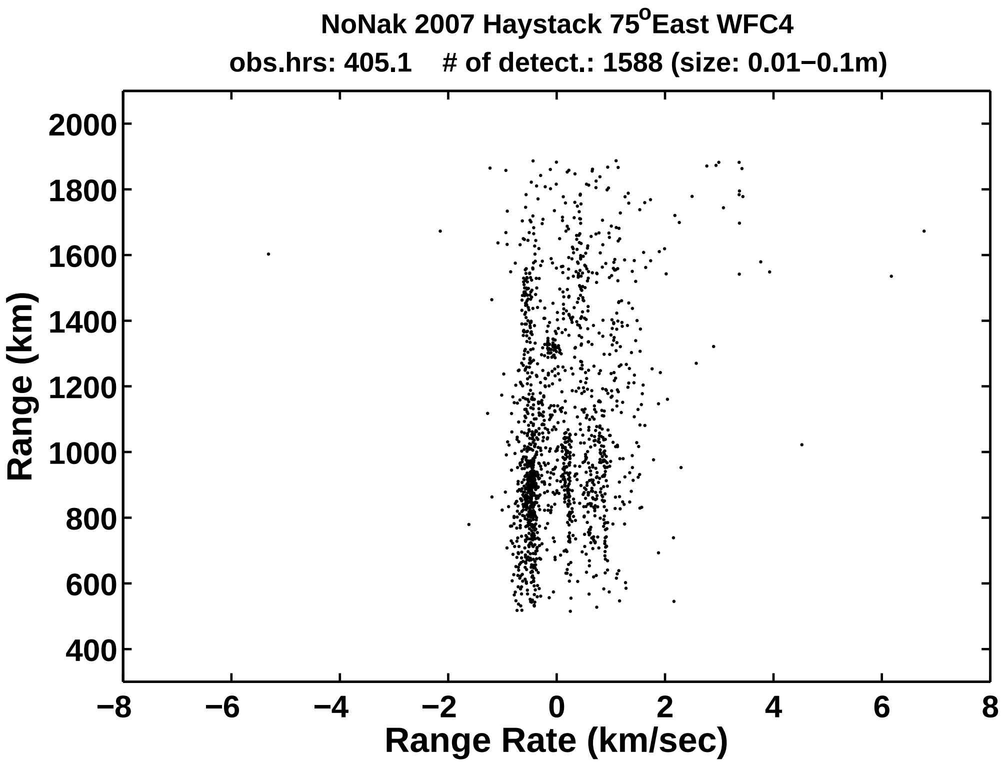
Observational Data	**Role**	**Region/Size**
SSN catalog (radars+ telescopes)	Intacts & large fragments	LEO > 10cm, GEO > 70cm
Special Cobra Dane observations (radar)	Compare with SSN	LEO > 4 cm
Haystack (radar)	Statistical populations	LEO > 1cm
Goldstone (radar)	Compare with Haystack	LEO >2 mm
STS windows and radiators (returned surfaces)	Statistical populations	LEO < 1mm
HST solar panels (returned surfaces)	Compare with STS	LEO < 1mm
MODEST (telescope)	Only sub-meter GEO data set	GEO > 30cm

ORDEM2000 vs. ORDEM 3.0

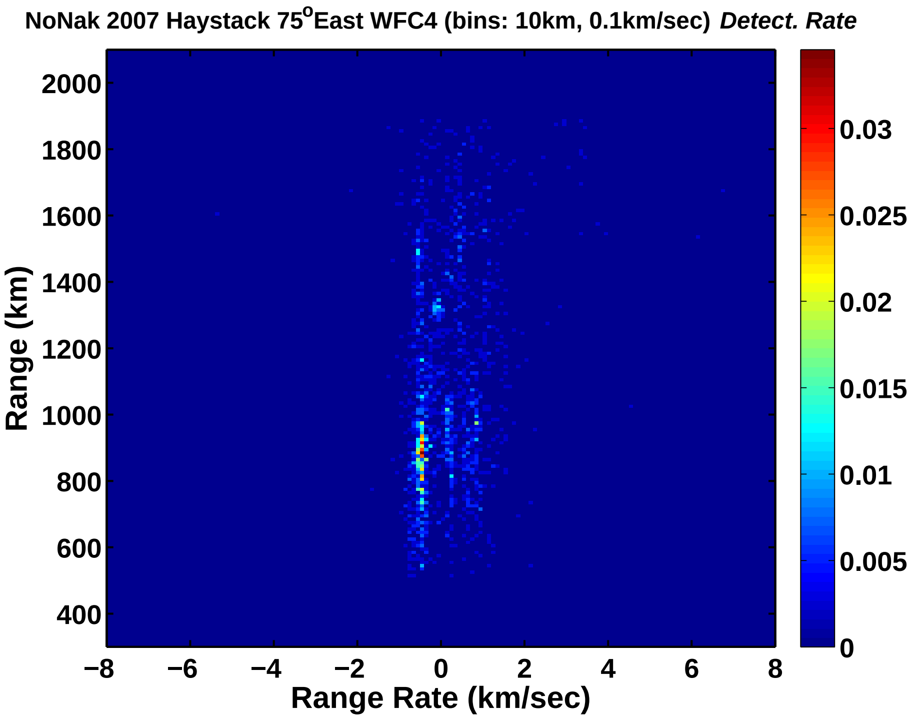
Parameter	**ORDEM2000**	**ORDEM 3.0**
Spacecraft and Telescope/Radar analysis modes	YES	YES
Time range	1991 to 2030	1995 to 2035
Altitude range with minimum debris size	200 to 2000 km (>10 μm)	200 to >34,000 km (>10 μm)* 34,000 to 38,000 km (>10 cm)
Model population breakdown	NO	Low-density fragments Medium-density fragments and degradation/ejecta High-density fragments and degradation/ejecta RORSAT NaK coolant droplets
Material density breakdown	NO	low-density (<2 g/cc) medium-density (2-6 g/cc) high-density (>6 g/cc) RORSAT NaK coolant (0.9 g/cc)
Model cumulative size thresholds	10 μm, 100 μm, 1mm, 1 cm , 10 cm, 1 m	10 μm, 31.6 μm, 100 μm, 316 μm, 1mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m
Population uncertainties	NO	YES
Total input file size	13.5 MB	128 MB
Meteoroids	NO	NO

*** Sub-millimeter population has been validated for LEO only**

Haystack Data

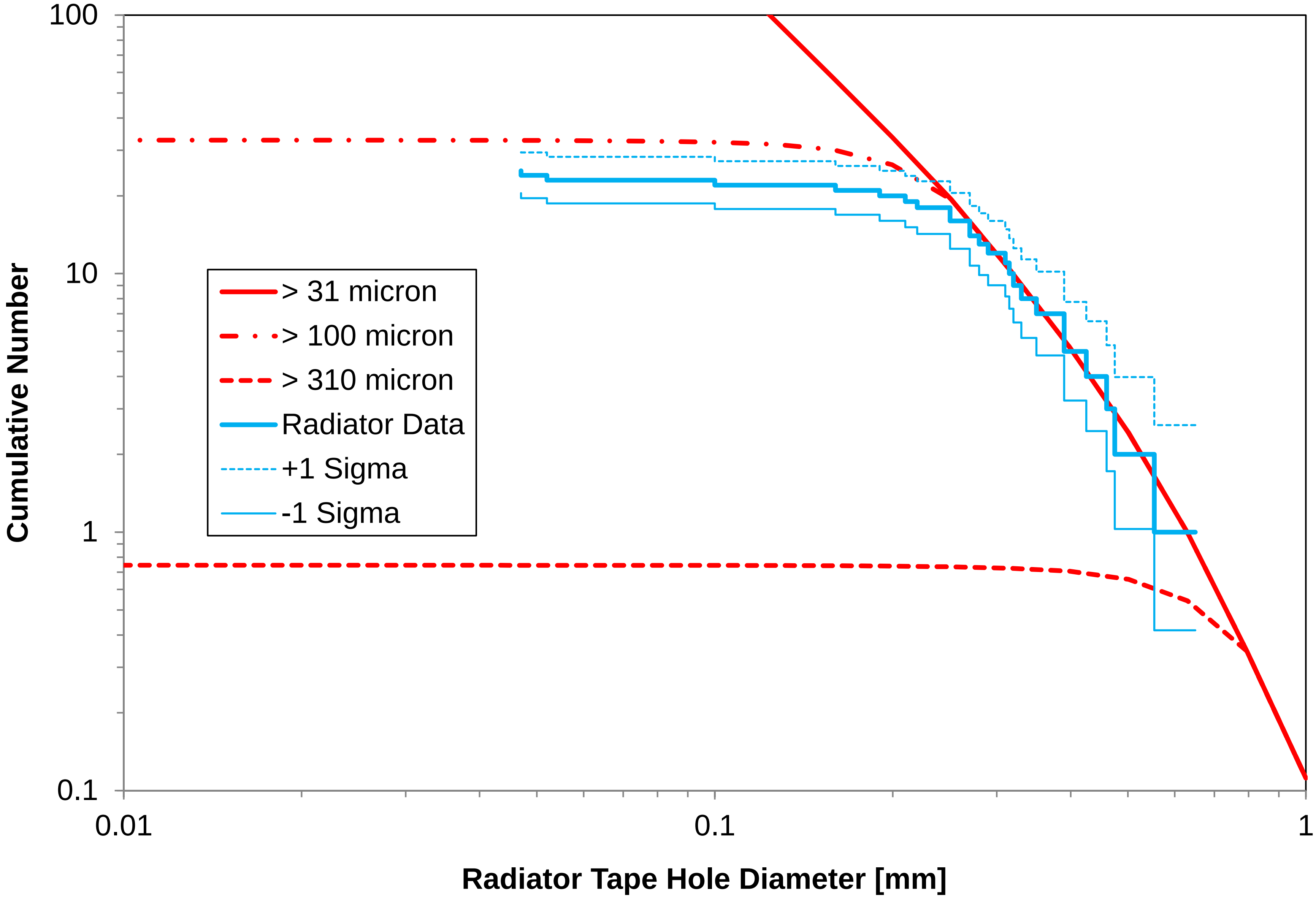

NoNak 2007 Haystack 75^{O}East WFC4

obs.hrs: 405.1 # of detect.: 1588 (size: 0.01−0.1m)

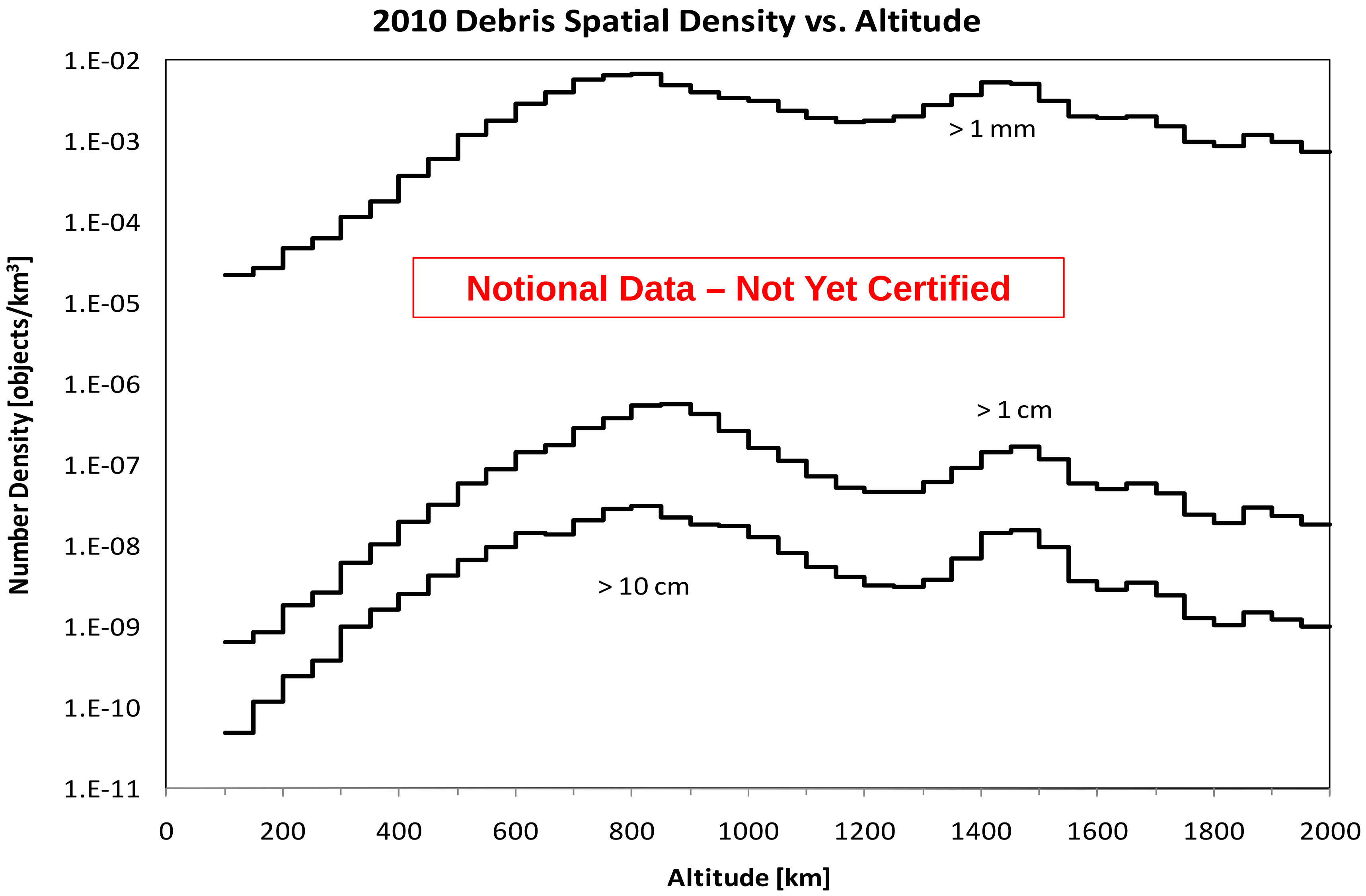

NoNak 2007 Haystack 75^{O}East WFC4 (bins: 10km, 0.1km/sec) *Detect. Rate*

- **A statistical method is used to adjust population parameters so that the predicted pattern of data (in this case range and Doppler range-rate) best matches the data. Uncertainties are a by-product of this analysis.**

Space Shuttle Radiator Data Fit



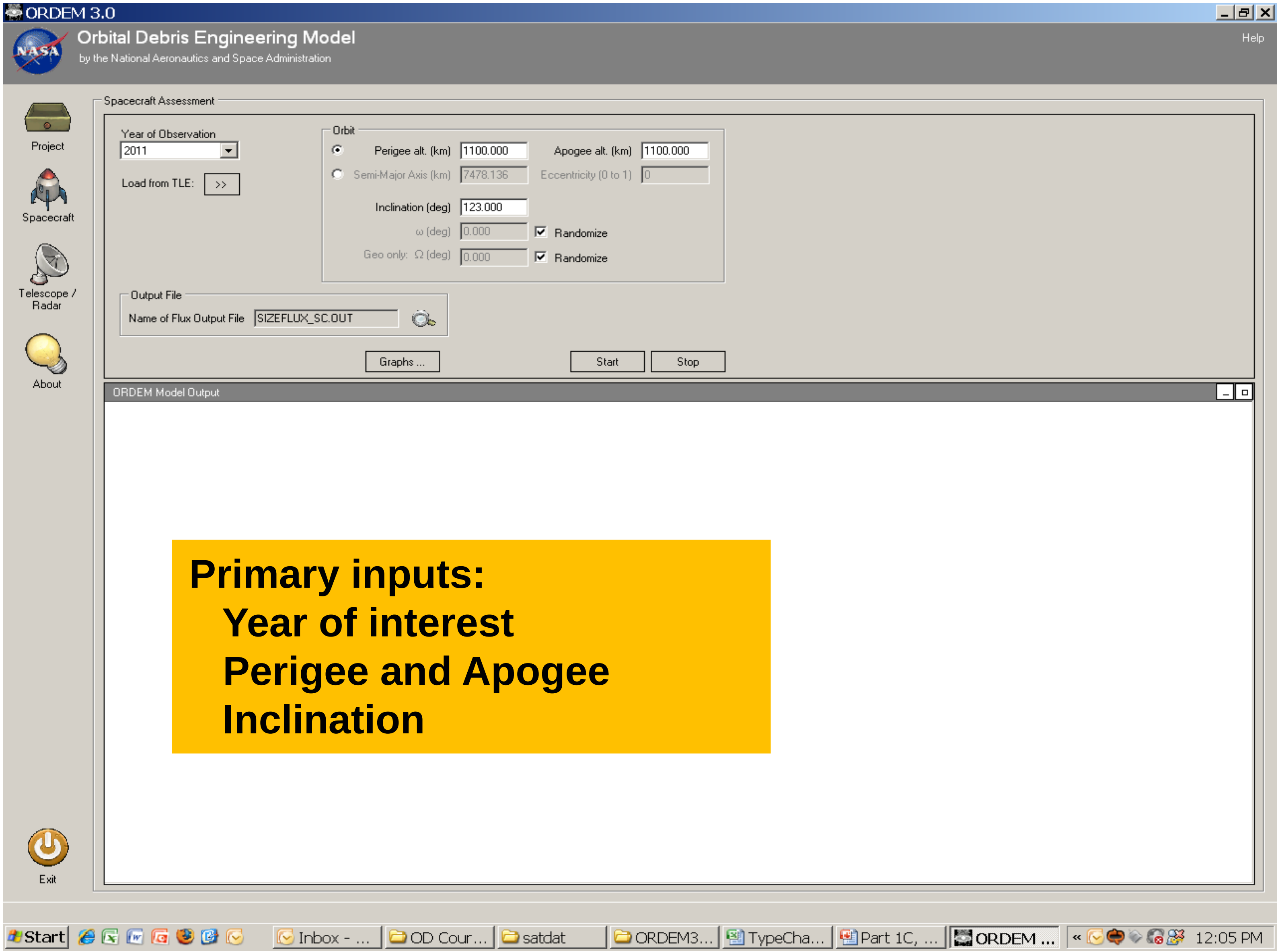
Space Object Distributions



Future Populations

- **ORDEM 3.0 populations are projected out to 2035.**
- **Future populations based on LEGEND model runs using nominal assumptions for breakup rates, launch rates, and solar activity.**
- **100 Monte Carlo runs executed by LEGEND.**
  - **Mean represents “average” future**
  - **Spread in results represents range of possible futures, treated as uncertainty value**

ORDEM 3.0 GUI



Orbital Debris Engineering Model
by the National Aeronautics and Space Administration

Spacecraft Assessment

Year of Observation: 2011
Load from TLE: >>

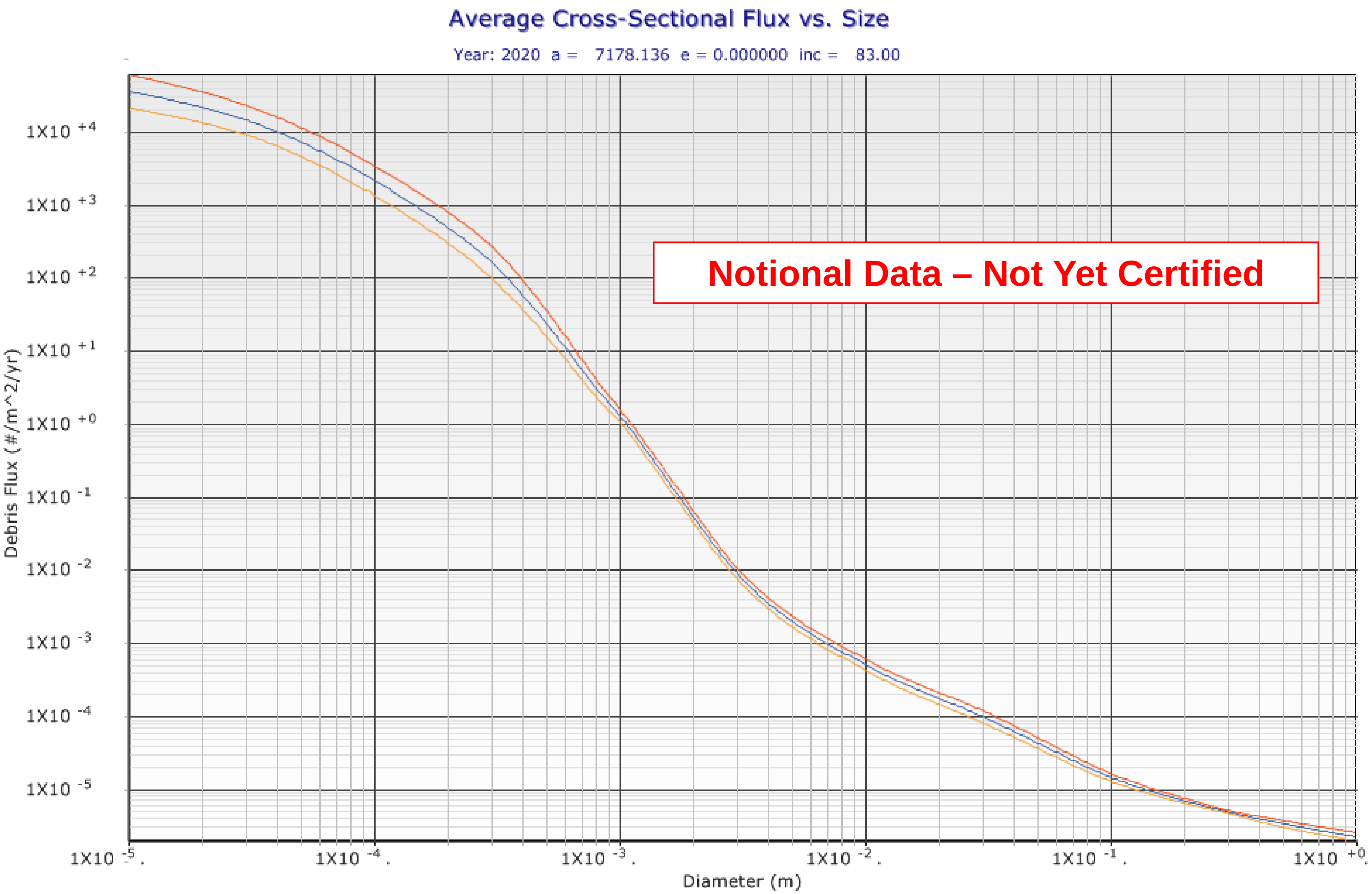
Orbit
● Perigee alt. (km) 1100.000 Apogee alt. (km) 1100.000
○ Semi-Major Axis (km) 7478.136 Eccentricity (0 to 1) 0
Inclination (deg) 123.000
ω (deg) 0.000 ☑ Randomize
Geo only: Ω (deg) 0.000 ☑ Randomize

Output File
Name of Flux Output File SIZEFLUX_SC.OUT

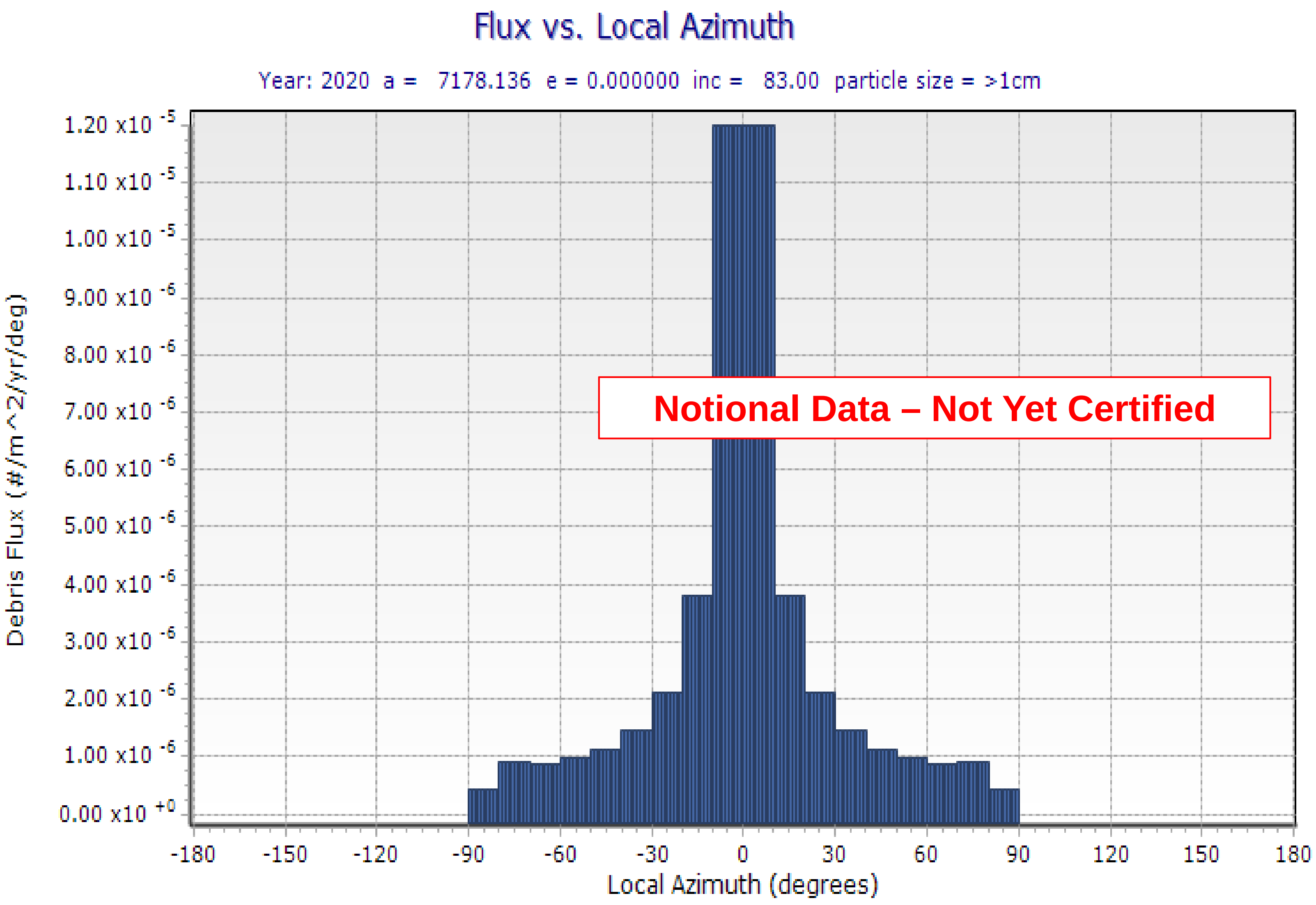
ORDEM Model Output

Primary inputs:
- **Year of interest**
- **Perigee and Apogee**
- **Inclination**

Orbit: 800 km, 83 deg; Year = 2020
(Source: ORDEM 3.0)

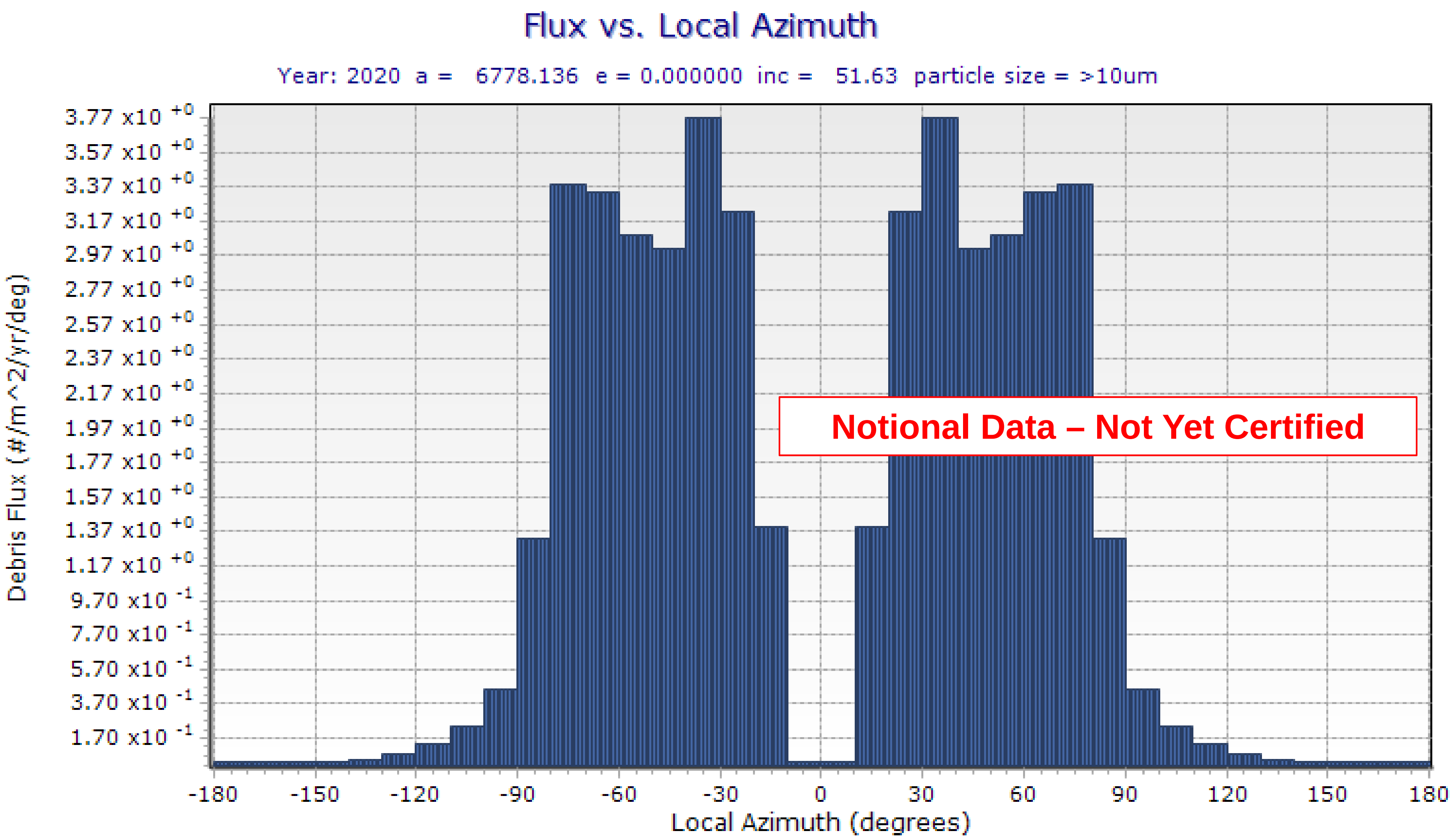


Orbit: 800 km, 83 deg; Year = 2020 (Source: ORDEM 3.0)



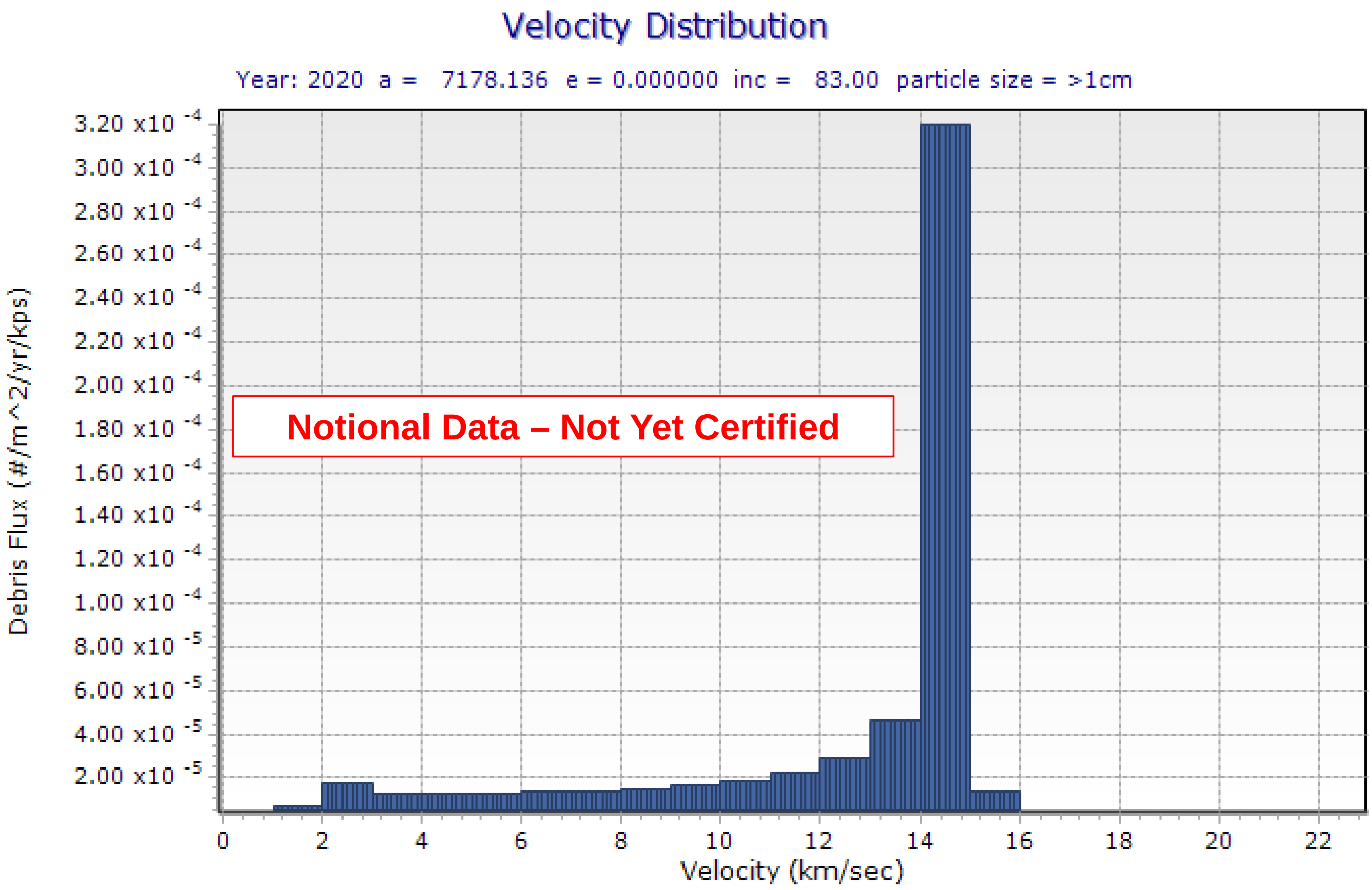
Notional Data – Not Yet Certified

Orbit: 400 km, 51.6 deg; Year = 2020
(Source: ORDEM 3.0)

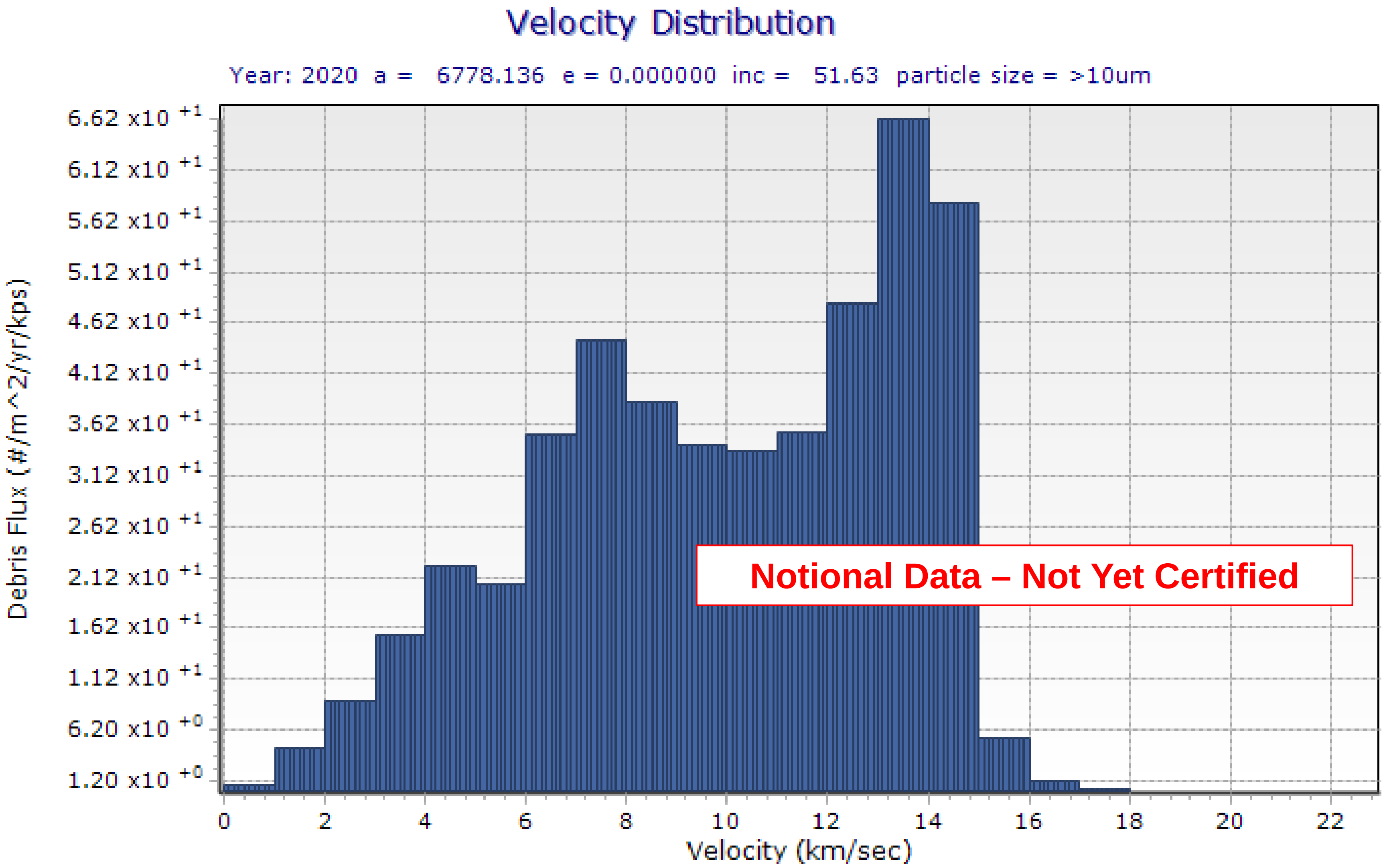


Notional Data – Not Yet Certified

Orbit: 800 km, 83 deg; Year = 2020
(Source: ORDEM 3.0)

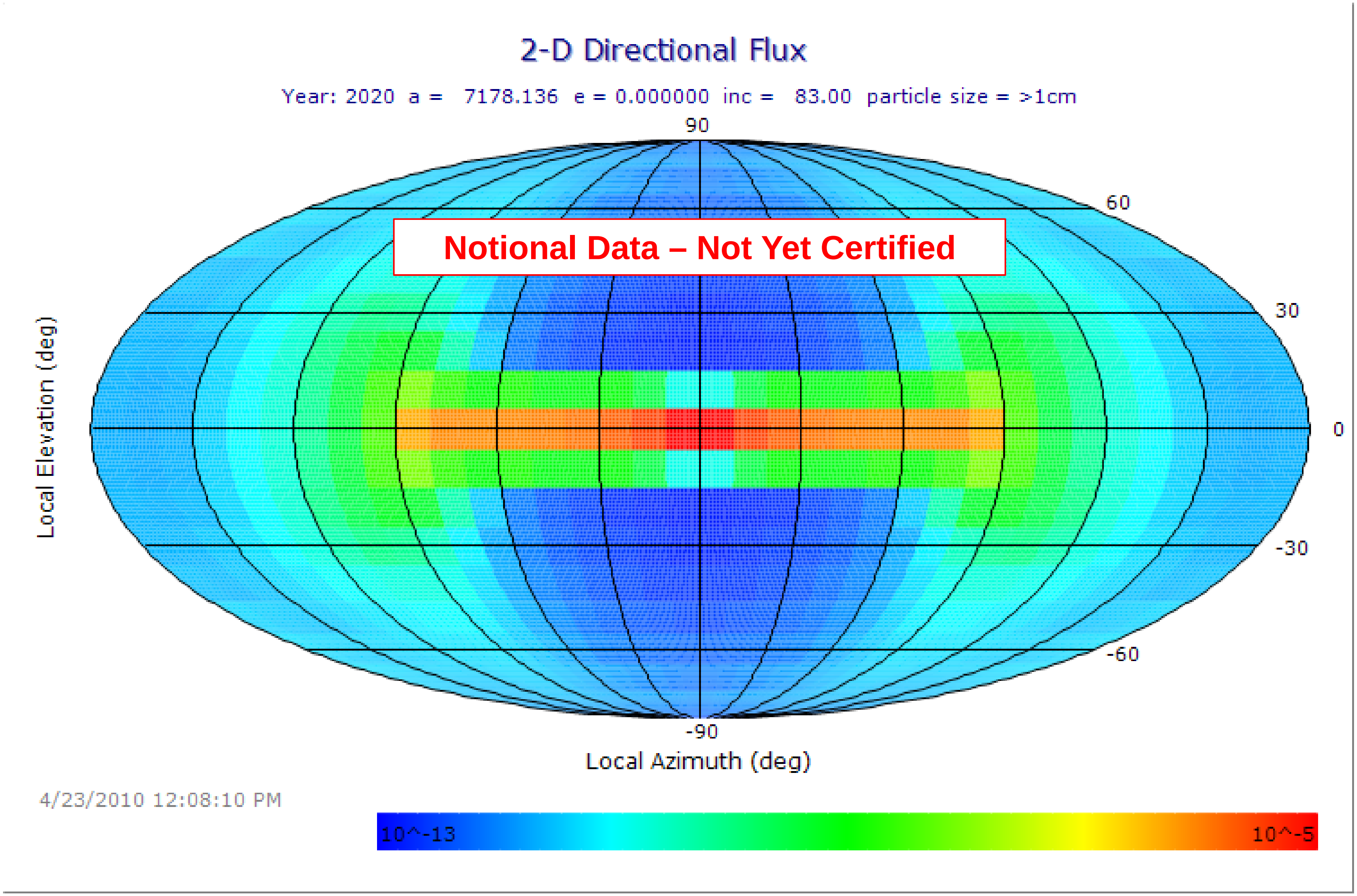


Orbit: 400 km, 51.6 deg; Year = 2020
(Source: ORDEM 3.0)



Notional Data – Not Yet Certified

Orbit: 800 km, 83 deg; Year = 2020 (Source: ORDEM 3.0)



Notional Data – Not Yet Certified

Summary

- **ORDEM 3.0 represents the latest generation of orbital debris engineering models**
- **New features:**
  - Extension beyond LEO
  - Full directionality for spacecraft flux
  - Material density breakdowns
  - Uncertainties in flux calculations computed

Probability and Consequences of Collisions

Orbital Debris Program Office
NASA Johnson Space Center

Collision Risk as a Function of Debris Size

- **Simplistic probability of collision:**
  - Pc for a given vehicle = (orbital debris flux) x (cross-sectional area) x (time) = FAT

    or = (average collision velocity) x (cross-sectional area) x (spatial density) x (time) =VAST

- **Collisions with debris are a concern for two reasons:**
  - success of the space mission
  - protection of the near-Earth space environment for future missions

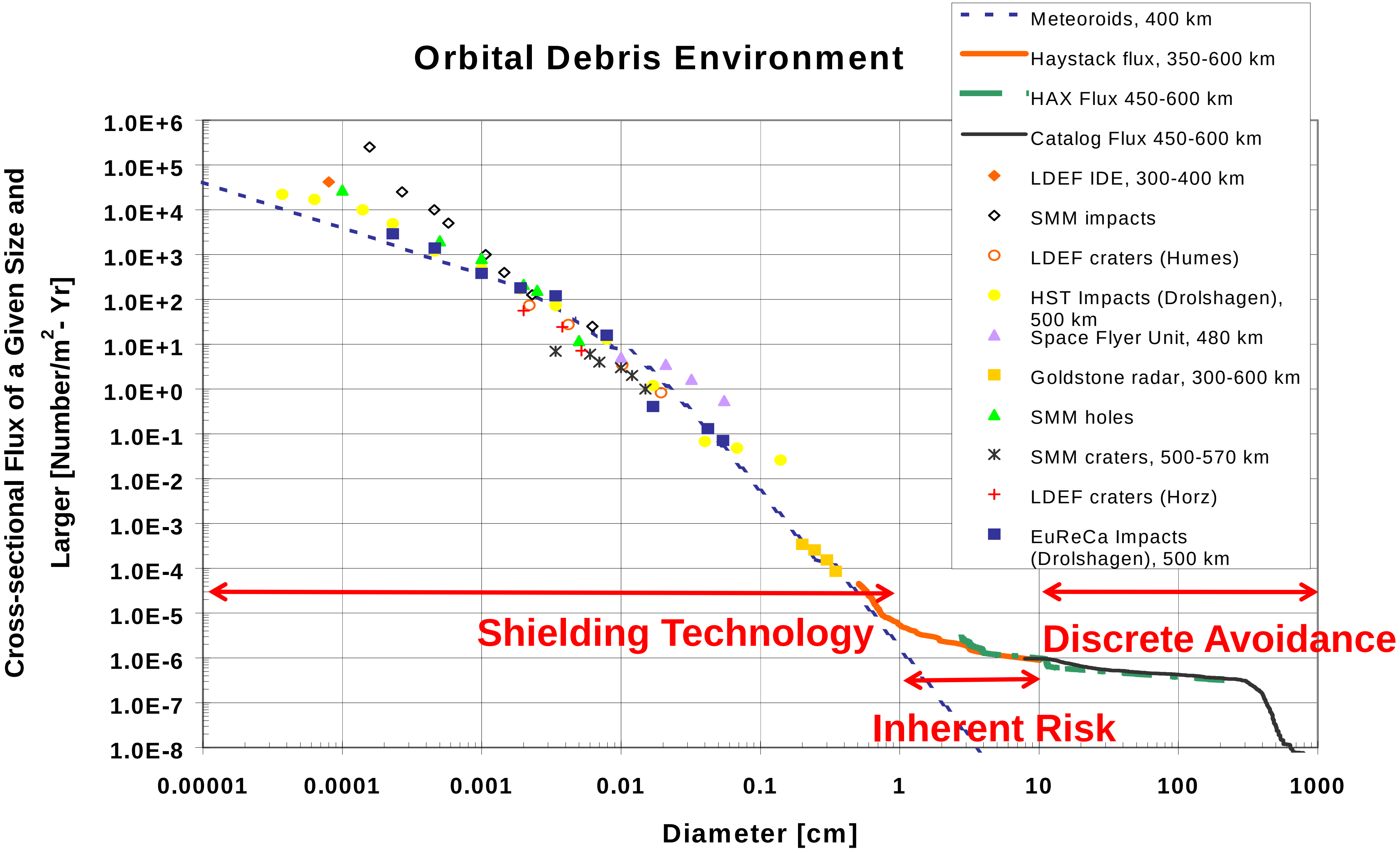
- **Consequences of collisions with debris can be categorized by size*:**

Debris Size	**Loss of Mission**	**Environmental Effect**	**Likelihood of Occurrence**
< 1 mm	Unlikely	None	Most likely
1 mm - 1 cm	Possible	Very limited	
1 - 10 cm	Likely	Limited	
> 10 cm	Highly likely	Potentially significant	Least likely

(* collisions with vehicle main body, rather than appendages)

Collision Risk Spectrum and Countermeasures

Orbital Debris Environment



Shielding Technology

Discrete Avoidance

Inherent Risk

Collision Avoidance for Human Spaceflight

- **A process to avoid collisions with tracked space objects (*i.e.*, > 10 cm) was implemented with STS-26 in 1988.**
  - The approach of another object within a box 4 km X 10 km X 4 km centered on the Space Shuttle represented a collision risk on the order of 1 in 100,000 and was grounds to execute a collision avoidance maneuver

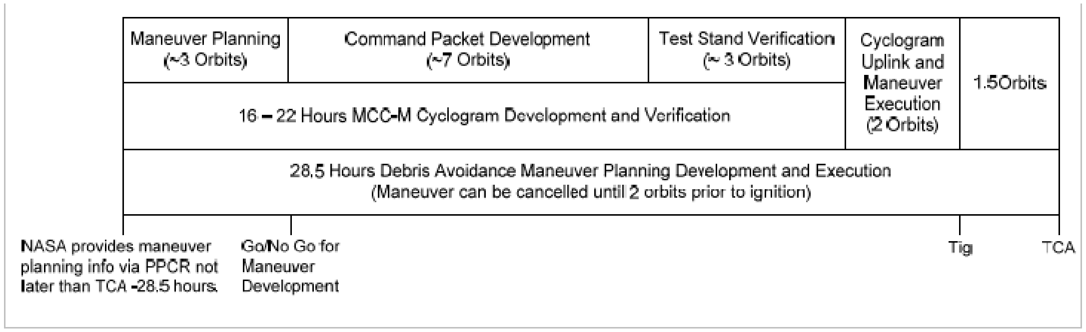
- **With the launch of the first module of the International Space Station in 1998, a new, higher fidelity, probability-based collision avoidance process was implemented.**
  - If collision risk is > 1 in 100,000, a collision avoidance maneuver would be performed, if it did not compromise mission objectives (yellow threshold)
  - If collision risk is > 1 in 10,000, a collision avoidance maneuver would be performed (red threshold).

- **Historically, the rate of collision avoidance maneuvers has been less than one per year for both the Space Shuttle and the ISS.**

ISS Conjunction Assessment Process

Conjunction Notification and Debris Avoidance Process

- An automated process is used by United States Strategic Command (USSTRATCOM) to detect any conjunctions within a ±10 X ±40 X ±40 km box centered on the ISS.
- Any object found within this box is tracked with higher priority with the intention of reducing uncertainty in its predicted orbital trajectory.
- USSTRATCOM notifies NASA if any object is found within a ±2 X ±25 X ±25 km box centered on the ISS (see Figure 2), then creates and sends an Orbital Conjunction Message to NASA which contains detailed information about the conjunction.
- An ISS Trajectory Operations Officer (TOPO) notifies the Mission Control Center (MCC)-Houston Flight Director and MCC-Moscow Ballistics Navigation Services (BNS) if a conjunction penetrates a ±0.75 X ±25 X ±25 km box centered on the ISS.
- TOPO computes a probability of collision using the information provided by USSTRATCOM.
- During ISS standalone operations, Russian propulsion assets are used to execute a DAM. TOPO and BNS jointly assess whether planning for a DAM is required, and begin working maneuver options as needed, making a joint recommendation to their respective flight teams.
- During ISS standalone operations, a minimum of 28.5 hours prior to the calculated TCA of the conjunction object is required for maneuver planning development, command packet development, test stand verification, uplink, and execution (see Figure 3).
- During mated operations with the shuttle, the shuttle is used to execute DAMs. The TOPO and the Flight Dynamics Officer work together with the Houston and Moscow flight control teams to design a debris avoidance maneuver. A shuttle maneuver can be planned and executed within 12 hours. A PC for conjunctions with an expected TCA more than 12 hours in the future can only be calculated if there are no trajectory perturbating operations (e.g. shuttle water dump) planned.
- A maneuver can be cancelled if improved PC calculations no longer require it.


Maneuver Planning (~3 Orbits)

Command Packet Development (~7 Orbits)

Test Stand Verification (~ 3 Orbits)

Cyclogram Uplink and Maneuver Execution (2 Orbits)

1.5Orbits

16 – 22 Hours MCC-M Cyclogram Development and Verification

28.5 Hours Debris Avoidance Maneuver Planning Development and Execution (Maneuver can be cancelled until 2 orbits prior to ignition)

NASA provides maneuver planning info via PPCR not later than TCA -28.5 hours

Go/No Go for Maneuver Development

Sample ISS Conjunction: 19 September 2009

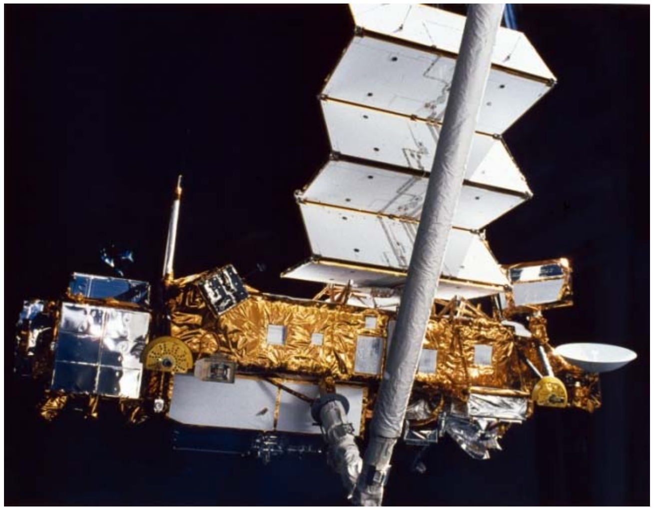
- **Conjuncting object: Satellite Number 35438 (Cosmos 2251 debris)**

OCM #	**UPDATE TIME (GMT)**	**TCA (GMT)**	**U [Radial] (KM)**	**V [Down Track] (KM)**	**W [Cross Track] (KM)**	**R [Spacing] (KM)**	**TIME TO TCA (HRS)**	**P_c**
1	09/18/09 04:57	09/19/09 17:27:56.654	-0.512	21.419	18.552	28.340	36.5	NC
2	09/18/09 09:22	09/19/09 17:27:57.648	-0.471	15.655	13.556	20.713	32.1	NC
3	09/18/09 13:38	09/19/09 17:27:58.115	-0.244	7.656	6.633	10.132	28.8	1.47E-04 Red
4	09/18/09 19:43	09/19/09 17:27:58.226	-0.229	6.701	5.806	8.869	21.7	2.59E-5 Yellow
5	09/18/09 01:10	09/19/09 17:27:58.377	-0.240	6.709	5.810	8.878	16.3	5.5E-6 Green
6	09/19/09 05:49	09/19/09 17:27:58.529	-0.215	5.528	4.784	7.313	11.7	8.28E-06 Green
7	**09/19/09 08:39**	**09/19/09 17:27:58.628**	**-0.203**	**4.923**	**4.264**	**6.516**	**8.8**	**7.23E-21 Green**

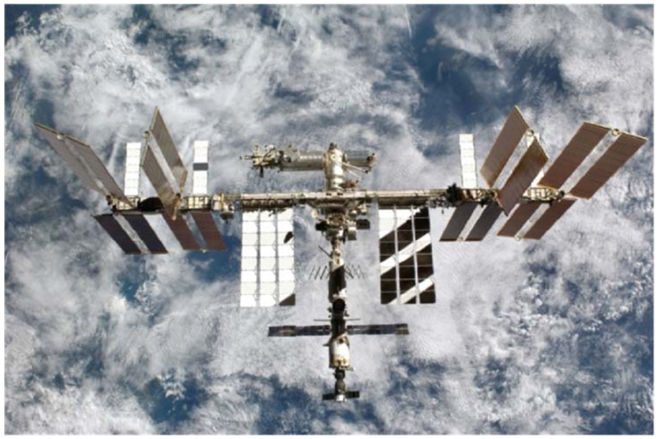
- **Late notification; planned maneuver was cancelled.**

ISS Collision Avoidance Maneuver in 2010

- **After a 14-year mission, NASA's Upper Atmospheric Research Satellite (UARS) was decommissioned in late 2005 and maneuvered into a lower altitude disposal orbit from which reentry will occur during 2011.**
- **In September 2010, a small fragment unexpectedly separated from UARS.**
- **Although the fragment remained in orbit only six weeks, the object was predicted to pass close by the International Space Station on 26 October, posing a collision threat of greater than 1 in 10,000.**
- **Using the Progress M-07M logistics vehicle, a small collision avoidance maneuver (+0.4 m/s) was conducted a little more than two hours before the predicted time of closest approach.**



UARS being deployed by Space Shuttle Discovery in 1991.



International Space Station

Robotic Spacecraft Collision Avoidance

- **In 2004, in response to the growing debris risk, NASA GSFC implemented a process for providing routine collision avoidance operations to protect the Earth Science Constellations.**
    - The missions are managed independently by several different NASA centers as well as International Partners, but the mission operators work together to ensure the health and safety of the constellations.
    - NASA JSC provided assistance in establishing the robotic process, which needed to be somewhat different from the manned process due to the different orbit regimes and different operations processes.

- **In August 2007, because of the increasing threat posed by orbital debris, NASA established a policy that requires routine collision avoidance operations for robotic assets that have maneuvering capability.**

- **In April 2009, the policy was expanded to require routine conjunction analysis for non-maneuverable and non-operational NASA assets in addition to the maneuverable assets.**
    - Therefore, the NASA Robotic Conjunction Assessment process has expanded and is currently being used to support ~65 spacecraft in a variety of orbit regimes.

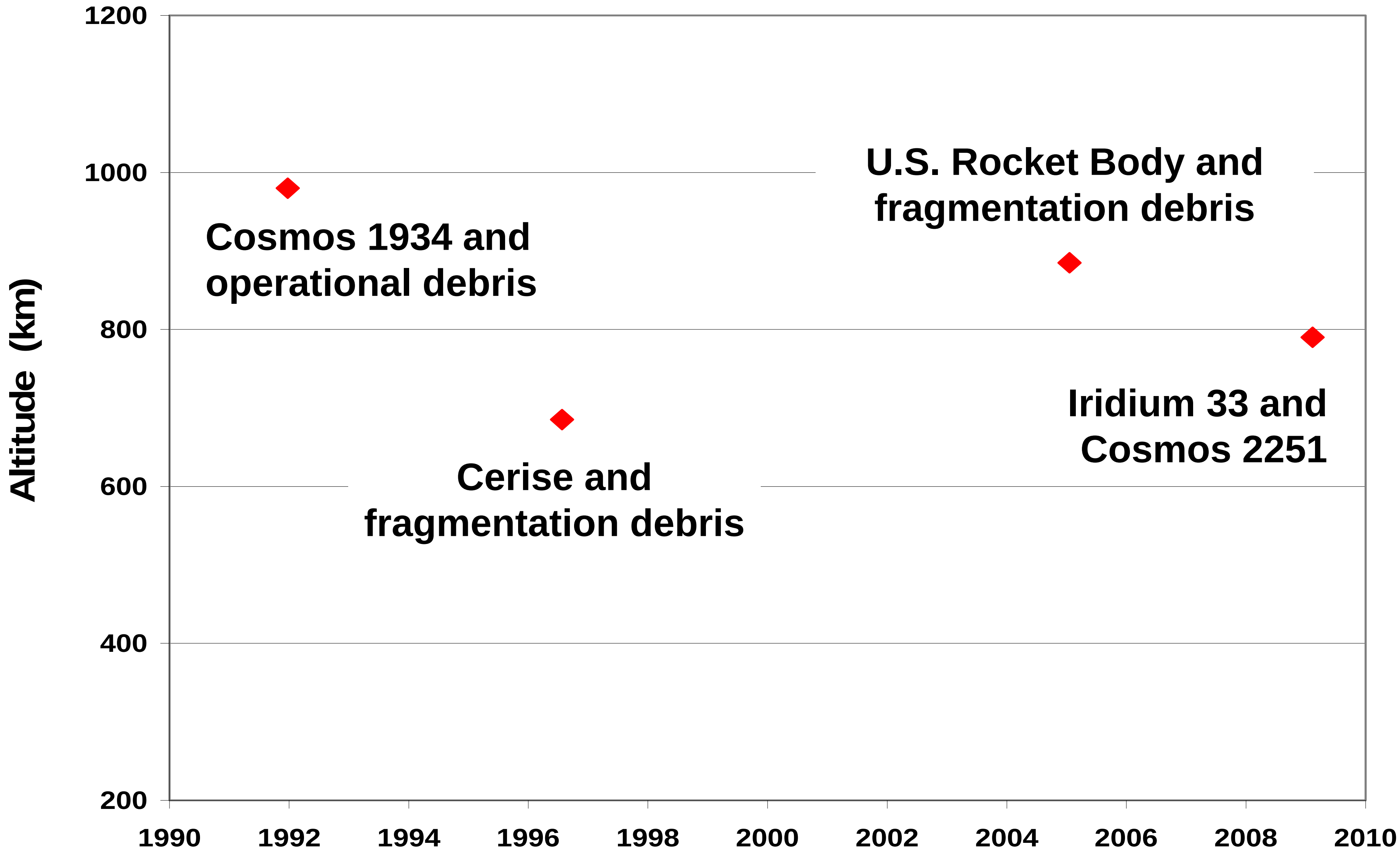
Robotic Collision Avoidance Maneuvers

- **Frequent conjunction assessments are required for all maneuverable NASA spacecraft in LEO and GEO. Collision avoidance maneuvers are conducted when established probability of collision thresholds are reached.**

NASA, USGS, and NOAA Robotic Satellite Collision Avoidance Maneuvers in 2012

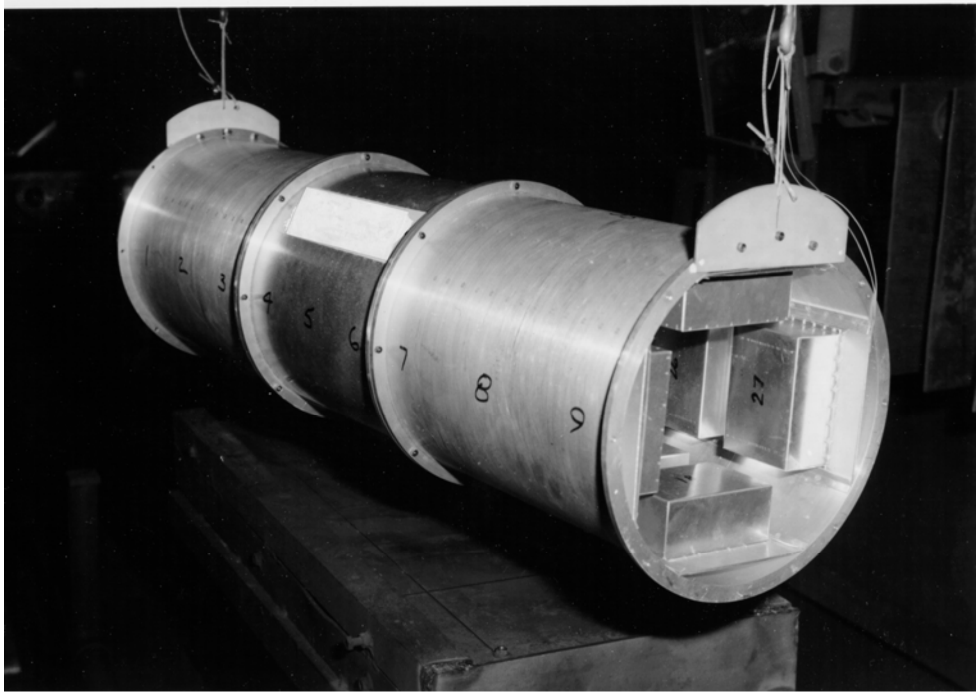
Mean Altitude	Spacecraft	Object Avoided	Maneuver Date
550 km	GLAST (2008-029A)	Cosmos 1805	3 April 2012
700 km	AURA (2004-026A)	Cosmos 2251 Debris	17 May 2012
	CALIPSO (2006-016B)	Cosmos 2251 Debris	2 October 2012
	CLOUDSAT (2006-016A)	Sinah 1	8 September 2012
	LANDSAT 5 (1984-021A)	Agena D stage Debris	1 July 2012
	LANDSAT 7 (1999-020A)	Fengyun-1C Debris	9 March 2012
		Meteor 1-10 Debris	17 April 2012
825 km	NPP (2011-061A)	Agena D stage Debris	1 February 2012

Known Accidental Hypervelocity Collisions



Subscale Hypervelocity Impact Tests, 1970's-1980's

- **During the late 1970's and early 1980's, a series of hypervelocity impact tests were conducted using large targets representative of subscale satellites.**
  - Target masses: ~ 26 kg
  - Projectile masses: 80-240 gm
  - Impact velocities: up to 6 km/s
  - Pressurized and unpressurized targets
  - Normal and oblique impact angles



- **Examination of debris sizes and velocities resulted in first satellite collision fragmentation models.**

Broadside Impact (1)

U.S. AIR FORCE PHOTO-AEDC
ARO, INC., AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
ARNOLD A.F. STATION, TENN.
NOT CLEARED FOR PUBLIC RELEASE
WITHOUT PRIOR WRITTEN APPROVAL
OF THE RESPONSIBLE AIR FORCE
OFFICE OF INFORMATION.

9905 (10-1-79) V41G-80 SHOT 5279
RECOVERED TEST OBJECT

Broadside Impact (2)

U.S. AIR FORCE PHOTO–AEDC
ARO, INC., AEDC DIVISION
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ARNOLD A.F. STATION, TENN.
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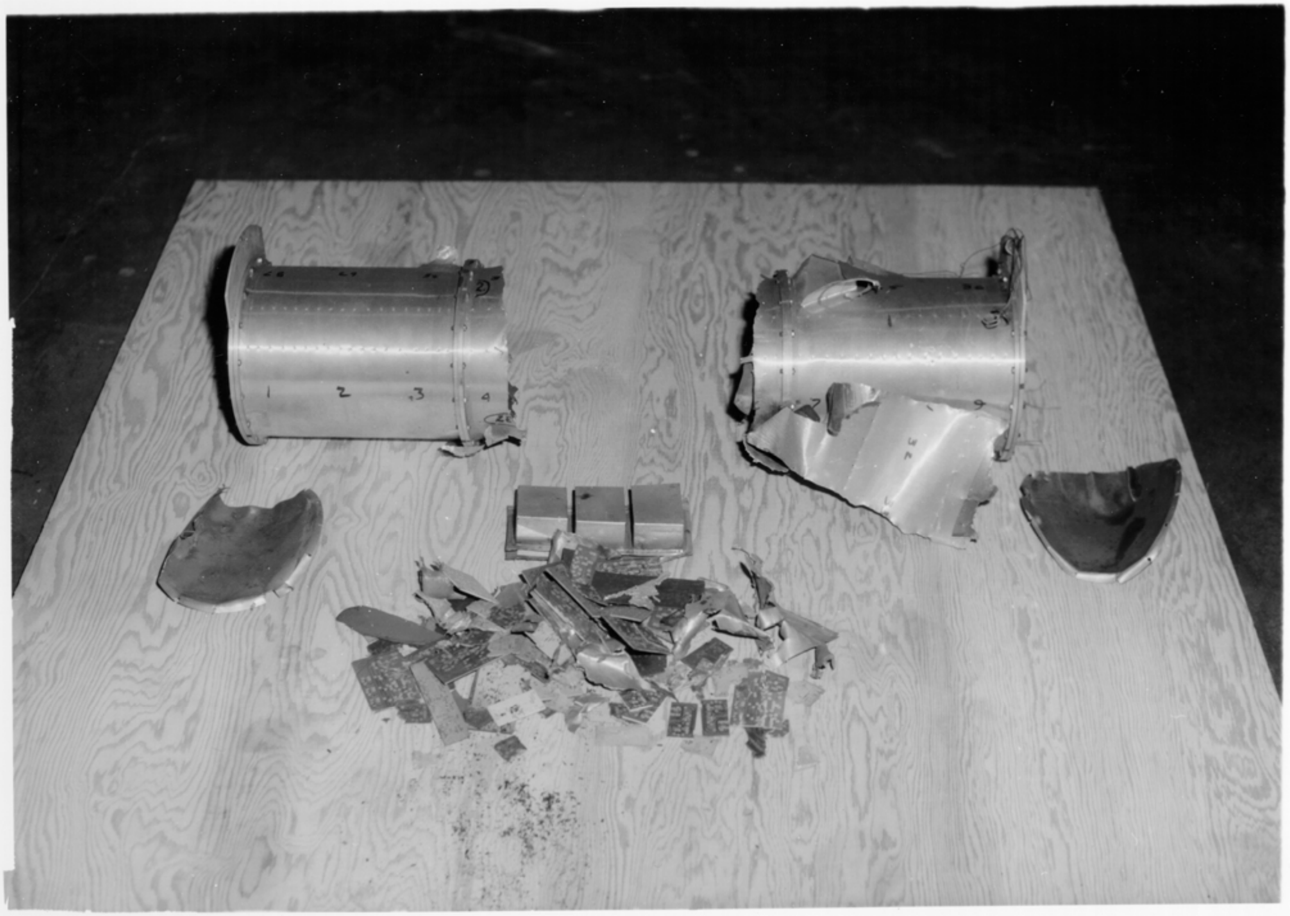

9303 (9-18-79) V41G-80 SHOT 5269
RECOVERED TEST OBJECT

Broadside Impact (3)

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ARO, INC., AEDC DIVISION
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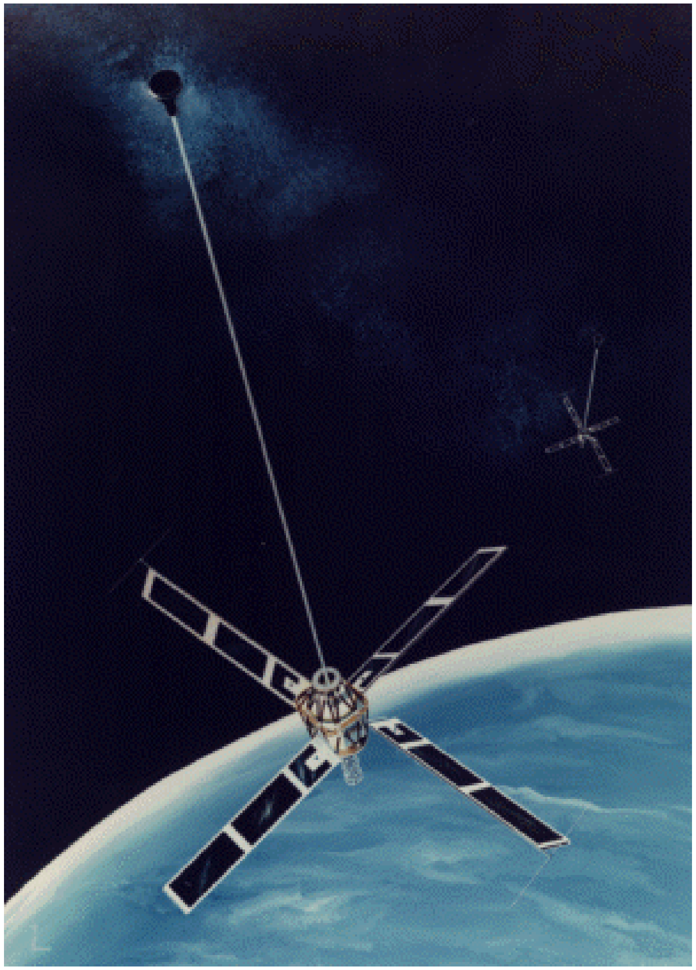
9897 (10-1-79) V41G-80 SHOT 5271
RECOVERED TEST OBJECT

Oblique Impact

Satellite Orbital Debris Characterization Impact Test (SOCIT)



Date: 10 January 1992 at the Arnold Engineering Development Center, Tullahoma, TN

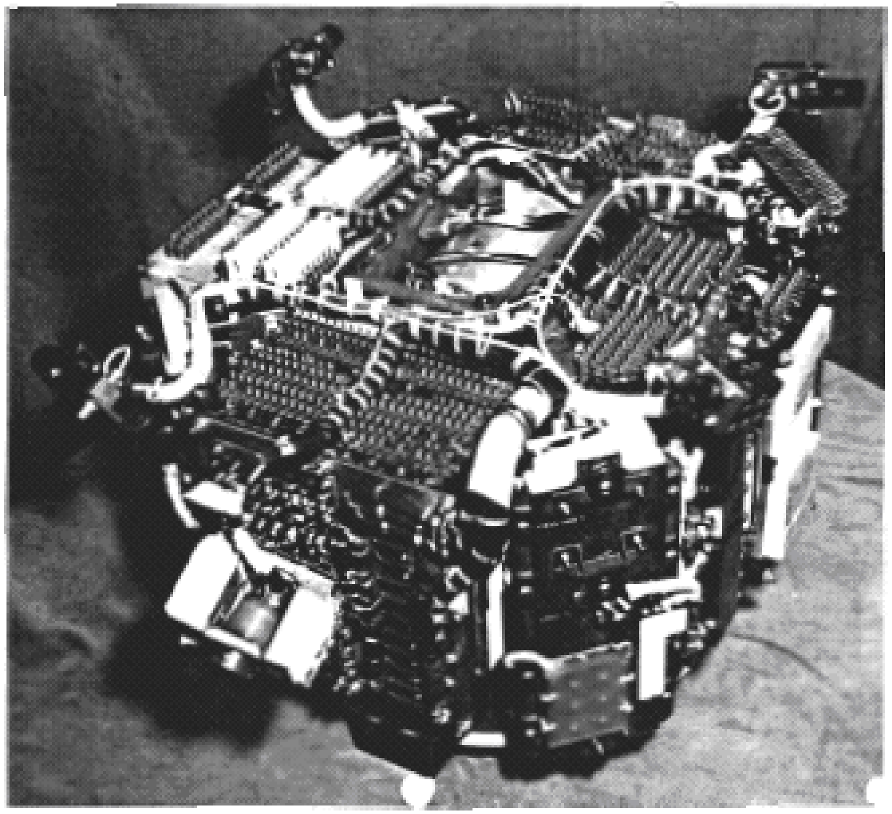
Subject: U.S. Navy Transit satellite Oscar 22 (NNS 30220)

Test Objective: Simulate the collision of a 5-cm piece of orbital debris on a functional satellite and characterize the resultant debris in terms of number, mass, velocity, shape, and composition.

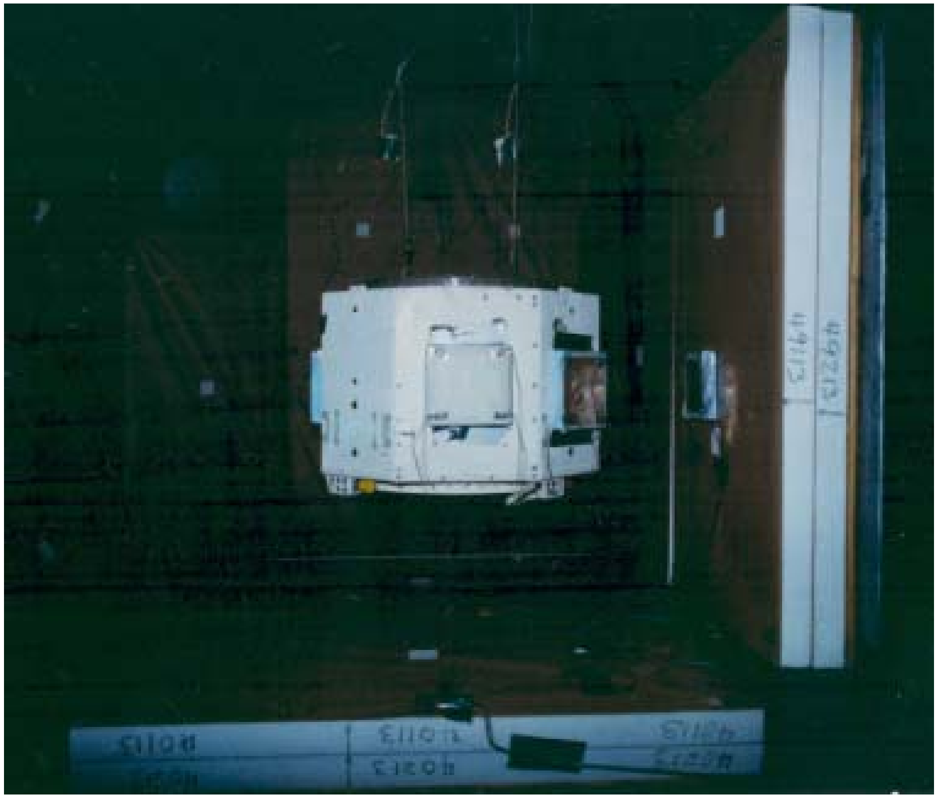
Test Condition: Satellite (sans solar arrays) was struck with a 150 gm projective traveling at 6 km per second.

Transit Oscar 22 prior to SOCIT (1)

Transit Oscar 22 prior to SOCIT (2)

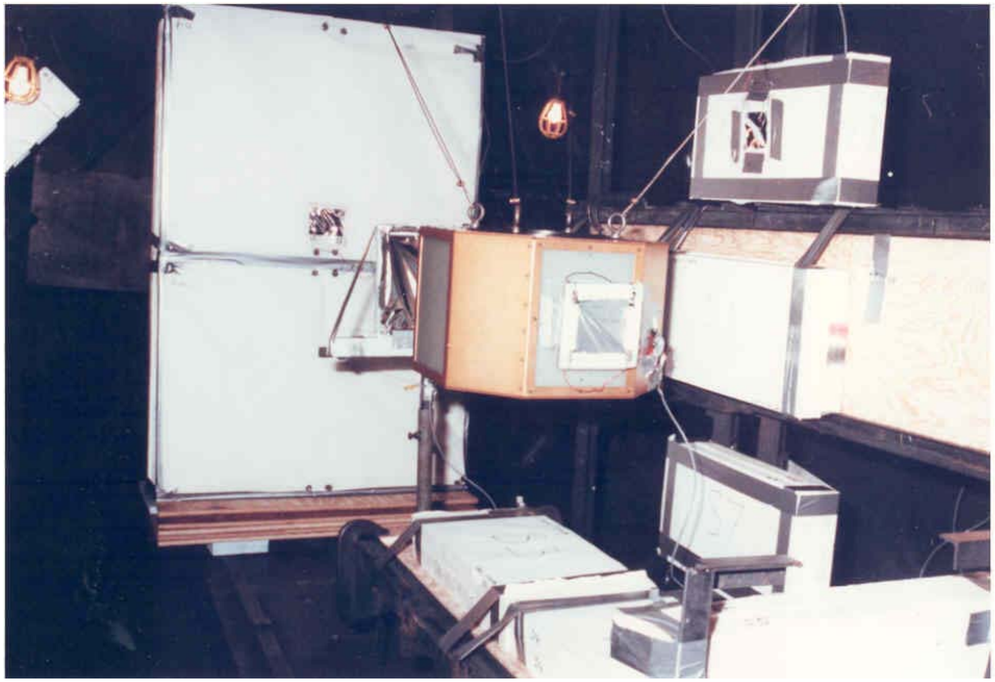


Transit Oscar with outer phenolic skin removed



Transit Oscar mounted in test chamber

Transit Oscar 22 Test Chamber: Before and After



Spacecraft Collision Risks from Breakup Debris

- **Orbital debris risks to spacecraft:**
  - Orbital debris left over from >50 years of space activity distributed over a variety of orbits – contribute to “background” risk.
    - **Large objects (> 5-10 cm) are tracked by the SSN.**
      - ➢ DoD routinely computes collision risks with these objects for NASA
    - **Risks from objects too small to be tracked are typically handled in a statistical manner using spacecraft shielding and orientation.**
      - ➢ Directionality, size distributions, and velocity distributions described by ORDEM models
  - New breakups can temporarily enhance this collision risk.
    - **Space asset may fly through region of debris enhancement.**
    - **Debris cloud is dynamic, and collision risk depends on details of debris cloud and asset orbit.**

Even Small Debris Can be Hazardous

Satellite Breakup Risk Assessment Model (SBRAM)

- **SBRAM was developed by NASA Orbital Debris Program Office to assess in real-time elevated collision risks to high value NASA assets (especially Space Shuttle and ISS) following new satellite breakups.**

- **NASA/JSC is informed 24/7 by DoD’s Joint Space Operations Center (JSpOC) whenever a new satellite breakup is detected.**

- **SBRAM uses NASA Standard Breakup Model (developed to describe near- and long-term evolution of debris environment) to create a Monte Carlo cloud:**
  - Size distribution
  - Ballistic coefficient distribution
  - Delta-velocity distribution

- **Various orbit propagation techniques are employed to model future TLEs (two-line element sets) for Monte Carlo debris cloud particles.**
  - Atmospheric drag; solar/lunar perturbations; J2, J3; solar radiation pressure

Satellite Breakup Risk Assessment Model (SBRAM)

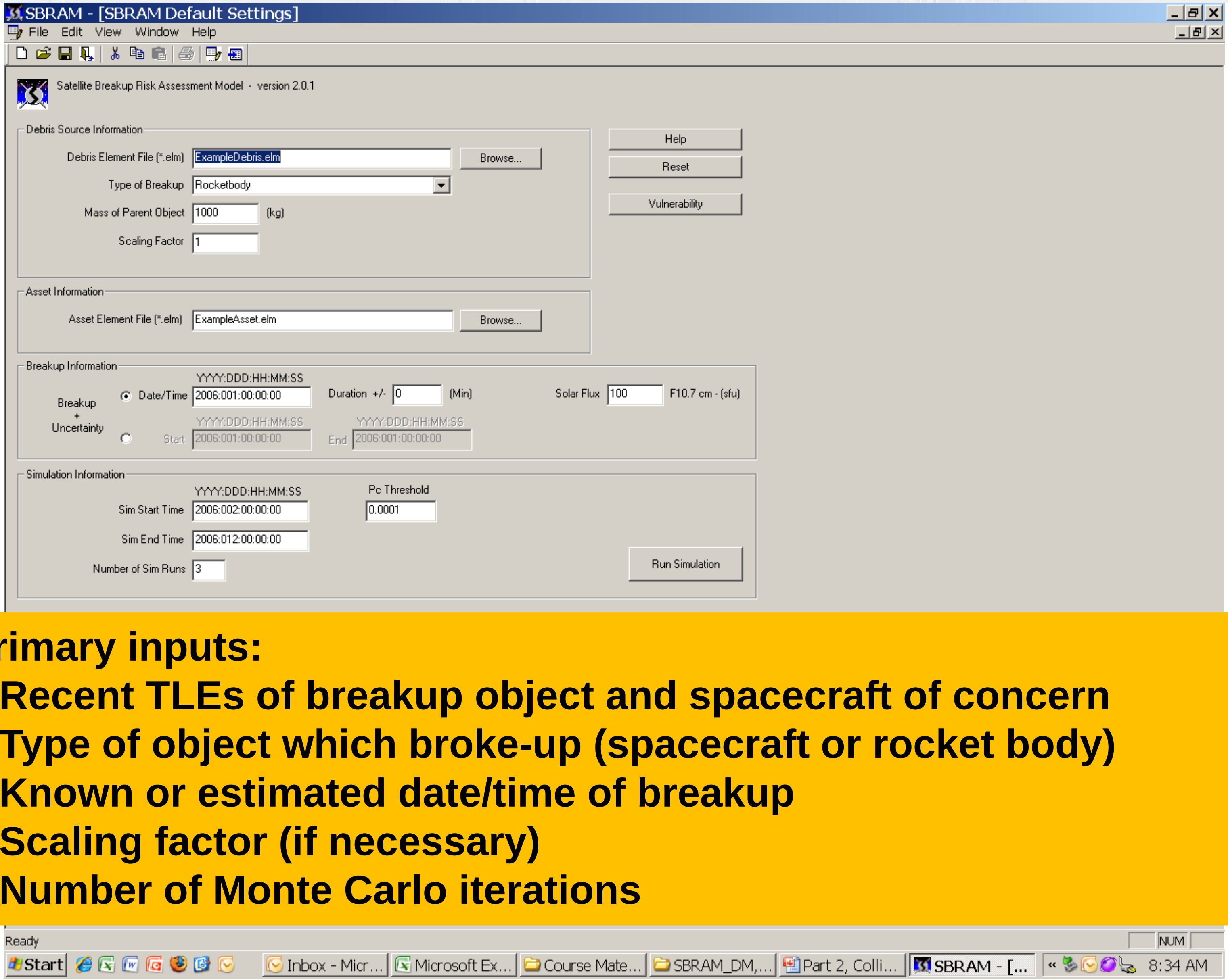
- **Conjunctions of space asset with cloud particles are computed to integrate risk.**

- **Debris-Asset conjunctions are tabulated.**
  - Timing
  - Directionality
  - Impact probability

- **The procedure is repeated and results are integrated using Monte Carlo approach until desired accuracies are obtained.**

- **Output results:**
  - Estimated cumulative risk to asset
  - Estimation of risk each time the asset encounters the cloud
  - Times and conditions of highest risk
  - Directionality of highest risk

Initial Screen for SBRAM



Satellite Breakup Risk Assessment Model - version 2.0.1

Debris Source Information

Debris Element File (*.elm) ExampleDebris.elm
Type of Breakup Rocketbody
Mass of Parent Object 1000 (kg)
Scaling Factor 1

Asset Information

Asset Element File (*.elm) ExampleAsset.elm

Breakup Information

● Date/Time YYYY:DDD:HH:MM:SS 2006:001:00:00:00
Duration +/- 0 (Min)
Solar Flux 100 F10.7 cm - (sfu)
○ Breakup + Uncertainty Start YYYY:DDD:HH:MM:SS 2006:001:00:00:00 End YYYY:DDD:HH:MM:SS 2006:001:00:00:00

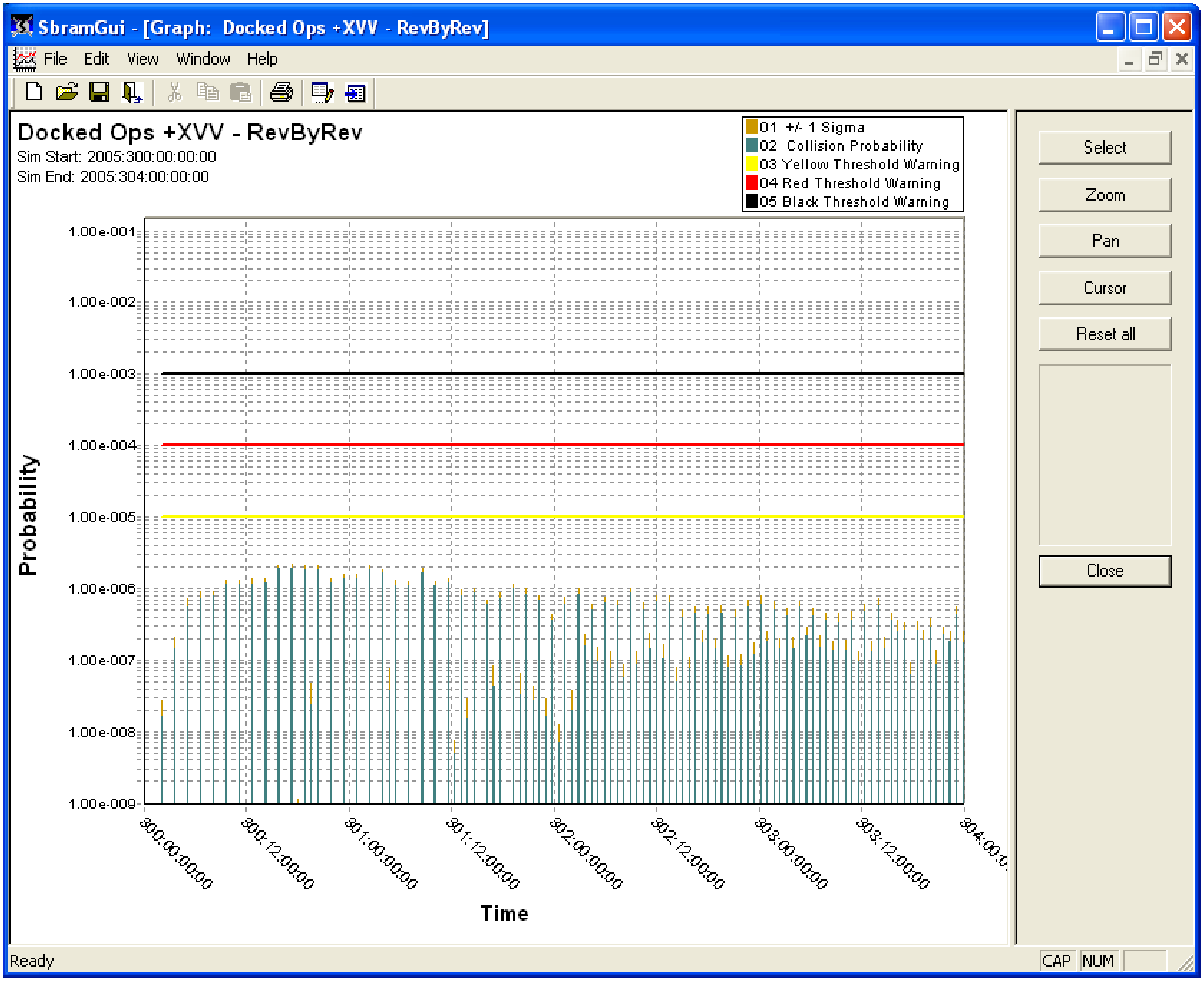
Simulation Information

Sim Start Time YYYY:DDD:HH:MM:SS 2006:002:00:00:00
Sim End Time 2006:012:00:00:00
Number of Sim Runs 3
Pc Threshold 0.0001

Primary inputs:

- **Recent TLEs of breakup object and spacecraft of concern**
- **Type of object which broke-up (spacecraft or rocket body)**
- **Known or estimated date/time of breakup**
- **Scaling factor (if necessary)**
- **Number of Monte Carlo iterations**

Sample Rev by Rev Risk Assessment

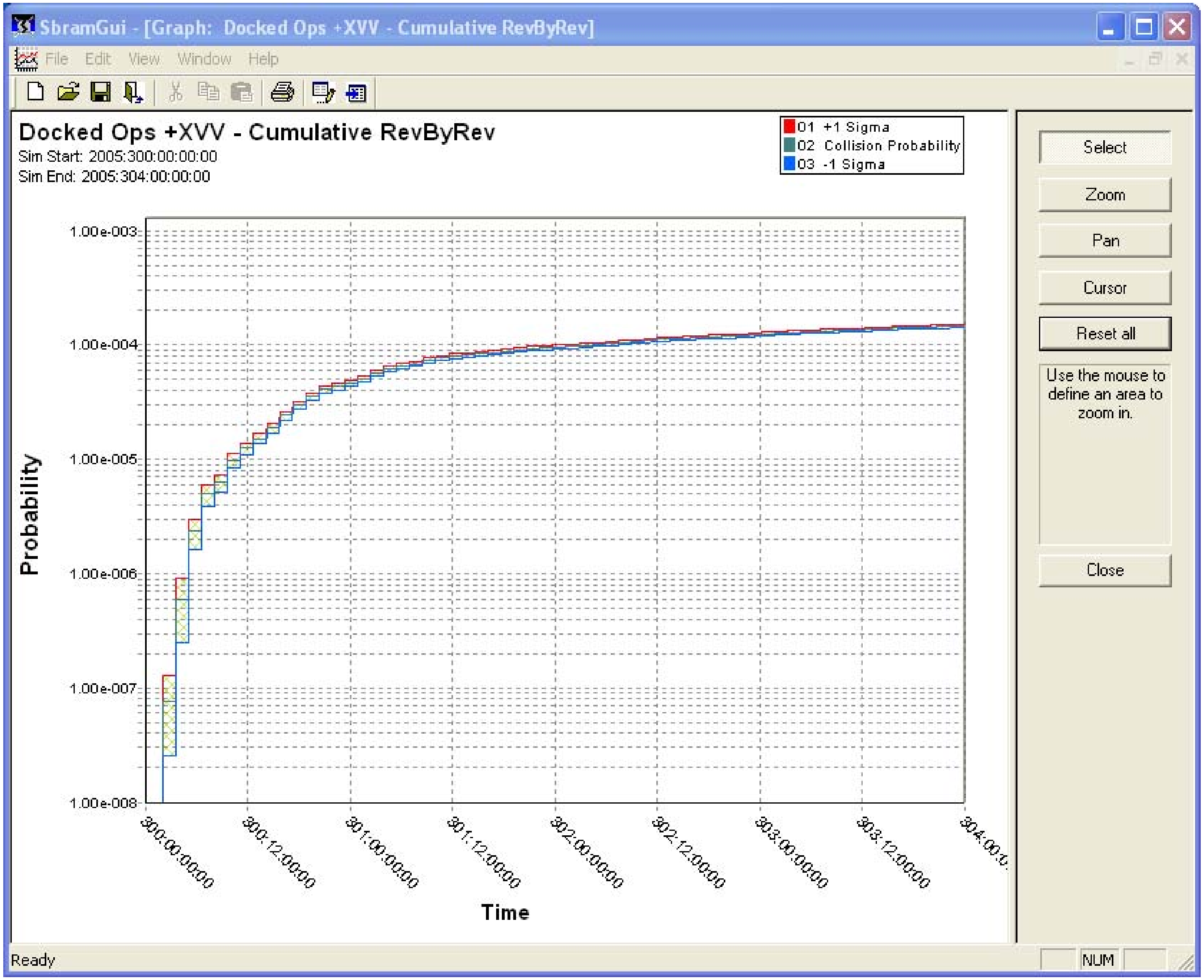


Docked Ops +XVV - RevByRev

Sim Start: 2005:300:00:00:00

Sim End: 2005:304:00:00:00

Sample Cumulative Risk Ouput



SbramGui - [Graph: Docked Ops +XVV - Cumulative RevByRev]

Docked Ops +XVV - Cumulative RevByRev

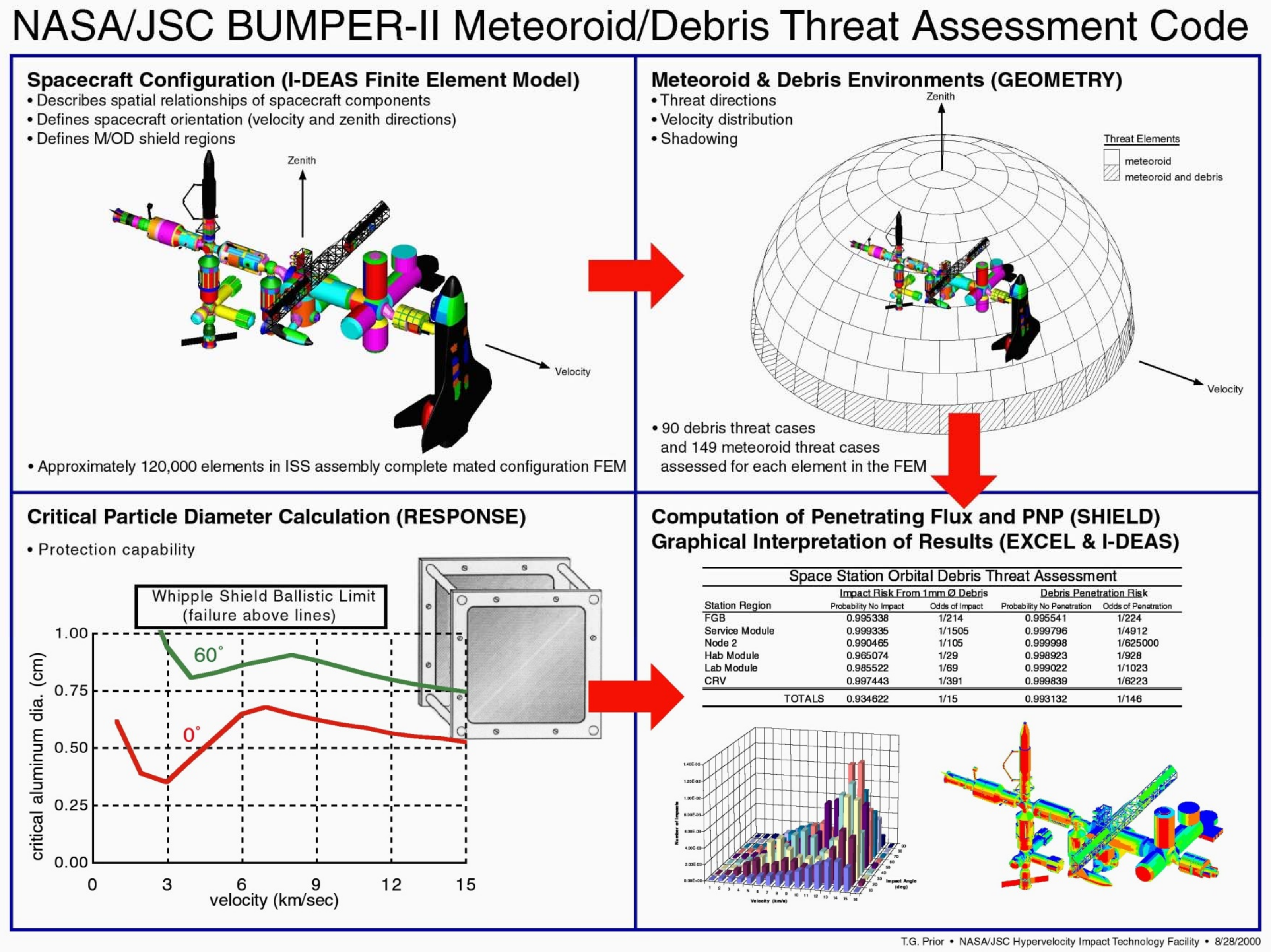
Sim Start: 2005:300:00:00:00

Sim End: 2005:304:00:00:00

Use the mouse to define an area to zoom in.

Ready

Detailed Impact Risk Assessment Process



NASA/JSC BUMPER-II Meteoroid/Debris Threat Assessment Code

Spacecraft Configuration (I-DEAS Finite Element Model)

- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions

- Approximately 120,000 elements in ISS assembly complete mated configuration FEM

Meteoroid & Debris Environments (GEOMETRY)

- Threat directions
- Velocity distribution
- Shadowing

- 90 debris threat cases and 149 meteoroid threat cases assessed for each element in the FEM

Critical Particle Diameter Calculation (RESPONSE)

- Protection capability

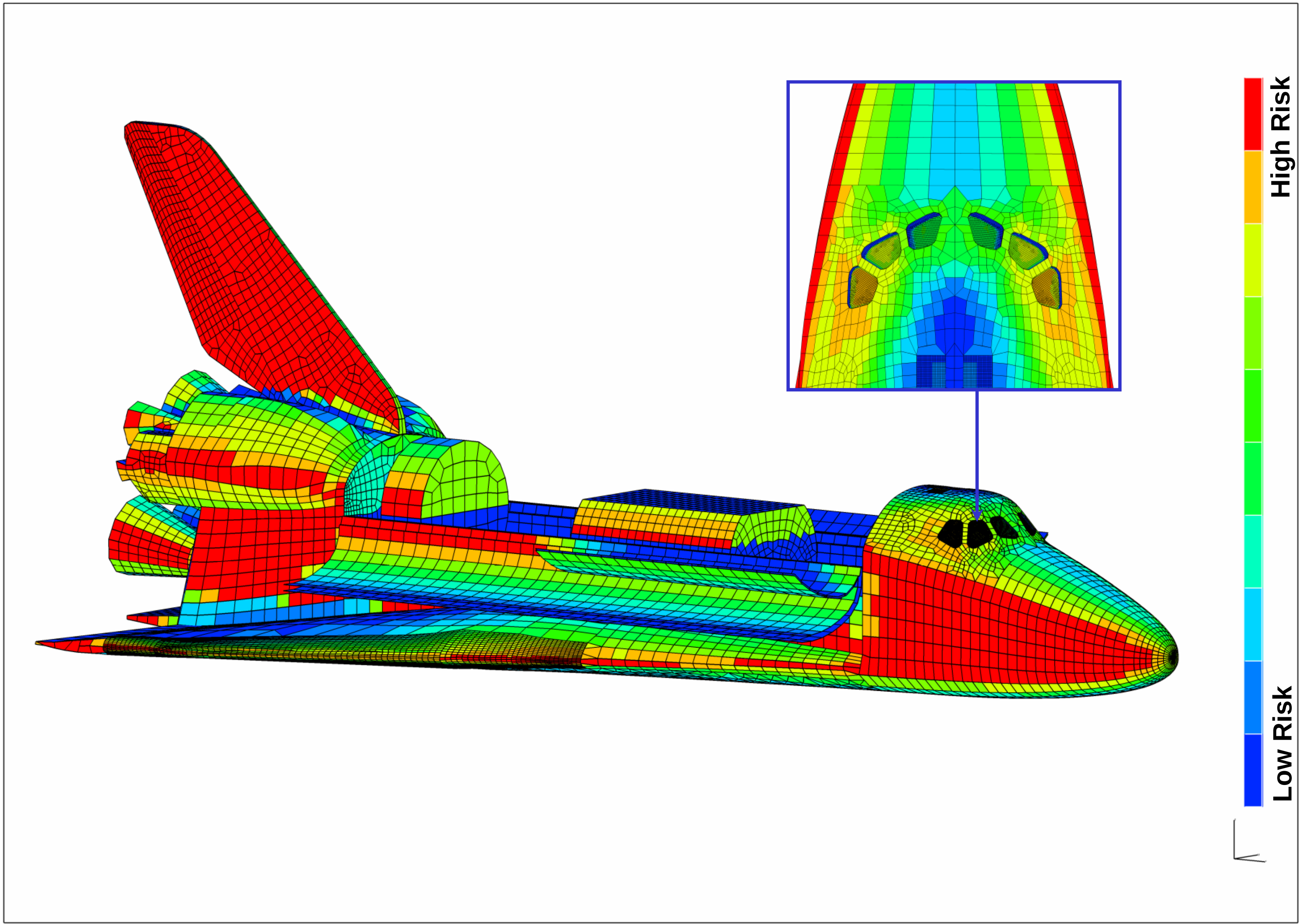
Computation of Penetrating Flux and PNP (SHIELD)
Graphical Interpretation of Results (EXCEL & I-DEAS)

Space Station Orbital Debris Threat Assessment

	Impact Risk From 1mm Ø Debris		Debris Penetration Risk	
Station Region	Probability No Impact	Odds of Impact	Probability No Penetration	Odds of Penetration
FGB	0.995338	1/214	0.995541	1/224
Service Module	0.999335	1/1505	0.999796	1/4912
Node 2	0.990465	1/105	0.999998	1/625000
Hab Module	0.965074	1/29	0.998923	1/928
Lab Module	0.985522	1/69	0.999022	1/1023
CRV	0.997443	1/391	0.999839	1/6223
TOTALS	0.934622	1/15	0.993132	1/146

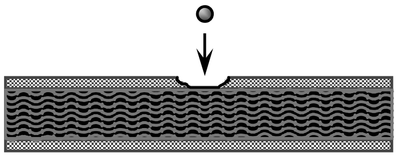
T.G. Prior • NASA/JSC Hypervelocity Impact Technology Facility • 8/28/2000

Shuttle Impact Risk from Orbital Debris ≥3mm Diameter



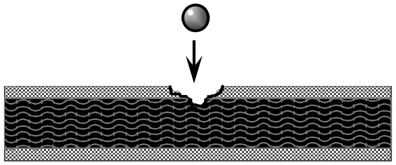
Example HVI Results: Space Shuttle

Reinforced Carbon-Carbon (RCC) Damage Modes



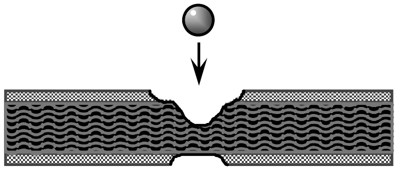
Surface Coating Damage

0.24mm diameter Al @ 7km/s, 0°



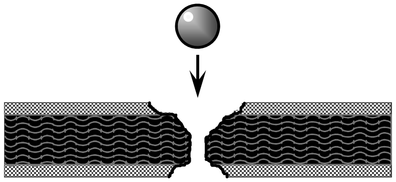
Carbon Substrate Penetration
K.E. = 0.5 J

0.6mm diameter Al @ 7km/s, 0°



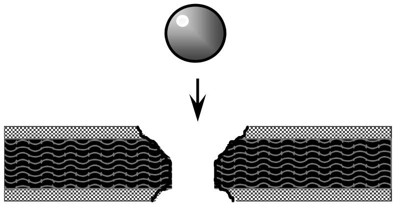
Rear-Side Spall
K.E. = 4 to 7 J

1.0mm diameter Al @ 7km/s, 0°

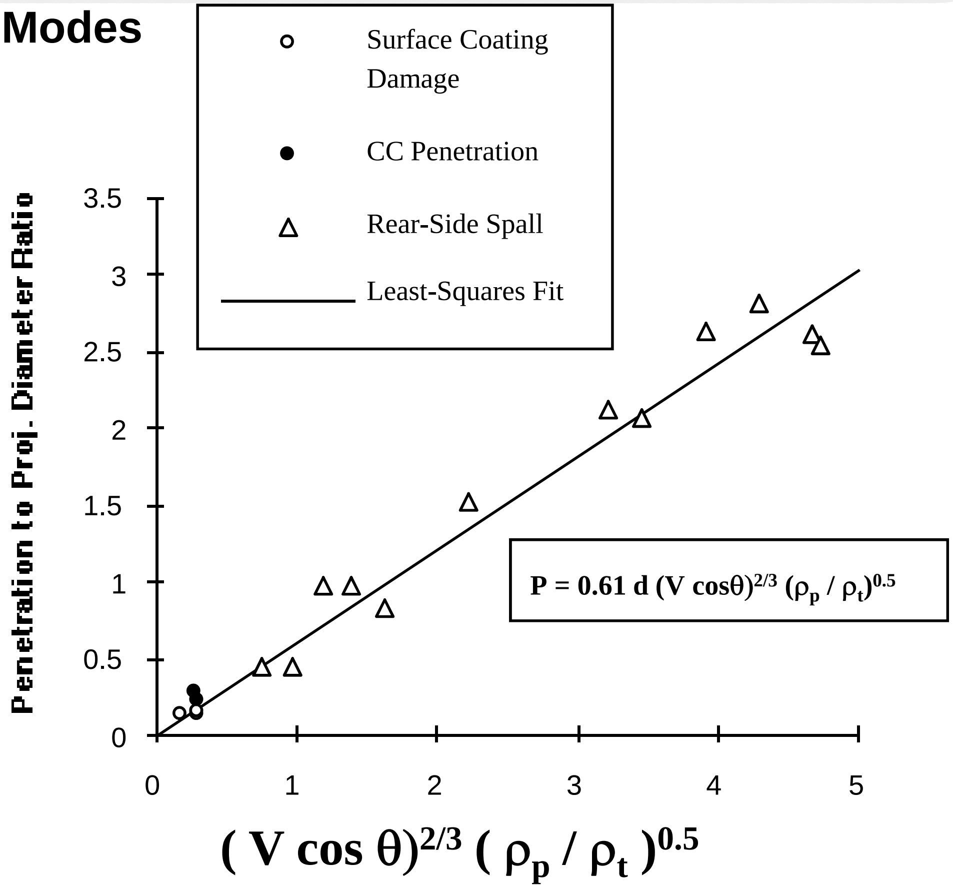


Complete Penetration
K.E. = 30 to 50 J

4.8mm diameter Al @ 7km/s, 0°

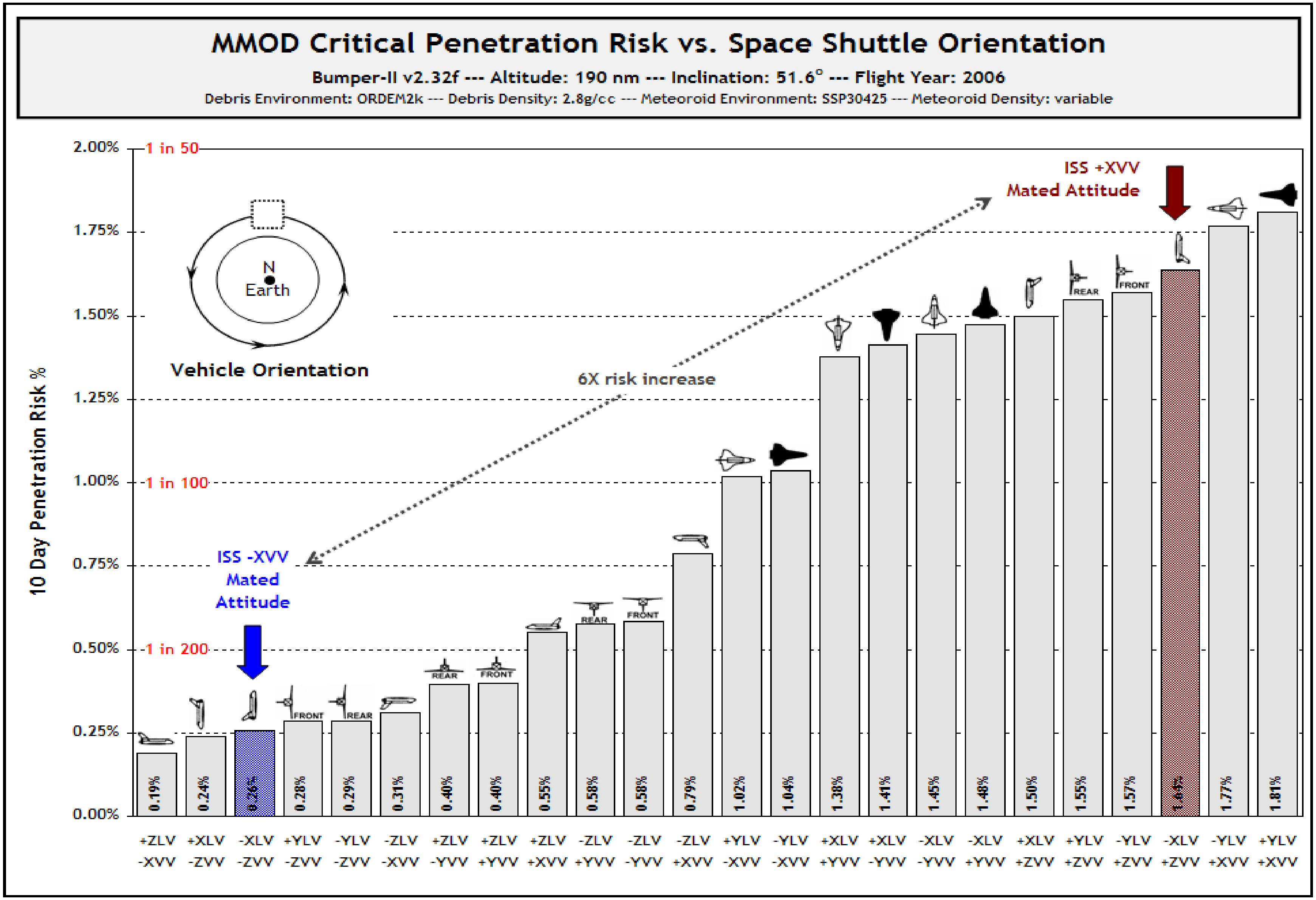


1" Hole
K.E. = 3700 J



RCC Penetration depth $P = 0.61\ d\ (V \cos\theta)^{2/3}\ (\rho_p/\rho_t)^{0.5}$
Thickness to Prevent Complete Penetration $t_p = 2.3 * P$
Thickness to Prevent Rear-Side Spall $t_s = 4.5 * P$

Shuttle Vulnerabilities by Vehicle Attitude


MMOD Critical Penetration Risk vs. Space Shuttle Orientation

Bumper-II v2.32f --- Altitude: 190 nm --- Inclination: 51.6° --- Flight Year: 2006

Debris Environment: ORDEM2k --- Debris Density: 2.8g/cc --- Meteoroid Environment: SSP30425 --- Meteoroid Density: variable

Sample Shuttle MMOD Risk Assessment: STS-119

- **Assessment conditions:**
  - **Attitude Time-Line:** 14 day mission, 119FIN (issued 1/23/09) - 02/12/09 liftoff
    - Includes 54 hours in ISS +XVV attitude (high MMOD risk attitude) for S6 thermal
  - **Late Inspection:** FD13 wing leading edge and nose cap, discern damages >0.35” diameter (WLE 90% success rate, NC 99.9% success rate)
  - **MMOD damage repair & LON:** Included effectiveness WLE/NC damage repair (NOAX and plug) & LON (Launch on Need) success rate (90% combined effectiveness)
  - **Damage Allowables:** No change since STS-126 for damage causing loss-of-crew & vehicle (LOCV)
  - **Meteor showers & Orbital Debris breakups:** No major meteor showers, Orbital debris breakups include COSMOS 2421 (triple breakup over March-June 2008)
    - Debris breakups increase MMOD risk by less than 2%
- **MMOD Risk for LOCV damage:**
  - **1 in 216 (with late inspection, and 90% repair/LON effectiveness)**
    - With FD2 inspection: 1 in 135
    - No FD2 or late inspection: 1 in 131
    - MMOD risk for radiator tube leak: 1 in 76; predicted window replacements: 4

Sample EVA MMOD Risk Assessment: STS-119

- **Cumulative MMOD risk for 4 EVAs & for two levels of damage assessed using Bumper code.**
  - Normal meteor shower activity included (minimal activity for Feb 2009)
  - Orbital debris breakups included (COSMOS 2421 triple breakup over March-June 2008)
  - Risk increases ~4% (due to orbital debris breakups)
    - 1 in 2,000 for any size leak
    - 1 in 6,600 for catastrophic impact

      (4mm or larger hole in bladder is catastrophic)

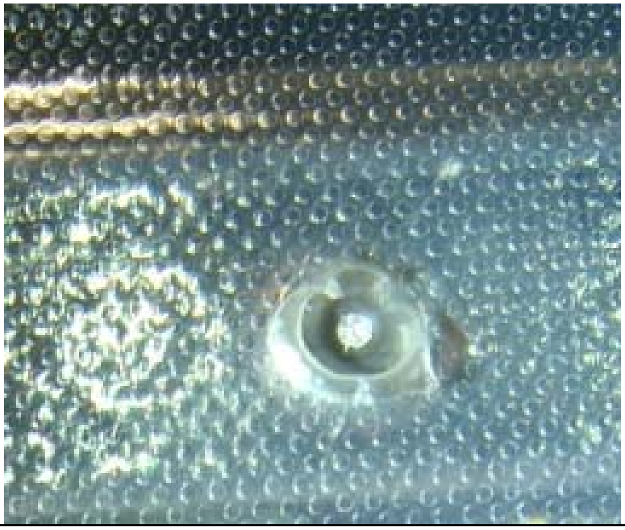
- **STS-119 EVA MMOD risk is 1/3rd of assessed MMOD risk for STS-125 HST-SM4 EVAs.**

Results from STS-119 EVA Timeline Analysis - 2/12/09 Launch

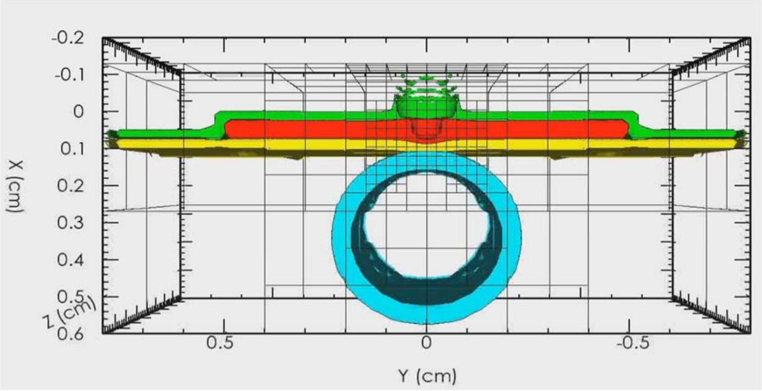
Summary			Penetration Odds (leak risk)				Catastrophic Odds (uncontrolled leak)			
	total EVA duration (hr)	duration exposed to MMOD (hr)	Total	EV1	EV2	EV3	Total	EV1	EV2	EV3
EVA1 (FD5)	6.58	6.42	1 in 7,800	1 in 15,100	1 in 16,000	na	1 in 26,100	1 in 50,700	1 in 53,700	na
EVA2 (FD7)	6.75	6.58	1 in 7,500	1 in 14,800	na	1 in 15,100	1 in 25,000	1 in 49,600	na	1 in 50,500
EVA3 (FD9)	5.92	5.75	1 in 7,700	na	1 in 14,900	1 in 15,900	1 in 25,700	na	1 in 49,800	1 in 53,200
EVA4 (FD11)	6.33	6.17	1 in 8,600	1 in 16,400	1 in 18,000	na	1 in 28,700	1 in 54,800	1 in 60,300	na
Total	25.58	24.92	1 in 2,000	1 in 5,100	1 in 5,400	1 in 7,700	1 in 6,600	1 in 17,200	1 in 18,100	1 in 25,900

STS-128 Radiator Impact

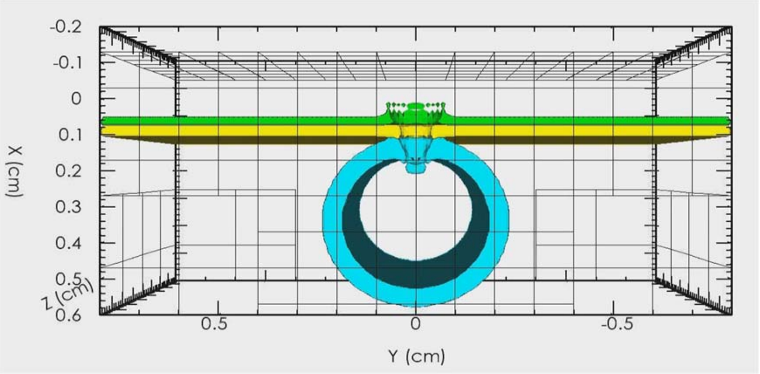
- **An impact occurred directly center on a doubler, which protects the radiator flow tubes from MMOD**
  - Impact crater penetrated through the thermal tape, completely through the 0.02” thick doubler, and damaged the facesheet below the doubler
  - Analysis indicates the same impact would have penetrated the flow tube if the doublers were not present
  - Doublers added in 1997-1999 time period, to provide additional protection for ISS missions
  - Conclusion: Doublers performed as designed/expected preventing a radiator tube puncture



MMOD impact into Radiator LH1 doubler protecting flow-tubes
Crater diameter = 0.8 mm
Crater depth = 0.58 mm
Doubler thickness = 0.51 mm



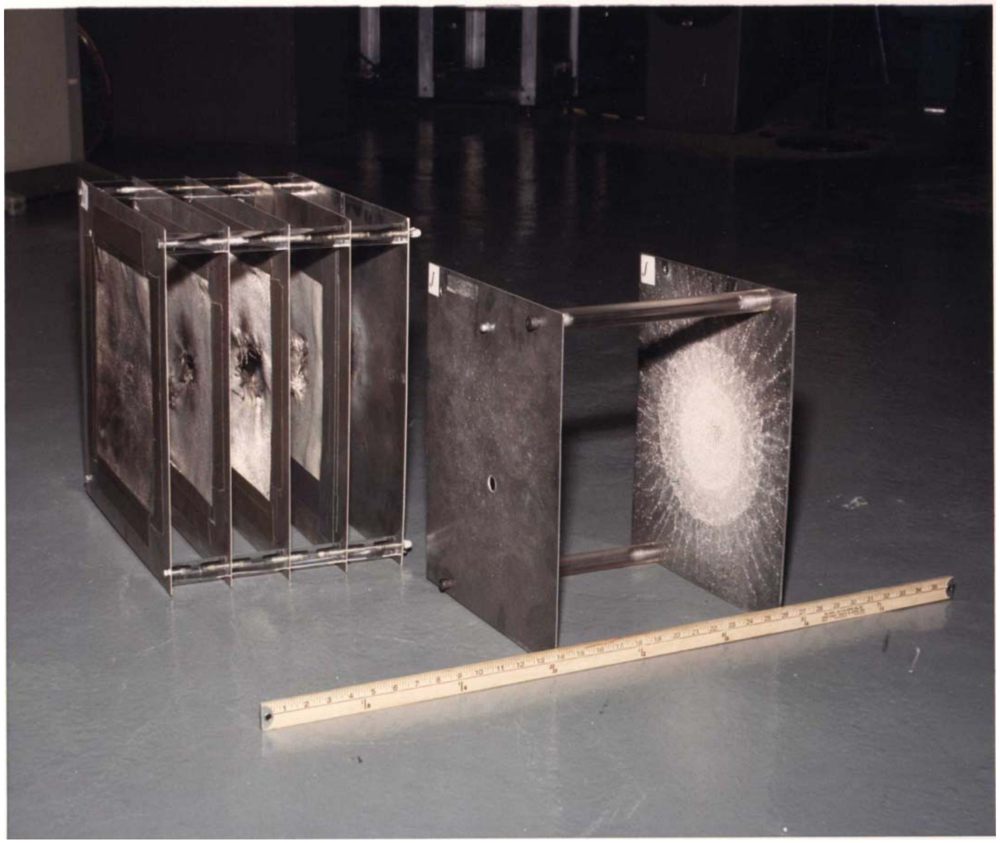
Simulation of impact after 2 micro-seconds <u>with doubler</u>: crater through thermal tape (green) and penetration nearly through doubler (red)…i.e., similar to actual damage.



Simulation of same impact after 2 micro-seconds <u>without doubler</u>: crater through thermal tape (green), through facesheet (yellow) and through flow tube wall (blue)…i.e., leak would have occurred without doubler.

Whipple and Stuffed Whipple Shields

- **A Whipple shield is a single, thin plate (bumper) used to break-up a high velocity particle before it strikes a critical spacecraft surface.**
  - Originally, designed for the meteoroid environment.
- **A stuffed-Whipple shield employs additional sheets of material to further absorb the energy of the fragmenting particle.**
  - Common interior materials are Kevlar and Nextel.

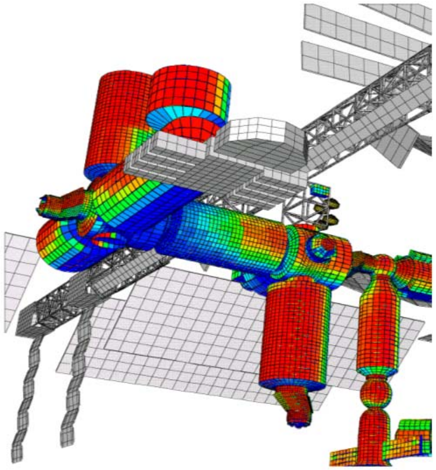


Whipple shield (right) and stuffed-Whipple shield (left).


TO RESCUE THE SATELLITE, I'LL NEED A SUIT LIKE IRON MAN'S TO PROTECT ME FROM SPACE DEBRIS.
METAL IS HARD TO WORK WITH.
brewrockit@yahoo.com www.gocomics.com/brewsterrockit
WELL, JUST MAKE IT OUT OF *SOMETHING* THAT WILL OFFER PROTECTION.
GOTCHA.
Richard
05/26 ©2010 Tribune Media Services, Inc. All rights reserved
THINK THE BUBBLE-WRAP WILL WORK?
"THINK" IS SUCH A STRONG WORD.

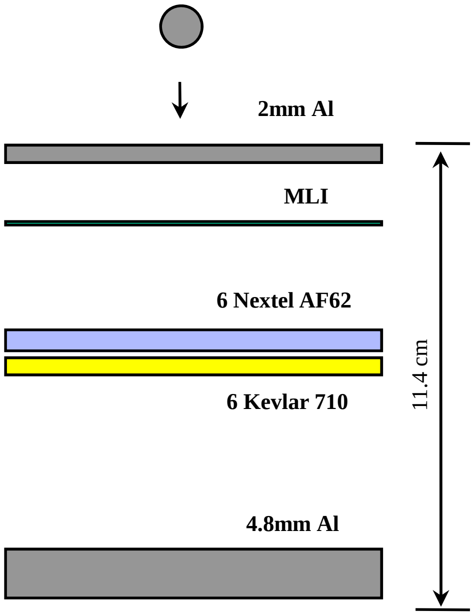
Protecting the International Space Station

- **The International Space Station is the most heavily protected space vehicle with more than 200 different types of shields to mitigate the effects of small particle hypervelocity impacts.**

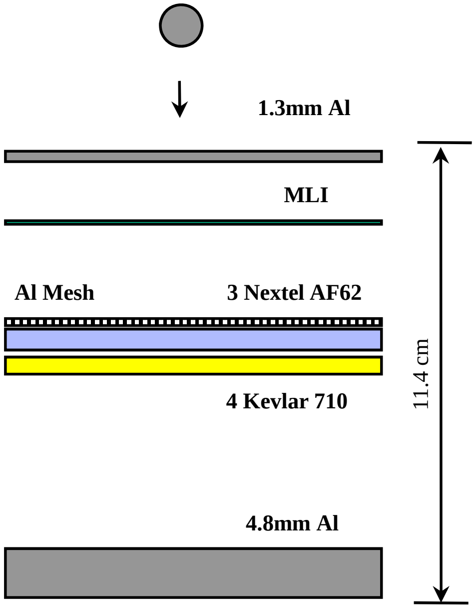


Sample ISS Stuffed Whipple Shields

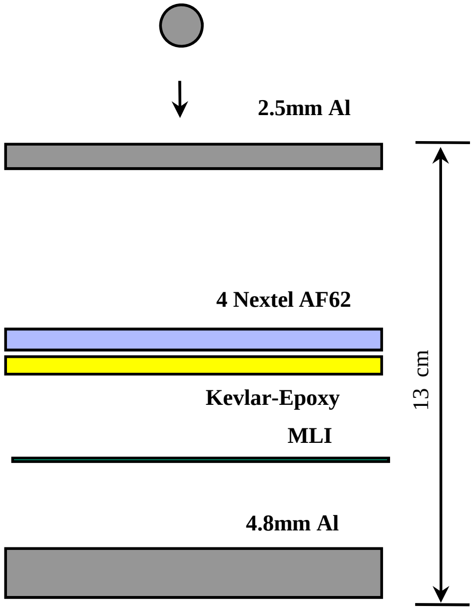
NASA



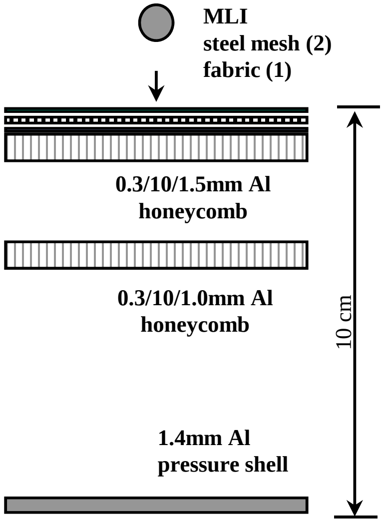
JAXA



ESA

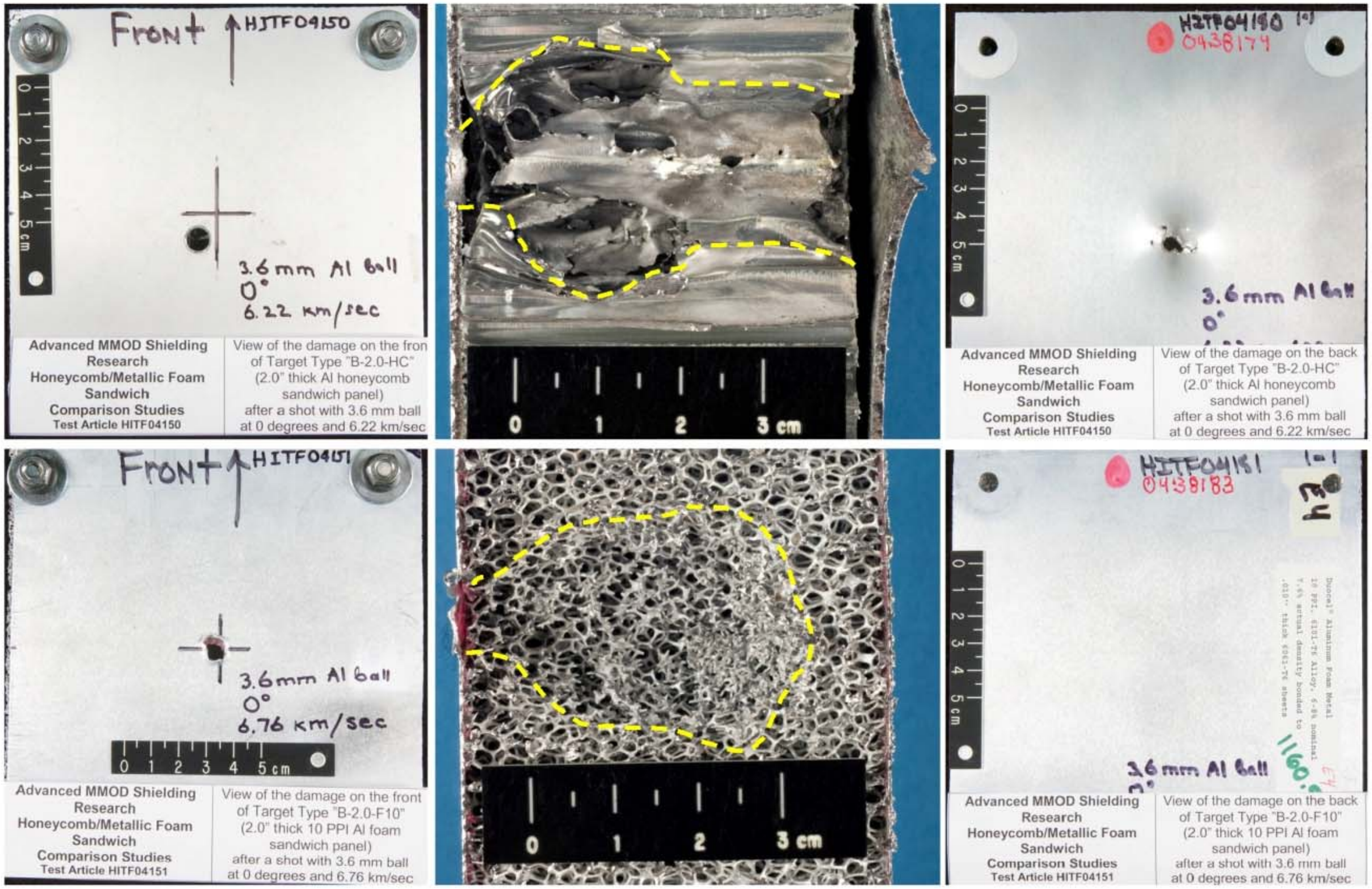


Russia



Advanced Orbital Debris Shielding Designs

- **Aluminum honeycomb and metallic foam Whipple shield fillers can provide even greater protection from hypervelocity particle impacts while also reducing total shield mass.**



Advanced MMOD Shielding Research
Honeycomb/Metallic Foam Sandwich
Comparison Studies
Test Article HITF04150

View of the damage on the fron of Target Type "B-2.0-HC" (2.0" thick Al honeycomb sandwich panel) after a shot with 3.6 mm ball at 0 degrees and 6.22 km/sec

Advanced MMOD Shielding Research
Honeycomb/Metallic Foam Sandwich
Comparison Studies
Test Article HITF04150

View of the damage on the back of Target Type "B-2.0-HC" (2.0" thick Al honeycomb sandwich panel) after a shot with 3.6 mm ball at 0 degrees and 6.22 km/sec

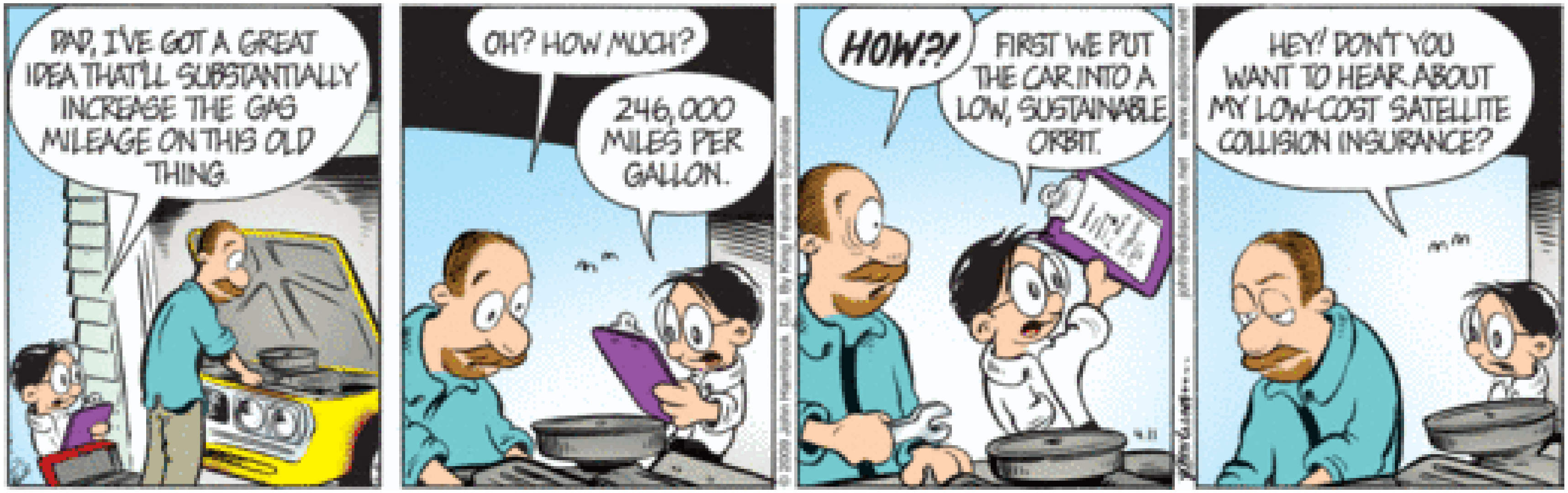
Advanced MMOD Shielding Research
Honeycomb/Metallic Foam Sandwich
Comparison Studies
Test Article HITF04151

View of the damage on the front of Target Type "B-2.0-F10" (2.0" thick 10 PPI Al foam sandwich panel) after a shot with 3.6 mm ball at 0 degrees and 6.76 km/sec

Duocel® Aluminum Foam Metal
10 PPI, 6101-T6 Alloy, 6-8% nominal
7.6% actual density bonded to
.010" thick 6061-T6 sheets

Advanced MMOD Shielding Research
Honeycomb/Metallic Foam Sandwich
Comparison Studies
Test Article HITF04151

View of the damage on the back of Target Type "B-2.0-F10" (2.0" thick 10 PPI Al foam sandwich panel) after a shot with 3.6 mm ball at 0 degrees and 6.76 km/sec


DAD, I'VE GOT A GREAT IDEA THAT'LL SUBSTANTIALLY INCREASE THE GAS MILEAGE ON THIS OLD THING.
OH? HOW MUCH?
246,000 MILES PER GALLON.
HOW?!
FIRST WE PUT THE CAR INTO A LOW, SUSTAINABLE ORBIT.
HEY! DON'T YOU WANT TO HEAR ABOUT MY LOW-COST SATELLITE COLLISION INSURANCE?
© 2009 John Hambrock Dist. by King Features Syndicate

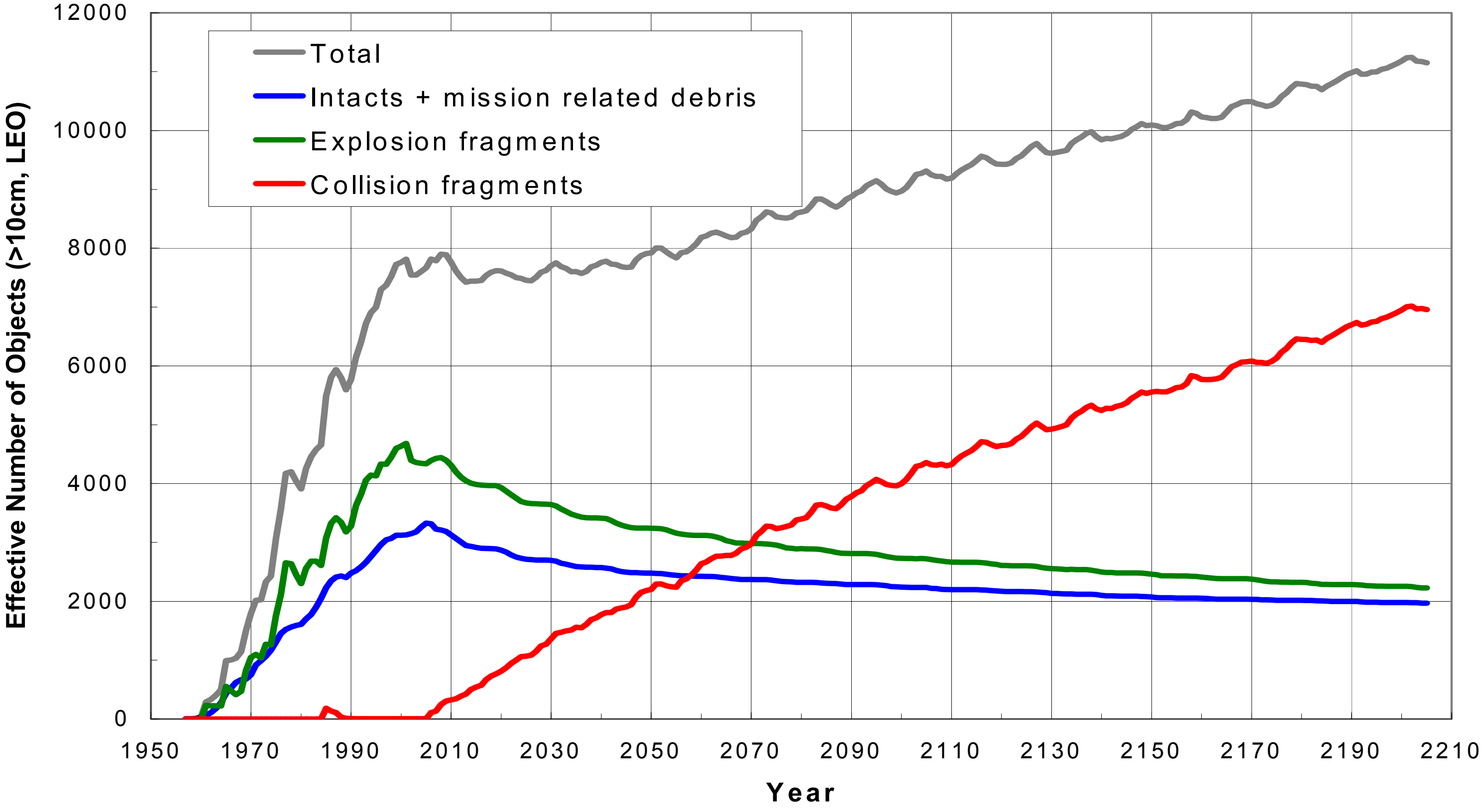
Future Growth of the Orbital Debris Environment

Orbital Debris Program Office
NASA Johnson Space Center

Instability of the Current LEO Populations
(<u>no new launches</u> beyond 2006)

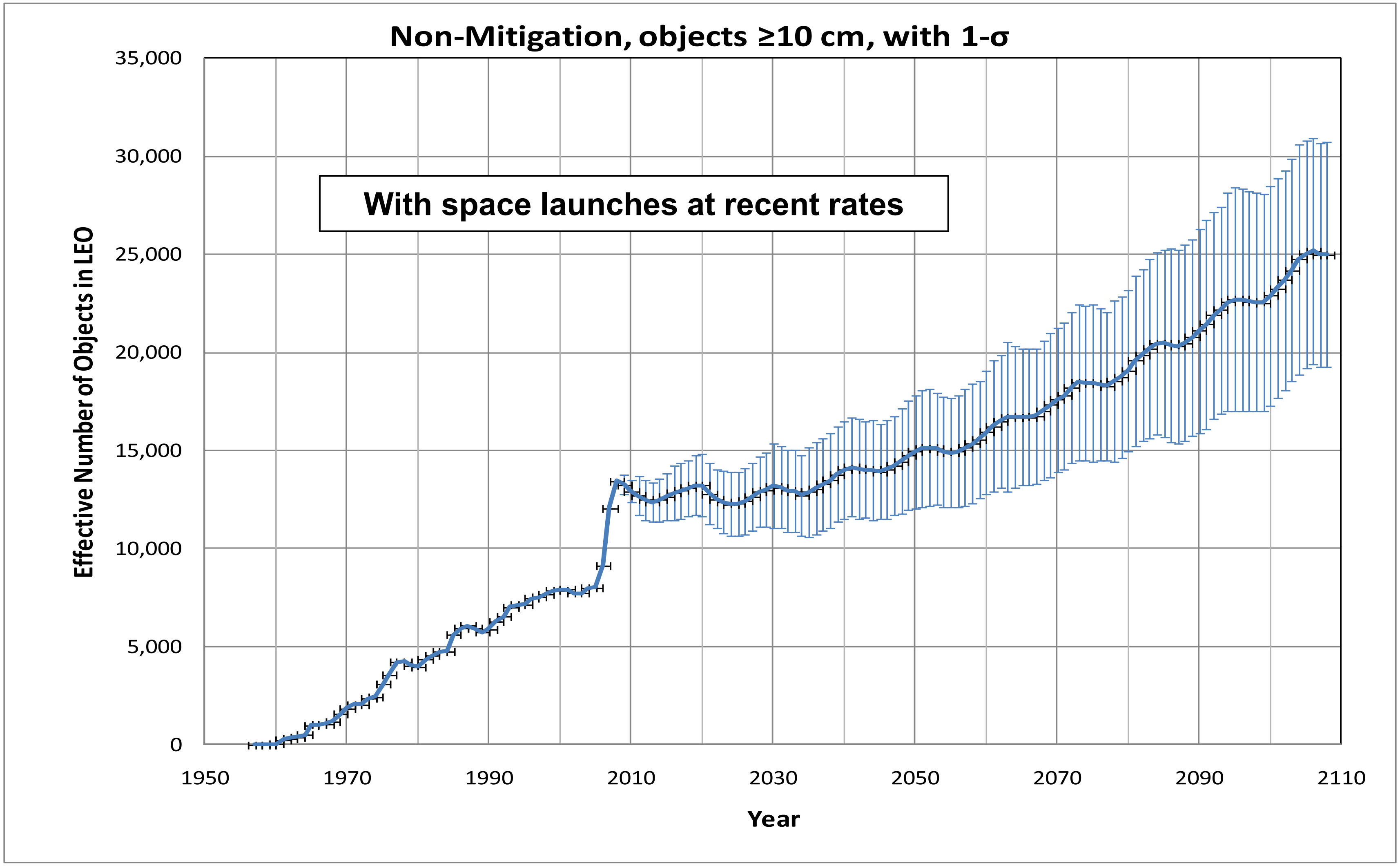
- "The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future"

— Liou and Johnson, ***Science***, 20 January 2006



Revised Projection in 2009

- **The effects of the Chinese ASAT test in 2007 and the collision of Iridium 33 and Cosmos 2251 in early 2009 made matters much worse.**



Future Environment Modeling Objectives

- **Evaluate the future debris population growth in the low Earth orbit (LEO) region under specified scenarios.**
- **Demonstrate the effectiveness of the commonly-adopted mitigation measures and active debris removal.**
- **Quantify the relative benefits of active debris removal in LEO to future space systems.**

Tool for the Study - LEGEND

- **LEGEND, a LEO-to-GEO Environment Debris model, is a high fidelity 3-D model developed by the NASA Orbital Debris Program Office**
  - Uses a deterministic approach to simulate the historical debris environment based on recorded launches and breakups
  - Uses a Monte Carlo approach and a reliable collision probability evaluation algorithm to simulate the future debris populations
  - Future debris environment is analyzed based on specified traffic cycle, postmission disposal, and active debris removal options

- **References in peer-reviewed journals:**
  - Liou, J.-C., *et al., Adv. Space Res*. **34**, 2004.
  - Liou, J.-C., *Adv. Space Res.* **38**, 2006.
  - Liou, J.-C. and Johnson, N.L., *Science* **311**, 2006.
  - Liou, J.-C., *Acta Astronautica* **62**, 2008.
  - Liou, J.-C. and Johnson, N.L., *Acta Astronautica* **64**, 2009.
  - Liou, J.-C., *et al., Acta Astronautica*, **66**, 2010.

Study Scenario Types

- **Non-Mitigation (NoM):**
  - 1957 to 2009 + 100 years future projection
- **Post-Mission Disposal (PMD):**
  - Move rocket bodies (R/Bs) to 25-year decay orbits or above-LEO collection orbits (depending on ΔV requirement) after launch
  - Move spacecraft (S/C) to 25-year decay orbits or above-LEO collection orbits (depending on ΔV requirement) after 8 years of mission lifetime
  - Set postmission disposal success rate to 90%
- **Active Debris Removal (ADR):**
  - Start active removal in 2020
  - Remove objects with the greatest [mass × P_c] product, where P_c is the instantaneous collision probability at the beginning of the year

Scenarios Examined

- **Eight scenarios were completed for the study:**
  - ☐ NoM
  - ☐ NoM + ADR02
  - ☐ NoM + ADR05
  - ☐ NoM + ADR10
  - ☐ PMD
  - ☐ PMD + ADR02
  - ☐ PMD + ADR05
  - ☐ PMD + ADR10

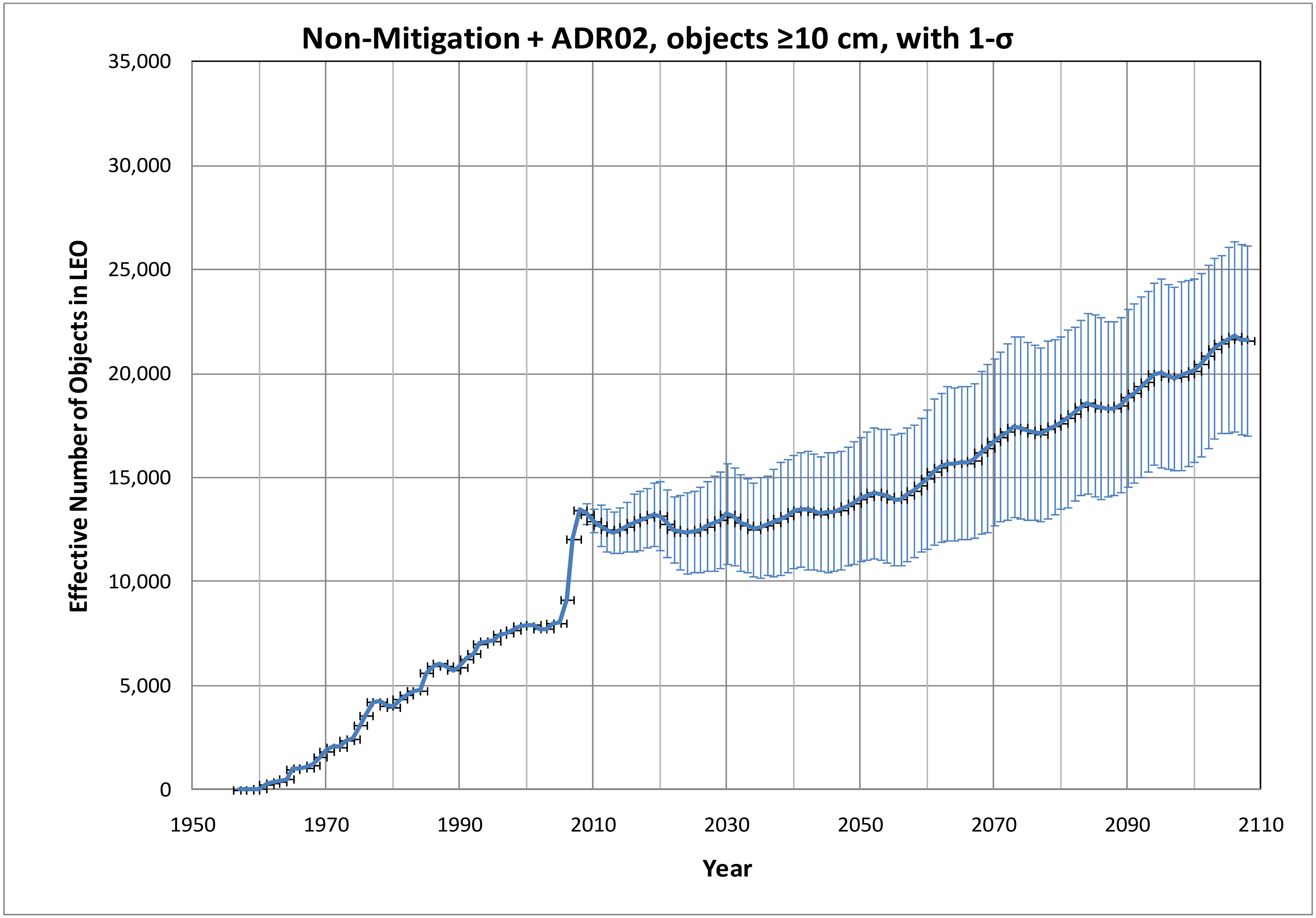
ADR02 = 2 objects removed annually

ADR05 = 5 objects removed annually

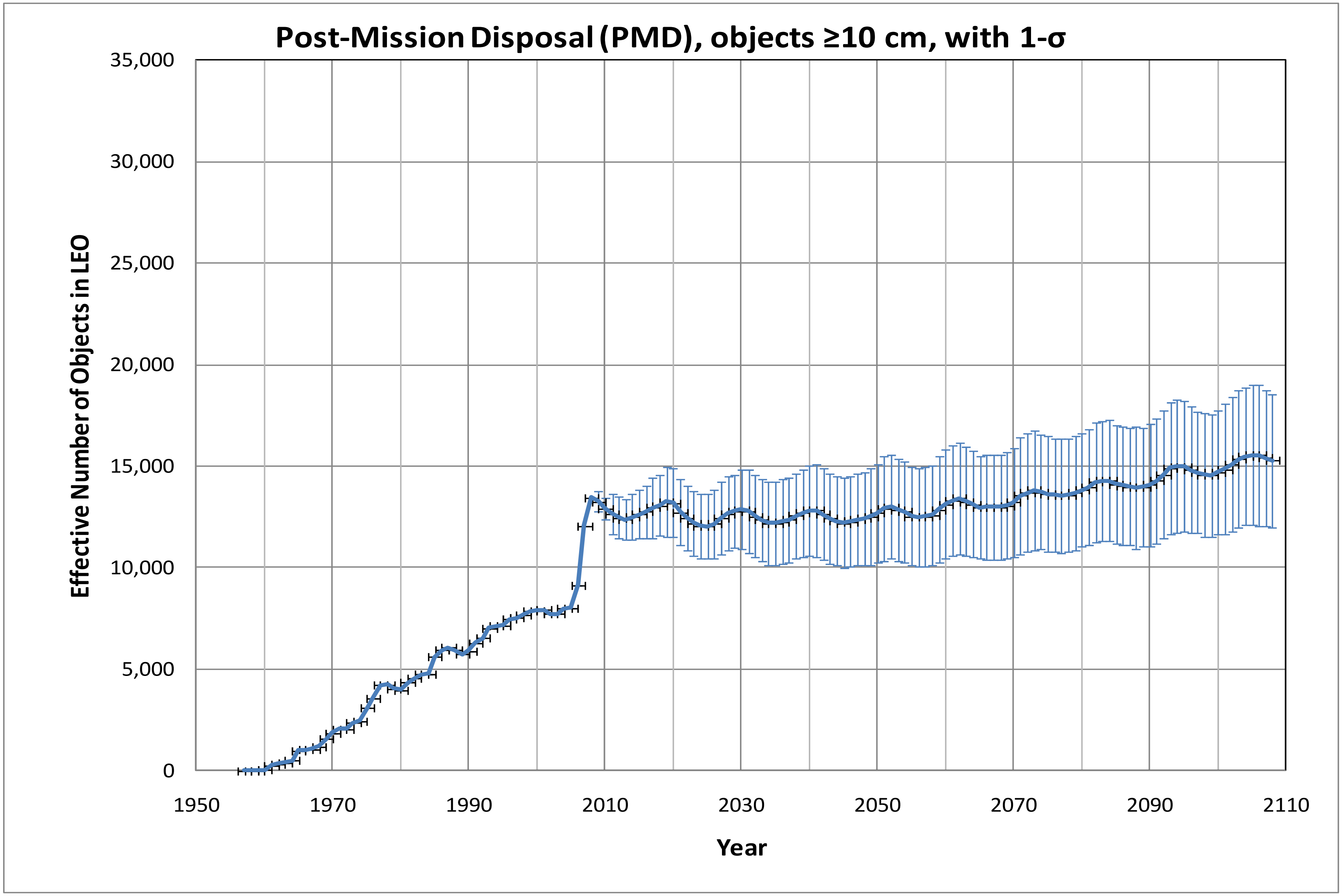
ADR10 = 10 objects removed annually

- **Evaluated 5 mm, 1 cm, and 10 cm populations.**

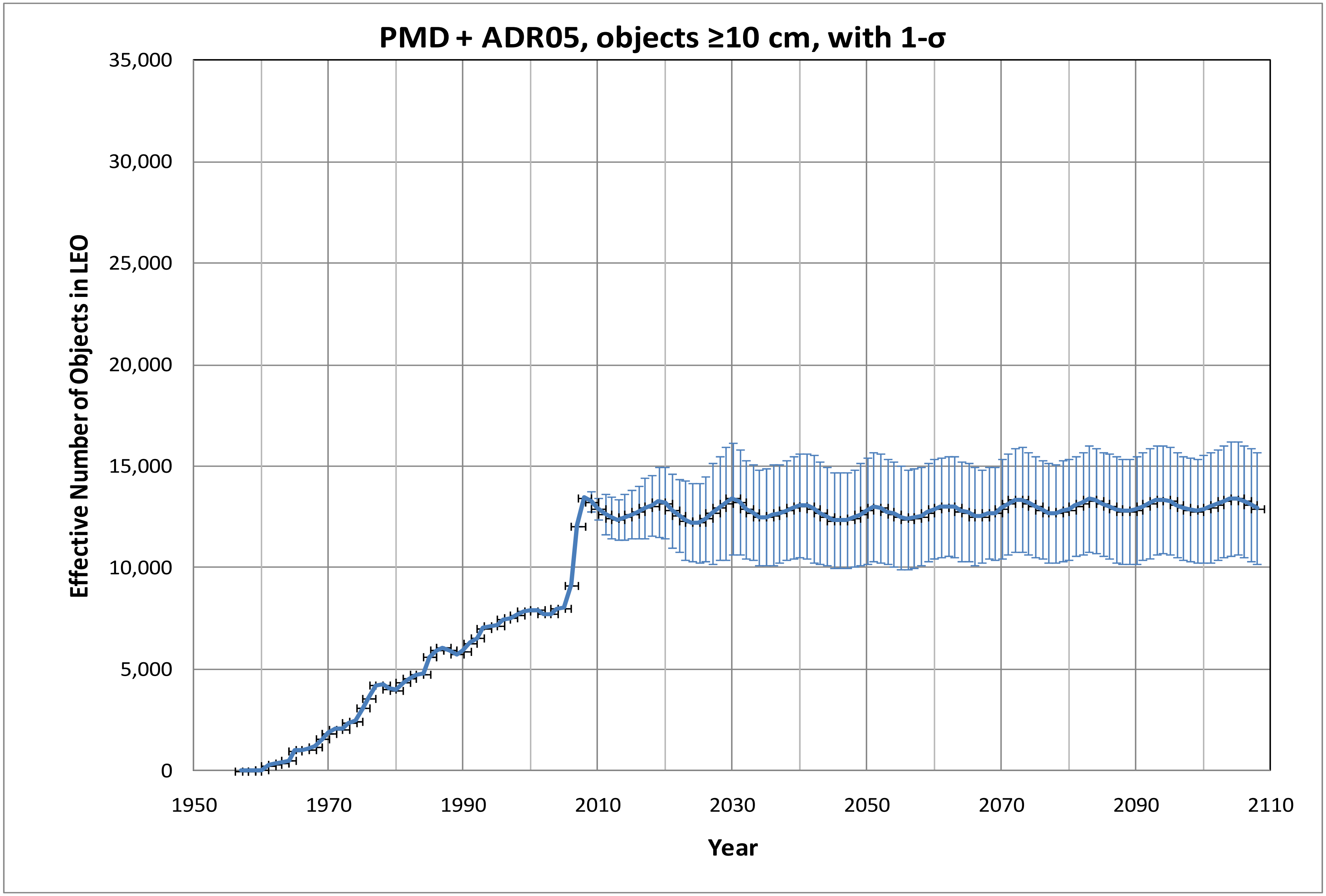
Active Debris Removal with No Mitigation



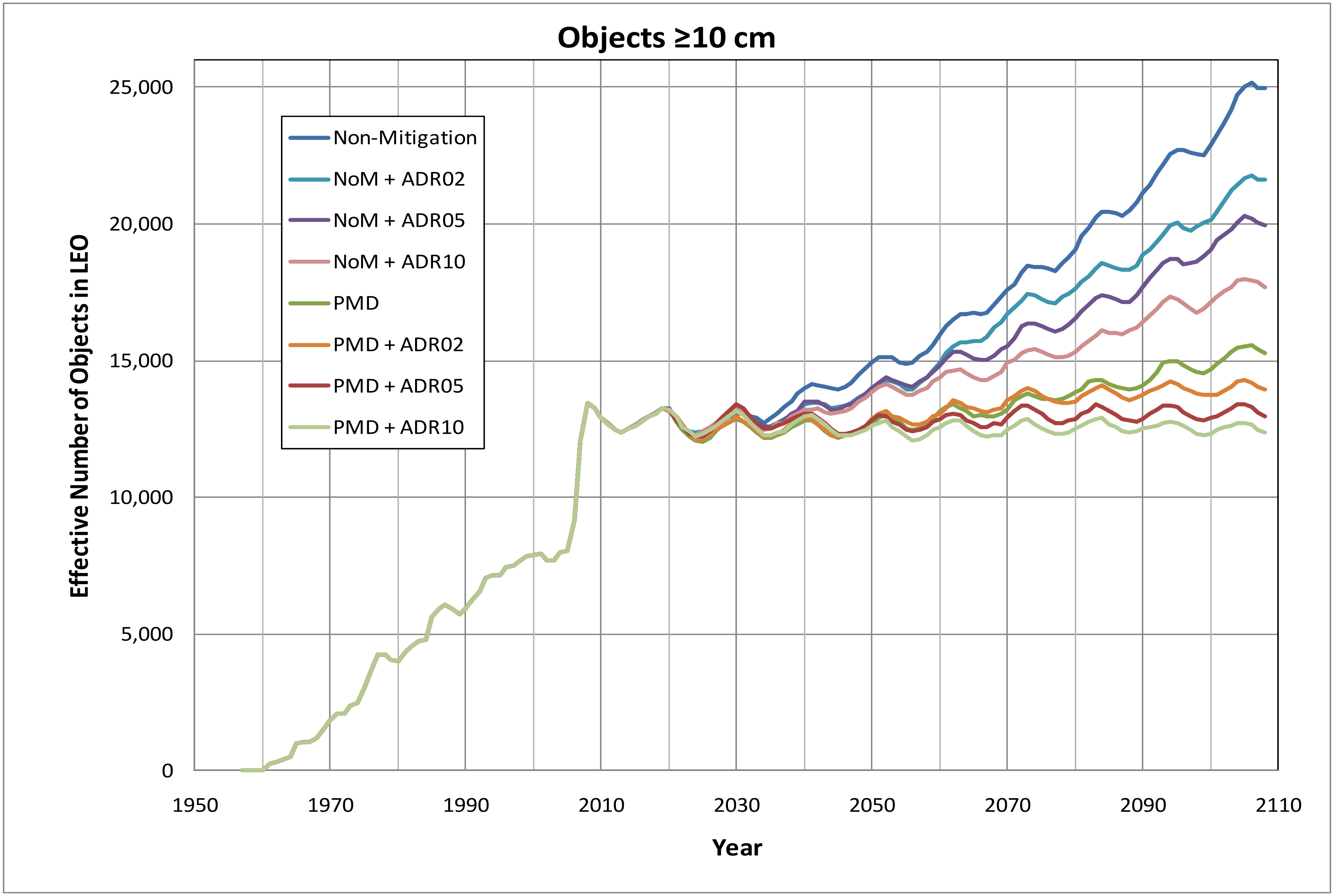
Post-Mission Disposal Only



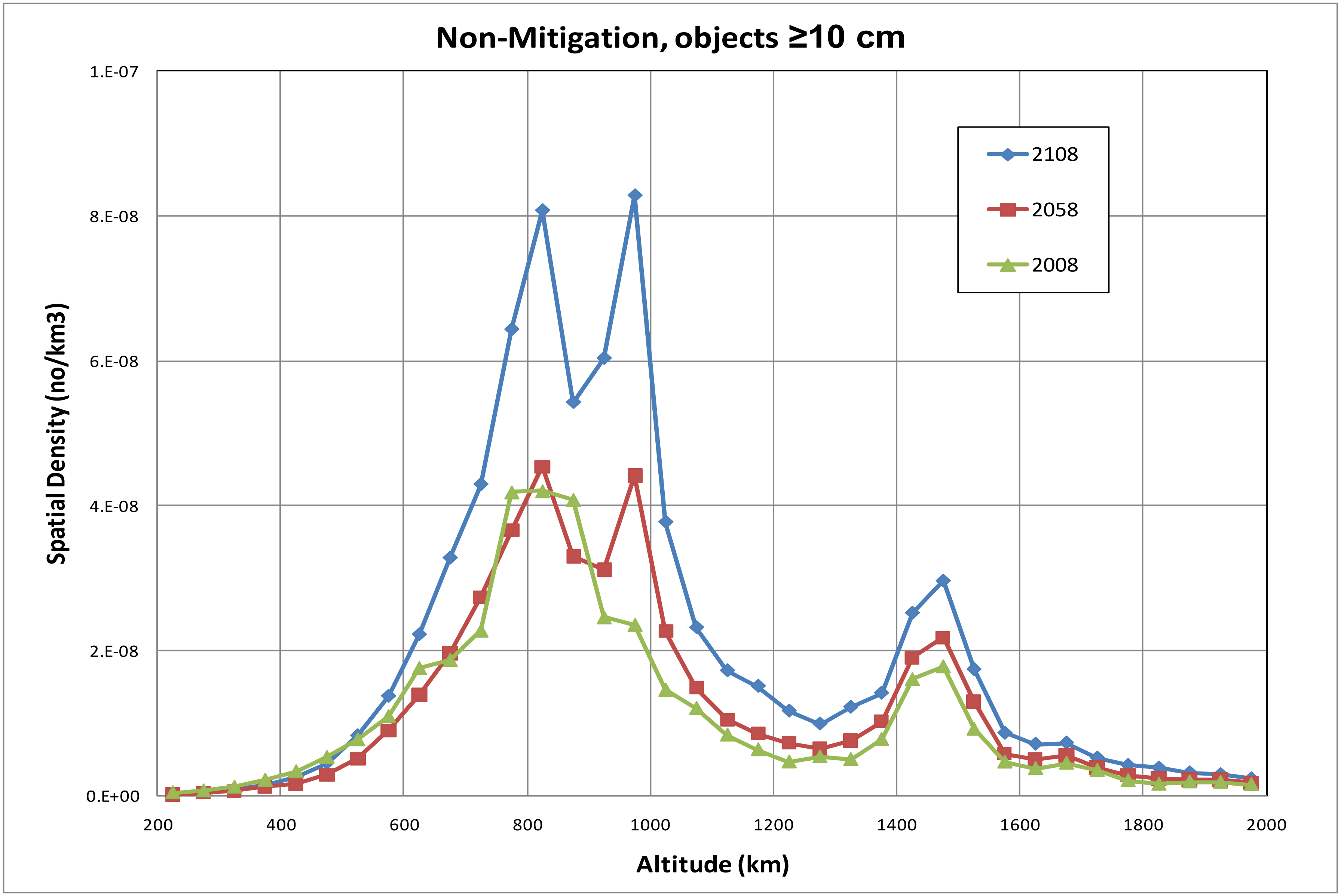
Active Debris Removal with PMD



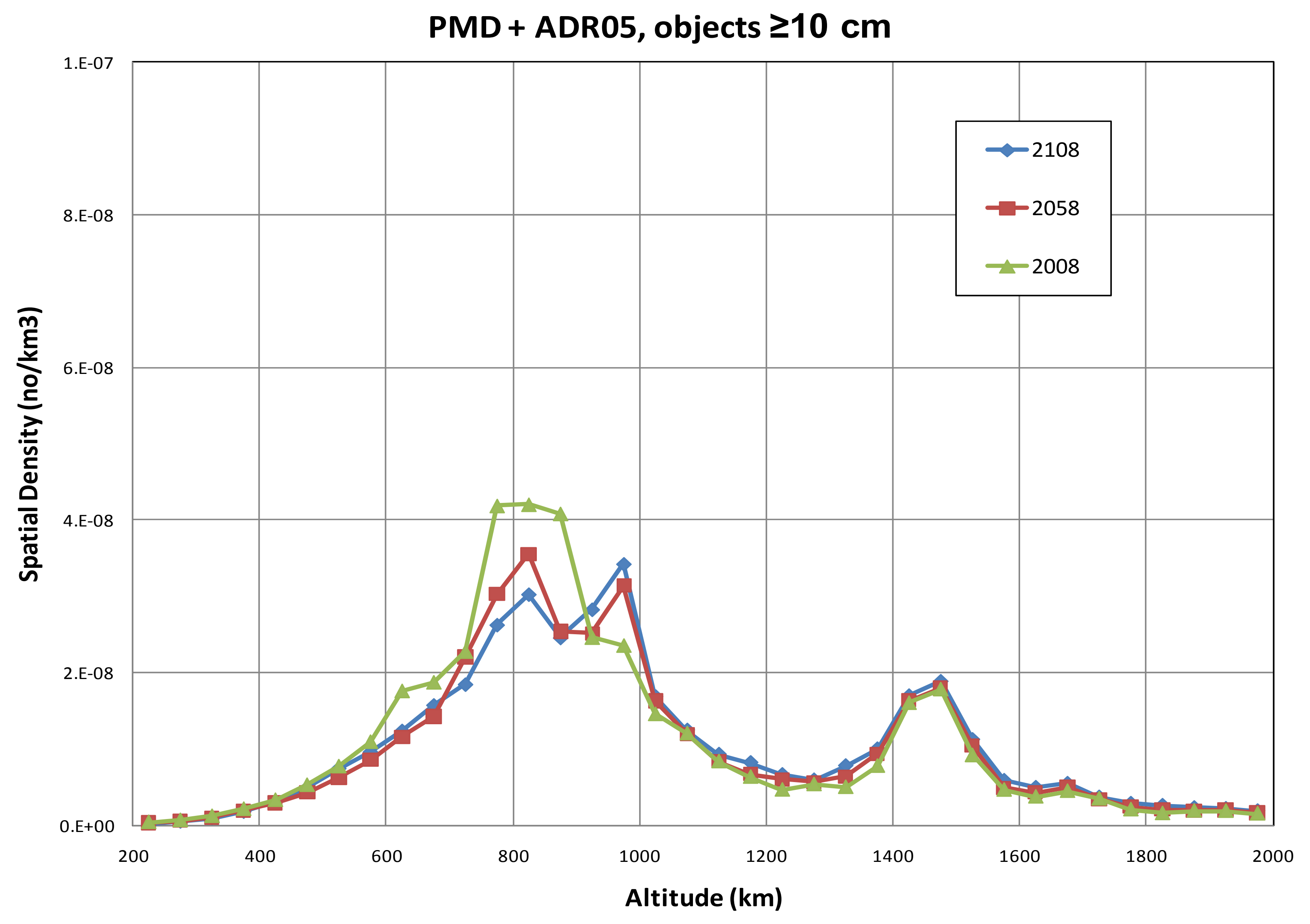
Collected Scenarios



Spatial Density with No Mitigation



Spatial Density with ADR05 + PMD



General Summary of Analysis

- **The resident space object population only remains stable with either scenario PMD + ADR05 or PDM + ADR10 for all three size regimes examined.**
  - The rate of population growth is non-linear for all other scenarios.
- **With no mitigation and no active debris removal, the resident space object population increases by a factor of 2 - 2.2 for all size regimes over the simulated period.**
- **The principal risk to operational space systems arises from the population of particles 5 mm or greater, which is two orders of magnitude greater than the cataloged (> 10 cm) population.**

Space Object Removal

Debris Removal Concept Principles

- **Must be technically feasible in the near-term.**
- **Must be economically viable.**
  - Affordable
  - Acceptable cost-benefit ratio
- **Must result in a meaningful improvement of the current or future near-Earth space environment.**

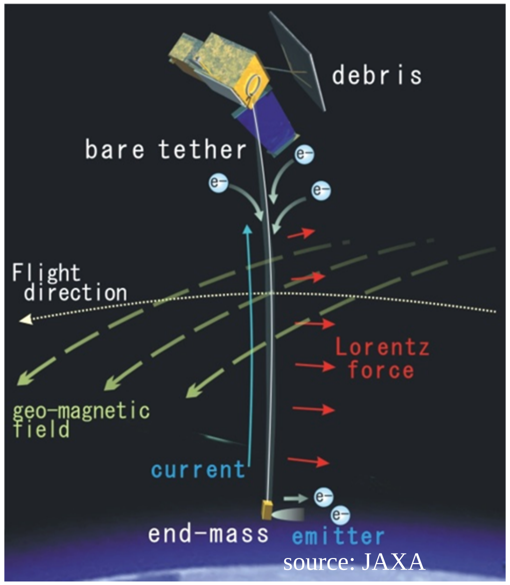
Debris Removal Categories

- **Debris removal concepts are often categorized by**
  - The size of the debris to be removed: typically < or > 10 cm (statistical or designated removal)
  - The altitude regime of removal: LEO, MEO, or GEO
  - The basing of the removal device: ground-based, air-based, or space-based
- **Removal of small debris normally affects the near-term environment by reducing collision probabilities for existing space systems, e.g., cleansing human space flight altitude regimes.**
- **Removal of large debris influences the mid-term and far-term environments by reducing the number of debris-generating collisions.**

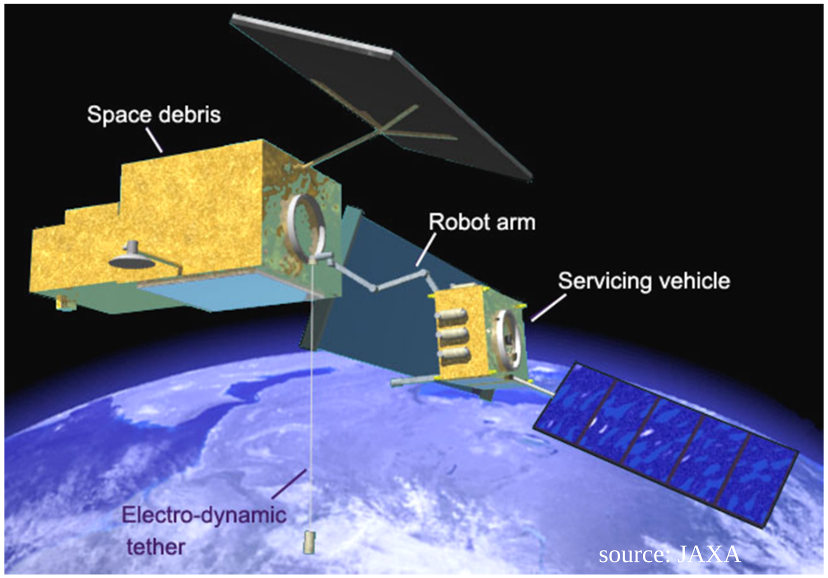
Sample of Debris Removal Concepts

Debris Removal Technique	Altitude Regime	Debris Size Regime
Ground-based Laser/Directed Energy	LEO	< 10 cm
Airborne Laser/Directed Energy	LEO	< 10 cm
Space-based Laser/Directed Energy	LEO, MEO, GEO	< 10 cm
Space-based Magnetic Field Generator	LEO	< 10 cm
Drag Augmentation Device	LEO	> 10 cm
Solar Sail	LEO, MEO, GEO	> 1 m
Magnetic Sail	LEO, MEO, GEO	> 1m
Momentum Tethers	LEO, GEO	> 10 cm
Electrodynamic Tethers	LEO	> 10 cm
Capture/Orbital Transfer Vehicle	LEO, MEO, GEO	> 1 m
Attachable Deorbit/Reorbit Module	LEO, MEO, GEO	> 1 m
Sweeping/Retarding Surface (balloon, film, foam ball, etc.)	LEO	< 10 cm

Mass Removal through Conductive Tethers



source: JAXA



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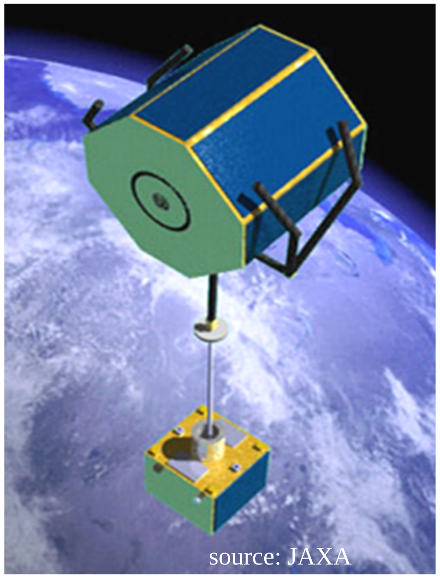
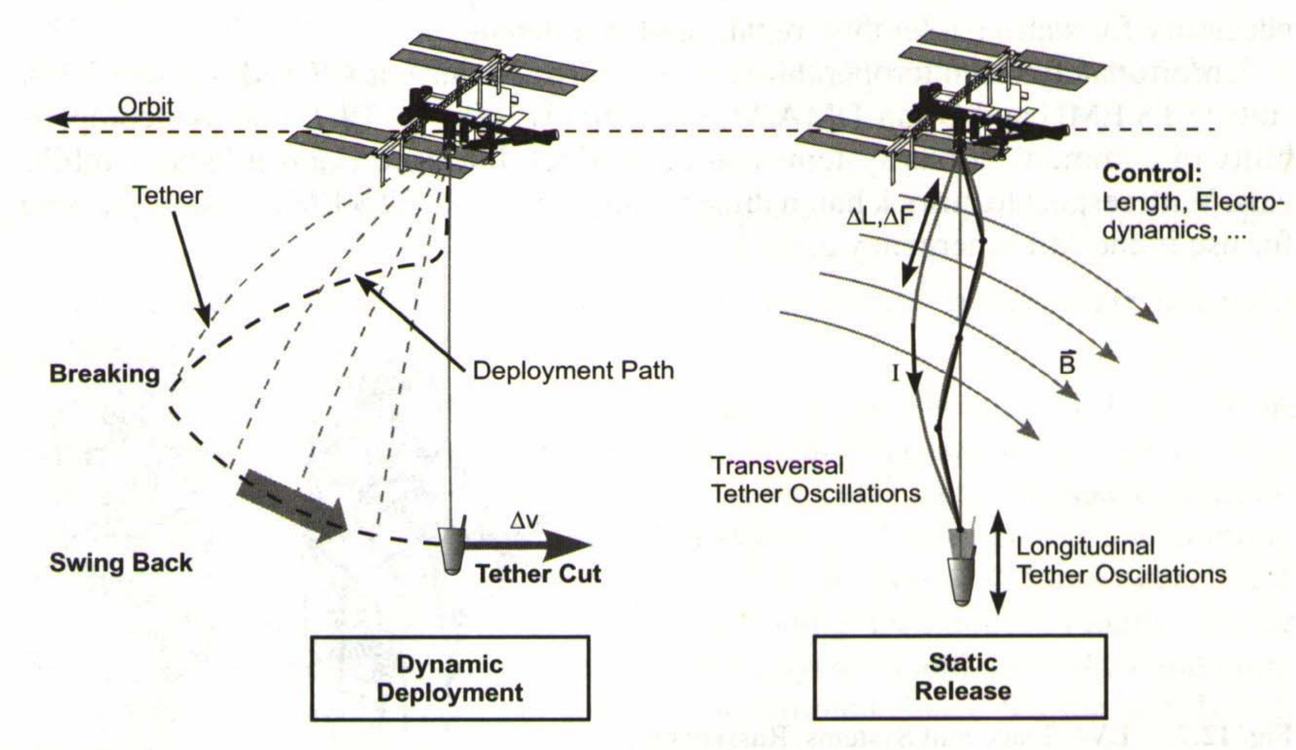


source: JAXA

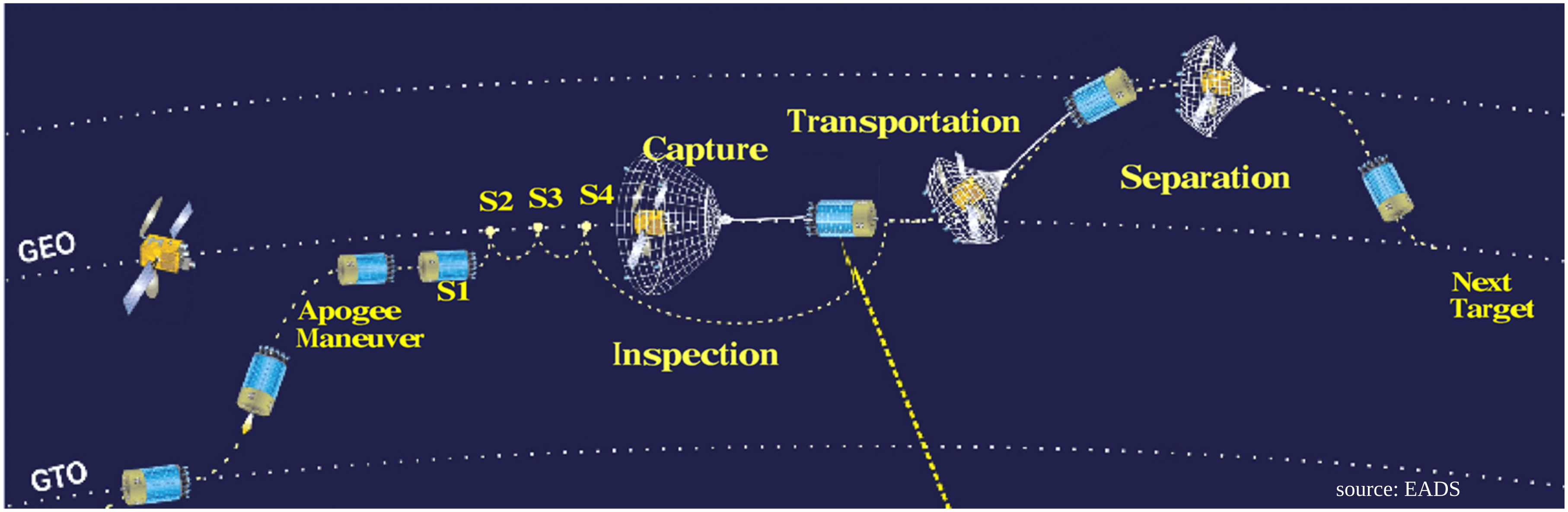
- **Principle ➡ attach a conductive tether & end-mass to a target object; deploy the tether to de-orbit the target via a retarding Lorentz force**
- **Pro ➡ effective for large de-orbit masses within LEO**
- **Con ➡ complex and costly launch, rendezvous, attachment, and deployment operations; tethers are vulnerable to space debris and other resident space objects, including operational satellites.**

Mass Removal through Momentum Tethers



- **Principle ➡ dynamic relase (allow in-plane tether oscillation; cut tether at lowest point during swing-back); static release (maintain tether near local vertical; cut tether at termination altitude) ; more de-orbit ΔV obtained for dynamic release; the active spacecraft could be a sufficiently sized vehicle**
- **Pro ➡ potentially effective for large de-orbit masses**
- **Con ➡ complex and costly launch, rendezvous, attachment, and deployment operations; significant tether loads**

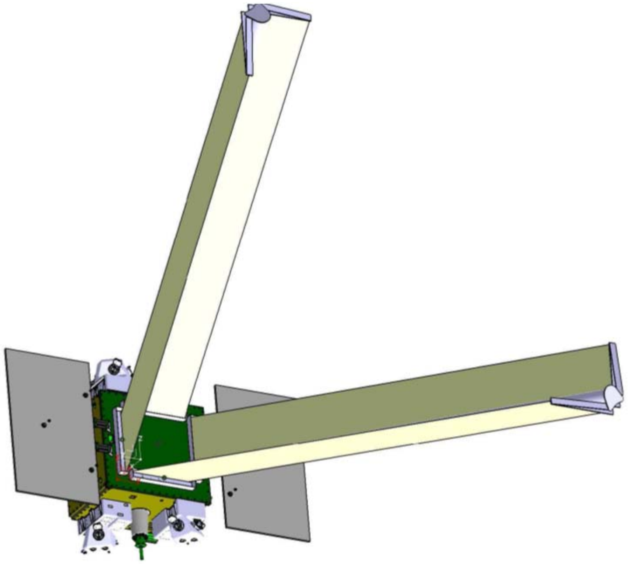
Mass Removal through Space Tugs



source: EADS

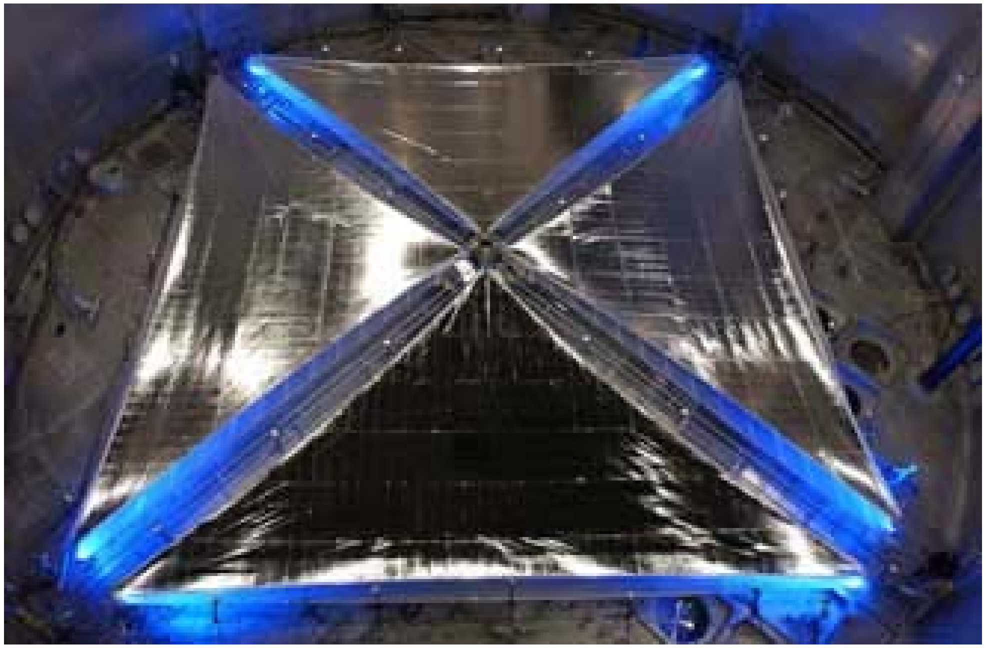
- **Principle ➨ deploy a tethered capture device (net or grapple fixture); move the compound to a disposal orbit; cut tethered attachment; perform the next rendezvous with another GEO object (ROGER concept)**
- **Pro ➨ effective for large (GEO) objects; multi-target capability**
- **Con ➨ complex and costly launch, rendezvous, and capture operations; potential limitations for non-GEO orbits and for rotating or tumbling target objects**

Mass Removal through Drag Augmentation



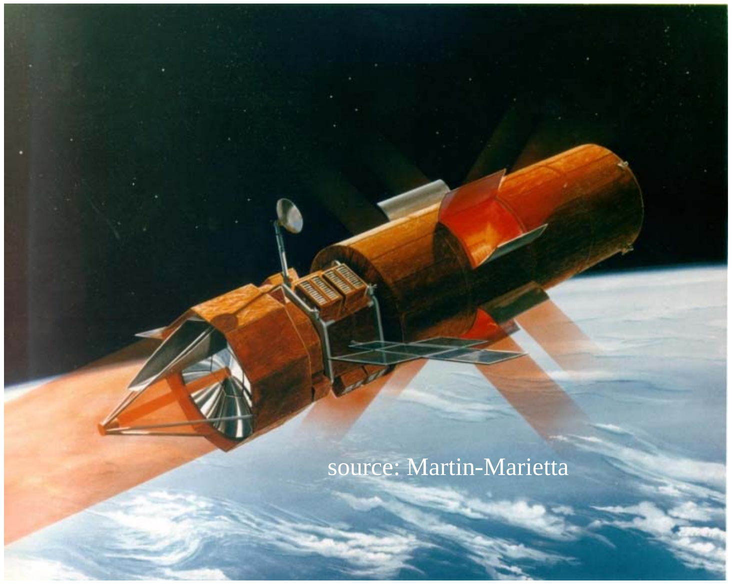
- **Principle ➡ deploy a drag augmentation device to increase aerodynamic cross-section, reducing the orbit lifetime; orbit lifetime scales linearly with $A_o/(A_o + A_{aug})$**
- **Pro ➡ potentially low mass, low-cost system; can be part of the spacecraft design for new spacecraft and launch vehicle stages**
- **Con ➡ collision cross-section scales linearly with $(A_o + A_{aug})/A_o$; efficiency decreases exponentially with increasing orbit altitude; complex and costly launch, rendezvous, and attachment operations for existing resident space objects**

Mass Removal through Solar Sails

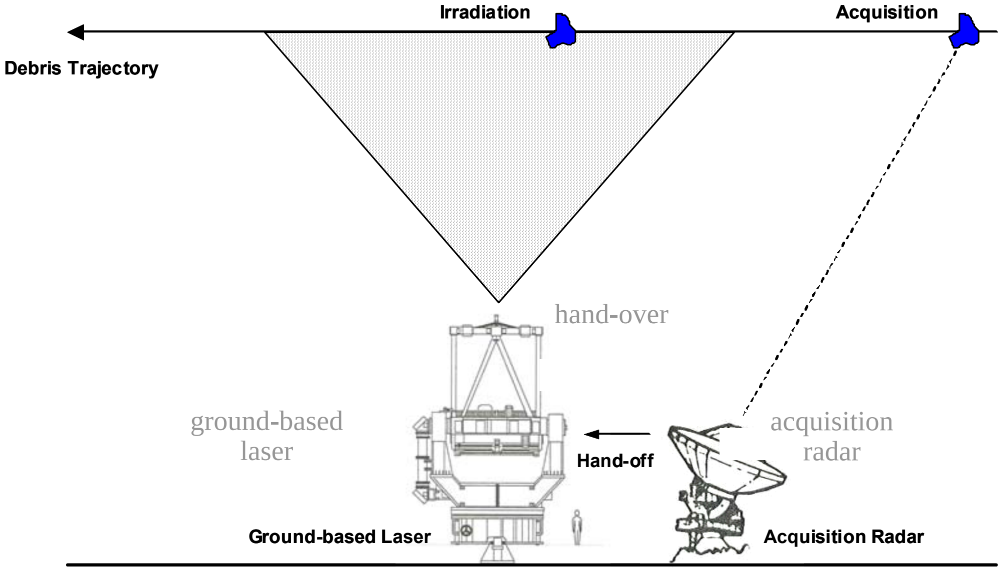


- **Principle ➨ deploy a solar sail (or reflective balloon) to combine effects of radiation pressure & aerodynamic drag, reducing the orbit lifetime**
- **Pro ➨ potentially low-mass, low-cost system; can be part of the spacecraft design for new spacecraft and launch vehicle stages; could be applicable at altitudes higher than drag augmentation alone**
- **Con ➨ collision cross-section scales linearly with $(A_o + A_{sol})/A_o$; complex and costly launch, rendezvous, and attachment operations for existing resident space objects; requires controlled attitude for greatest efficiency**

Mass Removal through Laser Technologies



source: Martin-Marietta



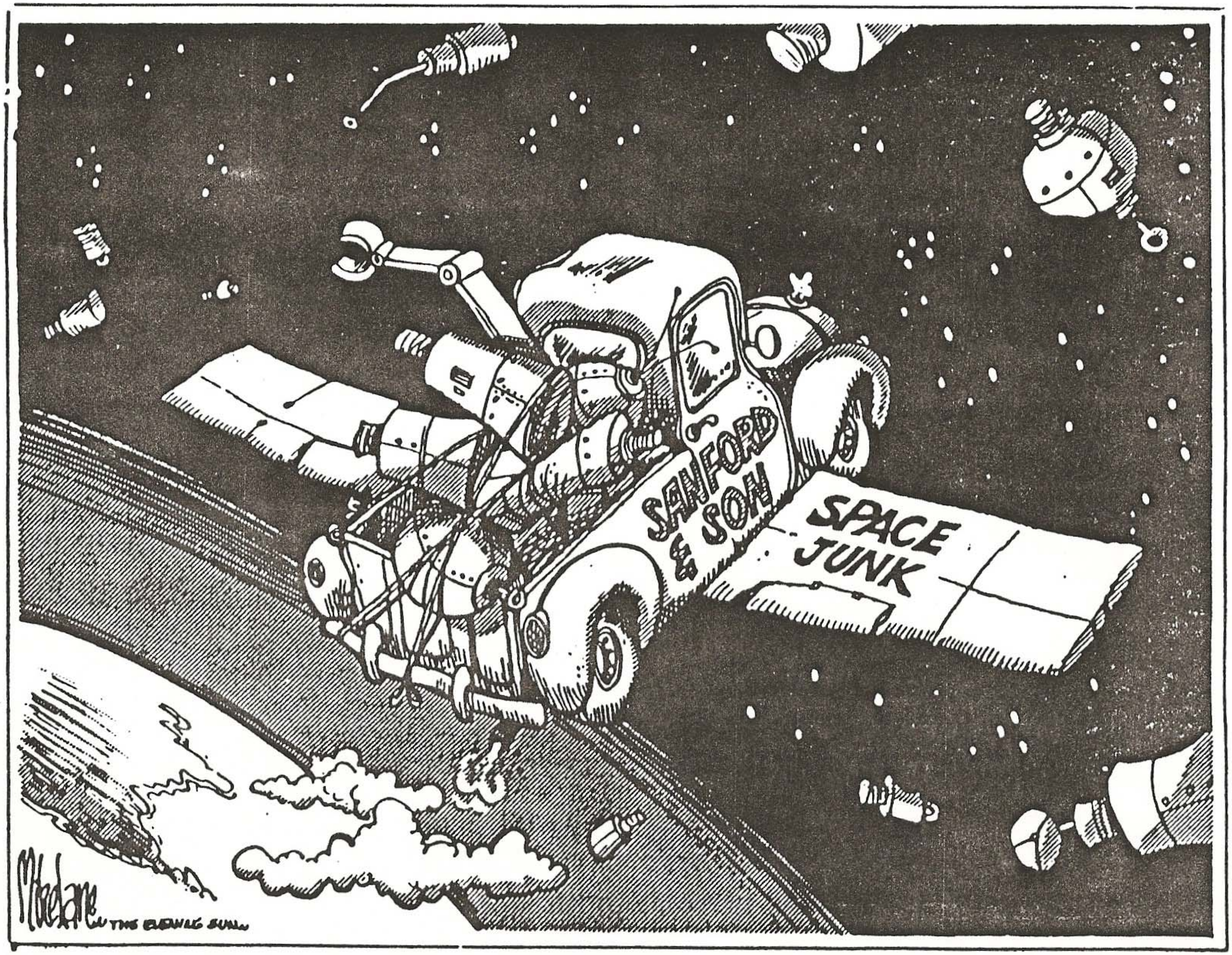
- Principle ➡ lock on to an orbital debris with ground-, air-, or space-based lasers; vaporize the target or parts thereof to cause a thrust to change the orbit and reduce its lifetime
- Pro ➡ potentially could remove a large number of small debris
- Con ➡ issues of arms control (for ground- and air-based lasers) and UN treaties (for space-based lasers); requirements on pointing accuracy and lock-on control; power demands (for air-/space-based) and atmospheric attenuation (for ground-based); debris size limitations

Other Sample Debris RemediationTechniques

- **Solid rocket propulsion modules:**
  - Principle ➡ attach in rendezvous operation; use for spin-up and de-orbit or re-orbit of the target object
  - Pro ➡ good fuel efficiency and system robustness; large ΔV
  - Con ➡ complex and costly launch and rendezvous; problems of mounting the module on unprepared targets; line of thrust

- **Magnetic sails:**
  - Principle ➡ attach in rendezvous operation; deploy as a loop of super-conducting material; the magnetic field created by a current interacts with the solar wind, producing a ΔV ~ area × current
  - Pro ➡ simple design; efficient also at high altitudes
  - Con ➡ complex and costly launch , rendezvous and attachment operations; needs electric power supply; efficiency decreases with $1/r^4$

- **Sweeping/momentum retarding surfaces:**
  - Principle ➡ induce a -ΔV on an impacting debris object, causing a loss of orbital energy and orbit lifetime reduction
  - Pro ➡ simple principle
  - Con ➡ costly launch; requires large cross-section to be effective; risk of collision with large resident space objects


SANFORD & SON
SPACE JUNK
THE EVENING SUN

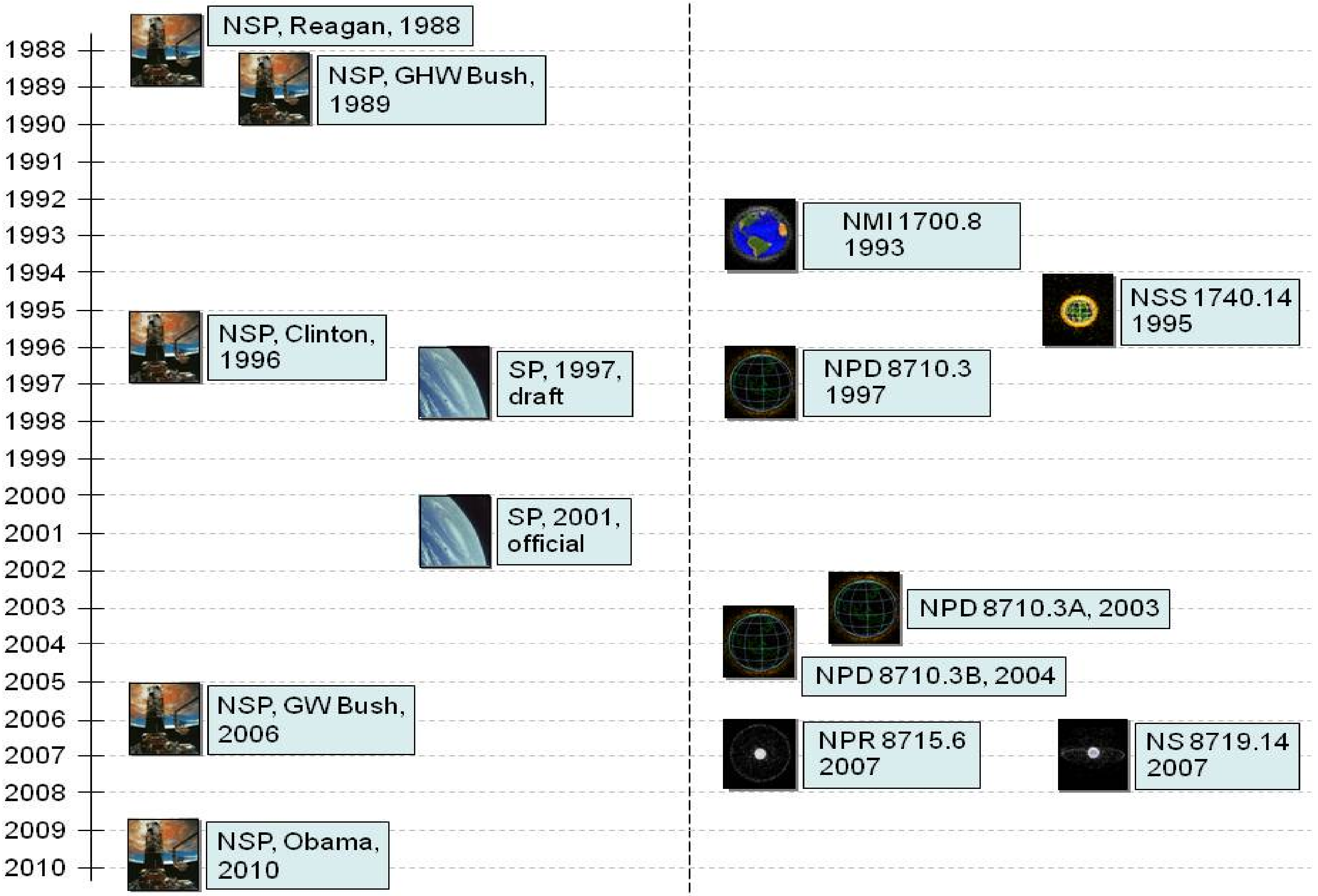
National and International Orbital Debris Mitigation Policies and Guidelines

Orbital Debris Program Office
NASA Johnson Space Center

Overview

- **Overview of NASA HQ OD Mitigation Documents**
- **U.S. National Policies and Regulations**
- **Inter-Agency Space Debris Coordination Committee (IADC)**
- **United Nations**
- **Foreign National Space Debris Mitigation Guidelines**
- **European Code of Conduct for Space Debris Mitigation**
- **International Academy of Astronautics (IAA)**
- **International Standards Organization (ISO)**

Evolution of U.S. and NASA Orbital Debris Mitigation Policies and Requirements



U.S. Orbital Debris Mitigation Policy and Standard Practices

- NSP, Reagan, 1988
- NSP, GHW Bush, 1989
- NSP, Clinton, 1996
- SP, 1997, draft
- SP, 2001, official
- NSP, GW Bush, 2006
- NSP, Obama, 2010

NASA Debris Mitigation Policy and Requirements

- NMI 1700.8 1993
- NSS 1740.14 1995
- NPD 8710.3 1997
- NPD 8710.3A, 2003
- NPD 8710.3B, 2004
- NPR 8715.6 2007
- NS 8719.14 2007

NASA Policy for Limiting Orbital Debris Generation

- **The first NASA HQ guidance on orbital debris mitigation was issued as NASA Management Instruction 1700.8 (5 Apr 1993).**
- **NASA Policy Directive 8710.3 superseded NMI 1700.8 in May 1997.**
- **NASA Procedural Requirements 8715.6 superseded NPD 8710.3 in August 2007; current version is NPR 8715.6A (14 May 2009) and it requires each program/project to:**
  - Prepare formal orbital debris mitigation assessments and end-of-mission plans at specified milestones
  - Design for safe disposal of spacecraft and launch vehicles at end of mission
  - Promote the adoption of international policies, standards, and practices to minimize OD and its associated risks, and the exchange of information on OD research, modeling, and mitigation techniques in the international community

NASA Orbital Debris Mitigation Requirements

- **NASA Safety Standard 1740.14 (1 August 1995) established the first detailed set of orbital debris mitigation guidelines for each NASA program and project.**

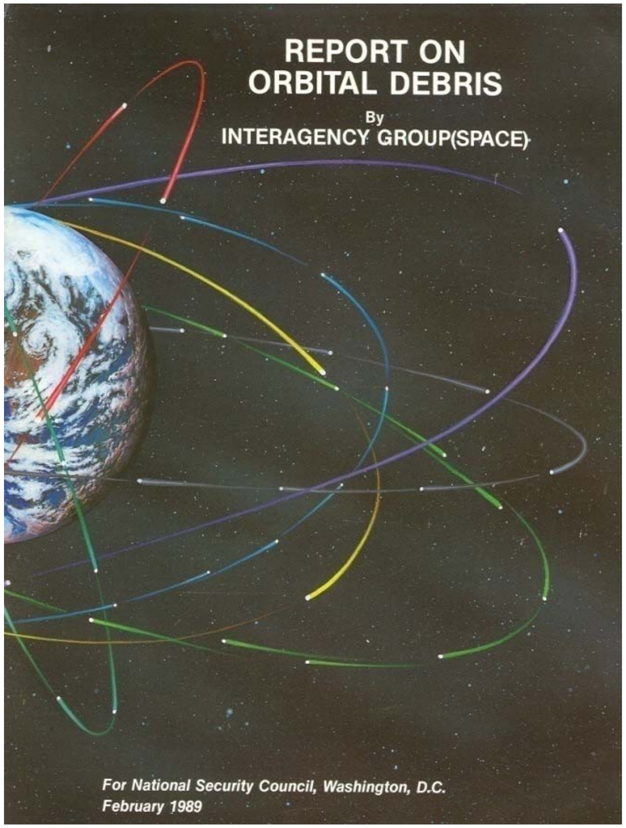
- **NSS 1740.14 was superseded by NASA Technical Standard 8719.14 in August 2007 to accompany new NPR 8715.6. Current version is NS 8719.14A (8 December 2011).**

- **Each space mission must assess its compliance with requirements in the following areas:**
  - Release of debris during normal mission operations
  - Accidental explosions
  - Intentional breakups
  - Collisions with small and large objects
  - Postmission disposal
  - Reentry risks

U.S Government Policy and Strategy

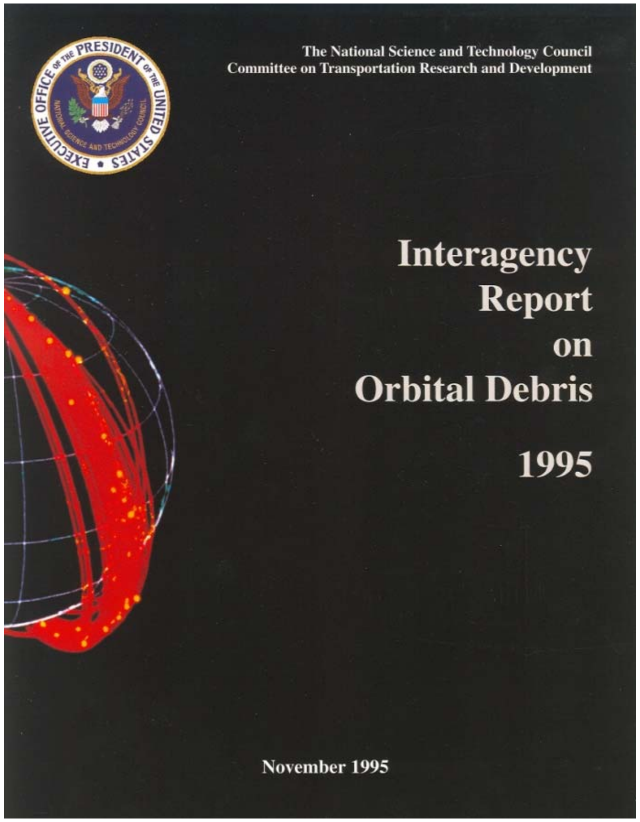
U.S. National Space Policy

1988 - Present



REPORT ON
ORBITAL DEBRIS
By
INTERAGENCY GROUP(SPACE)

For National Security Council, Washington, D.C.
February 1989



The National Science and Technology Council
Committee on Transportation Research and Development

Interagency
Report
on
Orbital Debris

1995

November 1995

U.S. Space Policy and Orbital Debris

- **Orbital debris has been included in all national space policies since 1988.**
- **1988 National Space Policy (signed 5 January 1988 by President Reagan) stated:**
  - “All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce the accumulation of space debris consistent with mission requirements and cost effectiveness.”
- **Less than two years later on 16 November 1989 President G. H. W. Bush signed the 1989 National Space Policy, adding the following statement to the Reagan policy:**
  - “The United States Government will encourage other spacefaring nations to adopt policies and practices aimed at debris minimization.”

1996 National Space Policy

- **On 14 September 1996 President Clinton included a stronger statement on orbital debris in his National Space Policy:**
  - "The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DoD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments and systems, will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness.
  - "It is in the interest of the U.S. Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The U.S. Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on debris research and the identification of debris mitigation options."

2006 National Space Policy

- **The 2006 National Space Policy (signed 31 August 2006 by President G. W. Bush) states:**

  “Orbital debris poses a risk to continued reliable use of space-based services and operations and to the safety of persons and property in space and on Earth. The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space in order to preserve the space environment for future generations. Toward that end:

  - Departments and agencies shall continue to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the operation of tests and experiments in space;

  - The Secretaries of Commerce and Transportation, in coordination with the Chairman of the Federal Communications Commission, shall continue to address orbital debris issues through their respective licensing procedures; and

  - The United States shall take a leadership role in international fora to encourage foreign nations and international organizations to adopt policies and practices aimed at debris minimization and shall cooperate in the exchange of information on debris research and the identification of improved debris mitigation practices.”

2010 National Space Policy

- **The 2010 National Space Policy (released 28 June 2010 by President Barack Obama) states:**

“Preserve the Space Environment. For the purposes of minimizing debris and preserving the space environment for the responsible, peaceful, and safe use of all users, the United States shall:

- Lead the continued development and adoption of international and industry standards and policies to minimize debris, such as the United Nations Space Debris Mitigation Guidelines;
- Develop, maintain, and use space situational awareness (SSA) information from commercial, civil, and national security sources to detect, identify, and attribute actions in space that are contrary to responsible use and the long-term sustainability of the space environment:
- Continue to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the conduct of tests and experiments in space;
- Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment; and
- Require the head of the sponsoring department or agency to approve exceptions to the United States Government Orbital Debris Mitigation Standard Practices and notify the Secretary of State.”

U.S. Government Orbital Debris Mitigation Standard Practices

- **In response to the 1995 Interagency report on orbital debris, NASA and DoD developed draft orbital debris mitigation standard practices based upon NASA Safety Standard 1740.14.**

- **The Standard Practices cover four major areas:**
  - Control of debris released during normal operations
  - Minimization of debris generated by accidental explosions
  - Selection of safe flight profile and operational configuration
  - Postmission disposal of space structure

- **After coordination with the U.S. aerospace industry, the Standard Practices were approved Feb 2001 by all relevant U.S. Government agencies, departments, and organizations and have been used as a foundation for the development of international guidelines.**

  - Cited in 2006 and 2010 U.S. National Space Policy

  - Each U.S. Government organization implements the Standard Practices according to established internal procedures

USG OD Mitigation Standard Practices, Objective 1

OBJECTIVE

1. CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS

Programs and projects will assess and limit the amount of debris released in a planned manner during normal operations.

MITIGATION STANDARD PRACTICES

1-1. *In all operational orbit regimes:* Spacecraft and upper stages should be designed to eliminate or minimize debris released during normal operations. Each instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified on the basis of cost effectiveness and mission requirements.

USG OD Mitigation Standard Practices, Objective 2

OBJECTIVE

2. MINIMIZING DEBRIS GENERATED BY ACCIDENTAL EXPLOSIONS

Programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.

MITIGATION STANDARD PRACTICES

2-1. *Limiting the risk to other space systems from accidental explosions during mission operations:* In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes.

2-2. *Limiting the risk to other space systems from accidental explosions after completion of mission operations:* All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.

USG OD Mitigation Standard Practices, Objective 3

OBJECTIVE

3. SELECTION OF SAFE FLIGHT PROFILE AND OPERATIONAL CONFIGURATION

Programs and projects will assess and limit the probability of operating space systems becoming a source of debris by collisions with man-made objects or meteoroids.

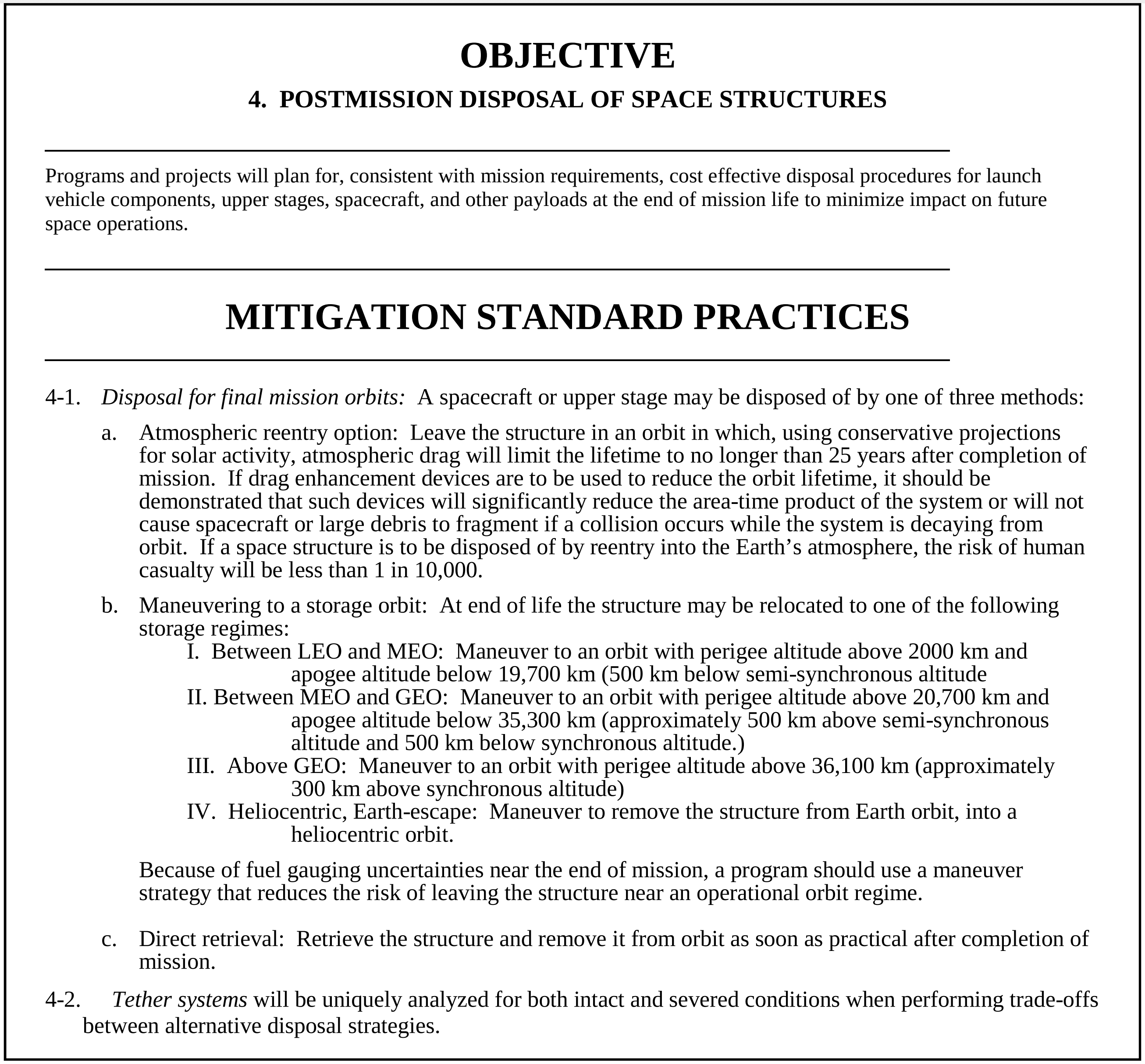
MITIGATION STANDARD PRACTICES

3-1. *Collision with large objects during orbital lifetime:* In developing the design and mission profile for a spacecraft or upper stage, a program will estimate and limit the probability of collision with known objects during orbital lifetime.

3-2. *Collision with small debris during mission operations:* Spacecraft design will consider and, consistent with cost effectiveness, limit the probability that collisions with debris smaller than 1 cm diameter will cause loss of control to prevent post-mission disposal.

3-3. *Tether systems* will be uniquely analyzed for both intact and severed conditions.

USG OD Mitigation Standard Practices, Objective 4



OBJECTIVE

4. POSTMISSION DISPOSAL OF SPACE STRUCTURES

Programs and projects will plan for, consistent with mission requirements, cost effective disposal procedures for launch vehicle components, upper stages, spacecraft, and other payloads at the end of mission life to minimize impact on future space operations.

MITIGATION STANDARD PRACTICES

4-1. *Disposal for final mission orbits:* A spacecraft or upper stage may be disposed of by one of three methods:

a. Atmospheric reentry option: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000.

b. Maneuvering to a storage orbit: At end of life the structure may be relocated to one of the following storage regimes:
  I. Between LEO and MEO: Maneuver to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous altitude
  II. Between MEO and GEO: Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude.)
  III. Above GEO: Maneuver to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude)
  IV. Heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit, into a heliocentric orbit.

Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime.

c. Direct retrieval: Retrieve the structure and remove it from orbit as soon as practical after completion of mission.

4-2. *Tether systems* will be uniquely analyzed for both intact and severed conditions when performing trade-offs between alternative disposal strategies.

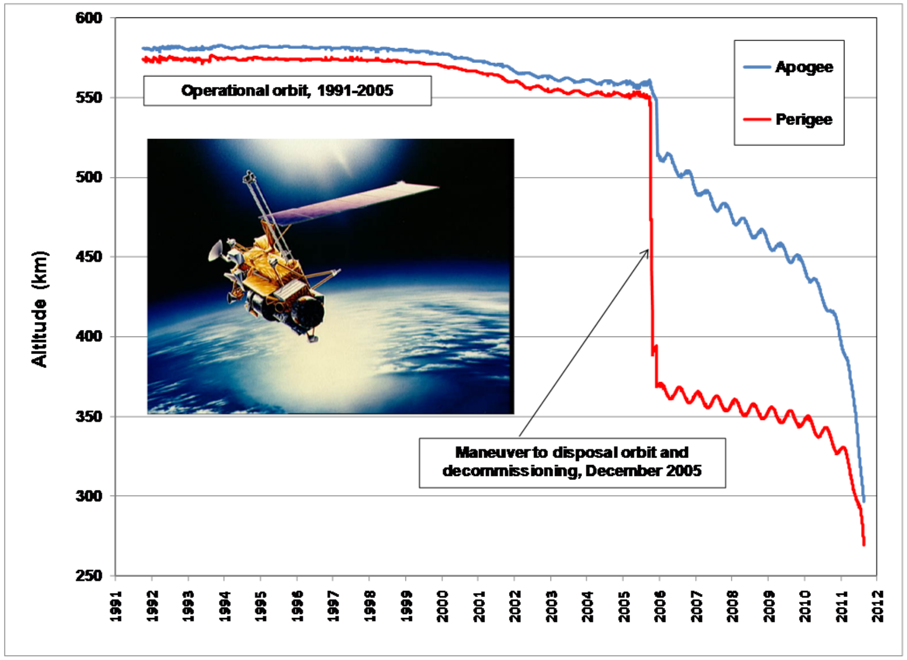
USG Orbital Debris Mitigation Standard Practices Highlights

- **Standard Practice 1:**
  - Eliminate or minimize mission-related debris;
  - Limit orbital lifetime of LEO debris to 25 years
- **Standard Practice 2:**
  - Use design and procedures to avoid breakups during mission operations and after disposal
- **Standard Practice 3:**
  - Protect against collisions with small debris and avoid collisions with large debris
- **Standard Practice 4:**
  - LEO: Limit post-mission orbital lifetime to 25 years limit human casualty reentry risk to 1 in 10,000
  - GEO: Maneuver to a disposal orbit ~300 km above GEO

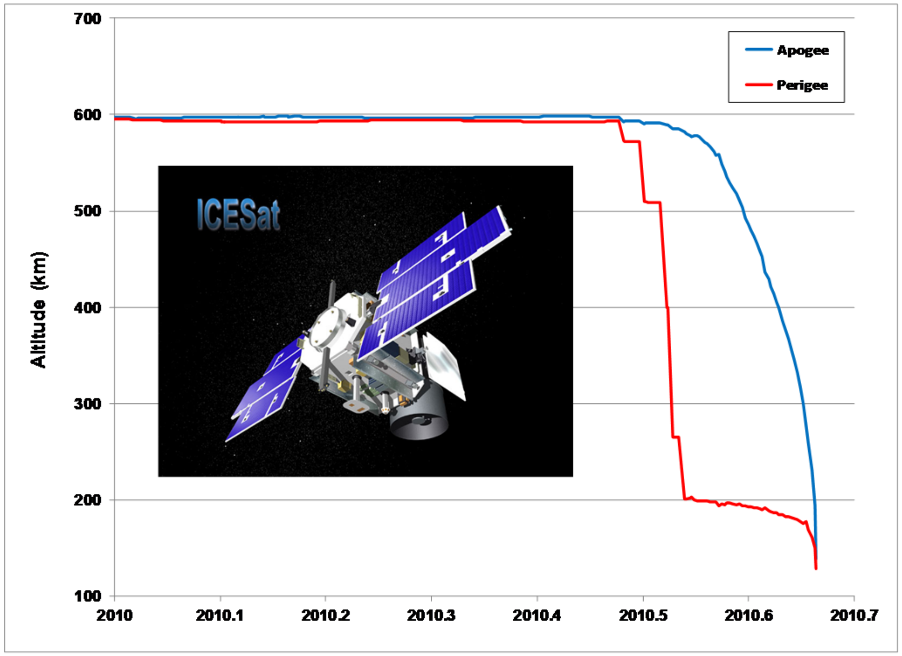
Disposal of NASA and USG LEO Spacecraft

- **Since 2001, several NASA and USG LEO spacecraft have maneuvered into lower disposal orbits at end of mission to accelerate natural orbital decay and atmospheric reentry. Examples include**
  - 2001: Landsat 4 2005: ERBS and UARS
  - 2008: GFO 2010: ICESat

UARS



ICESat

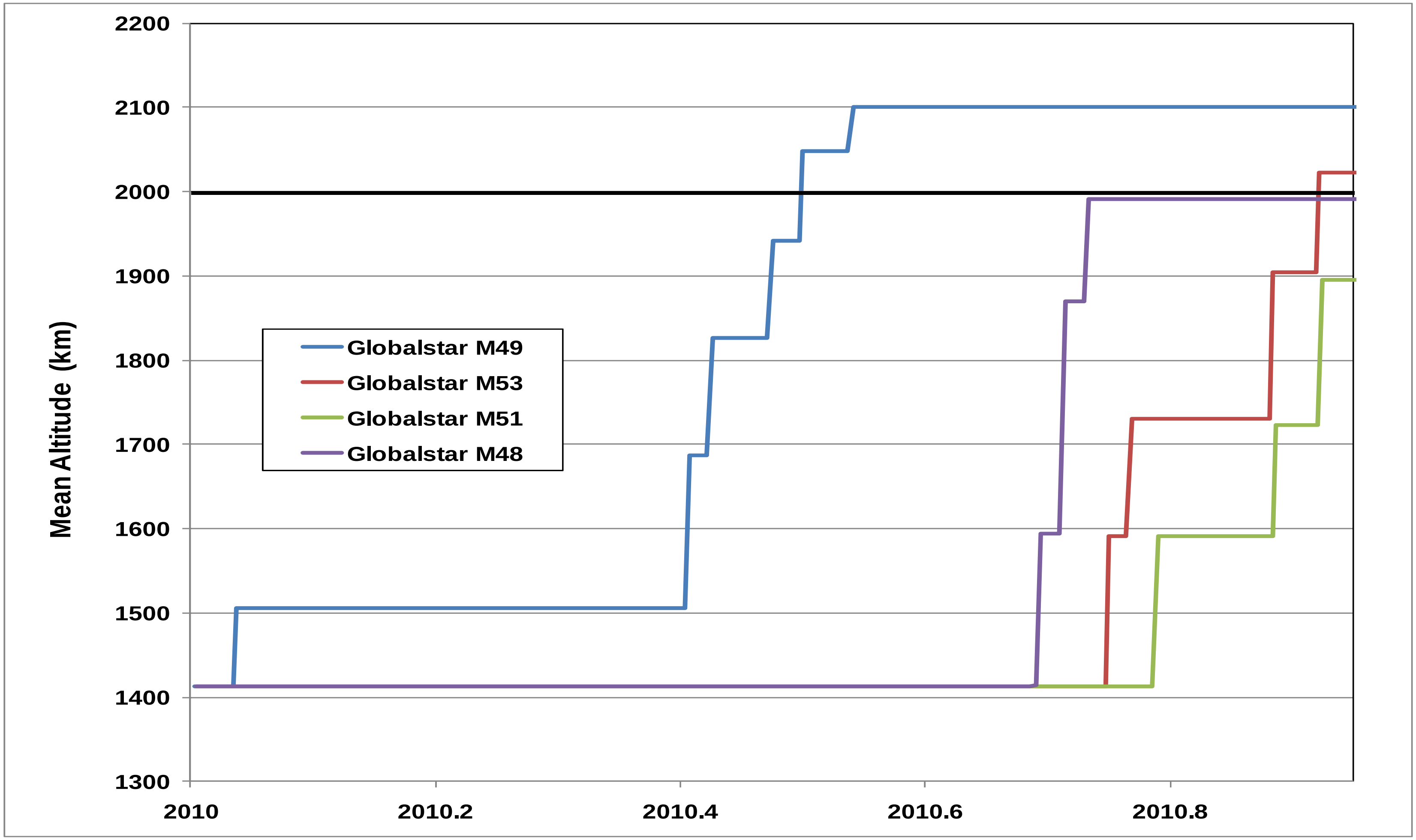


Challenge of High LEO Spacecraft

- **For LEO spacecraft operating near or above 1400 km, it is normally more energy-efficient to maneuver into a storage orbit beyond 2000 km rather than to lower perigee sufficiently to reenter within 25 years.**
  - However, to date most spacecraft at these altitudes do not carry sufficient propellant to reach 2000 km (see next page for exception).
- **The JASON 1 spacecraft, which operates near 1335 km, is a joint NASA-CNES mission established in 1996, before international standards for LEO satellite disposal were adopted. The vehicle has residual propellant to maneuver only a few hundred kilometers in semi-major axis.**
- **Since JASON 1 operates in a relative minimum of spatial density, passivating the spacecraft in place (*e.g.*, using depletion burns to change plane and/or inclination) is preferable to maneuvering to a more congested lower or higher orbit.**

Disposal Activities of Globalstar Satellites in 2010

- **Globalstar communications satellites operate near 1415 km. At mission completion, the objective is to maneuver each satellite to a higher disposal orbit, preferably above LEO, *i.e.*, above 2000 km.**



LEO Deployment Options and Launch Vehicle Stage Disposal

- **During the late 1990's three major LEO communications networks were deployed: Iridium, Orbcomm, and Globalstar.**

- **Iridium (780 km operational altitude)**
  - 88 spacecraft launched in 25 months (1997-1999) using three different launch vehicles from three countries
  - Spacecraft released at altitudes near 500-650 km
    - Proton orbital stages de-orbited; Delta and Long March orbital stages moved to lower orbits
  - Only 1 of 26 stages still in orbit (remaining stage malfunctioned)

- **Orbcomm (815 km operational altitude)**
  - 35 spacecraft launched as primary or secondary payloads
  - 8 orbital stages used for dedicated missions (31 spacecraft); only one orbital stage will fail to meet 25-year guideline due to lower stage malfunction

- **Globalstar (1415 km operational altitude)**
  - 52 spacecraft launched in 24 months (1998-2000) using Delta and Soyuz launch vehicles
  - Spacecraft released at altitudes near 900 km on 7 (6 Soyuz, 1 Delta) of 13 missions
  - Only 2 of 19 stages still in orbit; Soyuz-IKAR stages were de-orbited into Pacific

Disposal of TDRS 1 in 2010

- **NASA's first Tracking and Data Relay Satellite (TDRS) completed more than 26 years of valuable service in October 2009.**

- **During June 2010 the spacecraft conducted 12 separate maneuvers over an 8-day period to reach a disposal orbit with a perigee more than 300 km above GEO, in accordance with U.S. and UN guidelines.**

- **After reaching the disposal orbit, TDRS 1 still possessed more than 120 kg of hydrazine. This propellant was expended during 20 more hours of small thruster burns over a period of 10 days.**
  - To accomplish the depletion burns, the spacecraft was placed in a special spin-stable attitude, which had never before been used by TDRS 1.

- **TDRS 1 completed passivation actions on 27 June in an orbit 345 km by 525 km above GEO.**

TDRS 1 spacecraft

DOD and other USG Agencies

- **The Department of Defense has established an overall Directive on orbital debris mitigation (DoD Directive 3100.10, 1999).**
  - US Strategic Command, the former US Space Command, Air Force Space Command, and the National Reconnaissance Office have issued several policy directives and instructions to implement the DoD directive and National Space Policy.

- **The Department of Transportation/FAA has issued regulations promoting orbital debris mitigation for commercial launch vehicles.**

- **The Federal Communications Commission has issued regulations promoting orbital debris mitigation for transmitting spacecraft.**

- **The Department of Commerce/NOAA has issued regulations promoting orbital debris mitigation for remote sensing spacecraft.**

All of the above are consistent with and derived from the USG Orbital Debris Mitigation Standard Practices

U.S. National Research Council

- **Under the sponsorship of NASA, the U.S. National Research Council formed a committee of 11 technical experts from six spacefaring nations to perform an assessment of space debris and its consequences.**

- **The product of this committee, "Orbital Debris, A Technical Assessment", was published in 1995.**
  - This volume remains an excellent primer on space debris.

- **In addition to providing a summary of space debris research, the committee also offered "Techniques to Reduce the Future Debris Hazard".**
  - These techniques are very similar to those found in the U.S. Government Orbital Debris Mitigation Standard Practices.

- **The NRC also issued specific assessments for the Space Shuttle and Space Station programs in 1997.**

Inter-Agency Space Debris Coordination Committee (IADC)

- **Established in 1993:**
  - To exchange information on space debris research activities between member space agencies;
  - To facilitate opportunities for cooperation in space debris research;
  - To review progress of ongoing cooperative activities; and
  - To identify debris mitigation options
- **12 members include all the leading space agencies in the world from Canada, China, France, Germany, India, Italy, Japan, Russia, Ukraine, United Kingdom, and the United States, as well as ESA.**
  - NASA delegation has included personnel from DoD, State, the FAA, and the FCC
- **More than 100 orbital debris specialists meet annually to exchange information and to work on specified Action Items.**
- **IADC developed first consensus international orbital debris mitigation guidelines in October 2002; subsequently submitted to the United Nations.**

Website: www.iadc-online.org

IADC Space Debris Mitigation Guidelines

- **An Action Item (AI 17.2) to develop a consensus set of space debris mitigation guidelines was approved by the Steering Group of the IADC in October 1999.**

- **The “IADC Space Debris Mitigation Guidelines” (IADC-02-01) was adopted in October 2002 (slightly revised in 2007) and the complementary “Support to the IADC Space Debris Mitigation Guidelines” (IADC-04-06) was adopted in October 2004.**

- **The IADC Space Debris Mitigation Guidelines are quite similar to the U.S. Government Orbital Debris Mitigation Standard Practices with four major mitigation categories:**
  - Limiting debris released during normal operations
  - Minimizing the potential for on-orbit breakups
  - Postmission disposal
  - Prevention of on-orbit collisions

Orbital Debris at the United Nations

- Since 1994 the subject of orbital debris has been on the agenda of the Scientific and Technical Subcommittee (STSC) of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS).
- A multi-year work plan culminated in the 1999 "Technical Report on Space Debris" (A/AC.105/720), summarizing the world state-of-knowledge concerning measurements and modeling of the environment as well as identified orbital debris mitigation measures.
- At the 2001 meeting of the STSC a new multi-year work plan was adopted which anticipated the presentation of the IADC Space Debris Mitigation Guidelines to the STSC in 2003.
- The IADC Space Debris Mitigation Guidelines were reviewed and discussed at STSC in both 2003 and 2004.
- STSC Member States adopted a similar set of space debris mitigation guidelines in Feb 2007, followed by adoption of the full COPUOS in June 2007 and by the full General Assembly in late 2007.

UN COPUOS STSC Space Debris Mitigation Guidelines

- **The 2007 UN COPUOS STSC Space Debris Mitigation Guidelines contains seven numbered guidelines:**
  - Guideline 1: Limit debris released during normal operations
  - Guideline 2: Minimize the potential for break-ups during operational phases
  - Guideline 3: Limit the probability of accidental collision in orbit
  - Guideline 4: Avoid intentional destruction and other harmful activities
  - Guideline 5: Minimize potential for post-mission break-ups resulting from stored energy
  - Guideline 6: Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission
  - Guideline 7: Limit the long-term interference of spacecraft and launch vehicle orbital stages with geosynchronous Earth orbit (GEO) region after the end of their mission

National Orbital Debris Mitigation Guidelines

- **Since the establishment of the NASA policy and guidelines on orbital debris, an increasing number of countries have developed and adopted specific national guidelines promoting the mitigation of the growth of the orbital debris environment.**
  - Japan: Space Debris Mitigation Standard (NASDA-STD-18A), March 1996
  - France: CNES Space Debris – Safety Requirements (MPM-50-00-12), April 1999; new national space law in December 2010.
  - Russia: General Requirements for Mitigation of Space Debris Population (Branch Standard), July 2000
  - China: Requirements for Space Debris Mitigation (QJ 3221 – 2005), July 2005
- **ESA issued a Space Debris Mitigation Handbook in February 1999, followed by a draft Space Debris Safety and Mitigation Standard in September 2000.**
- **These guidelines are very similar in most of their recommendations with the U.S. Government Orbital Debris Mitigation Standard Practices.**

European Code of Conduct for Space Debris Mitigation

- **In June 2004 a draft European Code of Conduct for Space Debris Mitigation was completed by the five leading space agencies in Europe: ESA, ASI (Italy), BNSC (UK), CNES (France), and DLR (Germany).**
  - In 2006 the final signature of the document was recorded.

- **This new European document is divided into three main categories:**
  - Management Measures
  - Design Measures
  - Operational Measures

- **Following the precedent set by IADC, a “Support to Implementation of the European Code of Conduct for Space Debris Mitigation” has also been produced.**

- **The European Code of Conduct for Space Debris Mitigation does add specificity, *e.g.*, measures of effectiveness, similar to that of NASA’s NSS 1740.14 and NS 8719.14.**

International Academy of Astronautics

- **The IAA, established in 1960, is a professional organization of approximately 1200 individuals with demonstrated expertise in one or more fields of astronautics.**

- **The IAA published its first position paper on space debris in 1993. This was updated in 2000-2001.**
  - The position paper includes a section on "Implementation of Debris Control Methods"

- **A new "Position Paper on Space Debris Mitigation" was released in 2005.**
  - This position paper addresses space debris issues and recommended mitigation measures separately for spacecraft and launch vehicles.

- **An investigation of techniques to remediate the near-Earth space environment was conducted during 2007-2012.**

Orbital Debris and ISO

- **The International Standards Organization (ISO) was founded under the auspices of the United Nations in 1946 to promote standardization development for the facilitation of international exchange of goods and services.**
  - Members of ISO include government and industry representatives.
  - Compliance with ISO standards is voluntary.
- **The Orbital Debris Coordination Working Group was established under ISO Technical Committee 20, Subcommittee 14, in May 2003.**
  - Using the IADC Space Debris Mitigation Guidelines as a foundation, the working group is developing a series of space debris mitigation standards.
  - 24113, Space Debris Mitigation Requirements, is the overarching ISO space debris mitigation standard.

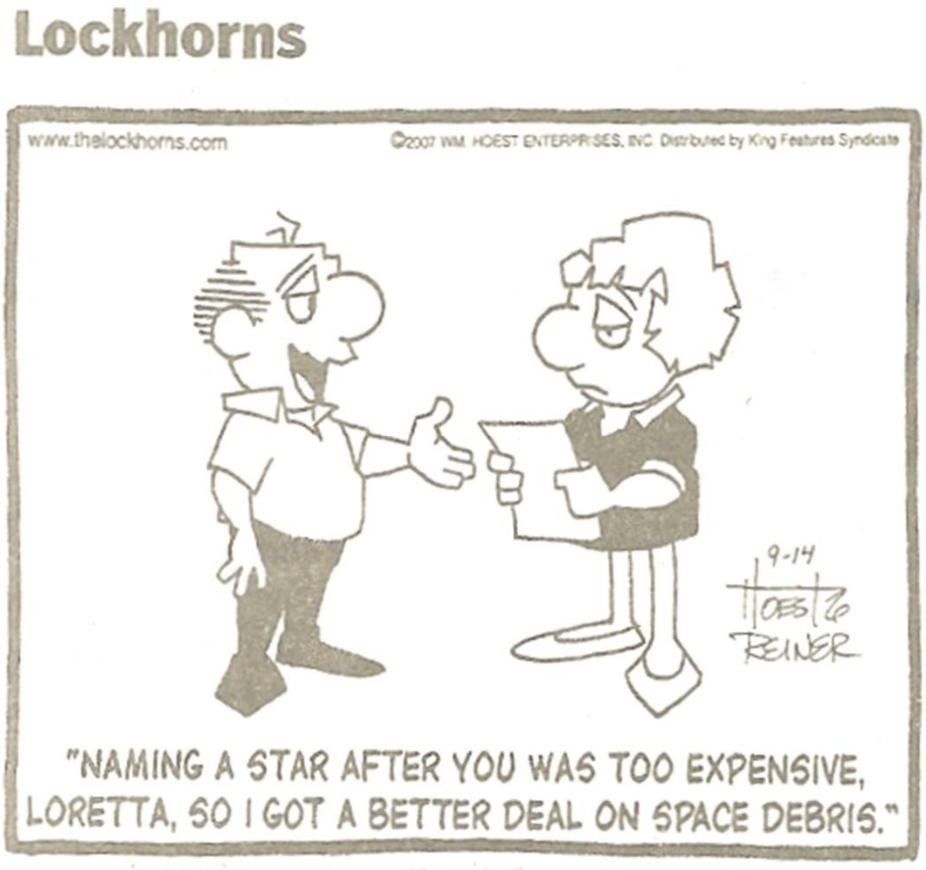
Summary

- **The current U.S. National Space Policy specifically calls on U.S. Government entities “to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the operation of tests and experiments in space.”**

- **A large number of U.S., foreign, and international guidelines for mitigating the creation of new orbital debris now exist.**

- **Although they vary in their level of detail, all the guidelines have in common many fundamental elements, which are found in both the U.S. Government Orbital Debris Mitigation Standard Practices and NASA Standard 8719.14.**

- **All NASA space programs and projects are required to address orbital debris mitigation issues for both their spacecraft and launch vehicles in accordance with NPR 8715.6A and NS 8719.14A.**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"NAMING A STAR AFTER YOU WAS TOO EXPENSIVE, LORETTA, SO I GOT A BETTER DEAL ON SPACE DEBRIS."

NASA Orbital Debris Mitigation Procedural Requirements, Standards, and Handbook

Orbital Debris Program Office
NASA Johnson Space Center

Outline

- **NASA Procedural Requirements for Limiting Orbital Debris**
- **NASA Standard for Limiting Orbital Debris**
- **NASA Handbook for Limiting Orbital Debris**

NPR 8715.6A

- **NASA Procedural Requirements for Limiting Orbital Debris, NPR 8715.6, was approved in August 2007 and replaced NASA Policy Directive 8710.3B.**
  - Highest level NASA document on orbital debris mitigation
  - NPR 8715.6A was released in February 2008 as a minor revision to NPR 8715.6.
- **The format of NPR 8715.6A is different than that of NPD 8710.3B and several new topics have been added.**
  - Chapter 1: Roles and Responsibilities of NASA personnel and offices
  - Chapter 2: Program/Project Development and Prelaunch Preparations
  - Chapter 3: Program/Project Operations (including disposal)
- **Orbital Debris Assessment Reports are still required in conjunction with the Preliminary Design Review and Critical Design Review milestones.**
  - Format and content of the reports are set forth in NASA Standard 8719.14A.

NPR 8715.6A Role and Responsibilities

- **NPR 8715.6A sets forth explicit roles and responsibilities for a wide variety of NASA personnel and organizations:**
    - Chief, Safety and Mission Assurance
    - Program's Mission Directorate Associate Administrator
    - Associate Administrator, Space Operations Mission Directorate
    - Associate Administrator, Exploration Systems Mission Directorate
    - Assistant Administrator, Office of External Affairs
    - Assistant Administrator, Office of Public Affairs
    - NASA Office of the General Counsel
    - NASA HQ Environmental Management Division
    - KSC Launch Services Program Manager
    - NASA Center Safety and Mission Assurance Directors
    - NASA Orbital Debris Program Office
    - SMA Technical Authority
    - NASA Program/Project Manager
    - NASA Planetary Protection Officer

Program’s Mission Directorate Associate Administrator

- **Responsibilities of the Program’s Mission Directorate Associate Administrator are as follows:**
  - 1.3.2.1 The MDAA shall be the NASA official accepting the orbital debris risk as determined by the SMA Technical Authority due to noncompliances to this NPR and NSS 1740.14 or NASA-STD 8719.14 as documented in the ODAR and EOMP (Requirement 56741).
  - 1.3.2.2 The MDAA shall ensure that a mission orbital debris assessment has been conducted in accordance with NSS 1740.14 or NASA-STD 8719.14, as applicable per paragraph P.2.4, to determine the potential for orbital debris generation from the launch vehicle and the payload (Requirement 57296).
  - 1.3.2.3 The MDAA shall ensure that orbital debris mitigation measures identified in the ODAR are implemented and included in the EOMP (Requirement 56743).
  - 1.3.2.4 The MDAA shall ensure that a formal review of the potential to generate orbital debris is conducted before implementing the EOMP (Requirement 56744).
  - 1.3.2.5 The program's MDAA shall provide to the Chief/OSMA, for Chief/OSMA concurrence, a phase-in plan and schedule for either development of new EOMPs, modification of existing EOMPs, or grandfathering of existing EOMPs within four months of the approval of this NPR (Requirement 56745).
  - 1.3.2.6 The MDAA shall ensure that the orbital debris requirements of this NPR are included as an integral part of their program/project, to include proposals and Announcements of Opportunity for future missions (Requirement 56746).

Orbital Debris Program Office

- **Responsibilities of the NASA Orbital Debris Program Office are as follows:**
  - 1.3.11.1 The NASA ODPO shall maintain a list of predicted reentry dates for NASA spacecraft and their associated orbital stages and notify the OSMA at least 60 days prior to their reentry (Requirement 56773).
  - 1.3.11.2 The NASA ODPO shall develop, maintain, and update the orbital debris environment models to support this NPR (Requirement 56774).
  - 1.3.11.3 The NASA ODPO shall assist NASA mission program/project managers in technical orbital debris assessments by providing information and/or directing queries to the knowledgeable technical staff (Requirement 56775).
  - 1.3.11.4 The NASA ODPO shall provide assistance to the Department of Defense and other U.S. Government departments and organizations on matters related to the characterization of the orbital debris environment and the application of orbital debris mitigation measures and policies for NASA space missions (Requirement 56776).
  - 1.3.11.5 The NASA ODPO shall participate in the determination, adoption, and use of international orbital debris mitigation guidelines through international forums such as the United Nations Committee on the Peaceful Uses of Outer Space, the IADC, and the ISO (Requirement 56777).

Orbital Debris Mitigation Program Setup and Control

- **Chapter 2.1 sets forth the responsibilities of the program/project manager in establishing an orbital debris mitigation process.**

- **PM shall**
  - implement OD requirements for those portions of a spaceflight program/project over which NASA has control;
  - include applicable OD design requirements in program/project requirements;
  - include NPR requirements in agreements and contracts necessary to ensure compliance with the NPR;
  - deliver an abbreviated ODAR to program/project integrator for missions jointly developed/built/managed by multiple NASA Centers/facilities;
  - deliver an abbreviated ODAR to non-NASA launching or lead Agency;
  - include a review of the orbital debris requirements as part of the program/project System Requirements Review.

Orbital Debris Assessment Reports (ODARs)

- **Requirement for preparation of ODARs is set forth in NPR 8715.6A, Chapter 2.2.1.**
  - Content and format for ODARs are set forth in NS 8719.14
- **ODARs are submitted by the Program/Project Manager to Mission Directorate Associate Administrator, who in turn forwards the ODARs to Chief/OSMA and AA/SOMD.**
- **Schedule: Initial ODAR submitted prior to PDR;**
  Updated ODAR submitted NLT 45 days prior to CDR;
  Final ODAR submitted 30 days prior to safety and mission assurance (SMA) launch readiness review

End-of-Mission Plans (EOMPs)

- **Requirement for preparation of EOMPs is set forth in NPR 8715.6A, Chapter 2.2.2.**
  - Content and format for EMOPs are set forth in NS 8719.14A
- **ODARs are submitted by the Program/Project Manager to Mission Directorate Associate Administrator, Chief/OSMA and AA/SOMD.**
- **Schedule: Initial EOMP submitted NLT 45 days prior to CDR;**
  Prelaunch EOMP submitted 30 days prior to SMA launch readiness review
  Annual review of EOMP during mission operations
  Final EOMP prior to 30 days before EOMP notification
- **Additional requirements for vehicles which will impact the Earth or travel beyond GEO.**

ODAR and EOMP Review and Risk Acceptance

- **All ODARs and EOMPs are reviewed by the Mission Directorate Associate Administrator, Chief OSMA, and AA/SOMD, as well as the NASA Orbital Debris Program Office (Chapters 2.2.1-2.2.3)**

- **OD Program Office reviews are submitted to OSMA utilizing formats specified in NS 8719.14A.**

- **MDAA will accept any risks associated with noncompliances, after coordination with Chief/OSMA, Chief Engineer, and AA/SOMD, indicating reasons and justification.**

Mission Operations

- **Chapter 3 of NPR 8715.6A sets additional requirements during mission operations, including**
  - monitoring of spacecraft and launch vehicle stages to detect intended or unintended operations that could generate debris around Earth, the Moon, and Mars or at an Earth-Sun Lagrange point;
    - special attention paid to critical items for vehicles in orbit about Earth or the Moon
  - notifications and assessment of debris generation events;
  - notifications when vehicle no longer serves any useful function or purpose;
  - notifications when redundancy or other key functionality is lost in the end-of-life disposal or deorbit system; and
  - notifications when propellant level required for controlled deorbit or disposal maneuvers is projected to occur within six months or propellant level falls to less than 115% for end-of-mission maneuvers.

End-of-Mission Actions

- **Chapter 3.3 of NPR 8715.6A sets additional requirements for end-of-mission planning and execution, including**
  - passivation of spacecraft designed for reentry into Earth's atmosphere or for disposal about the Earth or the Moon;
  - avoidance of lunar disposal orbits; and
  - examination of potential lunar landing or crash sites.

Conjunction Assessments

- **Chapter 3.4 of NPR 8715.6A sets requirements for avoiding accidental collisions of Earth-orbiting objects.**

  – 3.4.1 The NASA Program/Project Manager shall have conjunction assessment analyses performed routinely for all maneuverable Earth-orbiting spacecraft with a perigee height of less than 2000 km in altitude or within 200 km of GEO (Requirement 56891).

  – 3.4.2 Conjunction assessment analyses shall be performed using the USSTRATCOM high-accuracy catalog as a minimum (Requirement 56892).

  – 3.4.3 The NASA Program/Project Manager shall have a collision risk assessment and risk mitigation process in place for all maneuverable Earth-orbiting spacecraft that are performing routine conjunction assessment analyses (Requirement 56893).

NASA Standard 8719.14A

- **NASA Standard 8719.14 replaced NASA Safety Standard 1740.14 in August 2007. Revised as NS 8719.14A in December 2011.**
  - Specifies orbital debris mitigation requirements and performance standards
  - First change in 12 years.
- **For procedural reasons, the guidelines of NSS 1740.14 have become requirements in NASA Standard 8719.14A.**
  - Instances of non-compliance must now be handled via formal waiver process.
- **NASA Standard 8719.14A contains detailed directions on how each Orbital Debris Assessment Report (ODAR) and each End-of-Mission Plan (EOMP) shall be prepared.**
  - Spacecraft and launch vehicle topics are separated for ease of preparation.

Categories of Assessments

- Assessment of debris released during normal operations
- Assessment of debris generated by explosions and intentional breakups
- Assessment of debris generated by on-orbit collisions
- Postmission disposal of space structures
- Survival of debris from postmission disposal Earth atmospheric reentry option, including human casualty risk
- Assessment requirements for tether missions

Specific orbital debris mitigation requirements are provided at the end of your class notebook.

Handbook for Limiting Orbital Debris

- **The *Handbook for Limiting Orbital Debris* is a new type of NASA document for orbital debris mitigation.**

- **The handbook, NASA Handbook 8719.14, provides additional technical background information on a wide variety of orbital debris environment and mitigation topics.**

- **The handbook is divided into seven major sections:**
  - Current Orbital Debris Environment
  - Future Environment
  - Measurements of the Orbital Debris Environment
  - Modeling the Orbital Debris Environment
  - Micro-Meteoroid and Orbital Debris Shielding
  - Mitigation
  - Reentry

Summary

- **NASA's new procedural and technical requirements for limiting the generation of orbital debris are based upon 15 years of experience in establishing and enforcing orbital debris mitigation measures.**

- **The procedures and requirements are consistent with the orbital debris mitigation guidelines of the IADC and the United Nations.**

- **The procedures and requirements, like the near-Earth space environment itself, are evolutionary in nature and incorporate to the greatest extent possible lessons learned.**

- **NASA NPR 8715.6A, NASA Standard 8719.14A, and NASA Handbook 8719.14 can also be accessed via the website of the NASA Orbital Debris Program Office: www.orbitaldebris.jsc.nasa.gov/library/references.html**

Why Reentry Risk Management?

- **Limiting satellite orbital lifetimes can transfer an on-orbit risk for satellites to a terrestrial risk for people and property.**

- **President's National Space Policy directs agencies and departments to implement *U.S. Government Orbital Debris Mitigation Standard Practices*.**

  – The Standard Practices set a threshold of human casualty risk from reentering debris to 1 in 10,000 per reentry event.

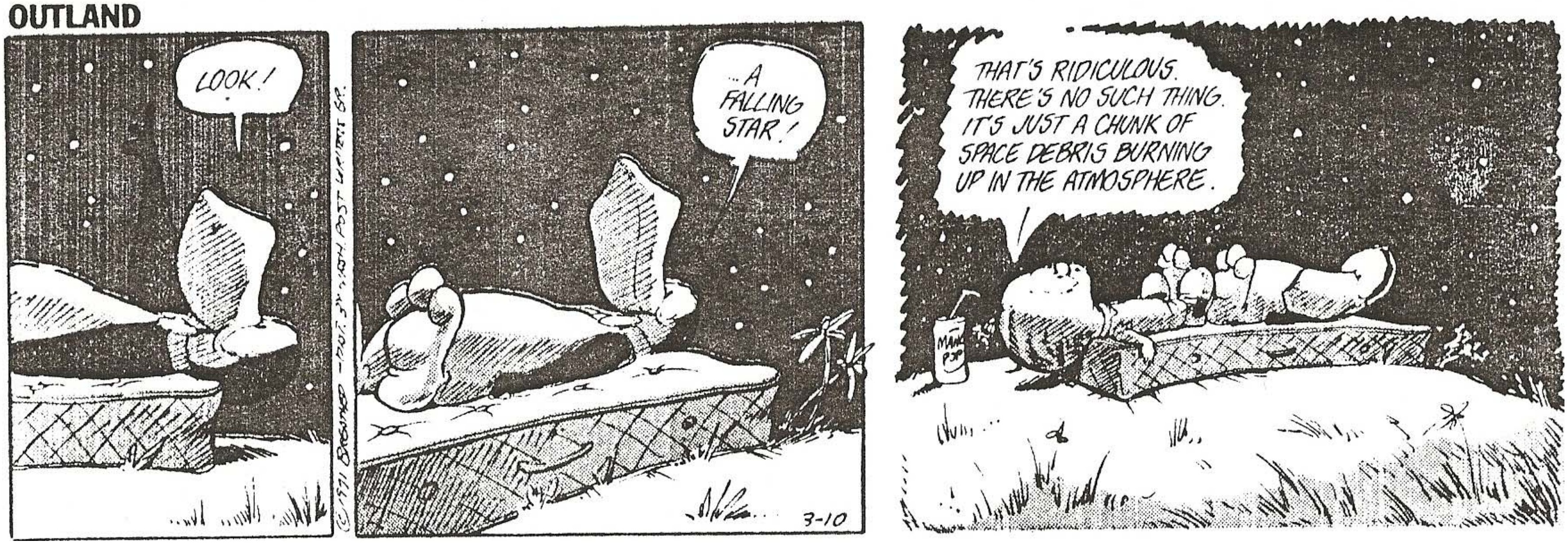
- **This risk threshold has been adopted by a growing number of foreign space agencies.**

To limit human casualties from surviving satellite debris

National Aeronautics and Space Administration

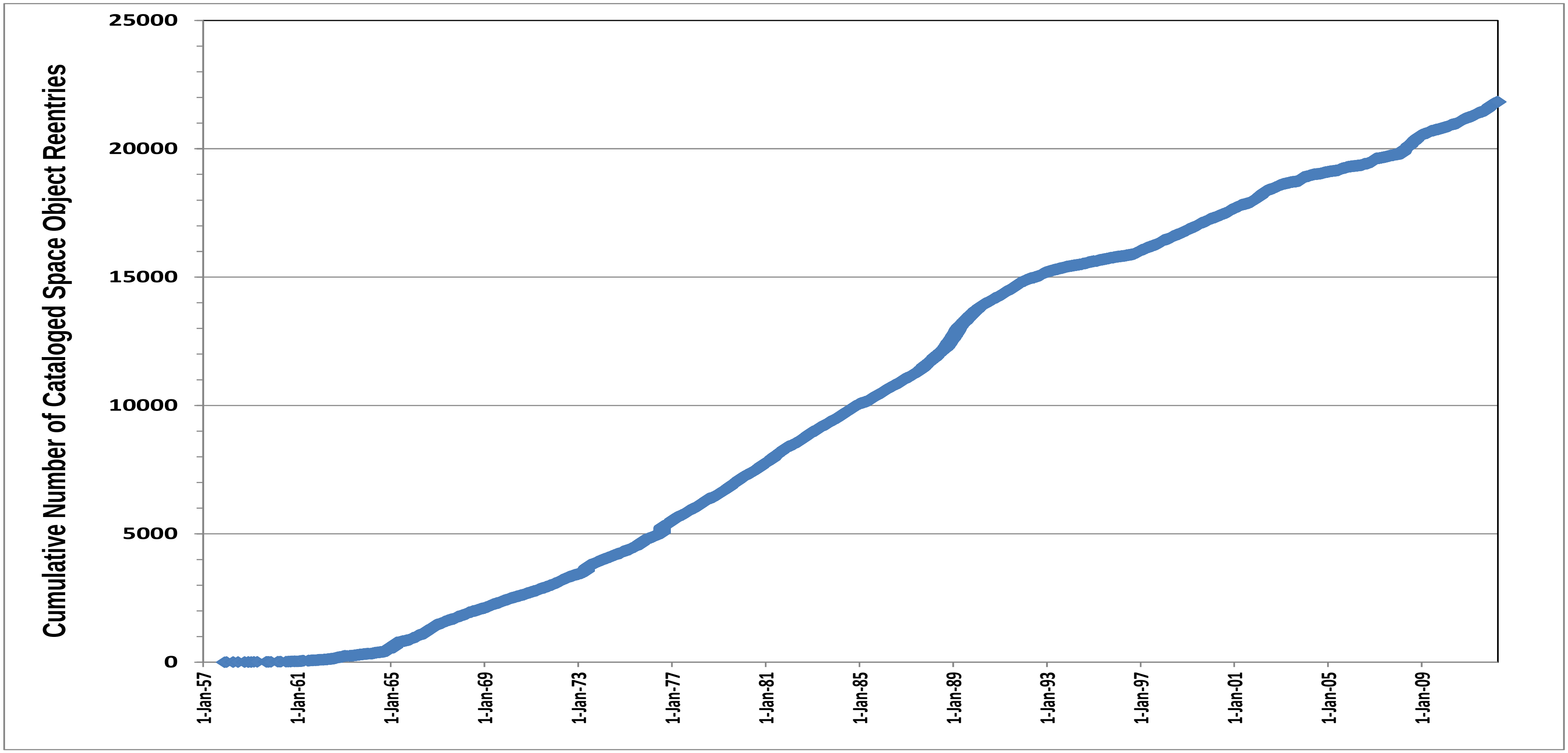
NASA, USG, and Foreign Human Casualty Reentry Risk Criteria

Orbital Debris Program Office
NASA Johnson Space Center


OUTLAND
LOOK!
...A FALLING STAR!
THAT'S RIDICULOUS. THERE'S NO SUCH THING. IT'S JUST A CHUNK OF SPACE DEBRIS BURNING UP IN THE ATMOSPHERE.
©1991 BREATHED—WASH. POST WRITERS GR.
3-10

Rate of Space Object Reentries

- **On average, one uncontrolled man-made object has fallen back to Earth each day for the past 50 years.**
  - Majority are small and burn up
  - Components which survive typically fall in bodies of water or sparsely populated regions



Examples of Recovered Satellite Components

Texas, 1997

South Africa, 2000

Saudi Arabia, 2001

Guatemala, 2003

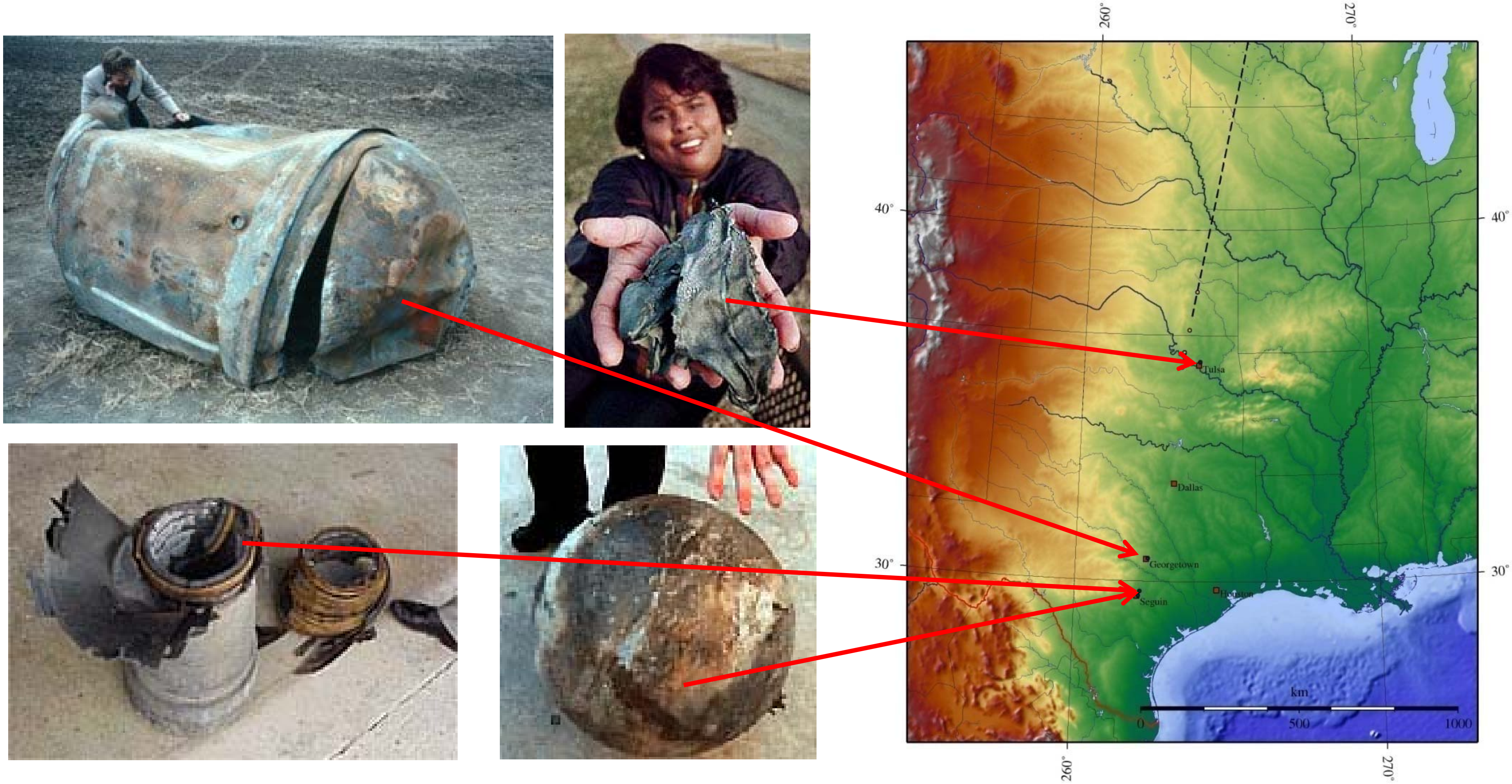
Argentina, 2004

Bangkok, 2005

Australia, 2007

MSX Rocket Body Reentry

- **Following the reentry of a Delta 2 second stage over Oklahoma and Texas in 1997, fragments were found in four separate locations.**



Space Stations and Related Vehicles

- Space Stations and their large modules are designed for controlled reentries over the Pacific Ocean due to their large numbers of survivable components. On four occasions malfunctions led to uncontrolled reentries.

Salyut 1	1971	20 metric tons	Controlled
Salyut 2	1973	20 metric tons	Uncontrolled
Cosmos 557	1973	20 metric tons	Uncontrolled
Salyut 3	1975	20 metric tons	Controlled
Salyut 4	1977	20 metric tons	Controlled
Salyut 5	1977	20 metric tons	Controlled
Cosmos 929	1978	20 metric tons	Controlled
Skylab	1979	75 metric tons	Uncontrolled
Salyut 6-Comos 1267	1982	40 metric tons	Controlled
Cosmos 1443	1983	20 metric tons	Controlled
Salyut 7-Cosmos 1686	1991	40 metric tons	Uncontrolled
Mir	2001	140 metric tons	Controlled

- More than 130 logistical vehicles (*i.e.*, Progress, ATV, HTV) have also been de-orbited in a controlled manner.

- A controlled reentry is also planned for the International Space Station.

The Reentry of Skylab

- **Plans to dispose of the Skylab space station safely went awry when (1) the maiden flight of the Space Shuttle slipped from the late 1970's to the early 1980's and (2) solar activity during Cycle 21 (peak in Dec 1979) was higher than anticipated.**

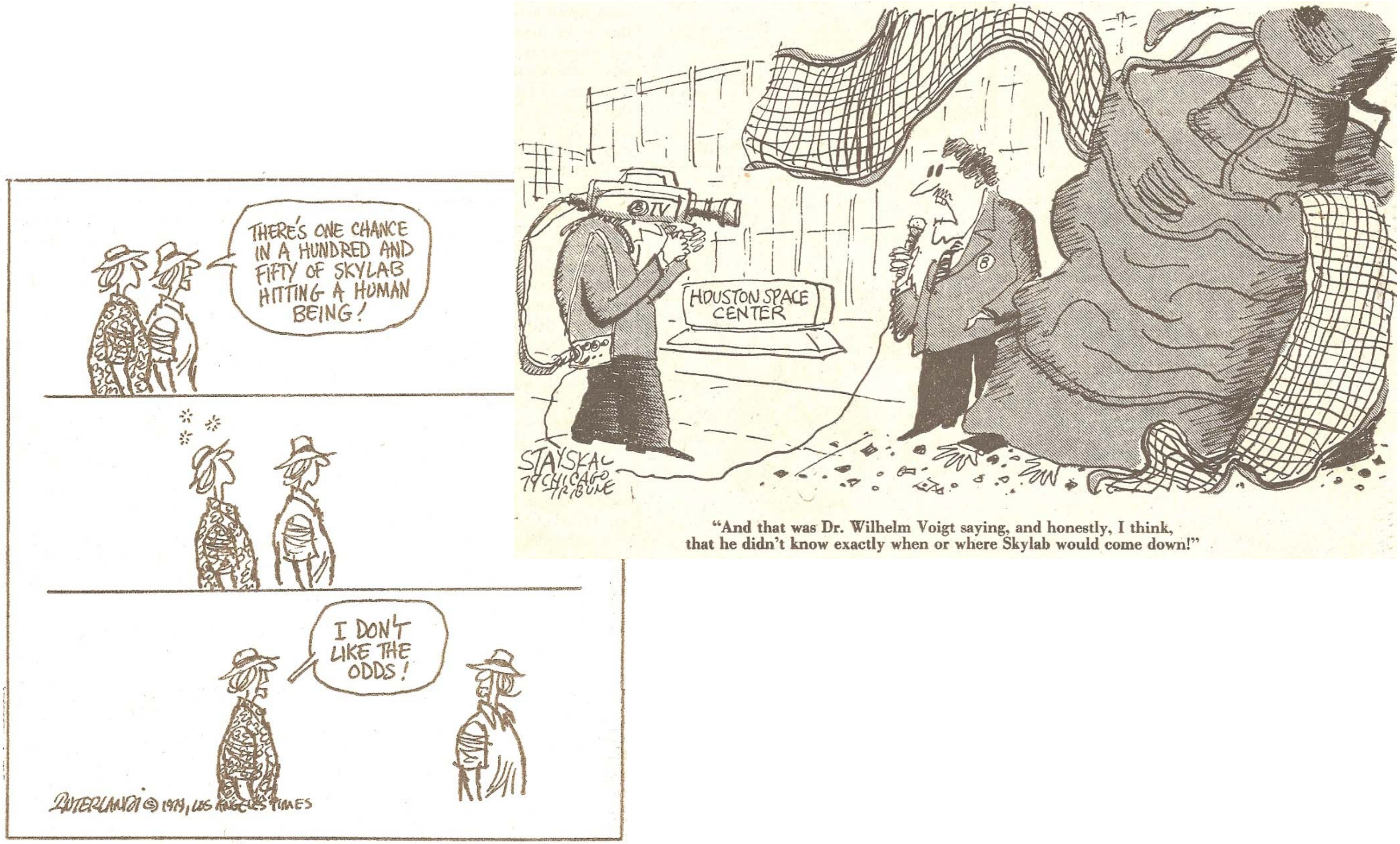
- **At the time, Skylab was the most massive satellite to approach reentry and was essentially uncontrollable.**

- **The imminent reentry cause concern in many parts of the world:**

  "Capital Jittery as Skylab Fall Nears" **LA Times, 1 Jul 79**

  "Panic Hits India as Skylab's Death Nears; Marcos Urges Calm; Swiss to Ring Bells" **LA Times, 4 Jul 79**

Preparing for Skylab Reentry



"And that was Dr. Wilhelm Voigt saying, and honestly, I think, that he didn't know exactly when or where Skylab would come down!"

Skylab Down Under

- **Skylab fell to Earth uncontrolled on 11 July 1979 spreading debris over the southern Indian Ocean and western Australia.**

"I told you so!"

NASA Fined For Skylab Litter

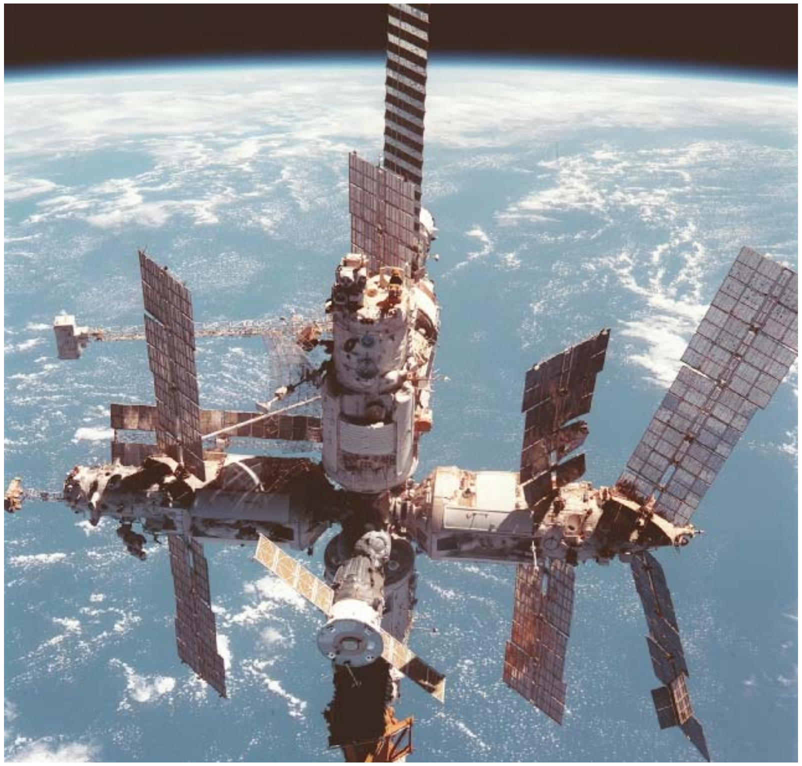
BERTH, Australia, July 19 (UPI)—The U.S. space agency team in western Australia to examine Skylab debris has been issued a littering citation by the Esperance county council.

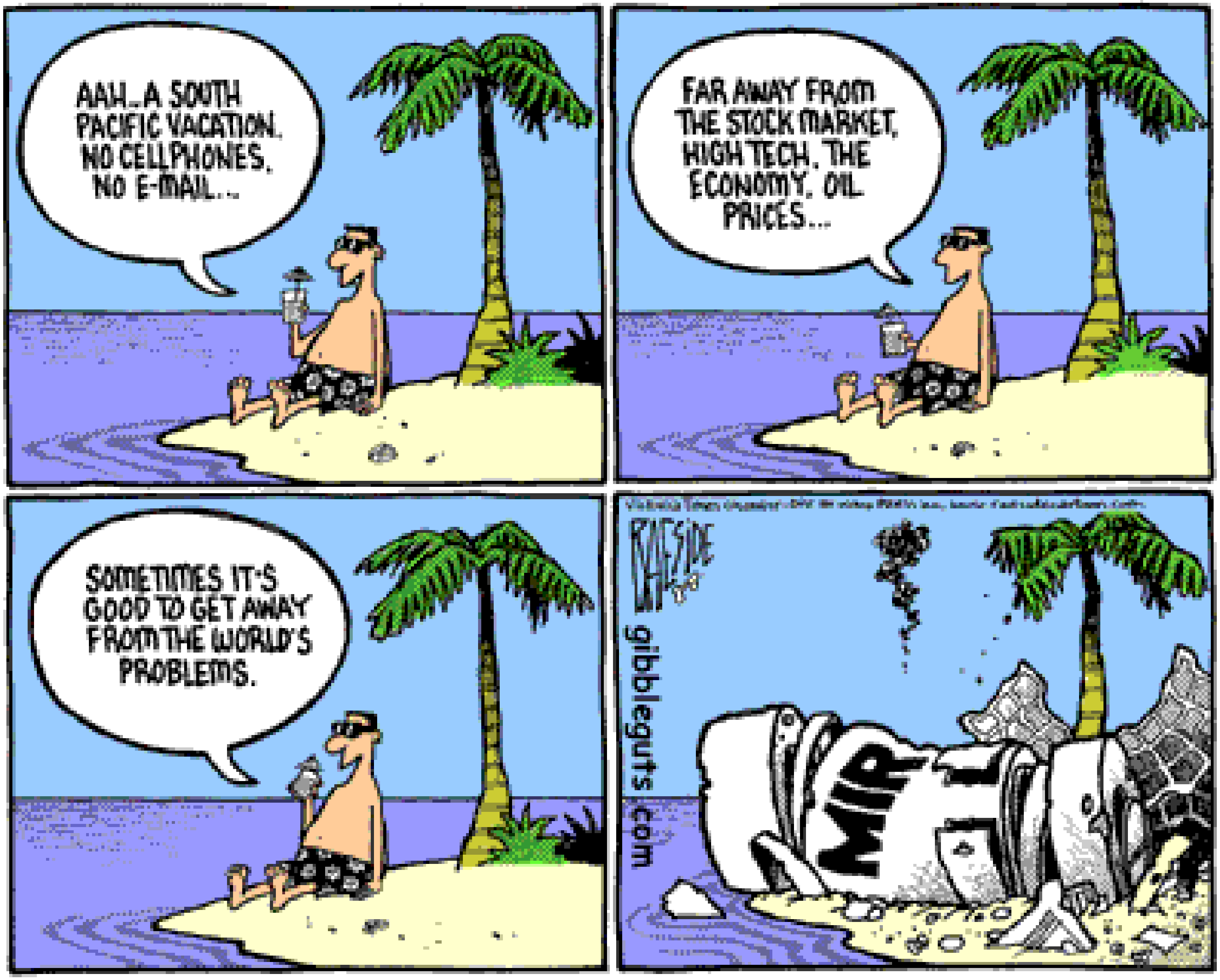
Esperance was the first Australian town to be hit by debris falling from the Skylab when it broke up last week.

Council President Merv Unbray said Wednesday that the notice was meant in fun. If the National Aeronautics and Space Administration paid the maximum littering fine of $400, the money would go to keep up the Esperance museum, Unbray said.

Reentry of the Mir Space Station

- **The Mir space station was de-orbited in a controlled manner over the Pacific Ocean on 23 March 2001.**
  - The U.S. Space Surveillance Network and NASA JSC provided support for the reentry operations.



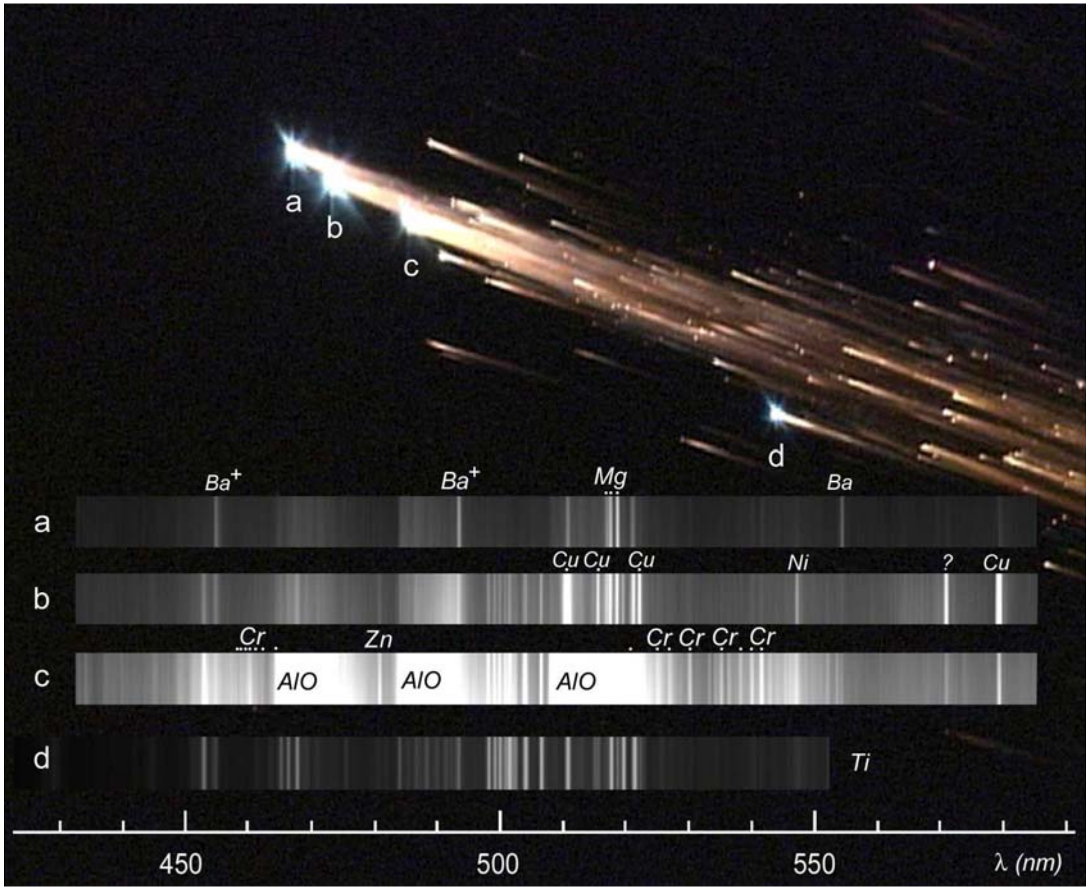

AAH...A SOUTH PACIFIC VACATION. NO CELLPHONES, NO E-MAIL...
FAR AWAY FROM THE STOCK MARKET, HIGH TECH, THE ECONOMY, OIL PRICES...
SOMETIMES IT'S GOOD TO GET AWAY FROM THE WORLD'S PROBLEMS.
RAESIDE
gibbleguts.com
MIR

Reentry of ATV-1

- **ATV-1, the first European logistics vehicle to ISS, was de-orbited over the Pacific Ocean on 29 September 2008.**

- **Two highly-instrumented aircraft were in position to record the vehicle's breakup.**

ATV-1 Debris Spectral Analysis



Different fragments have different emission signatures: a) Main cargo cabin: Mg, Al (not shown) and Ba emissions, but no Ti nor Cr; b) Ring with lithium batteries: strong Li (and Al) (not shown), Cu, and Ti, but no Cr; c) bottom propulsion bay: strong Ti and Cr (and Al) emissions; d) Minor fragment during a brief flare-up: strong Ti emission (one of the initial fragments generated during the main explosion).

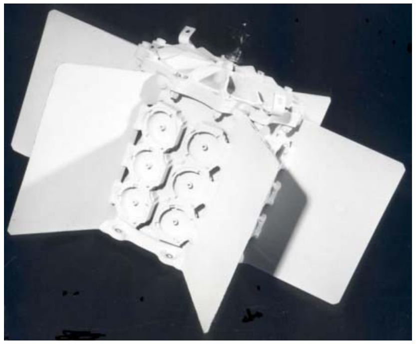
Data measured from GV aircraft with NIRSPEC instrument.

Reentry of Radioactive Materials

- **Due in large measure to public concern, the reentry of radioactive materials has been addressed thoroughly since the early 1960's.**

- **Two principal options for unanticipated reentries:**
  - Design for unit demise and dispersion of radioactive materials
  - Design for unit survivability and potential recovery

- **The April 1964 launch failure of Transit 5BN3 with the SNAP-9A radioisotope thermoelectric generator (RTG) led to a redesign of future RTGs to ensure intact reentry survivability.**



SNAP-9A

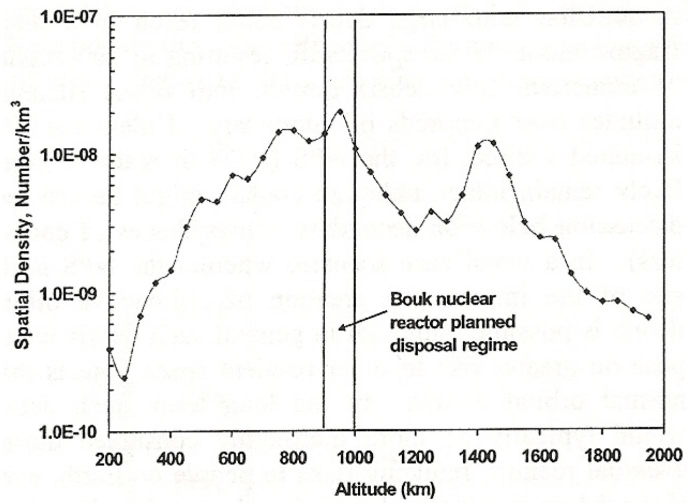
- **The subsequent launch failure in 1968 of Nimbus B with the SNAP-19B2 RTG proved the survivability of the unit, which was later recovered.**

Soviet Nuclear Reactors in Low Earth Orbit

- **After component testing in the late 1960’s, the former Soviet Union launched its first nuclear reactor in low Earth orbit in 1970 as part of a naval reconnaissance system. The spacecraft were known as RORSATs.**

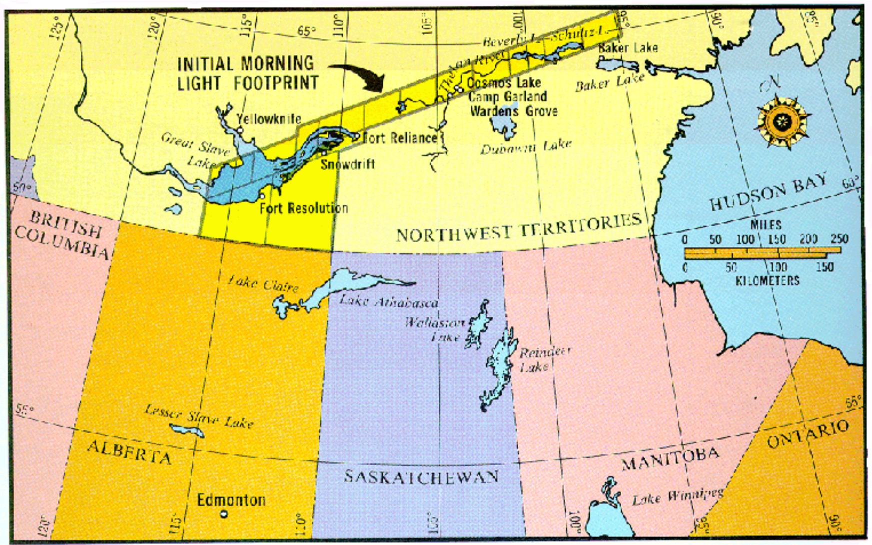
- **The spacecraft was designed to operate at an altitude of about 260 km for several months after which the section housing the reactor would be boosted to a storage orbit between 900 and 1000 km.**
  - Accidental reentries due to launch or spacecraft malfunctions were not adequately addressed.

- **Use of higher altitude disposal orbits permitted radioactive decay of the most hazardous materials prior to atmospheric reentry hundreds of years hence.**
  - However, the disposal orbits were in the most highly congested region of LEO.

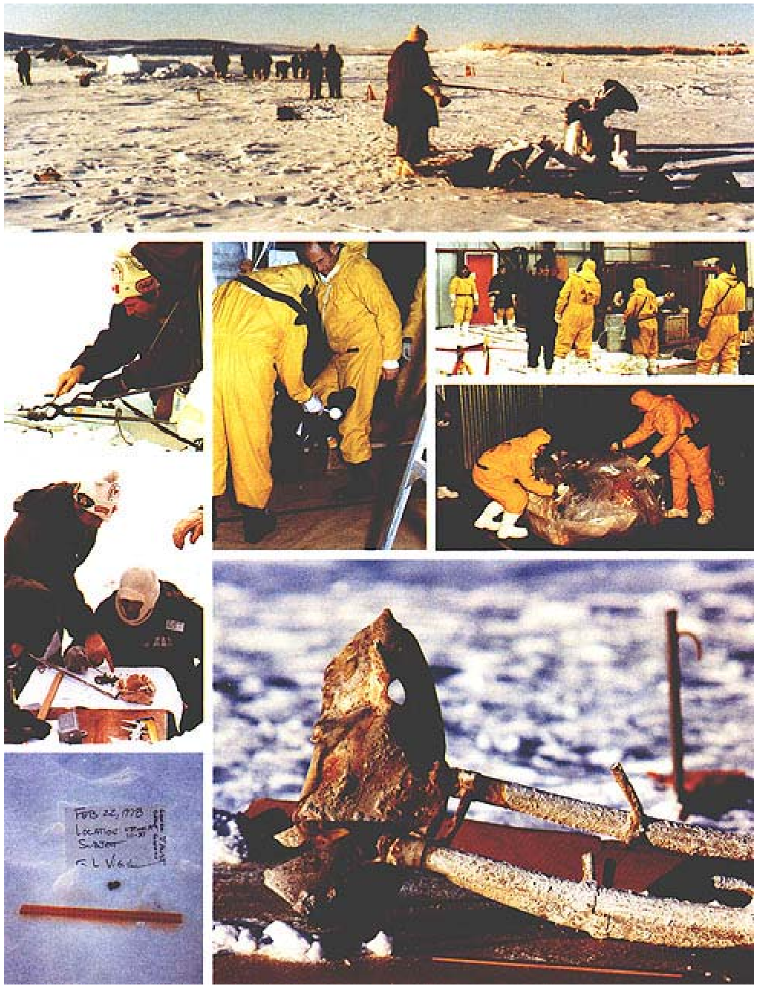


Reentry of Cosmos 954

- **Cosmos 954, a nuclear-powered Soviet RORSAT, malfunctioned in late 1977 and reentered in an uncontrolled manner over Canada in January 1978.**



Cosmos reentry footprint as calculated from data obtained on final orbit and from visual observations.

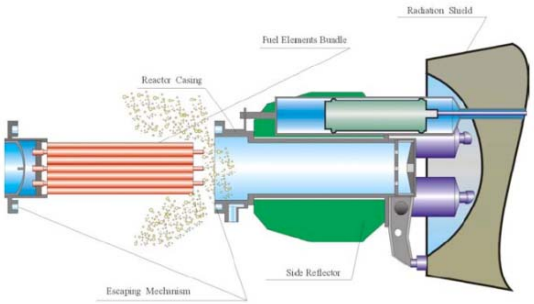


Redesign of RORSAT and Cosmos 1402

- **The survivability of radioactive components from Cosmos 954 was enhanced by the protection of the fuel core by the heavy reactor housing.**

- **Soviet engineers reasoned that another failure to boost the reactor to a higher altitude storage orbit could not be completely prevented. Therefore, they chose a solution which would mitigate the consequences of such a failure.**

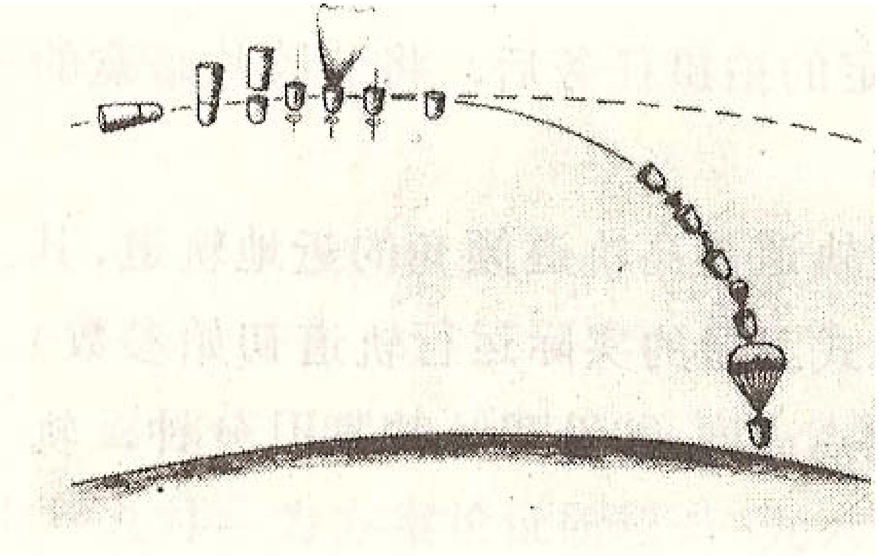
- **Future RORSAT vehicles employed an ability to eject the fuel core from the reactor. Reentering by itself, the fuel core would more completely be consumed.**



- **RORSAT flights resumed in 1980. In 1982 Cosmos 1402 also experienced a failure to boost to a storage orbit. The fuel core and the reactor reentered separately two weeks apart in early 1983 over broad ocean areas.**

Uncontrolled Chinese FSW 1-5 Capsule Reentry

- **A Chinese microgravity mission was launched on 8 October 1993 for a planned 8-day mission after which a reentry capsule was to be recovered.**
- **A misalignment of the vehicle at the time of the de-orbit burn, pushed the capsule into a higher, elliptical orbit.**
- **The capsule eventually reentered, amid great public interest, in an uncontrolled fashion in March 1996.**

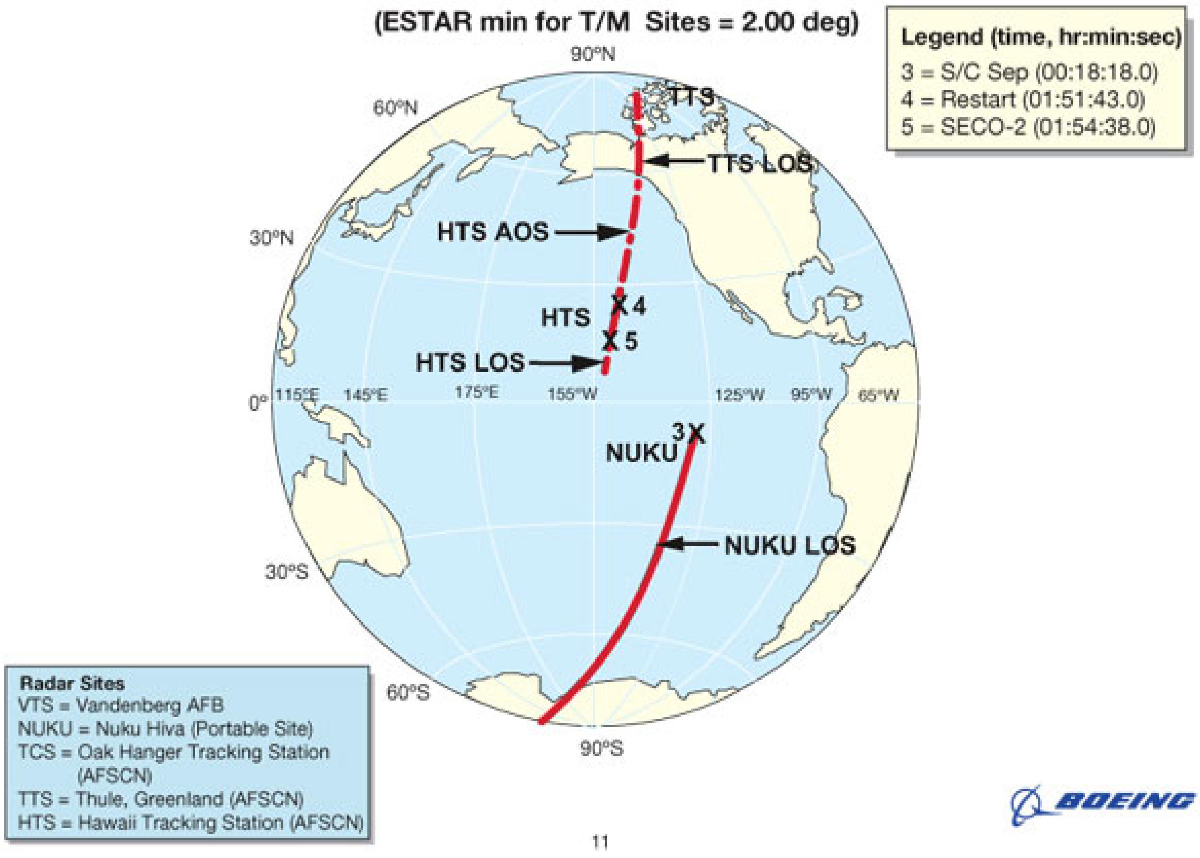


Nominal de-orbit sequence

Typical successful FSW recovery

Controlled Reentry of Delta IV Second Stage

- **To prevent potential human casualties and ground damage, in 2006 the DMSP 5D-3 F17 Delta IV second stage demonstrated the ability for a controlled reentry from a circular orbit of 850 km.**



Legend (time, hr:min:sec)
3 = S/C Sep (00:18:18.0)
4 = Restart (01:51:43.0)
5 = SECO-2 (01:54:38.0)

Radar Sites
VTS = Vandenberg AFB
NUKU = Nuku Hiva (Portable Site)
TCS = Oak Hanger Tracking Station (AFSCN)
TTS = Thule, Greenland (AFSCN)
HTS = Hawaii Tracking Station (AFSCN)

Origin of NASA Reentry Risk Metrics

- **NASA Safety Standard 1740.14 (August 1995) first established the guideline for all LEO spacecraft and launch vehicle orbital stages to remain in orbit for no more than 25 years after end of mission for the purpose of protecting the space environment for future operations.**
  - This guideline is now accepted by the U.S. Government and many foreign space agencies and international bodies.
- **The most practical and cost-effective strategy for compliance is disposal of the vehicle in a low altitude orbit from which a natural, uncontrolled reentry will occur within the allotted time.**
- **However, such uncontrolled reentries shift on-orbit satellite collision risks to human casualty risks on Earth. To limit human casualty risks from surviving satellite debris, NASA developed a specific risk criterion and risk assessment process.**

Reentry Risk Criterion

- **In NASA Safety Standard 1740.14 (1995), a total debris casualty area metric was established:**

$$D_A = \sum_{i=1}^{N} \left(0.6 + \sqrt{A_i}\right)^2$$

where N is the number of objects that survive reentry and A_i is the area of the surviving piece in m^2. The term 0.6 represents the square root of the average cross-sectional area of a standing person, as viewed from above. Debris with impacting kinetic energies less than 15 Joules are no longer considered.

- **Total human casualty expectation, E, can then be defined as**

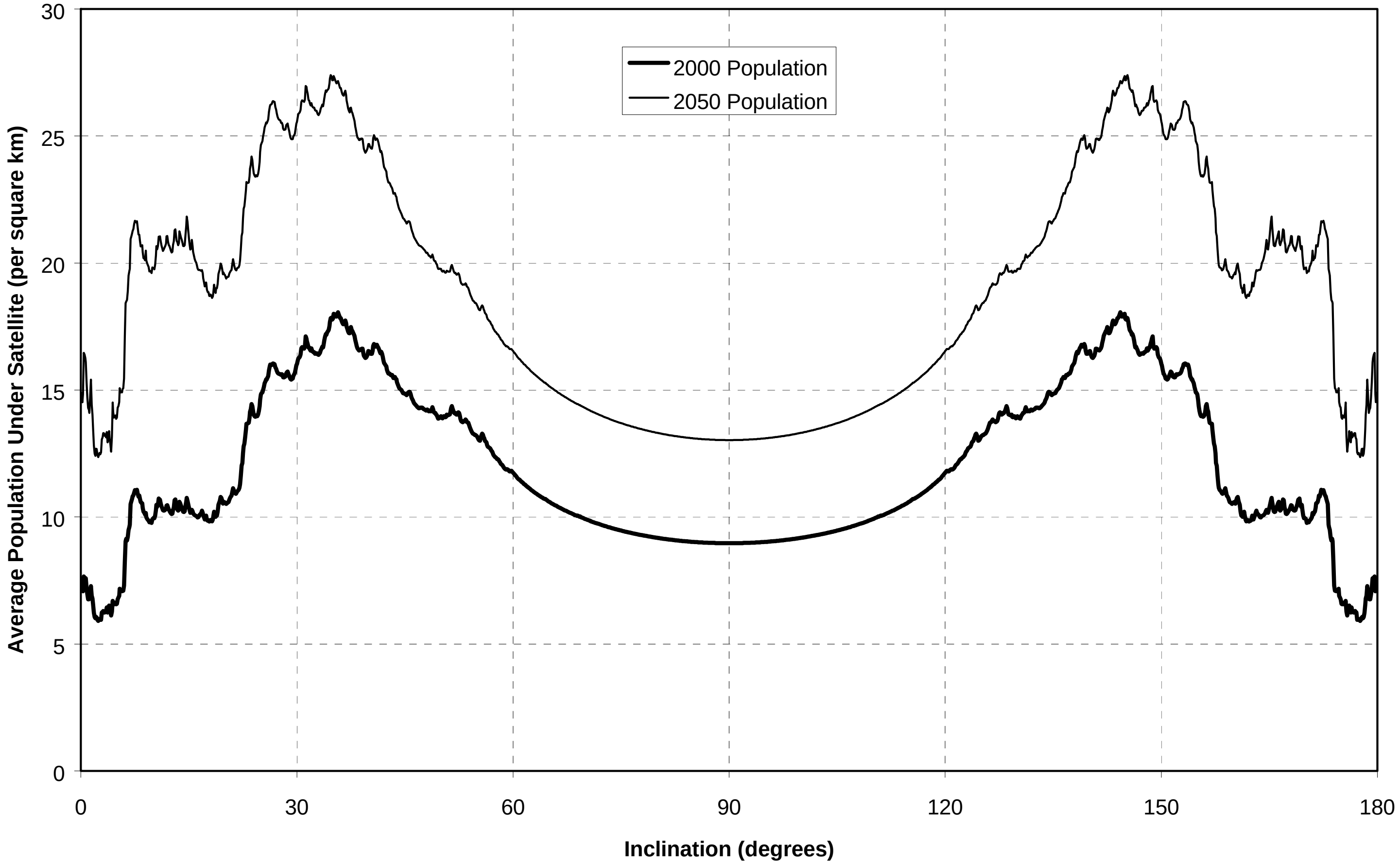
$$E = D_A \times P_D$$

where P_D is equal to the average population density for the particular orbital inclination and year of reentry.

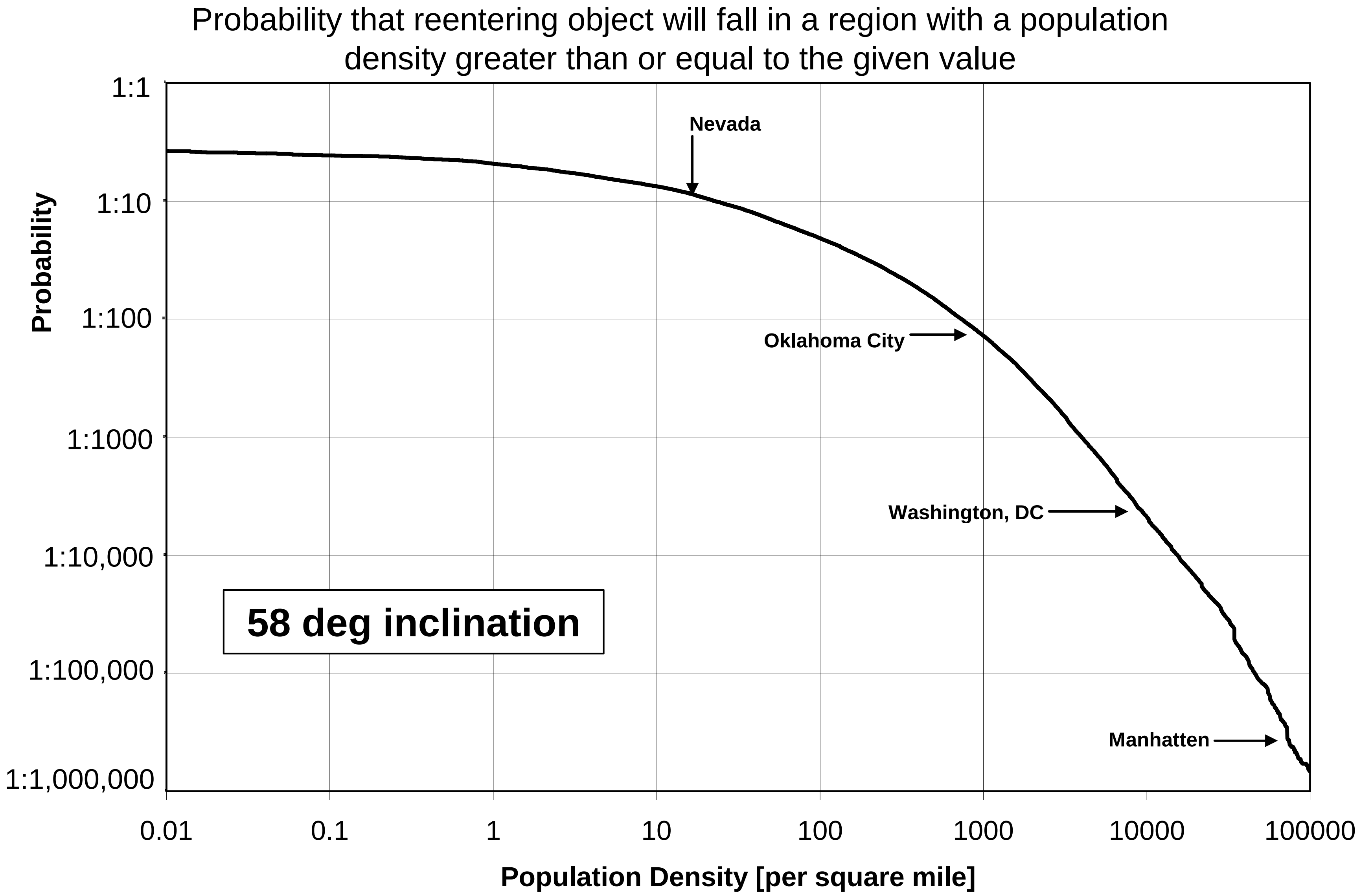
- **A fundamental human casualty risk threshold of 1 in 10,000 per reentry event was adopted by NASA in 1995, which was equivalent to a debris casualty area of no more than 8 m^2 averaged over all inclinations for that year.**

World Population Evolution

- **Using internationally recognized sources for the 2000 world population and its expected evolution through 2050, average population densities weighted by the fraction of time a satellite spends at different latitudes as a function of orbital inclination have been developed.**



Probability of Impact versus Population Density



Background for ISS Jettison Policy

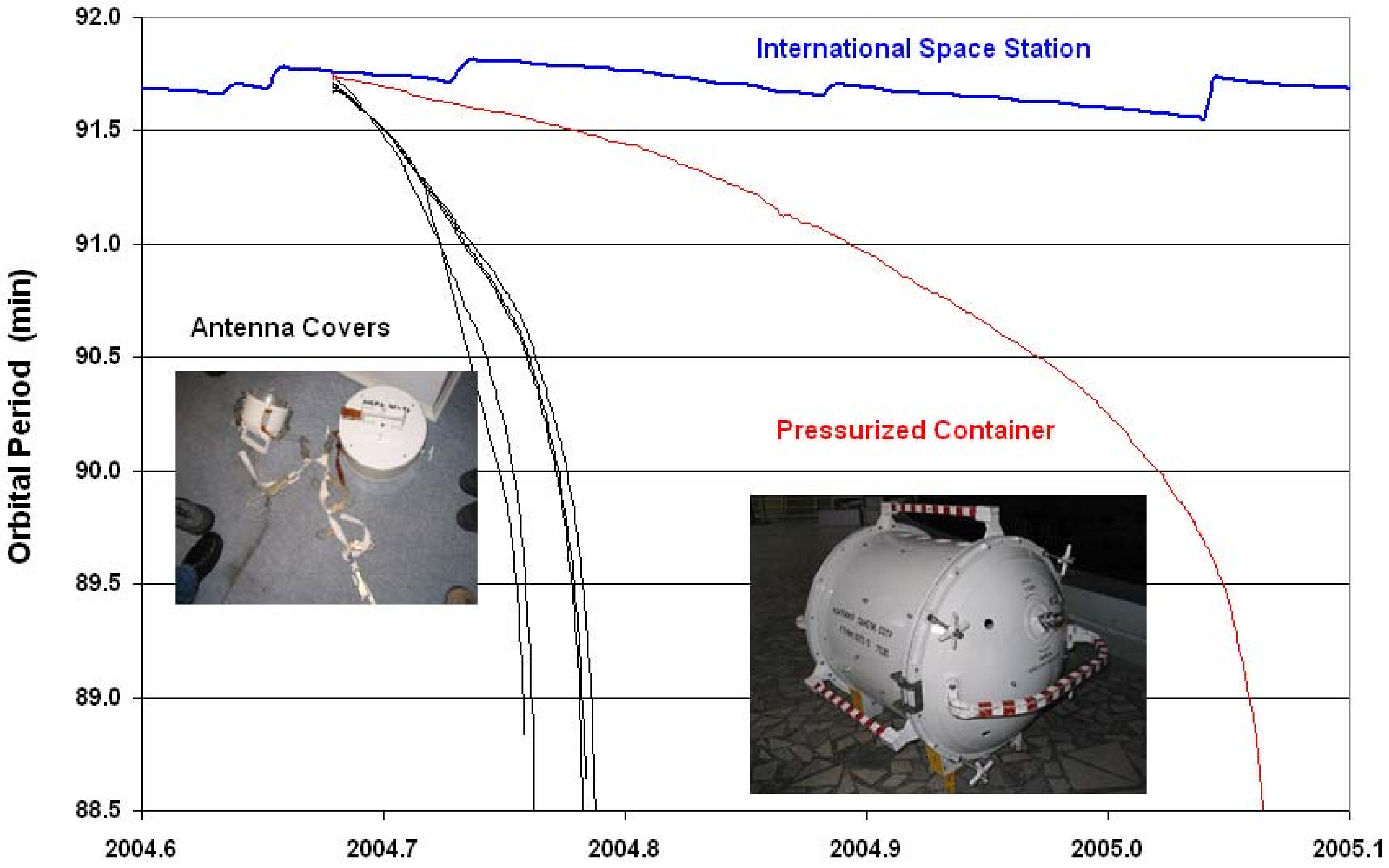
- Informal discussions on jettison policy begun by 2002, in part, due to accumulation of debris on ISS.
- Non-functional items inside and outside ISS can pose hazard to crew and/or impede productivity.
- Loss of Space Shuttle Columbia in February 2003 resulted in immediate cessation of shuttle flights, worsening the debris situation on ISS.
- Jettison policy must address safety of crew, ISS, visiting vehicles, other space objects, and people on Earth, as well as orbital debris mitigation guidelines.

Inside ISS, March 2002

Inside ISS, May 2005

Kick-off of ISS Jettison Policy

- **6 tracked (shown) and 7 untracked debris released intentionally in 2004 led to task for the development of formal ISS jettison policy.**



ISS Debris Mitigation

- **All approved ISS jettison activities should be compliant with NASA, U.S., and international orbital debris mitigation guidelines.**
  - Object should not pose a fragmentation risk prior to reentry in excess of 1 in 10,000
  - No object should remain in Earth orbit for more than 25 years
  - Cumulative object-time product for ISS jettisoned debris should be less than 100 object-years
  - Risk of human casualty from the reentry of a jettisoned object should not exceed 1 in 10,000
- **The above goals are normally easily met.**
  - Reentry risk assessments are conducted by the NASA Orbital Debris Program Office.

ISS Jettison of EAS in 2007

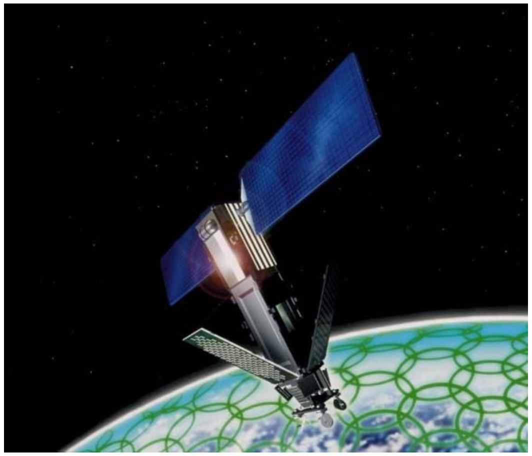
- **The Early Ammonia Servicer (EAS) was attached to the P6 truss of ISS in 2001. Removal of EAS was required before relocation of P6.**
- **EAS was too large or hazardous to return to Earth in the Space Shuttle or a logistics vehicle or to relocate on ISS.**
- **Although a survivability assessment for EAS yielded a reentry human casualty risk of about 1 in 5,000, no safer option was available.**

Testing EAS for Jettison

EAS Jettison

The Iridium Constellation Quandary

- **The Iridium constellation of communications satellites in low Earth orbit (altitude of 780 km) was initially deployed during 1997-1999.**



- **With 74 operational spacecraft (560 kg dry mass each), Iridium filed for bankruptcy in August 1999. The proposed disposal of Iridium assets called for initiating uncontrolled reentries of all working spacecraft.**
  - Controlled reentries were not possible due to small spacecraft thrusters.

- **Although each spacecraft was designed to satisfy the 1 in 10,000 recommended reentry risk threshold (assessed 1 in 18,400), the aggregate risk of human casualty from all 74 spacecraft was ~ 1 in 250.**

The Iridium Constellation Quandary (2)

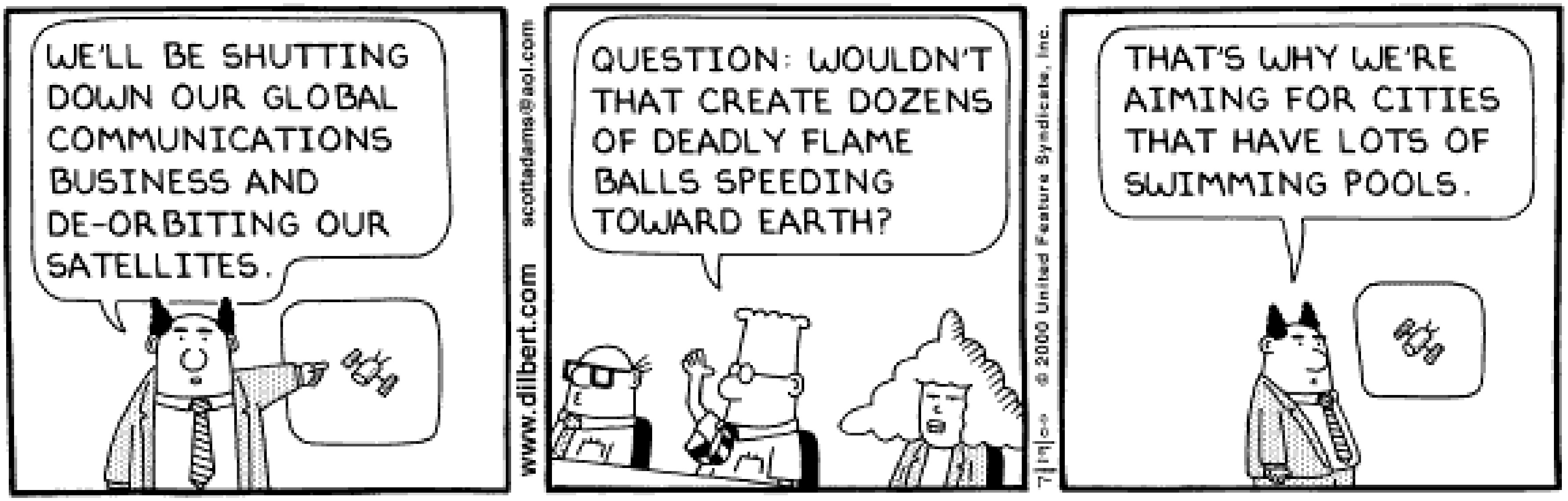
- **NASA component reentry survivability assessment (47 different component types) found only six surviving debris:**

Item No.	Component	Total Debris Casualty Area (m^2)	Original Total Mass (kg)	Impact Velocity (mph)
11	Sep Foot Bracket (3)	1.4	6.3	130
27	Propellant Tank	1.3	9.8	50
39	Battery	1.0	30.5	125
42	Electronic COM Panel	2.3	115.9	45
		6.1 m^2	162.5 kg*	

* surviving mass will normally be less

- **A new owner took control of the Iridium network and disposal of the spacecraft was postponed.**

The Other Option



NASA Reentry Risk Evaluation Process

- Reentry risk assessments are required for all NASA programs and projects in conjunction with the Preliminary Design Review (PDR) and Critical Design Review (CDR) milestones.

- NASA maintains two levels of reentry risk assessment software:

DAS (Debris Assessment Software)

and

ORSAT (Object Reentry Survival Analysis Tool)

- DAS is publicly available and can be used by program/project personnel.

- ORSAT is a higher fidelity, more capable model run by trained specialists at the NASA Johnson Space Center.

NASA Standard 8719.14A

- **NSS 1740.14 was replaced in 2007 with NASA Standard 8719.14.**
- **Section 4.7 of NASA STD 8719.14A is entitled "Survival of Debris from the Postmission Disposal Earth Atmospheric Reentry Option":**

"Requirement 4.7-1. Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting energy in excess of 15 joules:

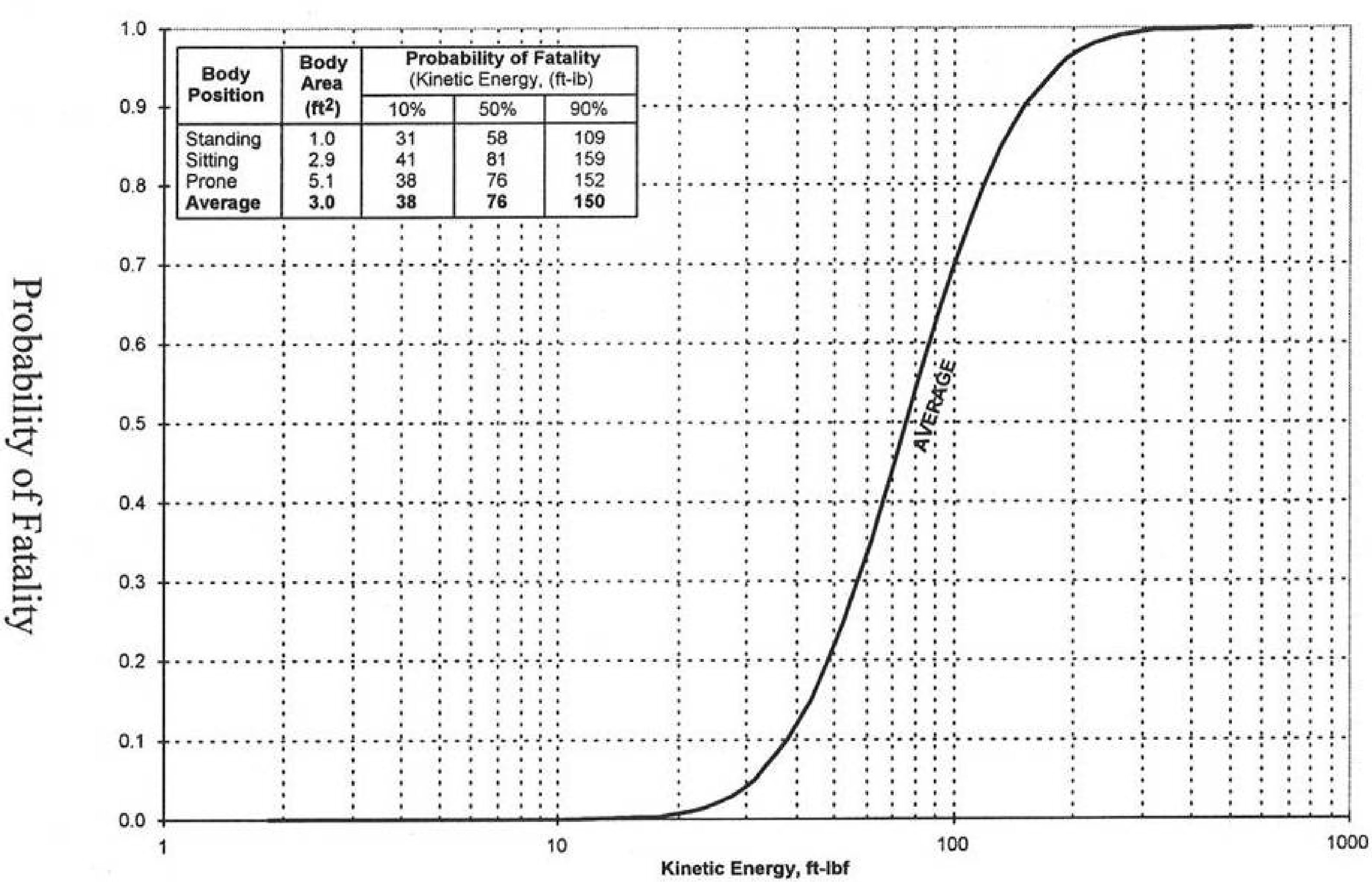
"a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

"b) For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).

"c) For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b.) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628)."

Kinetic Energy versus Probability of Fatality

- **The 15 J limit for human casualty was derived from various positions and medical considerations. Fatality is a subset of Casualty.**



Body Position	**Body Area (ft^2)**	**Probability of Fatality** (Kinetic Energy, (ft-lb))		
		10%	50%	90%
Standing	1.0	31	58	109
Sitting	2.9	41	81	159
Prone	5.1	38	76	152
Average	**3.0**	**38**	**76**	**150**

USG Orbital Debris Mitigation Standard Practices

- **The US Government Orbital Debris Mitigation Standard Practices were first developed in 1997, in response to direction from the White House Office of Science and Technology Policy.**

- **The draft Standard Practices were presented to industry in January 1998 and adopted via a USG Interagency process in early 2001.**

- **Standard Practice 4-1 addresses spacecraft and launch vehicle stage disposal options.**
  - For vehicles in low Earth orbit, the vehicle should be left in an orbit which will result in reentry within 25 years, taking into account potential human casualty risks on Earth.

US Government Orbital Debris Mitigation Standard Practice 4-1

"4-1. ***Disposal for final mission orbits:*** **A spacecraft or upper stage may be disposed of by one of three methods:**

a. Atmospheric reentry option: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000.

b. Maneuvering to a storage orbit: At end of life the structure may be relocated to one of the following storage regimes:

- **I. Between LEO and MEO: Maneuver to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous altitude**
- **II. Between MEO and GEO: Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude.)**
- **III. Above GEO: Maneuver to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude)**
- **IV. Heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit, into a heliocentric orbit.**

Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime.

c. Direct retrieval: Retrieve the structure and remove it from orbit as soon as practical after completion of mission."

Japanese Space Debris Standard

- **Japan quickly followed NASA’s 1995 lead in issuing orbital debris mitigation guidelines with the NASDA Space Debris Mitigation Standard (NASDA-STD-18) in 1996. This was followed by NASDA-STD-18A in 2003 and JMR-003A in 2004.**

- **NASDA-STD-18A Section 5.4 is Requirements for Re-entry or Natural Decay Disposal Options:**

“5.4.1 Lifetime reduction and natural decay

“If space systems are maneuvered to reduce the orbital lifetime or left as they are with expectation of natural decay, the following requirements should be complied.

(1) Hazard caused by ground impact of objects surviving atmospheric re-entry (estimated by “Number of Casualty”, “Probability of injury for Individual” and “Impact”) should be estimated prior to the launch event, and reconfirmed when the event time would be cleared. In case that the value of “Number of Casualty” would exceed 1×10^{-4} [human / event], the best effort to conduct controlled reentry into safe impact zone should be made with consideration of state-of-the-art and attitude of foreign space organizations.

(2) In both case of natural decay and controlled re-entry, the best effort to realize lower survivability should be paid with considering state-of-art and attitude of foreign space organizations.”

IADC Space Debris Mitigation Guideline

- **The Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) are essentially derived from the U.S. Government Orbital Debris Mitigation Standard Practices and were adopted in 2002 by the 11 IADC member agencies.**

- **Guideline 5.3.2 addresses reentry disposals for space vehicles.**

> “Whenever possible 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 a reduced lifetime. Retrieval is also a disposal option.
>
> “A spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post-mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.”

Support to the IADC Space Debris Mitigation Guidelines

- **In 2004, the IADC adopted and released a companion document to the "IADC Space Debris Mitigation Guidelines", entitled "Support to the IADC Space Debris Mitigation Guidelines". Excerpt pertaining to reentry risks:**

"One effective space debris mitigation measure is the removal of mission-terminated space objects from useful orbit regions and the disposal of them by aerodynamic heating during re-entry, if possible. However, the ground casualties that might be caused by fragments surviving atmospheric re-entry should be carefully considered in planning uncontrolled re-entry, particularly for large spacecraft.

"To assess the human casualty risk of impact by objects that survive re-entry, assessment parameters and their allowable levels, reliable analysis tools for survivability, and acceptable analysis conditions should be developed…

"Typical parameters to assess re-entry safety are casualty area and the casualty expectation (Ec). An allowable Ec is not currently recommended in the IADC Guidelines, while NASA Safety Standard 1740.14, the U.S. Government Orbital Debris Mitigation Standard Practices, and NASDA Space Debris Mitigation Standard (NASDA-STD18A) limit the value of Ec to less than 10^{-4} [persons per event]."

United Nations Space Debris Mitigation Guidelines

- **The United Nations Space Debris Mitigation Guidelines were developed within the Committee on the Peaceful Uses of Outer Space and adopted in 2007, followed by endorsement of the General Assembly the same year.**

- **Guideline 6 addresses space vehicle disposal in LEO:**

  - “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 which avoid their long-term presence in the LEO region.

    “When making determinations regarding potential solutions for removing objects from LEO, due consideration should be given to ensure that debris which survives to reach the surface of the Earth does not pose an undue risk to people or property, including through environmental pollution caused by hazardous substances.”

European Code of Conduct for Space Debris Mitigation

- **The European Code of Conduct for Space Debris Mitigation entered into force in 2006. This document was signed by the heads of the Italian, French, German, and UK space agencies, as well as the Director General of ESA.**

- **Design Measures, Paragraph 4.4.2, addresses re-entry issues.**

- **SD-DE-12**

“a) A space project should limit the risk from re-entering space debris to a safe level

“b) The end of life operations should take into account the applicable on ground safety rules, which depend on the launching state.

“c) The casualty risk on ground should not exceed 10^{-4} per re-entry.

ESA Instruction for Reentry Risks

- **In 2008 the Director General of the ESA issued an instruction to implement the European Code of Conduct for Space Debris Mitigation. Two operational requirements address reentry risks:**

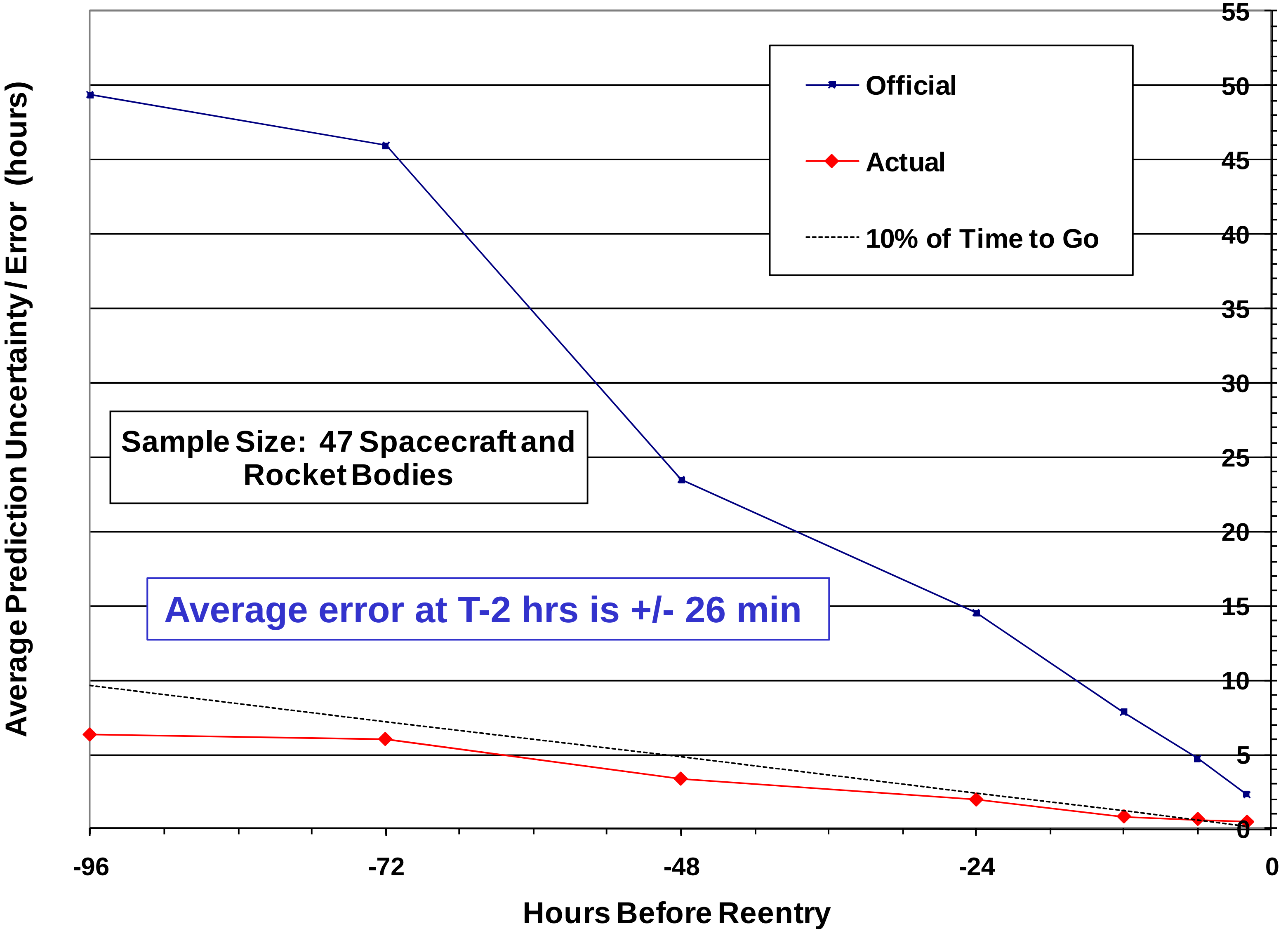
OR-06: "For space systems that are disposed of by re-entry, the prime contractor shall perform an analysis to determine the characteristics of fragments surviving to ground impact, and assess the total casualty risk to the population on the ground assuming an uncontrolled re-entry."

OR-07: "In case the total casualty risk is larger than 10^{-4}, uncontrolled re-entry is not allowed. Instead, a controlled re-entry must be performed such that the impact foot-print can be ensured over an ocean area, with sufficient clearance of landmasses and traffic routes."

U.S. Reentry Prediction Process

- **The U.S. Space Surveillance Network (SSN) conducts Reentry Assessments (RAs) [aka TIPs, Tracking and Impact Prediction] for spacecraft, rocket bodies, and selected other space objects.**
- **Official RAs are published at specified intervals prior to anticipated reentry:**
  - T – 4 days, T – 3 days, T – 2 days, T – 24 hours, T – 12 hours, T – 6 hours, T – 2 hours
- **However, the uncertainties of these projections for reentry time and location are subject to substantial errors and cannot be used for warning purposes**
  - Even the final T – 2 hour prediction for an object in a circular orbit has an error on the order of +/- 25 minutes, which is equivalent to +/- ~12,000 km (next chart).
- **The Orbital Debris Program Office informs NASA HQ and other organizations concerning the reentries of NASA spacecraft and rocket bodies.**

Reentry Prediction Uncertainty



Sample Size: 47 Spacecraft and Rocket Bodies

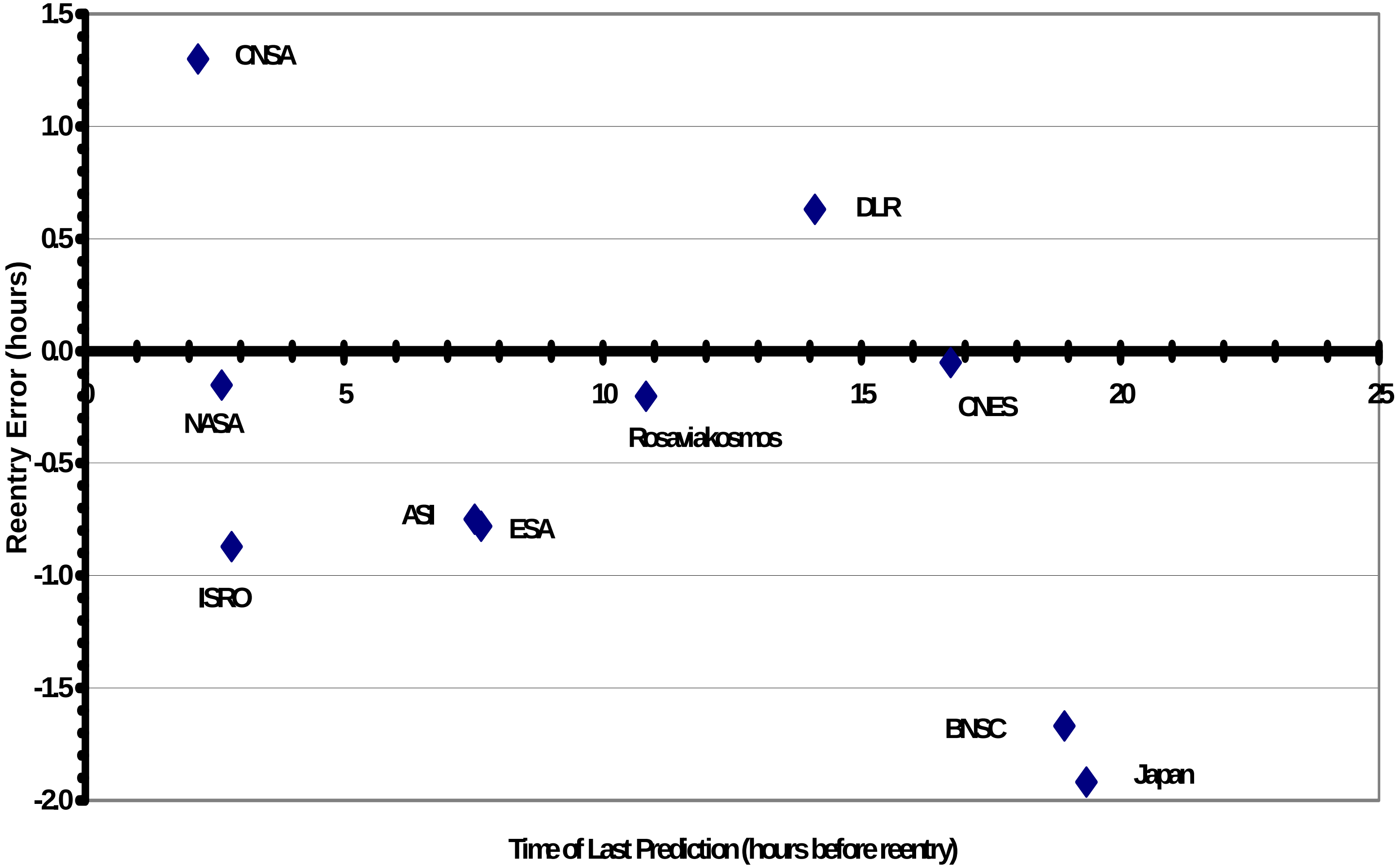
Average error at T-2 hrs is +/- 26 min

IADC and Reentries

- **In 1996 the IADC began discussions aimed at implementing a Risk Object Reentry Communications Network. The concept was adopted in 1998 and added to the IADC Terms of Reference in 1999 (Annex VI).**
  - Interest pre-dated Mars 1996 accident (Nov 96)
  - Preliminary exercise involved reentry of FSW 1-5 in Mar 1996
  - NASA-DoD agreement to support IADC concept in Aug 1996
  - Final IADC process received USG Interagency approval
- **The objective of the internet-based communications network is to relay tracking and reentry prediction information in real-time in the event of the uncontrolled reentry of a risk object.**
  - A Risk Object is normally defined as a satellite (1) with a mass of more than 5 metric tons, (2) containing hazardous (*e.g.*, radioactive) materials, or (3) of a special nature
  - Data and information is hosted on a server at ESA ESOC (Darmstadt, Germany)
- **IADC Risk Object Reentry Exercises are conducted annually to test communications links and processes.**

Sample IADC Final Reentry Prediction Summary

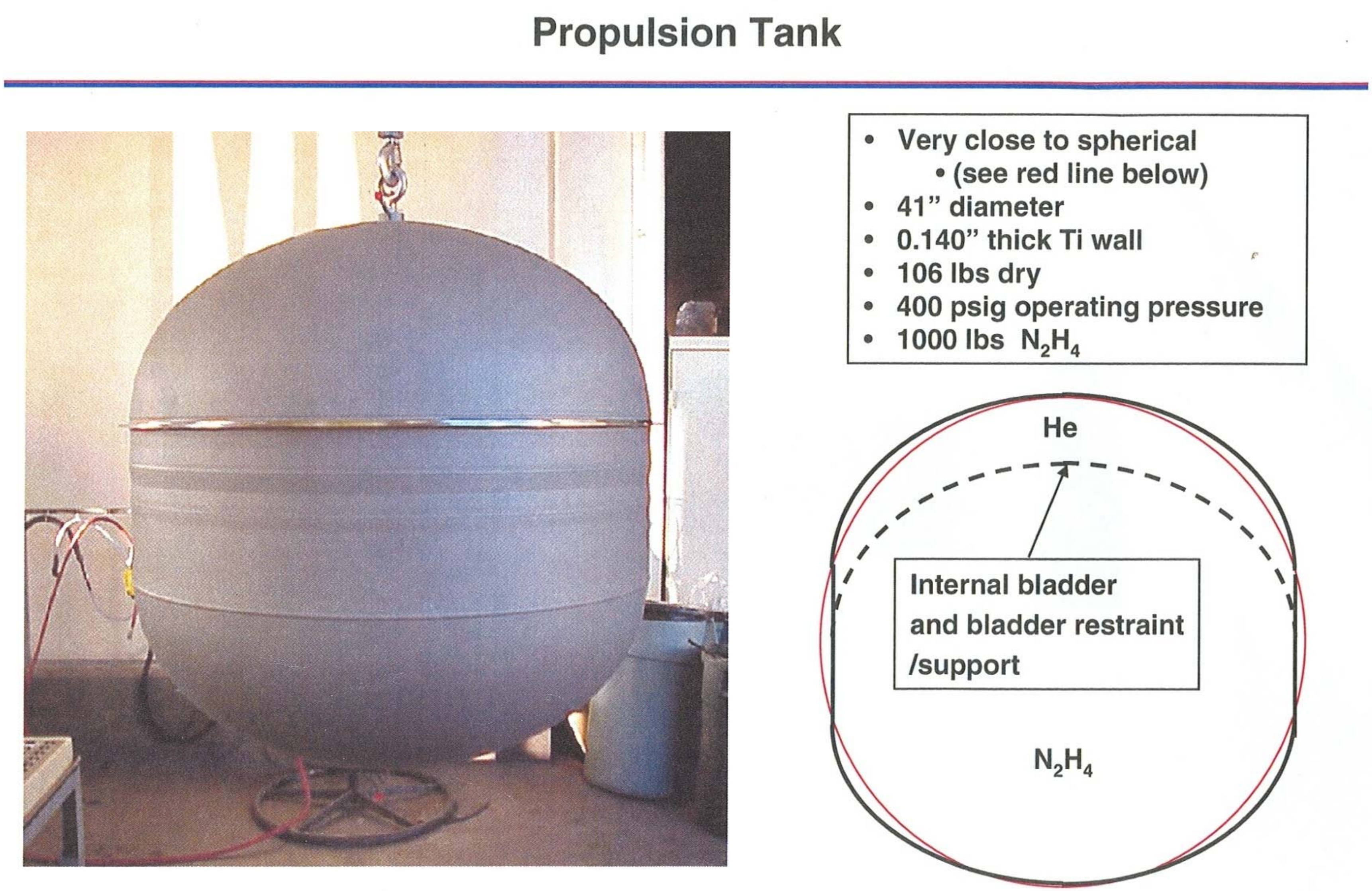
Reentry of Sat. No. 25947, SL-4 Rocket body, 4 March 2000



Special Case of USA-193

- **A US government spacecraft (USA-193) was launched in December 2006 and failed immediately after entering a low altitude orbit.**
- **The spacecraft propulsion tank contained ~450 kg of hydrazine, which soon froze.**
- **An uncontrolled reentry of USA-193 was predicted for March 2008.**
- **NASA was tasked to evaluate the survivability of the propellant tank and its contents and to estimate the reentry human casualty risk.**
  - The NASA Orbital Debris Program Office conducted these assessments.
- **A Presidential decision was made to engage USA-193 with a sea-launched missile to eliminate the threat to people from surviving hydrazine.**

USA-193 Propellant Tank



Propulsion Tank

- Very close to spherical
    - (see red line below)
- 41” diameter
- 0.140” thick Ti wall
- 106 lbs dry
- 400 psig operating pressure
- 1000 lbs N_2H_4

He

Internal bladder and bladder restraint /support

N_2H_4

USA-193 Reentry Preparations

- **The intention to engage USA-193 was announced to the public on 14 February.**

- **IADC member countries were notified that the IADC Risk Object Reentry Communications Network would be activated in the event that the engagement of USA-193 was unsuccessful.**

- **A presentation was made by the US to the Scientific and Technical Subcommittee of the United Nation's Committee on the Peaceful Uses of Outer Space (COPUOS) on 19 February to summarize the anticipated effects of a successful engagement on the near-Earth space environment.**

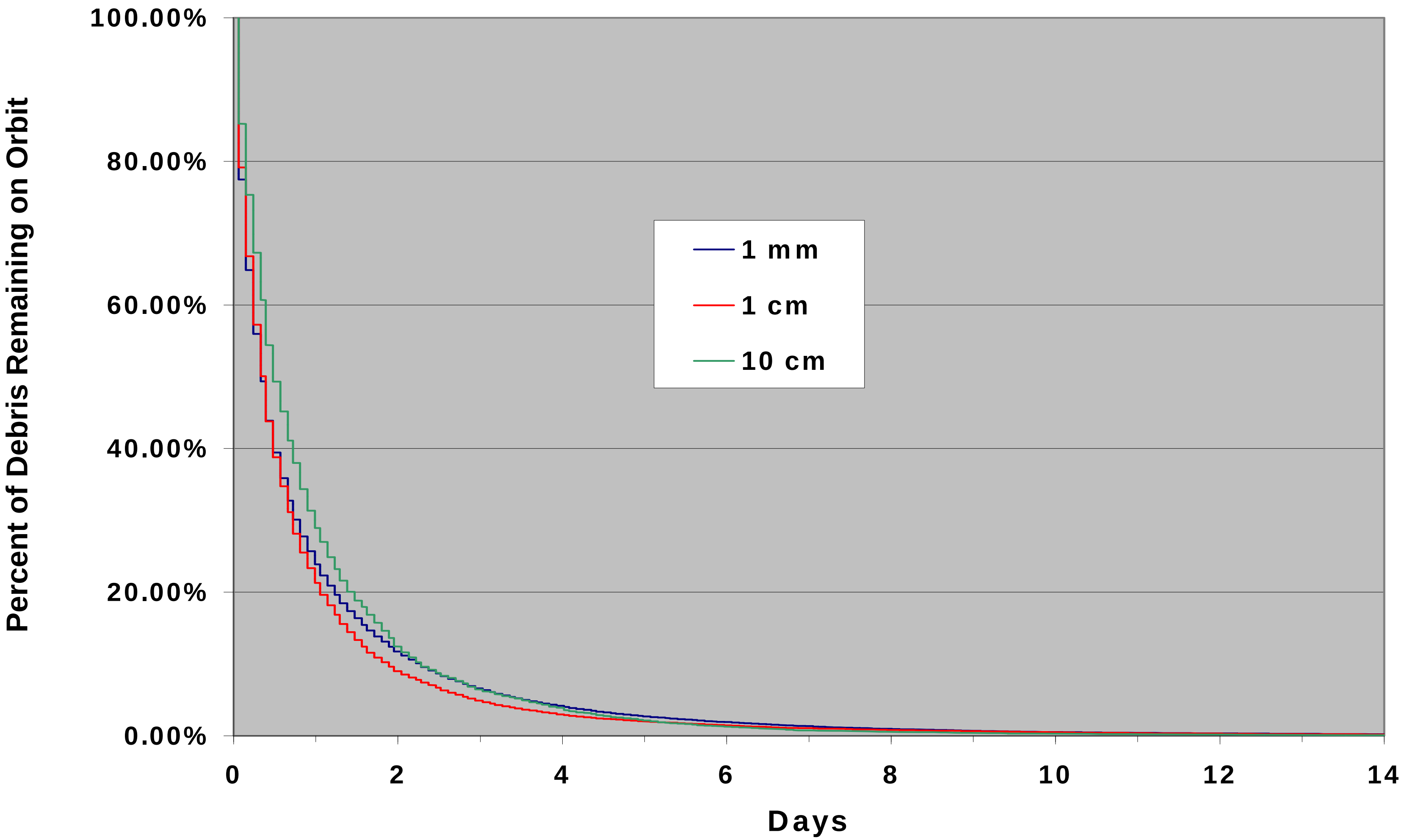
    – The planned engagement was completely compliant with all US, IADC, and UN space debris mitigation recommendations.

- **The engagement was successful: USA-193 was destroyed at an altitude of ~ 250 km on 21 February 2008 (20 February in US).**

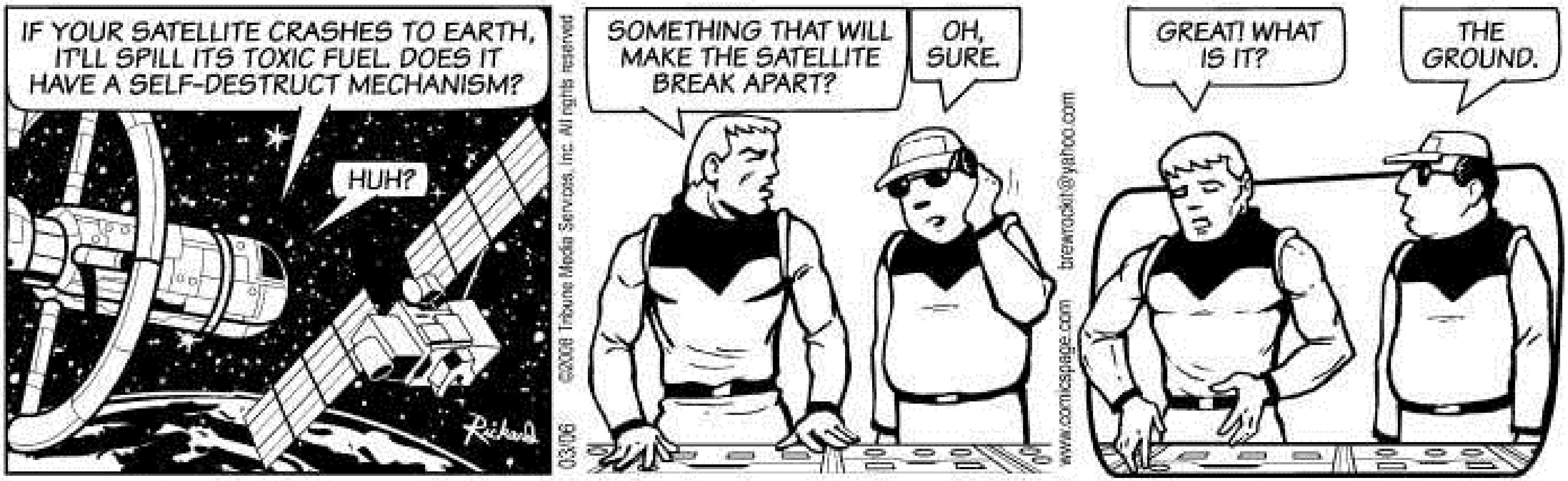
(This chart was presented to the UN COPUOS STSC on 19 February 2008)

Maximum Longevity of Debris

- **Assuming a worst case scenario of fragmentation at 250 km, 99% of the debris placed in orbit will reenter within one week.**



Engagement of USA-193


IF YOUR SATELLITE CRASHES TO EARTH, IT'LL SPILL ITS TOXIC FUEL. DOES IT HAVE A SELF-DESTRUCT MECHANISM?
HUH?
Rickard
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SOMETHING THAT WILL MAKE THE SATELLITE BREAK APART?
OH, SURE.
www.comicspage.com brewrocket@yahoo.com
GREAT! WHAT IS IT?
THE GROUND.


beep
AVIATION PARANOIA HOTLINE, KLYDE MORRIS LATE NIGHT PART-TIME COUNSELOR SPEAKING... HOW CAN I HELP YOU?
AVIATION PARANOIA HOTLINE
© 2008 WES OLESZEWSKI
WHAT'RE THE CHANCES THAT CRASHING SPY SATELLITE'S PIECES WILL FALL ON ME?
SINCE ABOUT 70% OF THE PLANET IS COVERED BY WATER THERE'S ABOUT A 70% CHANCE IT'LL HIT WATER BUT...
I HAVE A DRIPPING SINK FAUCET AND AN AQUARIUM, DOES THAT INCREASE MY ODDS OF BEING DOOMED?
..THAT'S NOT WHAT I'M SAYING...
www.klydemorris.com
THE DESERT! SHOULD I MOVE TO THE DESERT?!
SUGGEST BUYING ONE OF THOSE LITTLE WILE E. COYOTE UMBRELLAS.
sigh

Failure of EUTELSAT W3B Satellite

- **Shortly after its launch and injection into a highly elliptical geosynchronous transfer orbit on 28 October 2010, the EUTELSAT W3B spacecraft suffered a major leak in the oxidizer section of its main propulsion system.**

- **After an assessment determined that the spacecraft could not be maneuvered into a useful geosynchronous orbit, a preliminary decision was made to conduct a controlled reentry to remove the vehicle as a hazard to other resident space objects or people and property on Earth.**
  - A controlled reentry of the Astra 1K spacecraft was executed after it was stranded in a GTO in 2002.

- **However, before deorbit plans could be prepared the EUTLESAT W3B fuel began to freeze, preventing any further maneuvers.**
  - The 3-metric-ton dry mass spacecraft might remain in Earth for another two decades or more before reentering in an uncontrolled manner.

Recent High Profile Reentries

- **During September 2011 – January 2012, three spacecraft uncontrolled reentries received significant international attention.**
  - NASA's UARS reentered on 24 September 2011
  - Germany's ROSAT reentered on 23 October 2011
  - Russia's Phobos-Grunt reentered on 15 January 2012
- **UARS was the most massive (5.7 metric tons) NASA uncontrolled reentry in over 30 years.**
- **Phobos-Grunt had a total mass of 13.5 metric tons of which ~11 metric tons were propellants.**

NASA Provision for Intentional Breakups

- **NASA Standard 8719.14A permits the intentional breakup of a space vehicle under special conditions, if necessary.**

4.4.2.2.1 *Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups:* Planned explosions or intentional collisions shall:

a) Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years (Requirement 56453). For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.

b) Not generate debris larger than 1 mm that shall remain in Earth orbit longer than one year (Requirement 56454).

4.4.2.2.2 *Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups:* Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be verified to not exceed 10^{-6} (Requirement 56455).

Summary of Deliberate Satellite Breakups

Russian Federation

	Number of Events	Total Number of Cataloged Debris	Number of Cataloged Debris in orbit on 1 March 2012
- Malfunction of Recoverable Vehicle	15	1045	0
- Fractional Orbit Bombardment System	2	93	0
- Co-Orbital Antisatellite Tests	9	743	296
- Early Warning	17	167	144
- Designed End-of-Mission	8	81	0

United States

- Engineering Test	1	35	0
- Air-launched Antisatellite Test	1	285	0
- Technology Test	1	18	0
- Reentry Risk Mitigation	1	175	0

China

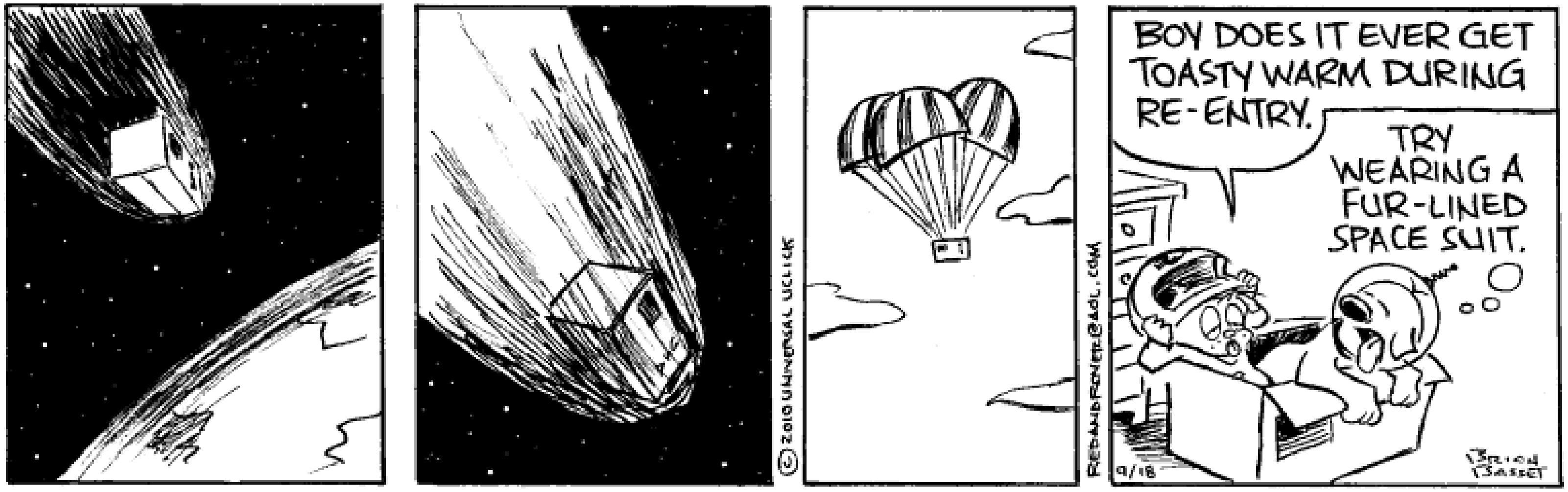
- Ground-launched Antisatellite Test	1	3218	2989

Summary

- **NASA, the U.S. Government, the Inter-Agency Space Debris Coordination Committee (IADC), the United Nations, ESA, France, Germany, Italy, Japan, and the UK all recognize that the reentry of spacecraft and launch vehicle stages pose potential risks to people on Earth from surviving debris.**

- **All established quantitative human casualty risk criteria are consistent with limiting human casualties to less than 1 in 10,000 per reentry event.**

- **When initial risk estimates exceed 1 in 10,000, risk reduction via vehicle redesign or via controlled reentry are the principal options.**


© 2010 UNIVERSAL UCLICK
REDANDROVER@AOL.COM
BOY DOES IT EVER GET TOASTY WARM DURING RE-ENTRY.
TRY WEARING A FUR-LINED SPACE SUIT.
9/18
BRIAN BASSET

Applications of DAS and ORSAT

Orbital Debris Program Office
NASA Johnson Space Center

DAS and ORSAT

- **The Debris Assessment Software (DAS) is a multi-functional set of software tools used to evaluate program/project compliance with NASA orbital debris mitigation requirements.**
  - It contains a moderate fidelity reentry risk assessment module.
- **The Object Reentry Survival Analysis Tool (ORSAT) is a specialized code designed to provide a high fidelity assessment of space vehicle and component reentry survivability.**
- **Excerpt from NASA Standard 8719.14A (paragraph 4.7.4.d):**
  - “Due to the complexity of satellite reentry physics and material responses, NASA programs and projects are required in paragraph 1.1.3 of this NASA-STD to employ either DAS or a higher fidelity model called ORSAT (Object Reentry Survival Analysis Tool) to determine compliance with Requirement 4.7-1.”

DAS and ORSAT (continued)

- **Both software tools require a detailed description of each component comprising the space vehicle in question.**
    - Material properties, shape, dimensions, aero and thermal masses, and, if applicable, internal construction, *e.g*., electronics box.

Debris Assessment Software (DAS)

- **DAS was developed in 1995 explicitly to support NASA programs and projects in their evaluation of orbital debris mitigation guidelines and the preparation of orbital debris assessment reports required by then NASA Safety Standard 1740.14.**

- **DAS X.9 was released in 1996, followed by DAS 1.0 in 1998.**

- **DAS 2.0 (2007) represents a significant improvement over DAS 1.0 (and its subsequent minor revisions) and is specifically designed to accompany NASA Standard 8719.14A.**

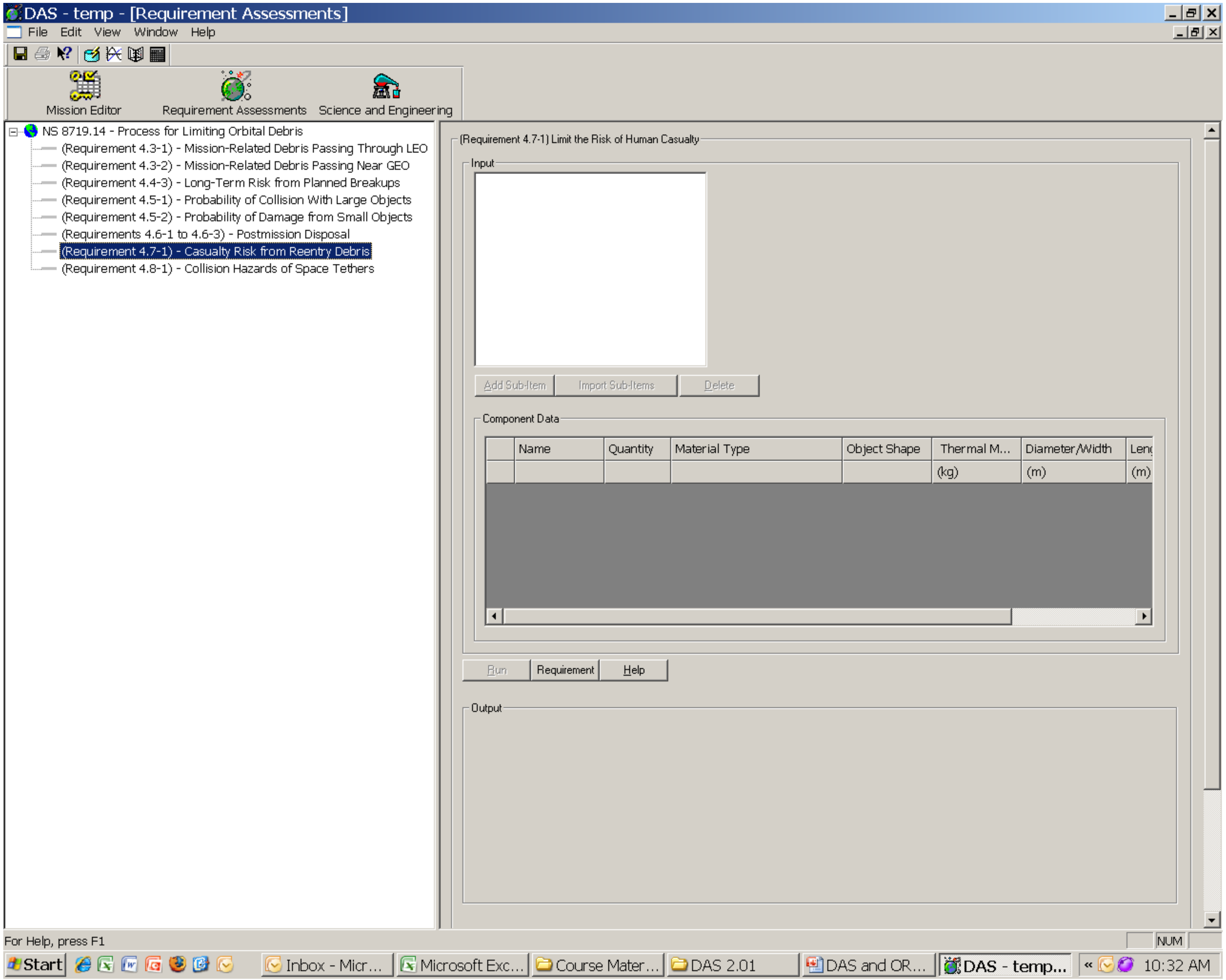
- **The DAS 2.0 software and its documentation are available for download at www.orbitaldebris.jsc.nasa.gov/mitigate/das.html.**

- **All versions of DAS contain routines to perform a first-order assessment of human casualty risks associated with uncontrolled space vehicle reentries.**

DAS Reentry Assessment Philosophy

- **DAS is designed for use by individuals who are not familiar with reentry physics.**
- **DAS simplifies some of the phenomenologies involved in the reentry and by design yields a slightly conservative result.**
  - If a program/project is found to be compliant for reentry risk using DAS, then further assessments are normally not required.
  - If a program/project is found to be not compliant for reentry risk using DAS, then an evaluation using ORSAT is normally required.
- **DAS only applies to natural reentries from nearly circular orbits.**
  - More complex orbits or controlled reentries must be evaluated by ORSAT

DAS GUI for Reentry Assessment



NS 8719.14 - Process for Limiting Orbital Debris
- (Requirement 4.3-1) - Mission-Related Debris Passing Through LEO
- (Requirement 4.3-2) - Mission-Related Debris Passing Near GEO
- (Requirement 4.4-3) - Long-Term Risk from Planned Breakups
- (Requirement 4.5-1) - Probability of Collision With Large Objects
- (Requirement 4.5-2) - Probability of Damage from Small Objects
- (Requirements 4.6-1 to 4.6-3) - Postmission Disposal
- (Requirement 4.7-1) - Casualty Risk from Reentry Debris
- (Requirement 4.8-1) - Collision Hazards of Space Tethers

(Requirement 4.7-1) Limit the Risk of Human Casualty

Component Data

Name	Quantity	Material Type	Object Shape	Thermal M... (kg)	Diameter/Width (m)	Len (m)

For Help, press F1

Object Reentry Survival Analysis Tool (ORSAT)

- **In 1992 GSFC contacted JSC for assistance in assessing the reentry survivability of the EOS-AM (now called Terra) spacecraft.**
  - This was the start of the development of ORSAT at JSC
- **Major versions of ORSAT were released in 1993, 1999, 2001, 2002, and 2006.**
  - Version 6.0 (January 2006) documented in JSC-62861.
- **Current version is ORSAT 6.1 (November 2006).**
- **NASA-wide ORSAT Tutorial held at JSC in 2001.**
- **ORSAT requires specialized technical knowledge in reentry physics and training with the operation of ORSAT.**

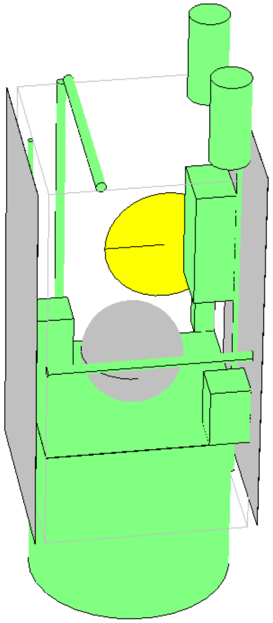
ORSAT Applications

- **NASA has conducted a large number of reentry survivability assessments for a wide variety of spacecraft, rocket bodies, and special objects in support of NASA, DoD, FAA, NOAA, DOJ, and foreign entities.**
  - Sample assessments for NASA: HST, TRMM, CGRO, GLAST, UARS, EUVE, Aura, Aqua, Terra, GPM, Genesis, ODERACS, Space Shuttle, ISS jettisons, Atlas V, Delta IV, Pegasus, JPL tank designs
  - U.S. Government Interagency: Iridium, USA-193
  - Sample assessments for others: TACSAT, Taurus, NPP, Delta IV (sub-orbital), ROSAT (Germany), ADEOS (Japan)

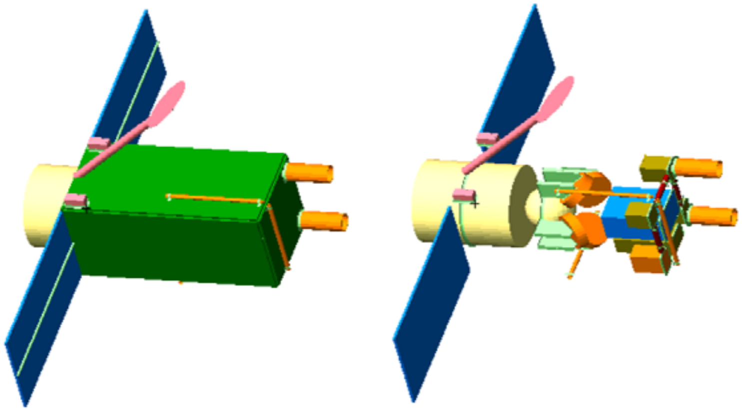
- **Validation with actual reentries is undertaken to the greatest extent possible, *e.g*., Delta 2 second and third stages and Sandia fuel rod.**

- **Few reentry survivability models are comparable to ORSAT.**
  - German/ESA SCARAB model is independent; results are similar.
    - Explicit comparisons conducted since 1999, bilaterally and under auspices of the IADC
  - Japanese model is derived from older version of ORSAT.

ORSAT-SCARAB Generic Satellite Comparison



Early generic satellite concept sketch by ORSAT Team



SCARAB model for generic satellite

- **Joint effort between ORSAT team at JSC and the SCARAB team in Germany during 2007-2008**
  - 35 unique objects representing simplified models of typical satellite components
  - Approximately 400 kg mass
  - Initial trajectory conditions
    - Altitude – 122 km
    - Inclination – 52°
    - Velocity – 7.41 km/s
    - Flight Path Angle – -0.1°
  - Environmental Conditions
    - Zonal Harmonics up to J4
    - Earth Flattening
      - Eccentricity of Earth = 0.08182
    - U.S. Standard 1976 Atmosphere

Study Conclusions

- **Careful examination revealed that ORSAT and SCARAB arrived at very similar results**
  - Of 33 unique objects modeled both codes strongly agree on the fates of 31 of those
    - Predicted 29 to demise in a similar fashion
    - Predicted 2 (LH2 tank, RWA flywheels) to demise in much the same way
  - Only 2 objects showed notable variance
    - The result for one object was very close (near the demise/survive threshold)
- **The difference in the debris casualty area which resulted form the contents of a battery box (1 item in SCARAB, 3 unique items in ORSAT) was not an effect of the differing methods employed to model the reentry physics, but instead reflected a difference in safety philosophy associated with geometric description of components.**

ORSAT Sample Summary Table: Surviving Components

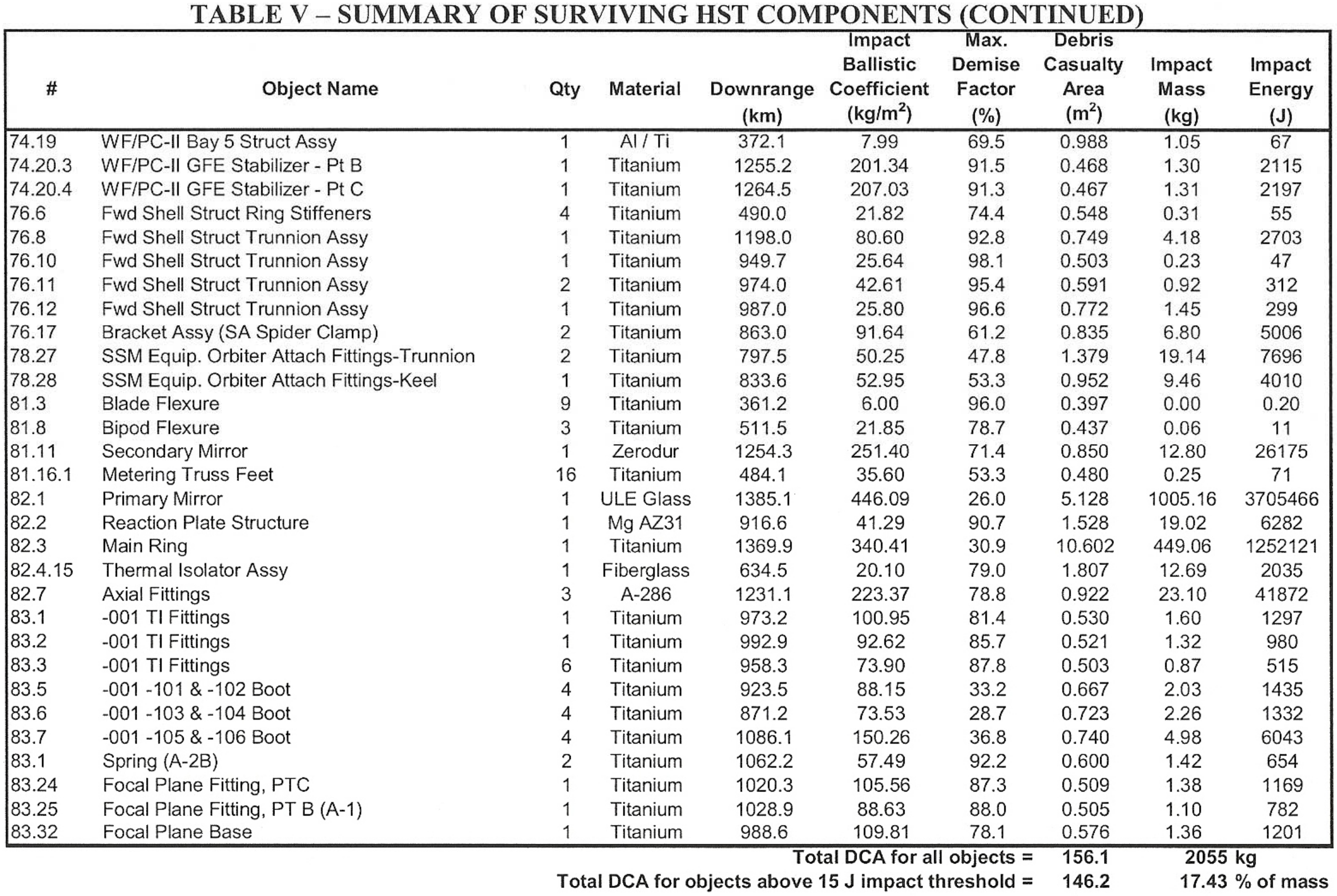


TABLE V – SUMMARY OF SURVIVING HST COMPONENTS (CONTINUED)

#	Object Name	Qty	Material	Downrange (km)	Impact Ballistic Coefficient (kg/m^2)	Max. Demise Factor (%)	Debris Casualty Area (m^2)	Impact Mass (kg)	Impact Energy (J)
74.19	WF/PC-II Bay 5 Struct Assy	1	Al / Ti	372.1	7.99	69.5	0.988	1.05	67
74.20.3	WF/PC-II GFE Stabilizer - Pt B	1	Titanium	1255.2	201.34	91.5	0.468	1.30	2115
74.20.4	WF/PC-II GFE Stabilizer - Pt C	1	Titanium	1264.5	207.03	91.3	0.467	1.31	2197
76.6	Fwd Shell Struct Ring Stiffeners	4	Titanium	490.0	21.82	74.4	0.548	0.31	55
76.8	Fwd Shell Struct Trunnion Assy	1	Titanium	1198.0	80.60	92.8	0.749	4.18	2703
76.10	Fwd Shell Struct Trunnion Assy	1	Titanium	949.7	25.64	98.1	0.503	0.23	47
76.11	Fwd Shell Struct Trunnion Assy	2	Titanium	974.0	42.61	95.4	0.591	0.92	312
76.12	Fwd Shell Struct Trunnion Assy	1	Titanium	987.0	25.80	96.6	0.772	1.45	299
76.17	Bracket Assy (SA Spider Clamp)	2	Titanium	863.0	91.64	61.2	0.835	6.80	5006
78.27	SSM Equip. Orbiter Attach Fittings-Trunnion	2	Titanium	797.5	50.25	47.8	1.379	19.14	7696
78.28	SSM Equip. Orbiter Attach Fittings-Keel	1	Titanium	833.6	52.95	53.3	0.952	9.46	4010
81.3	Blade Flexure	9	Titanium	361.2	6.00	96.0	0.397	0.00	0.20
81.8	Bipod Flexure	3	Titanium	511.5	21.85	78.7	0.437	0.06	11
81.11	Secondary Mirror	1	Zerodur	1254.3	251.40	71.4	0.850	12.80	26175
81.16.1	Metering Truss Feet	16	Titanium	484.1	35.60	53.3	0.480	0.25	71
82.1	Primary Mirror	1	ULE Glass	1385.1	446.09	26.0	5.128	1005.16	3705466
82.2	Reaction Plate Structure	1	Mg AZ31	916.6	41.29	90.7	1.528	19.02	6282
82.3	Main Ring	1	Titanium	1369.9	340.41	30.9	10.602	449.06	1252121
82.4.15	Thermal Isolator Assy	1	Fiberglass	634.5	20.10	79.0	1.807	12.69	2035
82.7	Axial Fittings	3	A-286	1231.1	223.37	78.8	0.922	23.10	41872
83.1	-001 TI Fittings	1	Titanium	973.2	100.95	81.4	0.530	1.60	1297
83.2	-001 TI Fittings	1	Titanium	992.9	92.62	85.7	0.521	1.32	980
83.3	-001 TI Fittings	6	Titanium	958.3	73.90	87.8	0.503	0.87	515
83.5	-001 -101 & -102 Boot	4	Titanium	923.5	88.15	33.2	0.667	2.03	1435
83.6	-001 -103 & -104 Boot	4	Titanium	871.2	73.53	28.7	0.723	2.26	1332
83.7	-001 -105 & -106 Boot	4	Titanium	1086.1	150.26	36.8	0.740	4.98	6043
83.1	Spring (A-2B)	2	Titanium	1062.2	57.49	92.2	0.600	1.42	654
83.24	Focal Plane Fitting, PTC	1	Titanium	1020.3	105.56	87.3	0.509	1.38	1169
83.25	Focal Plane Fitting, PT B (A-1)	1	Titanium	1028.9	88.63	88.0	0.505	1.10	782
83.32	Focal Plane Base	1	Titanium	988.6	109.81	78.1	0.576	1.36	1201

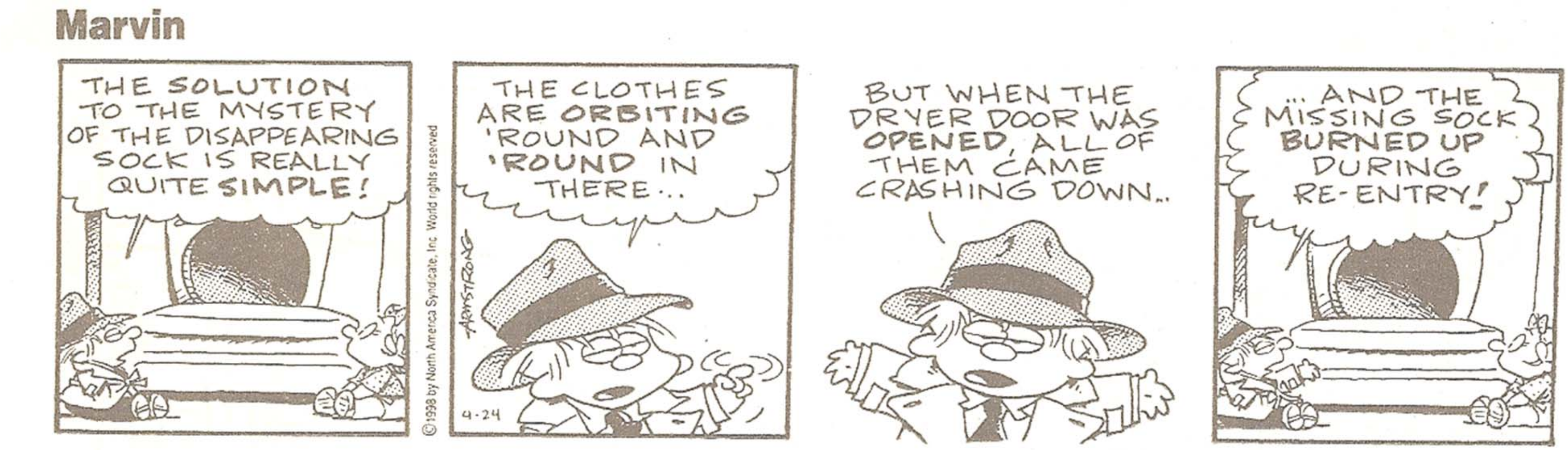
Total DCA for all objects = 156.1 2055 kg

Total DCA for objects above 15 J impact threshold = 146.2 17.43 % of mass

Summary

- **Initial reentry risk assessments should be performed with DAS for anticipated uncontrolled reentries from low eccentricity orbits.**
  - provides moderate fidelity solution
  - parametric assessments of individual components possible
  - software available on NASA orbital debris website

- **ORSAT analysis should be requested if**
  - controlled reentry is planned
  - reentry orbit will be highly elliptical
  - DAS results indicate that human casualty risks exceed 1 in 10,000
  - special component design analyses are desired, *i.e.*, design for demise


Marvin
THE SOLUTION TO THE MYSTERY OF THE DISAPPEARING SOCK IS REALLY QUITE SIMPLE!
THE CLOTHES ARE ORBITING 'ROUND AND 'ROUND IN THERE...
BUT WHEN THE DRYER DOOR WAS OPENED, ALL OF THEM CAME CRASHING DOWN..
... AND THE MISSING SOCK BURNED UP DURING RE-ENTRY!
ARMSTRONG
4-24
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Overview of NASA's Object Reentry Survival Analysis Tool (ORSAT)

Orbital Debris Program Office

NASA Johnson Space Center

ORSAT Principal Applications

- **Assessments of spacecraft, launch vehicle stage, and other man-made space object component survivability during atmospheric entry from sub-orbital, orbital, and deep space trajectories.**

- **Assessments of human casualty risk associated with uncontrolled reentries.**

- **Characterization of surviving debris footprints associated with controlled reentries for the purpose of avoiding inhabited regions and the Antarctic permanent ice pack.**

- **Investigation of reentry effects on individual components to aid in "design for demise" activities.**

The principal outputs of ORSAT are component demise altitude or location, surviving mass, and kinetic energy of impact.

Basic Elements of ORSAT

- **ORSAT is divided into six major portions:**

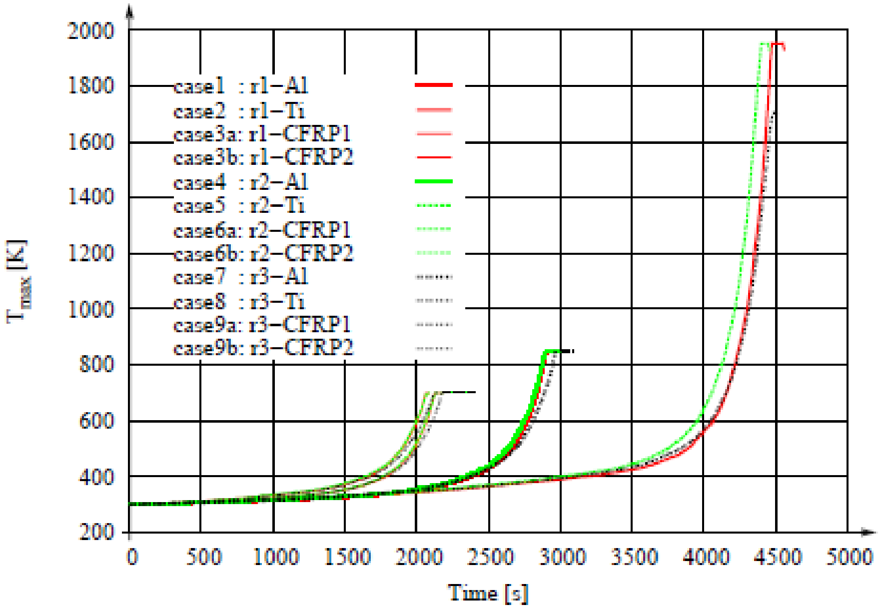
1. Trajectory
2. Atmosphere
3. Aerodynamics
4. Aerothermodynamics
5. Thermal / ablation
6. Debris casualty area

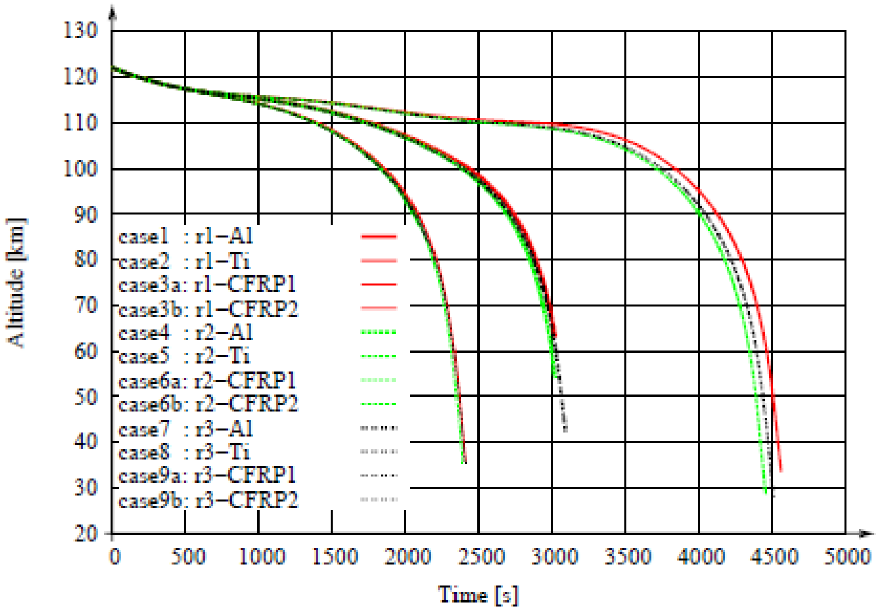
Partial ORSAT Input Satellite Data: WISE Spacecraft

Object Number	Object Description	Qty	Material	Density	Body Type	Object Width/Diameter (m)	Object Length (m)	Object Height (m)	Object (Thermal) Mass (kg)	Aero mass
	Bus		Al 5052	2684.6	Cylinder	1.27	0.838		39.099	123.233
1.1	Bus Structure Flat Panel 1	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0050300	4.330	
1.2	Bus Structure Flat Panel 2	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0025440	2.190	
1.3	Bus Structure Flat Panel 3	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.4	Bus Structure Flat Panel 4	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.5	Bus Structure Flat Panel 5	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.6	Bus Structure Flat Panel 6	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.7	Bus Structure Flat Panel 7	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.8	Bus Structure Flat Panel 8	1	Al 5052	2684.6	Flat Plate	0.504	0.610	0.0024050	2.070	
1.9	Top Deck	1	Al 5052	2684.6	Box	1.27	1.27	0.0270000	14.910	
1.10	Aft Ring Frame	1	Al 6061-T6	2707	Cylinder	0.024	3.990	--	5.249	
1.11	Corner Posts	8	Al 6061-T6	2707	Cylinder	0.017	0.610	--	0.391	
1.12	Star Tracker Bracket	1	Al 6061-T6	2707	Box	0.0415	0.0415	0.0414913	0.200	
1.13	Reaction Wheel Bracket	1	Al 6061-T6	2707	Box	0.0608	0.0608	0.0607898	0.629	
1.14	+Y LGA Bracket	1	Al 6061-T6	2707	Box	0.0464	0.0464	0.0464159	0.280	
1.15	-Y LGA AFT Ring Bracket	1	Al 6061-T6	2707	Box	0.0497	0.0497	0.0497126	0.344	
1.16	-Y LGA Mast	1	Al 6061-T6	2707	Box	0.0416	0.0416	0.0415604	0.201	
1.17	IMU Mounting Plate Slotted Array Ku-Band Standoff	4	Al 6061-T6	2707	Box	0.0304	0.0304	0.0304432	0.079	
1.18	Balance Mass A	1	Tungsten	16995.1	Box	0.102326	0.102326	0.1023264	3.000	
1.19	Balance Mass B	1	Tungsten	16995.1	Box	0.10232641	0.10232641	0.1023264	3.000	
1.20	Balance Mass C	1	Tungsten	16995.1	Box	0.10232641	0.10232641	0.1023264	3.000	
1.21	Balance Mass D	1	Tungsten	16995.1	Box	0.07094917	0.07094917	0.0709492	1.000	
1.22	Reaction Wheel Assembly, minus the steel bearings; Ithaco TW-4A12	3	Al 5052	2684.6	Box	0.205	0.205	0.0640000	1.550	4.550
1.22.1	Reaction Wheel bearings	3	SS 304L	8000	Box	0.071	0.071	0.0709492	1	
1.23	Reaction Wheel Electronics	1	Al 6061-T6	2707	Box	0.190	0.320	0.1500000	0.910	
1.24	Torque Rod Ithaco TR60CFR Qty.3	3	Iron	7860	Cylinder	0.023	0.493		1.7	
1.25	Magnetometer	1	Al 6061-T6	2707	Box	0.043	0.155	0.0360000	0.231	
1.26	Star Tracker	2	Al 6061-T6	2707	Box	0.135	0.142	0.0290000	0.348	
1.27	Coarse Sun Sensor	14	Al 6061-T6	2707	Box	0.017	0.017	0.0169235	0.014	
1.28	LN-200S Rate Sensor	1	Al 6061-T6	2707	Box	0.086	0.089	0.0349024	0.748	
1.29	Battery box	1	Al 6061-T6	2707	Box	0.2159	0.3175	0.1651000	2.76	5.400
1.29.1	Battery cell case; 8-30Ahr cells (NCP25-1)	8	SS 304L	8000	Box	0.0947928	0.1397	0.0274320	0.149	0.330
1.29.1.1	Battery electrode, graphite	8	graphite	2250	Box	0.0947928	0.1397	0.0137160	0.181	
1.30	Spacecraft Control Avionics	1	Al 6061-T6	2707	Box	0.22	0.28	0.2200000	16.46	
1.31	TDRSS Transponder S-Band	1	Al 6061-T6	2707	Box	0.16	0.2	0.1400000	3.2	
1.32	Hybrid Coupler	2	Al 6061-T6	2707	Box	0.05	0.06	0.0200000	0.05	
1.33	Antenna Assy S-Band	2	Al 5052	2684.6	Box	0.114	0.254	0.0060000	0.73	

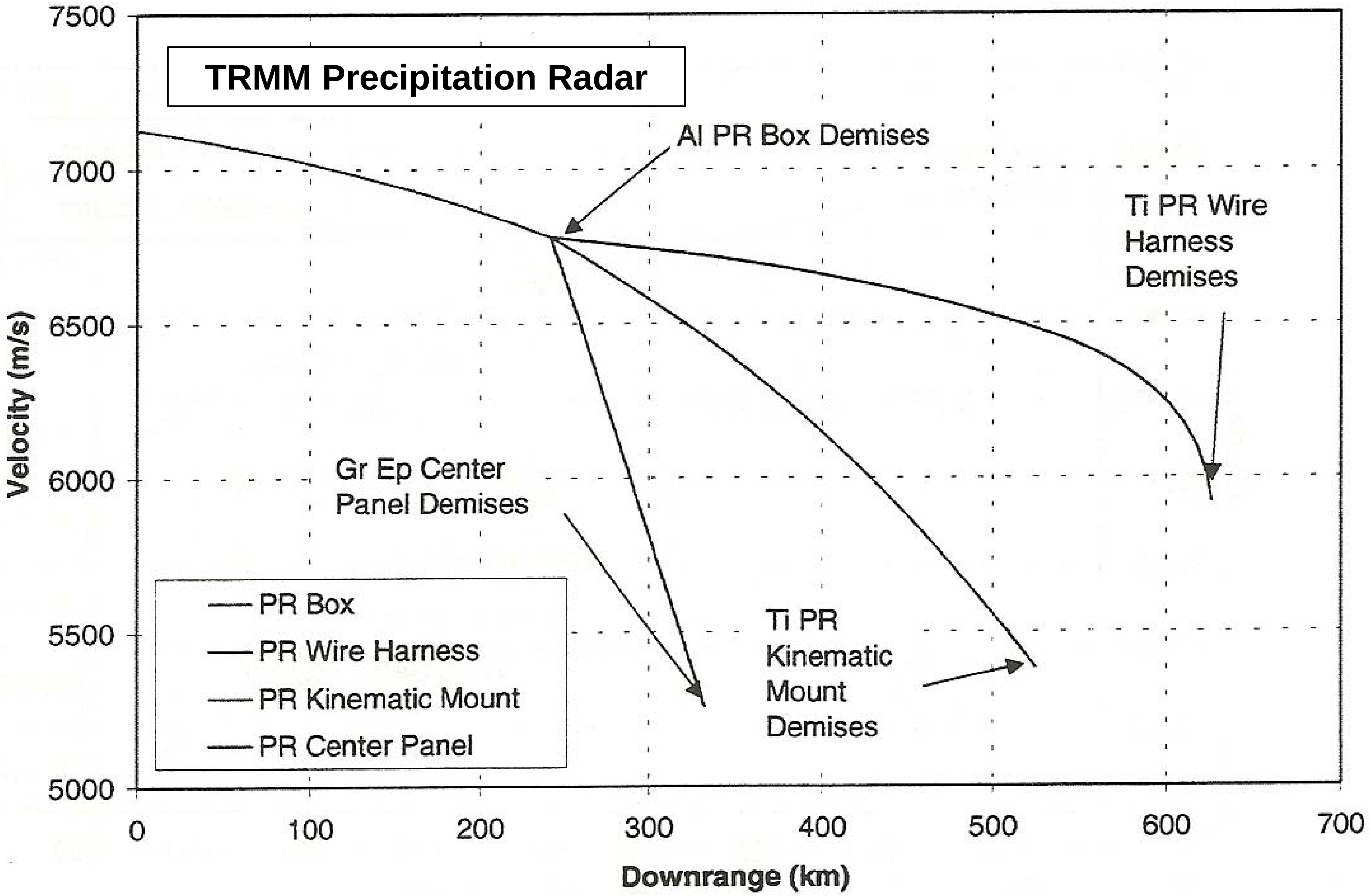
Effects of Materials and Mass: Spheres

- **The trajectories and survivability of simple spheres are greatly influenced by their materials and mass (size).**
  - Cases 1-3: Spheres with 0.25 m diameters (10-30 kg)
  - Cases 4-6: Spheres with 0.50 m diameters (40-115 kg)
  - Cases 7-9: Spheres with 1.00 m diameters (160-450 kg)
- **Different shapes will also lead to varying reentry results**

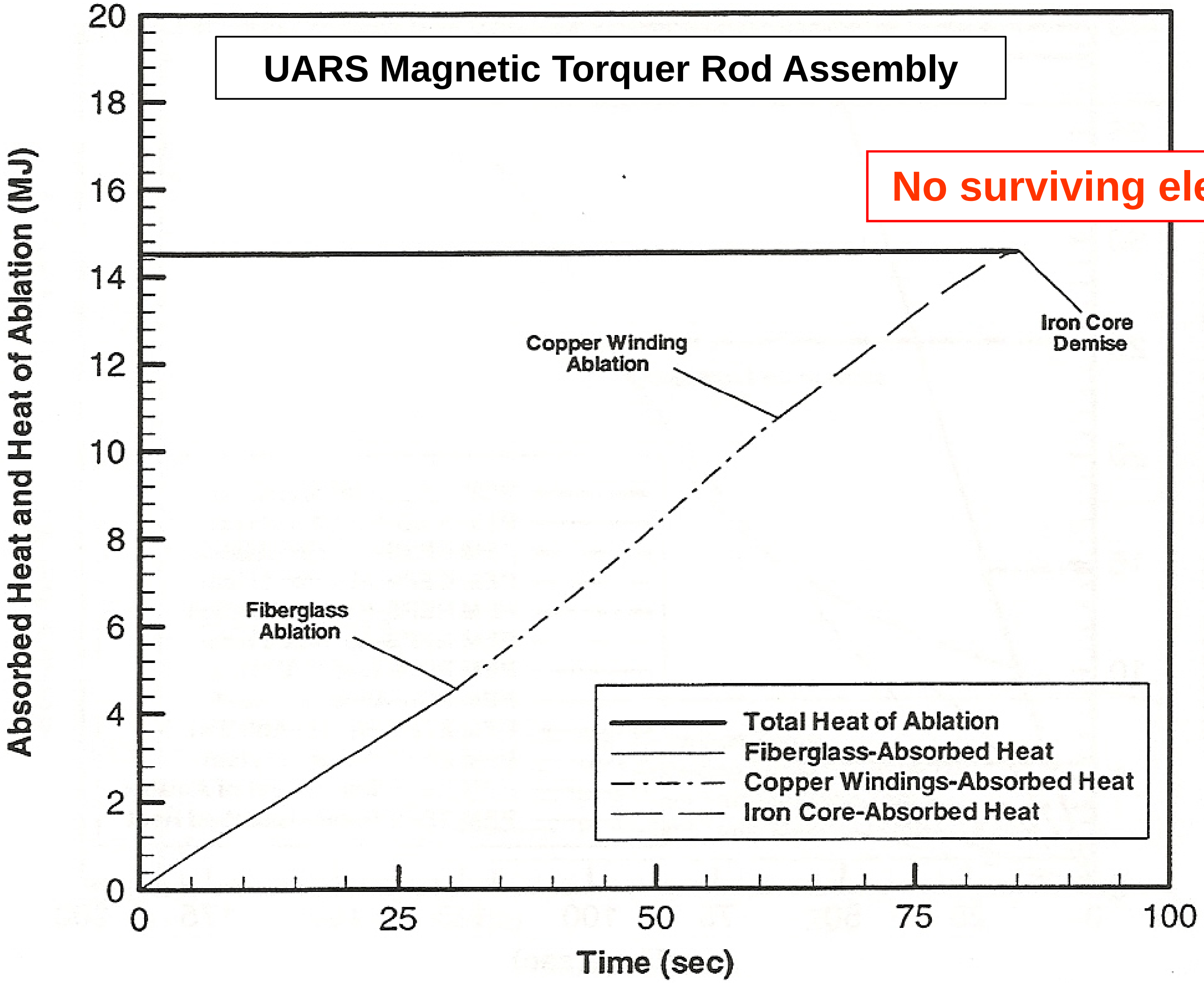




Evaluation of a Complex Component: Nested



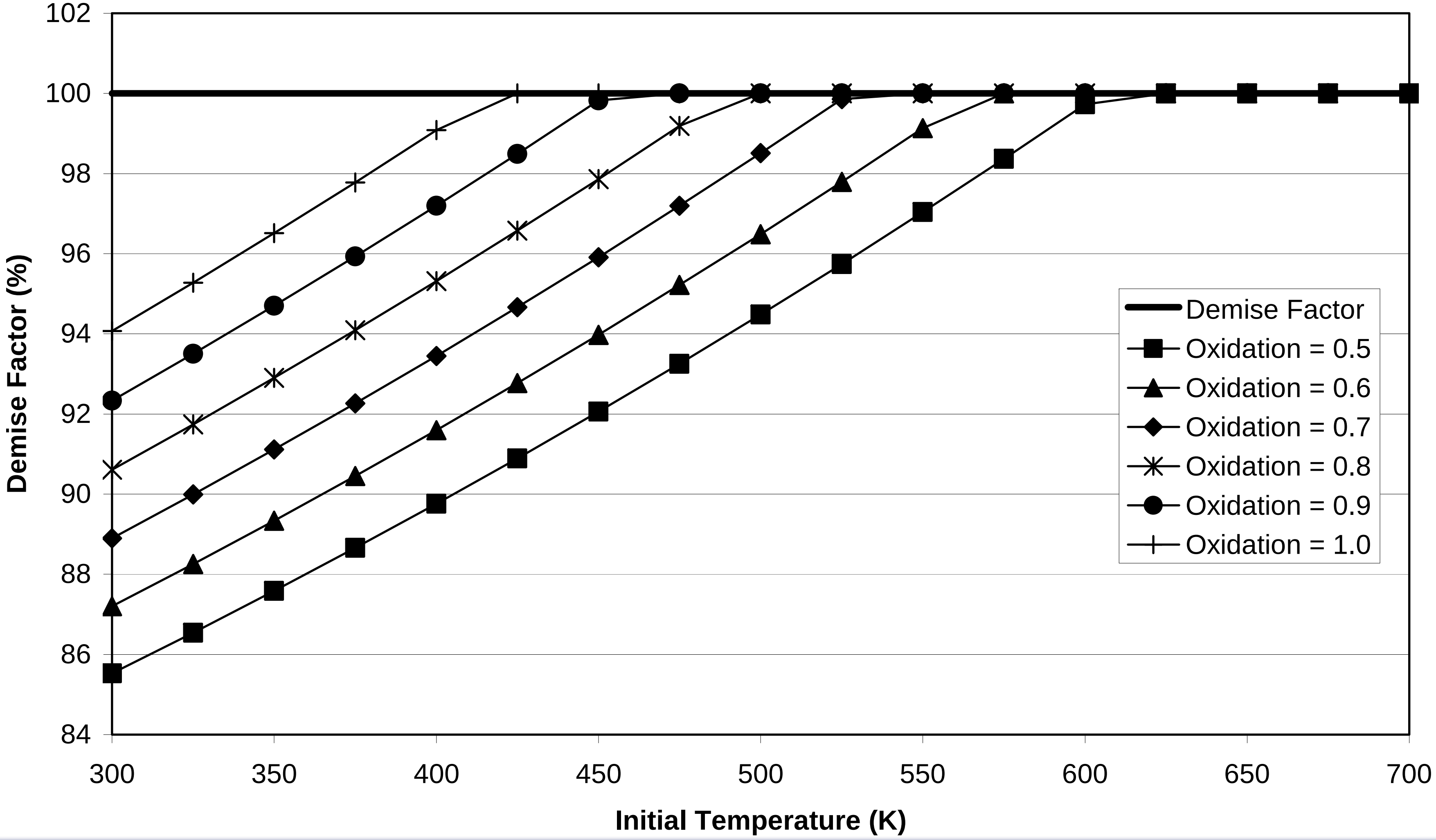
Evaluation of a Complex Component: Composite



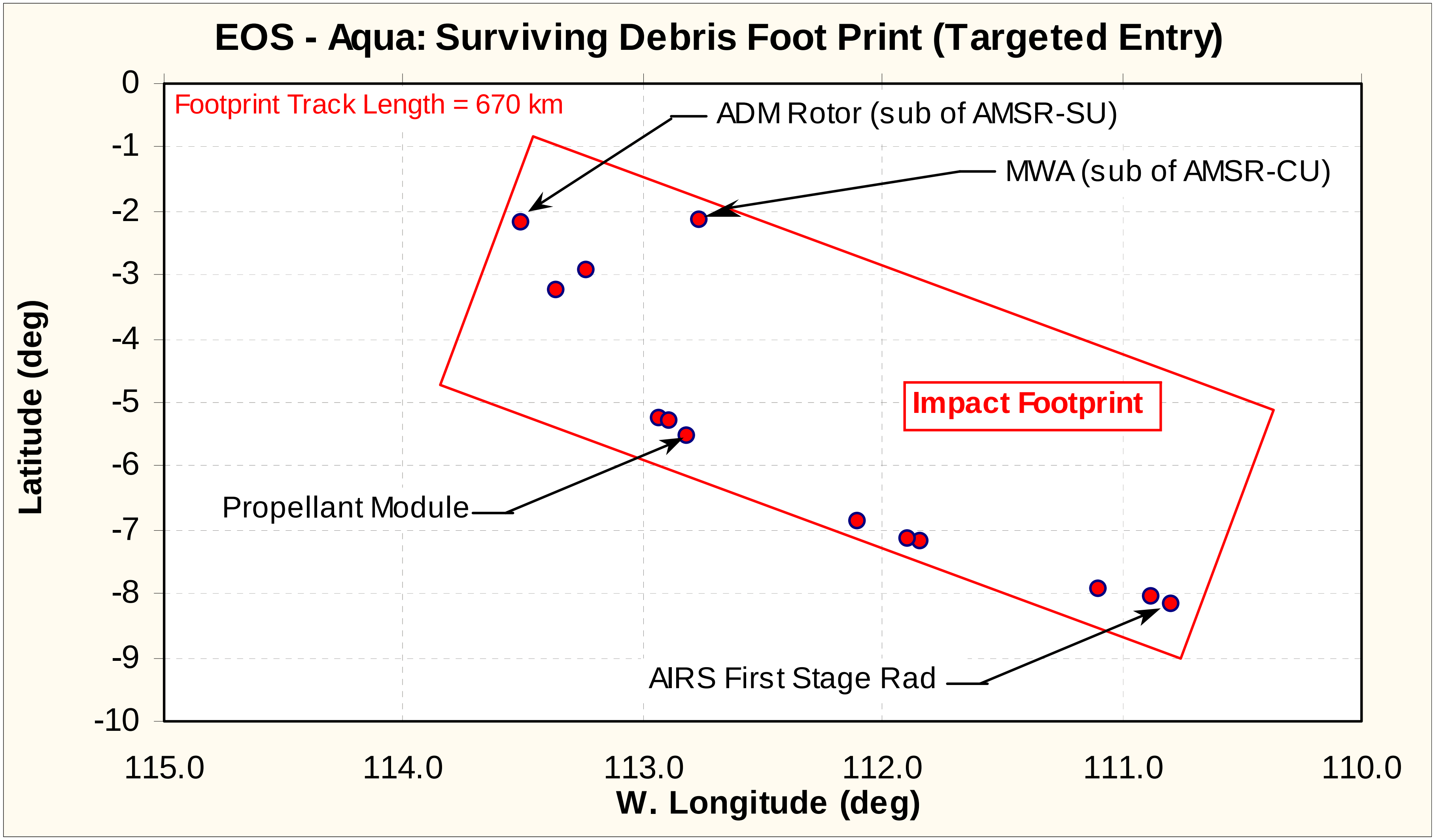
No surviving elements

Parametric ORSAT Analysis of Different Initial Temperatures and Oxidation Heating Efficiencies

Survivability Factor vs. Initial Temperature for UARS Forward Bulkhead Fitting

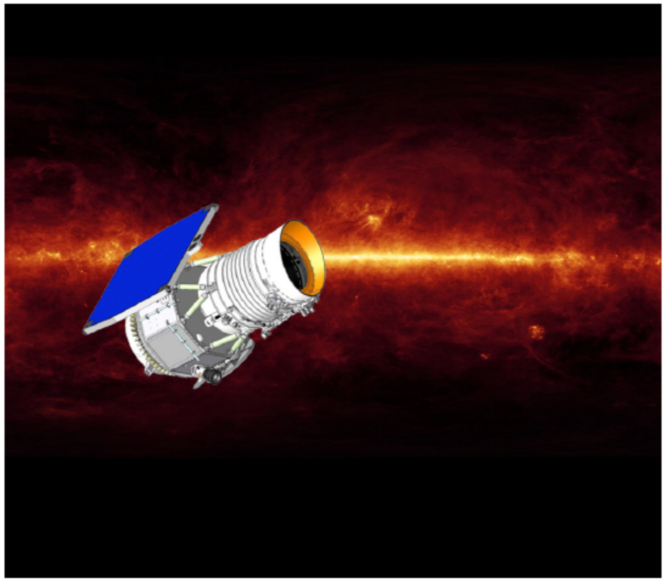


Sample Debris Footprint Assessment

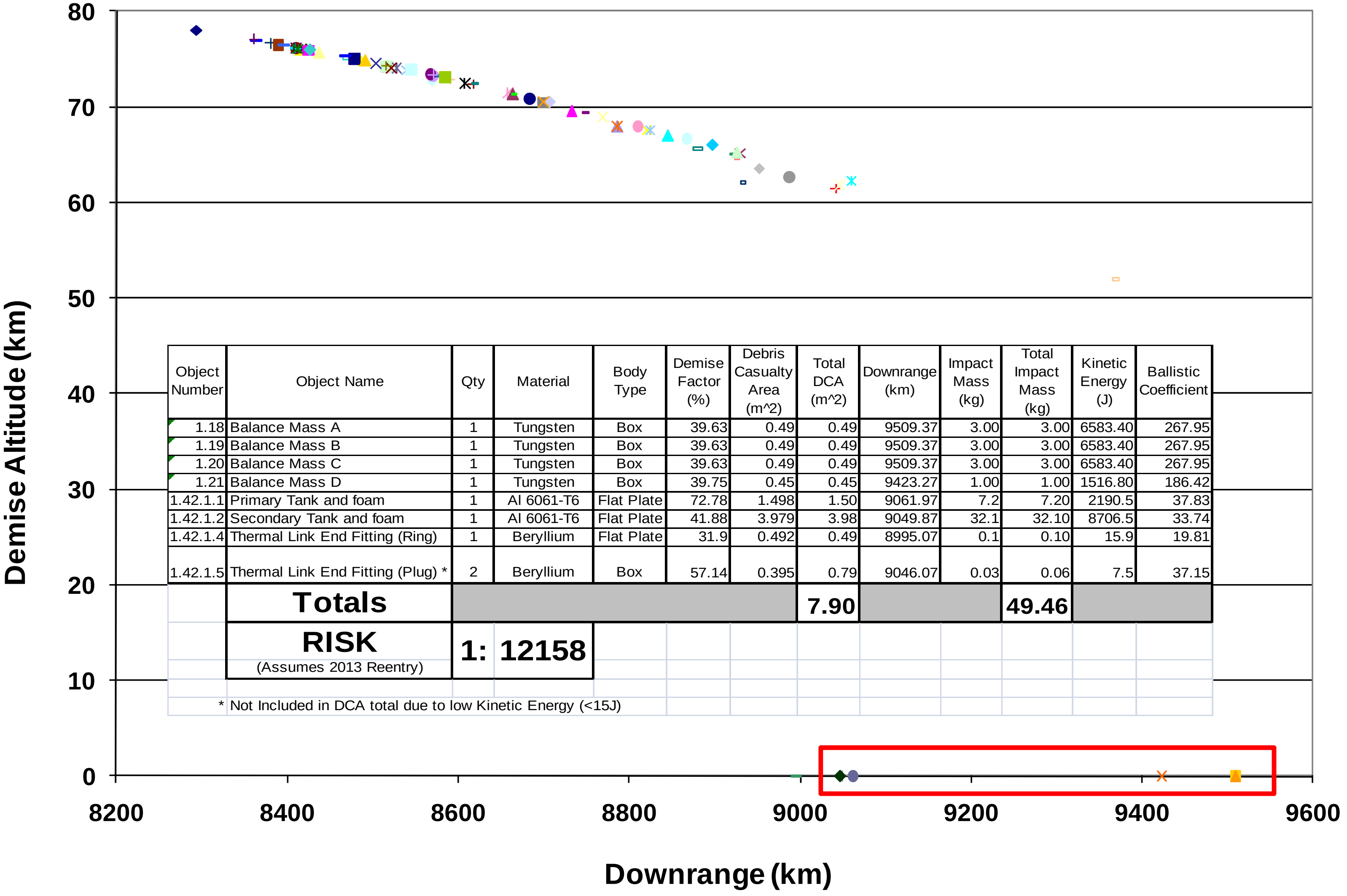


Example ORSAT Case: WISE

- The Wide-field Infrared Survey Explorer (WISE) was launched on 14 December 2009 into a low Earth orbit (~525 km, 97.5 deg inclination).
- The 645 kg (dry mass) spacecraft is now expected to reenter about 2021, depending on solar activity.
- An aperture cover was ejected on 30 December and is predicted to reentry about 2013.



WISE Surviving Component Assessment

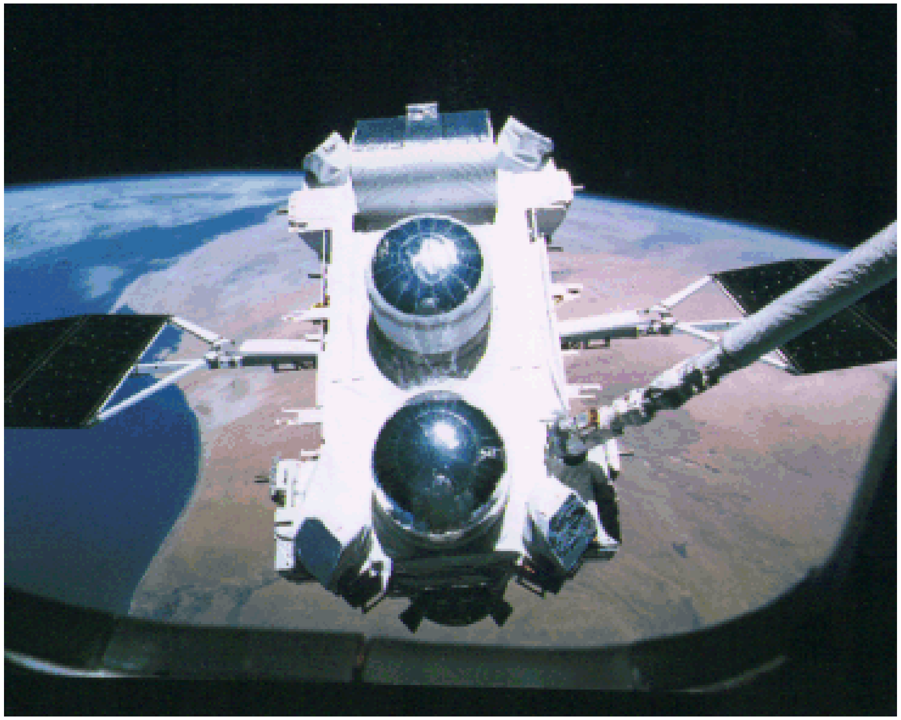


Object Number	Object Name	Qty	Material	Body Type	Demise Factor (%)	Debris Casualty Area (m^2)	Total DCA (m^2)	Downrange (km)	Impact Mass (kg)	Total Impact Mass (kg)	Kinetic Energy (J)	Ballistic Coefficient
1.18	Balance Mass A	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.19	Balance Mass B	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.20	Balance Mass C	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.21	Balance Mass D	1	Tungsten	Box	39.75	0.45	0.45	9423.27	1.00	1.00	1516.80	186.42
1.42.1.1	Primary Tank and foam	1	Al 6061-T6	Flat Plate	72.78	1.498	1.50	9061.97	7.2	7.20	2190.5	37.83
1.42.1.2	Secondary Tank and foam	1	Al 6061-T6	Flat Plate	41.88	3.979	3.98	9049.87	32.1	32.10	8706.5	33.74
1.42.1.4	Thermal Link End Fitting (Ring)	1	Beryllium	Flat Plate	31.9	0.492	0.49	8995.07	0.1	0.10	15.9	19.81
1.42.1.5	Thermal Link End Fitting (Plug) *	2	Beryllium	Box	57.14	0.395	0.79	9046.07	0.03	0.06	7.5	37.15
	Totals						**7.90**			**49.46**		
	RISK (Assumes 2013 Reentry)	**1:**	**12158**									

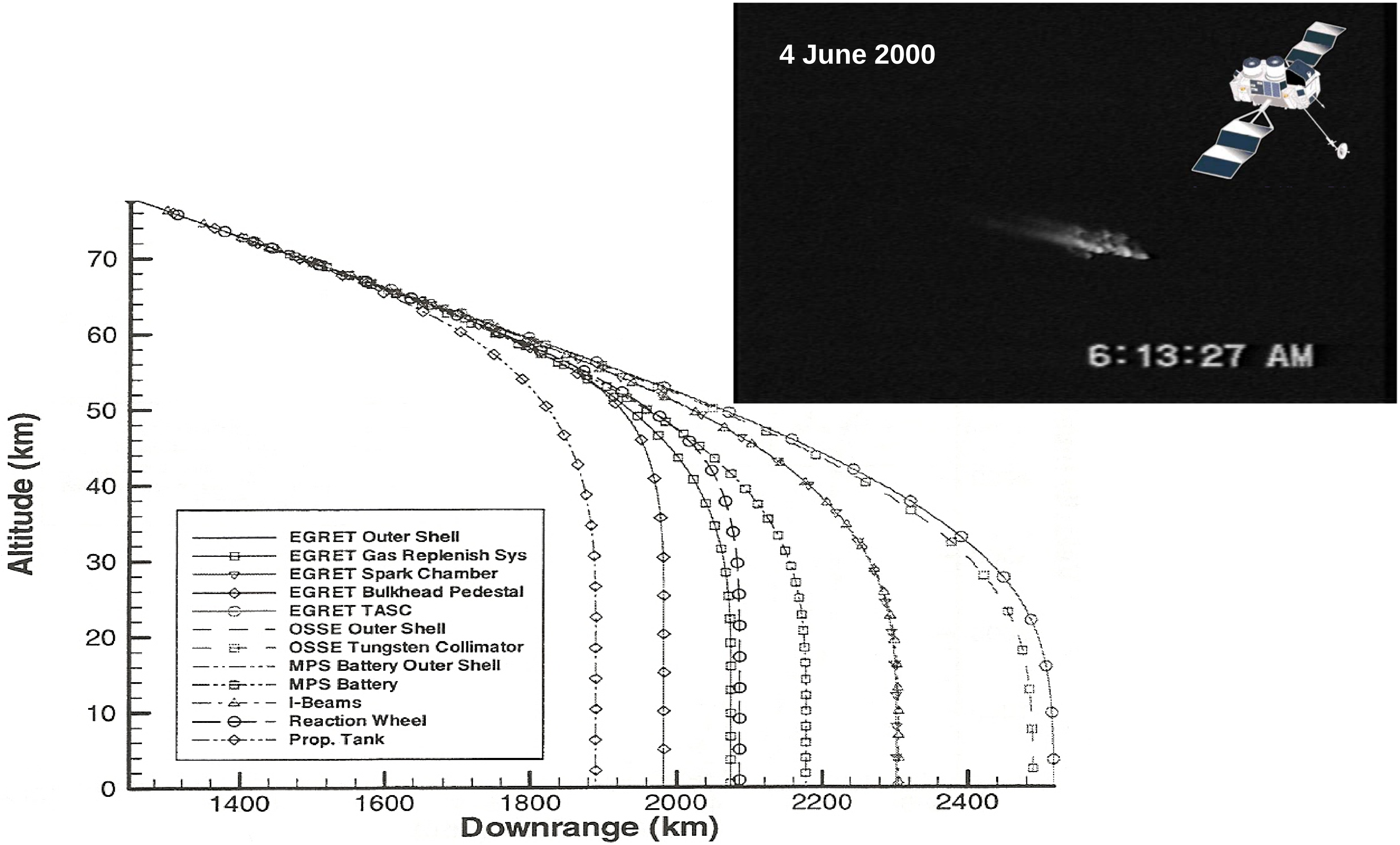
* Not Included in DCA total due to low Kinetic Energy (<15J)

Sample Assessment:
Compton Gamma Ray Observatory

- **CGRO was deployed by the Space Shuttle in April 1991.**
- **Failure of a gyro on CGRO in December 1999 left the spacecraft zero-fault tolerant for a planned controlled reentry.**
- **A re-evaluation of the human casualty risk for CGRO using ORSAT yielded a total debris casualty area of 52.5 m^2, *i.e.*, a human casualty risk of 1 in 1200.**
- **Consequently, CGRO was commanded to a controlled reentry over the Pacific Ocean on 4 June 2000.**



CGRO Reentry

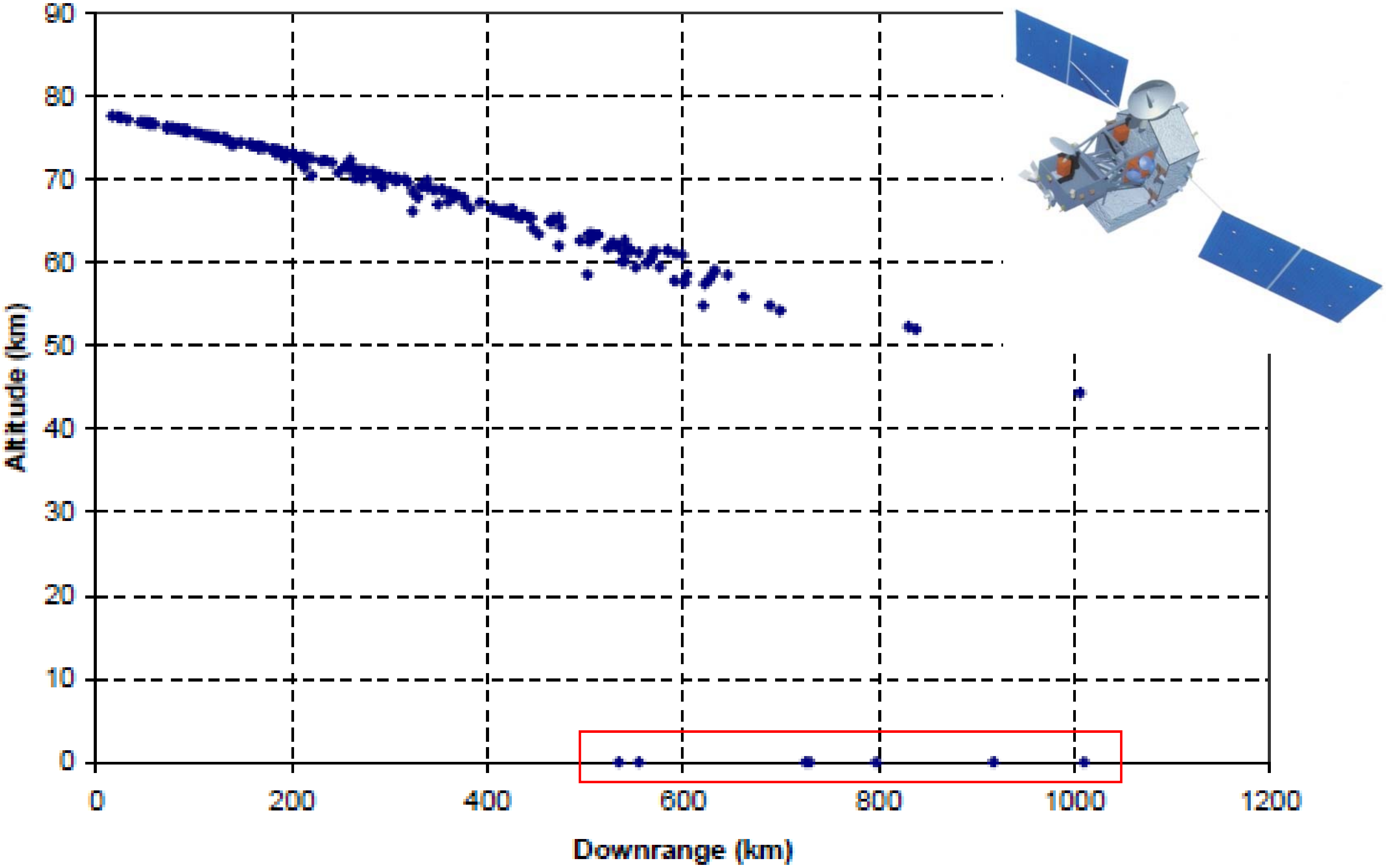


TRMM Reentry Case

- **The Tropical Rainfall Measuring Mission (TRMM) is a joint US-Japan Earth science spacecraft launched in 1997 on a 3-year mission.**
  - Dry mass of TRMM is 2620 kg
  - Designed for controlled reentry
- **ORSAT assessment in 2002 found the human casualty risk from an uncontrolled reentry to be ~ 1 in 4600, *i.e.*, non-compliant with NASA safety standards.**
- **Mission given extensions until 2005 when residual propellant would reach minimum required for controlled reentry from 400 km altitude.**
- **After considerable debate, TRMM was relieved of controlled reentry requirement to prolong mission until Global Precipitation Measurement (GPM) spacecraft could be launched (then predicted to be 2010).**
  - Rationale was that TRMM, through its hurricane tracking and other capabilities, had the potential to save lives, out-weighing the risk of human casualty from uncontrolled reentry

TRMM Reentry Case (2)

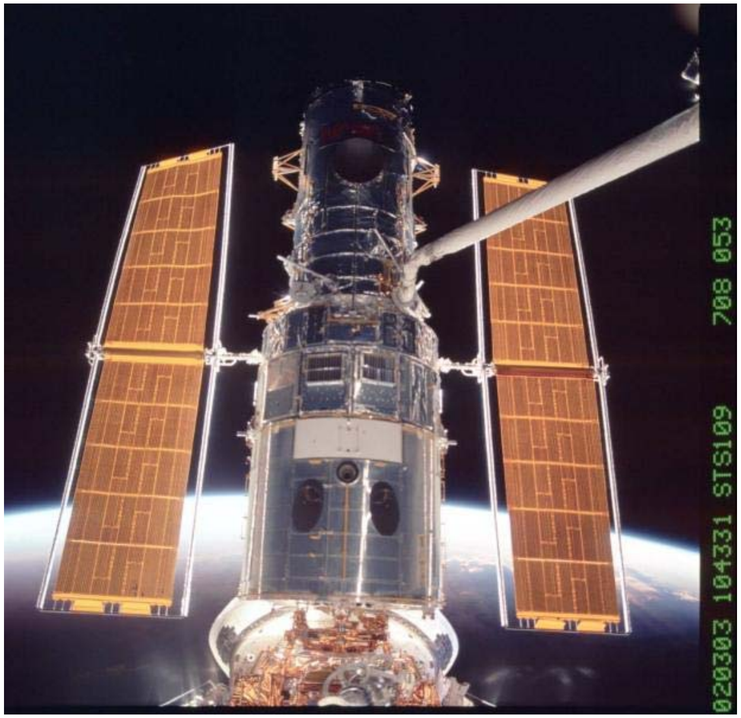
- **A total of 12 objects with an aggregate mass of 112 kg are expected to survive reentry and impact along a 475 km footprint.**



Sample Assessment: Hubble Space Telescope

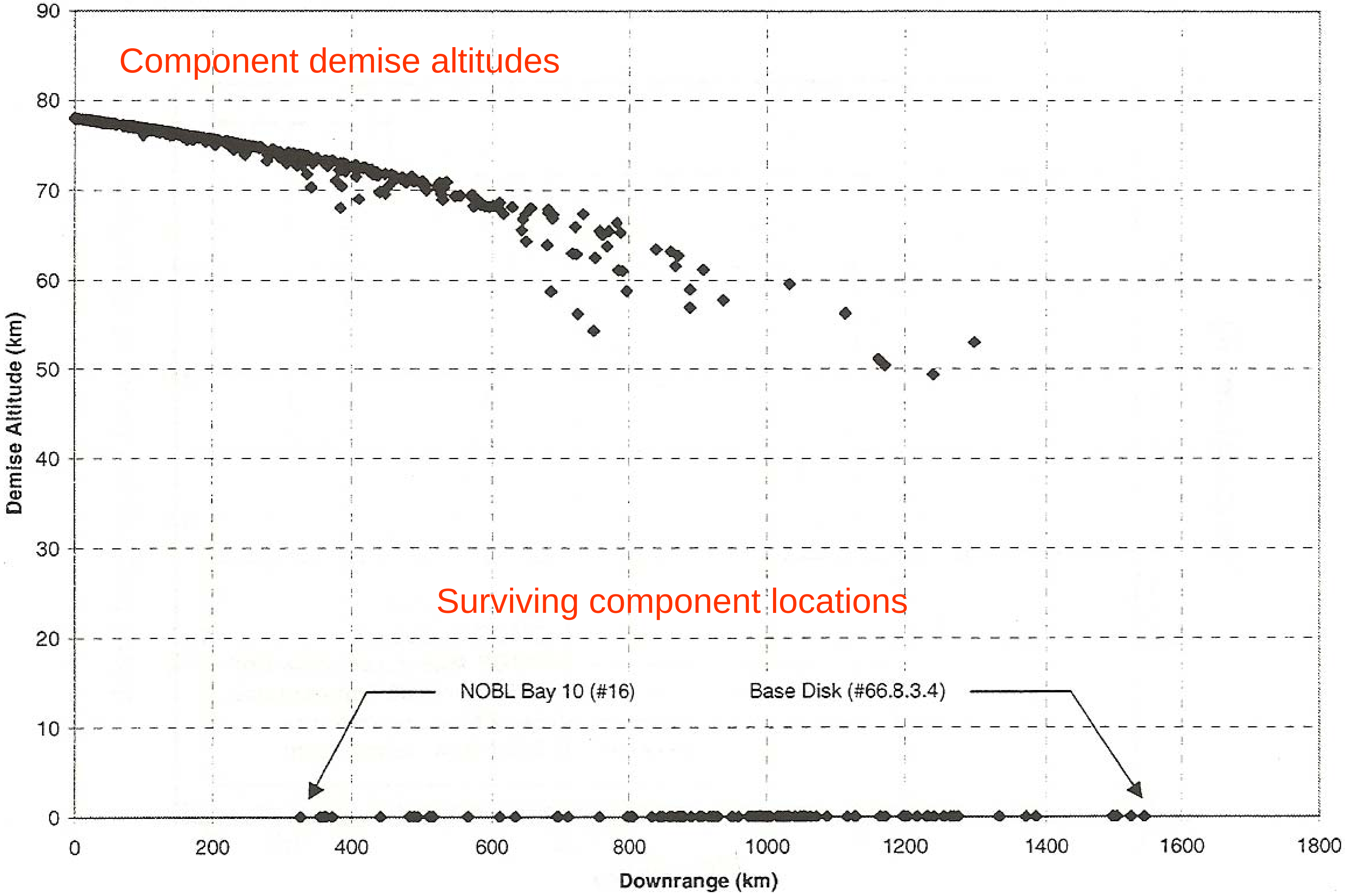
- **HST has a mass of ~11 metric tons and no maneuver capability.**

- **An ORSAT assessment of the human casualty risk arising from an uncontrolled reentry of HST found a casualty area of more than 150 m^2 and a risk on the order of 1 in 250 for a reentry in 2020.**
  - 627 different components analyzed



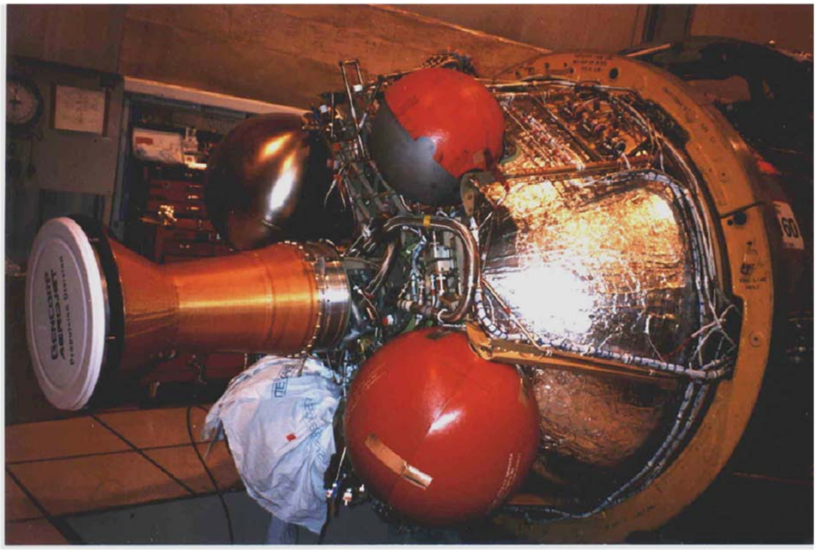
- **Consequently, NASA has reiterated its intention of conducting a controlled reentry with the future attachment of a specialized propulsion unit.**

Predicted Demise Altitudes and Impact Locations for HST Components: Uncontrolled Reentry



Sample Assessment: Delta 2 Second Stage

- **Delta 2 launch vehicles have been used frequently by NASA to launch Earth-orbiting and deep space payloads.**
- **Delta 2 second stage is known to have at least six surviving components.**
  - ORSAT analyses confirm survivability of these six components



Stainless Steel Propellant Tank (270 kg)

Titanium Spheres
- 2 small (10 kg)
- 2 large (30 kg)

Engine Nozzle (30 kg)

Delta IV and Atlas V Orbital Stages

- **The Evolved Expendable Launch Vehicle (EELV) program was undertaken by DoD in the 1990’s and led to the development of the Delta IV and the Atlas V, which both had maiden launches in 2002.**
- **Both ELVs have large second stages which reach Earth orbit.**
- **ORSAT reentry survivability assessments of both stages revealed severe non-compliance for human casualty risk.**
  - Risks on the order of 1 in 1,000 for both stages
- **Delta IV missions: second stages left in a storage orbit between LEO and GEO (GOES 13-15). DoD has demonstrated controlled reentry on multiple missions.**
- **Atlas V missions: second stages placed in a storage orbits between LEO and GEO (SDO and TDRS-11), on interplanetary trajectory (MRO, New Horizons, and Juno), or lunar impact trajectory (LRO/LCROSS). Controlled deorbit has been demonstrated by NASA for RBSP mission and by DoD).**

Sample Assessment: Spacecraft Propellant Tanks

- **Spacecraft and launch vehicle stage propellant tanks are routinely evaluated by ORSAT.**
  - These tanks are often made of titanium or stainless steel and survive reentry.
  - These tanks are either evacuated prior to reentry or are emptied very early in the reentry scenario.
- **In 2007 ORSAT was used to determine the survivability of a tank with a large amount of frozen hydrazine.**
  - A majority of the hydrazine was projected to survive reentry in a slush state, posing a special hazard of human casualty after impact.
  - Consequently, a decision was made to destroy prior to reentry the vehicle containing the tank (USA-193).
- **Due to the lessons of USA-193, since 2008 the survivability of several tank designs from JPL and GSFC have been evaluated for a variety of scenarios, including both orbital and ballistic reentry.**

Sample Assessment: Spacecraft Propellant Tanks (continued)

- **Assessments were made for numerous initial conditions**

122 km Initial Altitude

Vehicle	Initial Fuel Mass (kg)	Mass Liquid Fuel (kg)	% Fuel Melted	Tank Demise Altitude (km)	Bursts w/ Pressurant (Y/N)	Burst Altitude w/ Pressurant	Bursts w/o Pressurant(Y/N)	Burst Altitude w/ Pressurant
Cassini	135	133.0	98.55%	0.0				
CGRO	470	313.1	66.61%	0.0				
Juno	358	207.6	58.00%	51.7				
MRO	1149	596.2	51.89%	0.0				
MSL Cruise Stage	36	36.0	100.00%	75.4	Y	71.5	Y	63.4
MSL Descent Stage	129	97.4	75.54%	49.7				

78 km Initial Altitude

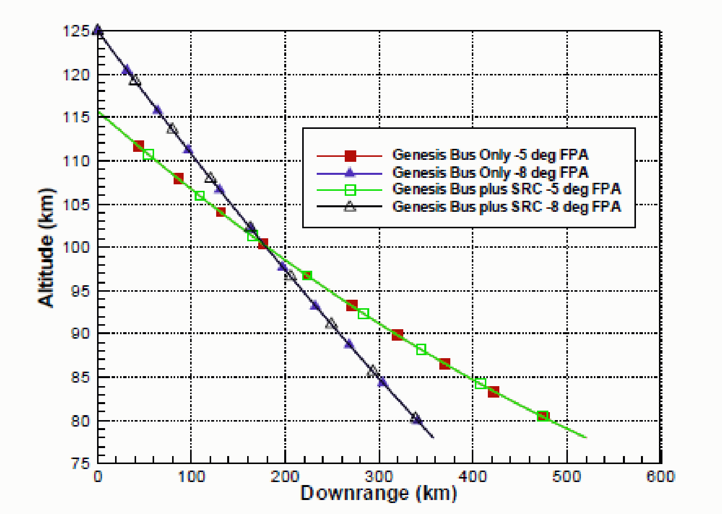
Vehicle	Initial Fuel Mass (kg)	Mass Liquid Fuel (kg)	% Fuel Melted	Tank Demise Altitude (km)	Bursts w/ Pressurant (Y/N)	Burst Altitude w/ Pressurant	Bursts w/o Pressurant(Y/N)	Burst Altitude w/ Pressurant
Cassini	135	126.2	93.51%	0.0				
CGRO	470	286.9	61.04%	0.0				
Juno	358	186.2	52.01%	47.3				
MRO	1149	530.2	46.14%	0.0				
MSL Cruise Stage	36	36.0	100.00%	66.5	Y	62.9	Y	51.2
MSL Descent Stage	129	97.9	75.91%	0.0				

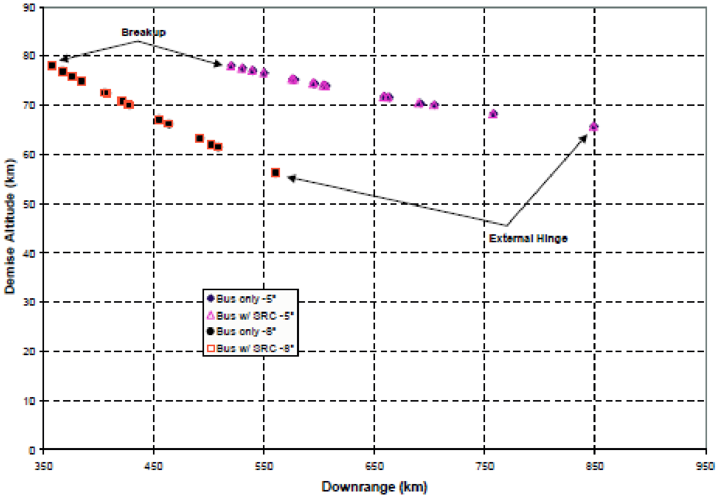
Reentries from Deep Space

- **ORSAT can also assess reentries from extremely elliptical Earth orbits or reentries from deep space, e.g., Genesis and Stardust.**

- **ORSAT was employed to evaluate potential off-nominal trajectories of the Genesis spacecraft bus.**

  - Scenarios: Initial flight path angles of -5 and -8 degrees
    With and without Genesis capsule attached
  - Results: All bus components demised in all four scenarios





General Reentry Survivability Observations

- **First Law of Reentry Survivability Assessments:**

  The vast majority of components will always survive or demise over a range of realistic initial conditions.

- **Second Law of Reentry Survivability Assessments:**

  A reentry risk assessment is only as good as the vehicle technical definition.

- **Surviving objects tend to fall into one or more of the following categories:**
  - High melting-point materials, *e.g*., titanium, beryllium
  - Low ballistic coefficients, *i.e*., large area-to-mass ratio
  - Internal (buried) components

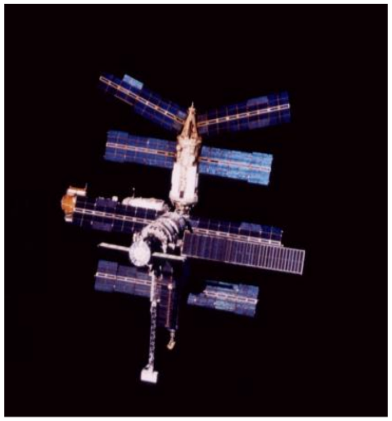
Wizard Of Id

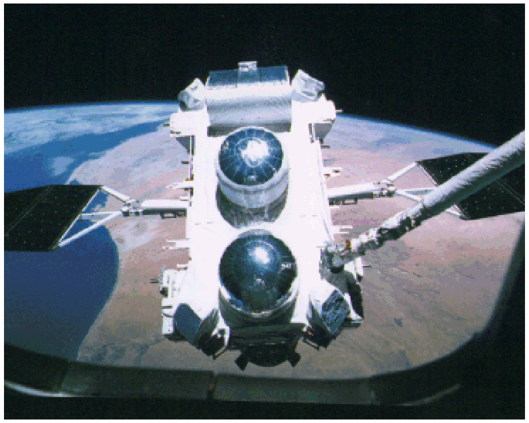
WHIF
WHIF
WHIFF
GRRRRRRRR....
9.26
THE NICE THING ABOUT TITANIUM IS IT DOESN'T BURN UP ON RE-ENTRY
PARKER

Comparative Satellite Survival Assessments

Spacecraft	Total Mass, kg	Est. Surviving Mass, kg (%)
Mir/Progress M	140,000	30,000 (20%) *
Skylab	74,800	18,200-22,700 (24-30%) *
Gamma Ray Obs.	13,700	5,800 (42%)
Delta 4 second stage	4,000	1,895 (47%) +
Delta 2 second stage	920	340 (37%) +
Iridium	560	163 (29%)

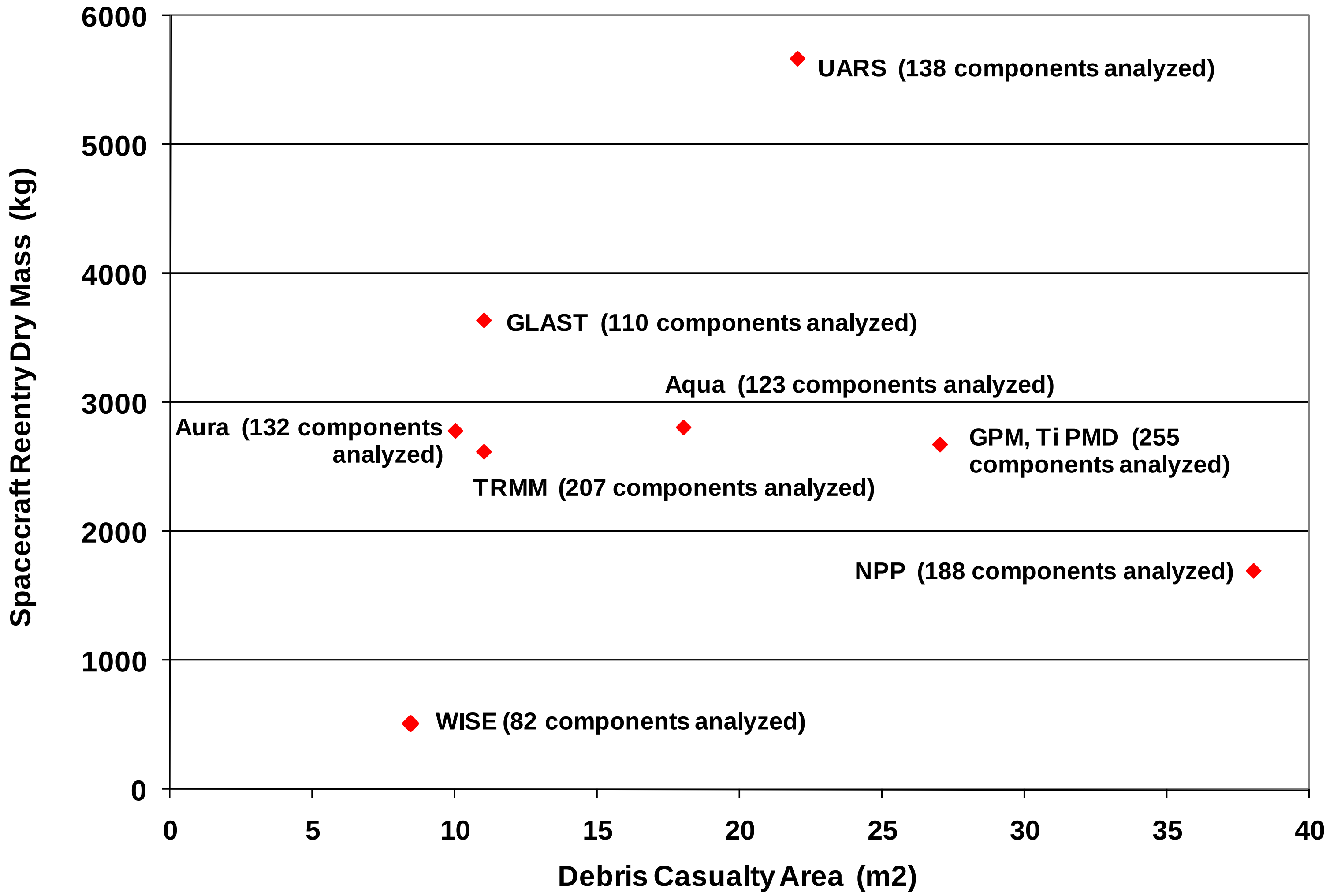
* Not evaluated by ORSAT   + Inclination dependent





Sample Comparisons of S/C Mass and DCA

- **No simple relationship exists between reentering satellite mass and surviving component hazard.**



Summary

- **ORSAT is NASA's highest fidelity model for evaluating the survivability of space vehicle components following controlled or uncontrolled reentries.**

- **ORSAT assessments require detailed reentry orbit characteristics and descriptions of all vehicle components:**
  - material type, size, shape, mass, number, placement

- **The survivability of most components is easily determined and is insensitive to initial conditions.**

- **Special evaluations can be required for some components.**

National Aeronautics and Space Administration

Design for Demise

Orbital Debris Program Office
NASA Johnson Space Center

Design for Demise

- **Most space vehicles with a mass exceeding 500 kg are likely to pose a reentry risk of human casualty greater than 1 in 10,000.**

- **To avoid such risks, three basic options are available to a space system operator:**
  - execute a controlled reentry over a broad ocean area;
  - maneuver the space system to a long-lived storage orbit above 2000 km; or
  - redesign the space system to reduce the reentry risk of human casualty.

- **The first two options are often not viable due to inherent limitations of the space system, *e.g.*, due to no propulsion system or one which is inadequate for a controlled reentry (insufficient propellants or thrust).**

- **In such cases, redesigning the space system to promote more complete component demise, *i.e.*, design for demise (D4D), might be the most cost-effective means of compliance with NASA Standard 8719.14A.**

Application of Design for Demise

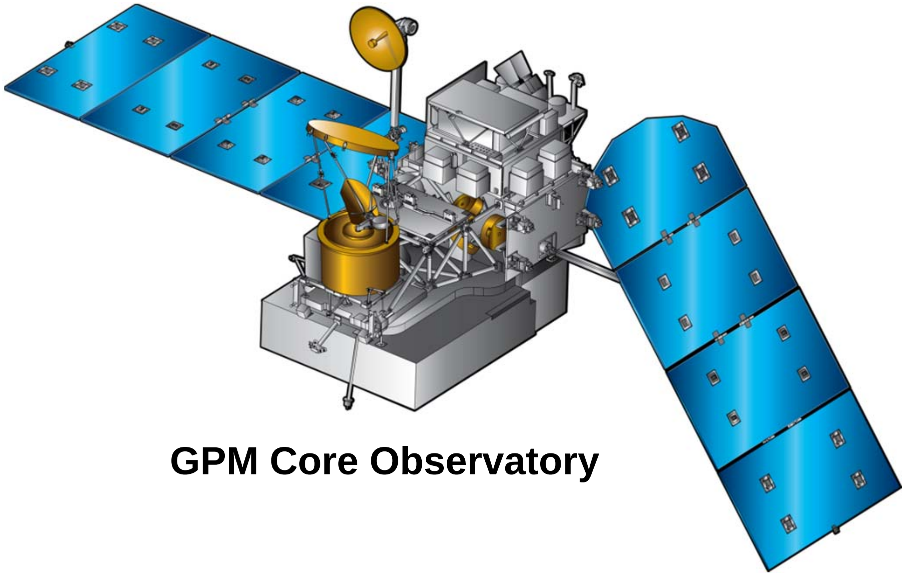
- **The output of ORSAT will identify which components of a space vehicle are expected to survive reentry. Those components with the greatest aggregate debris casualty area (an individually large DCA or numerous copies of a lesser DCA) can then be examined for potential redesign.**
  - Items which are commonly found to survive reentry in whole or in part are propellant and pressurant tanks, reaction wheel assemblies, valves, hinges, and solar array drive mechanisms.
- **Space systems with a mass of 1000 kg or more typically cannot be made reentry risk compliant by design for demise alone.**
  - However, a reduction in debris casualty area can relax reliability requirements on subsystems needed for controlled reentries (NASA Standard 8719.14, Requirement 4.7-1.c.)
- **Components redesigned for demise can potentially be employed by other spacecraft, off-setting or reducing future costs.**

Potential Solutions

- **Whenever feasible, low-melting temperature materials can be substituted for high-melting temperature materials.**
  - Other material property requirements (*e.g.*, coefficient of thermal expansion) might limit such substitutions.
- **Large structural elements can sometimes be machined to reduce mass and decrease the likelihood of survival, while still meeting structural requirements.**
- **Single simple components (*e.g.*, a plate) can sometimes be redesigned in layers which would individually demise or impact the Earth with a kinetic energy of less than 15 joules.**
- **A container which hosts multiple surviving components can be redesigned to survive, thereby preventing the release of the internal components.**

Global Precipitation Measurement (GPM) Spacecraft

- **GPM was the first major spacecraft which adopted a comprehensive design-for-demise philosophy at the start of the project.**
  - Started approximately eight years before planned launch.



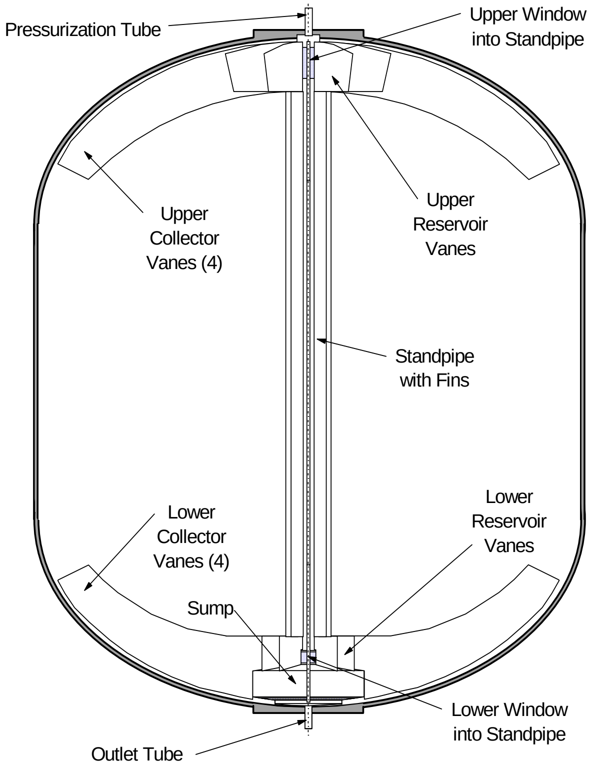
GPM Core Observatory

- **One of the objectives was to avoid having to size the propulsion system for a controlled reentry, since GPM was to be a multi-ton spacecraft.**

- **Two major design efforts were undertaken (the propellant tank and the reaction wheel assemblies), although other elements were also identified early in the project as having potential reentry survivability.**

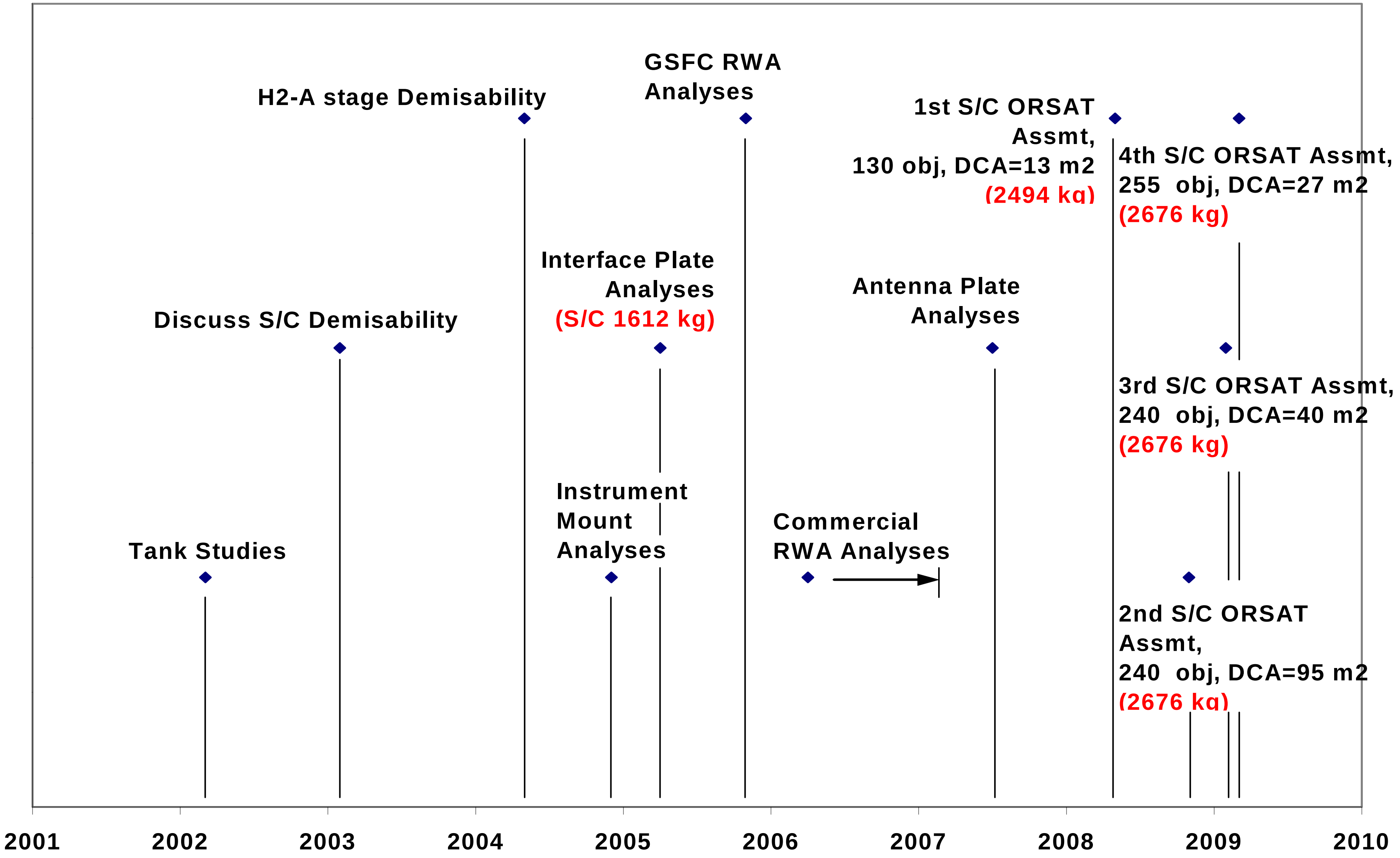
Global Precipitation Measurement (GPM) Spacecraft (continued)

- **Due to the large size of GPM (3000 kg class), compliance with the human casualty risk requirement for reentry could not be achieved by vehicle design.**
  - The project elected to baseline a controlled reentry, which had been held in reserve as an option.
- **The D4D effort for GPM did yield valuable results:**
  - A demisable aluminum tank for hydrazine was developed.
  - A demisable aluminum propellant management device (PMD) for the propellant tank was developed.
  - Demisable reaction wheel assemblies were developed.
- **These successes will be available for use on future NASA spacecraft.**



Demisable Hydrazine Tank

Highlights of Survivability Assessments for GPM



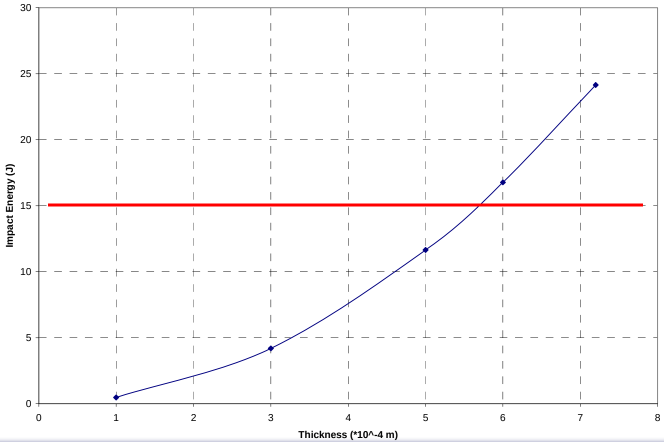
GPM Results (March 2009)

- **15 out of 255 components were assessed to survive reentry with impacting energies greater than 15 joules (vehicle variant with aluminum propellant management device)**

ID No.	Name	Qty	Material	Body Type	Thermal Mass	Aero Mass	Diameter/ Width	Length	Height	Radius	Demise Factor (%)	Debris Casualty Area (m^2)	Impact Mass (kg)	Kinetic Energy (J)	**Total DCA (15 J Limit)**	**Total DCA (20 J Limit)**
0	Spacecraft	1	Aluminum 6061-T6	Box	1334.0	2676.0	2.54	4.28	2.39	2.39					**23.4**	**15.6**
3	X Stiff +Y	1	Gr\Ep Honeycomb	Box	5.2	5.2	0.42	2.33	0.02	0.02	94	1.658	0.82	16.0	**1.7**	**0.0**
4	X Stiff -Y	1	Gr\Ep Honeycomb	Box	5.2	5.2	0.42	2.33	0.02	0.02	94	1.658	0.83	16.3	**1.7**	**0.0**
83	LB Structure + Y	1	Aluminum 6061-T6	Box	26.2	26.2	1.24	1.26	0.05	0.03	93	2.199	6.5	612.0	**2.2**	**2.2**
84	LB Structure -Y	1	Aluminum 6061-T6	Box	26.2	26.2	1.24	1.26	0.05	0.03	93	2.199	6.5	612.0	**2.2**	**2.2**
86	LB Structure +X (Bottom Deck)	1	Aluminum 6061-T6	Box	59.5	59.5	1.46	1.97	0.06	0.03	94	1.606	8.64	1894.8	**1.6**	**1.6**
132	GMI MR Interface Bracket	2	Titanium (6 Al-4 V)	Box	0.5	0.5	0.13	0.15	0.11	0.11	73	0.536	0.5	115.3	**1.1**	**1.1**
136	GMI Calibration Structure	1	Albemet	Box	1.5	1.5	0.42	0.67	0.36	0.36	63	1.228	1.5	76.4	**1.2**	**1.2**
140	GMI Fitting Calibration	1	Titanium (6 Al-4 V)	Box	0.5	0.5	0.09	0.11	0.04	0.04	89	0.469	0.35	153.3	**0.5**	**0.5**
145	GMI RDA F. A. - Larger	2	Titanium (6 Al-4 V)	Box	0.1	0.1	0.09	0.10	0.01		80	0.452	0.1	19.2	**0.9**	**0.0**
166	GMI Spin Mechanism Assy+Despin	1	Titanium (6 Al-4 V)	Cylinder	22.3	22.3	0.45	0.69		0.22	66	1.339	22.34	15824.1	**1.3**	**1.3**
170	GMI ISS A-Bipod Int. Fit. - End	6	Titanium (6 Al-4 V)	Box	0.2	0.2	0.11	0.13	0.01		78	0.474	0.24	76.1	**2.8**	**2.8**
172	GMI IBA Lau. Rest. Fit. Rect. End	8	Titanium (6 Al-4 V)	Box	0.1	0.1	0.08	0.11	0.01		88	0.451	0.1	19.5	**3.6**	**0.0**
206	SA MOOG MC464	2	Titanium (6 Al-4 V)	Cylinder	10.3	10.3	0.11	0.25		0.06	76	0.564	7.03	22697.4	**1.1**	**1.1**
221	HGAS Elbow (SS piece)	1	Stainless Steel 17-4 ph	Box	0.6	0.7	0.12	0.14	0.03	0.03	77	0.494	0.56	284.1	**0.5**	**0.5**
224	HGAS Gimbal Assembly	1	Titanium (6 Al-4 V)	Box	5.8	15.7	0.39	0.45	0.27	0.27	60	0.972	5.82	1909.9	**1.0**	**1.0**

Gamma-ray Large Area Space Telescope (GLAST) Spacecraft

- **In 2000 GSFC requested assistance in evaluating the reentry risk hazard associated with the primary instrument of the GLAST spacecraft, then expected to launch in 2006.**
  - The instrument accounted for 3000 kg of the 4500 kg total spacecraft mass.
  - As with GPM, an objective was to determine whether or not a spacecraft propulsion system would need to be sized for a controlled reentry (propulsion not required for science mission).
- **The unique construction of the GLAST primary instrument led to a very large amount of surviving debris (> 2000 m^2 debris casualty area). However, these debris were very light-weight and posed no risk of human casualty.**
  - An ORSAT analysis led to a halving of the foil sheets to reduce impact energy below 15 J.



15 J Limit

Gamma-ray Large Area Space Telescope (GLAST) Spacecraft (continued)

- **Optical Bench Struts**
  - Eight titanium optical bench struts were found to survive with impact energies greater than 15 J.
  - ORSAT assessments found that graphite epoxy struts would demise.
- **Large Area Telescope Flexures**
  - Titanium flexures were found to survive, but a change of material to stainless steel or aluminum was not desirable.
  - However, a change in shape of the flexures led to a change in ballistic coefficient, which in turn yielded a demisable flexure.

Radiation Belt Storm Probes (RBSP) Ballast

- **The RBSP mission employs two 550-kg-class spacecraft in highly elliptical Earth orbits. At the end of mission, the two probes will be maneuvered into a lower orbit for natural reentry within the 25-year requirement.**

- **Each probe carries balance weights with a total mass of approximately 30-40 kg. The original design called for the use of 1-kg weights made of tungsten. However, an ORSAT analysis found that each weight would survive reentry with impact energies greater than 15 J, making the vehicle non-compliant for reentry risks.**

- **Different materials were also evaluated with ORSAT: tantalum (also survived) and lead (demised).**

- **A final design using very thin plates of tungsten bound together with a thin aluminum band was found to meet reentry risk requirements.**

Miscellaneous Design for Demise Efforts

- **D4D activities are now a routine part of ORSAT assessments for NASA spacecraft.**
- **Components which show a potential for survival are reevaluated for means to promote demise, including material changes and construction designs.**
  - The use of titanium, beryllium, and stainless steel is discouraged.
- **In supporting one of the ISS COTS contractors, the amount of surviving hazardous material has been significantly reduced by replacing the material of numerous components with aluminum.**

NASA Debris Assessment Software (DAS)

Orbital Debris Program Office
NASA Johnson Space Center

Introduction

- **The NASA Debris Assessment Software (DAS) is actually a set of custom tools designed to assist space programs and projects in preparing orbital debris assessment reports.**
  - Assessment requirements are described in NASA Standard 8719.14A, “Process for Limiting Orbital Debris”
  - DAS 2.0 addresses most requirements point-by-point

- **Reasons for the upgrade to DAS 2.0 are numerous, including:**
  - Issuance of NS 8719.14 to replace NSS 1740.14, *i.e.*, changes in debris mitigation guidelines
  - Improvements to the orbit propagators and debris environment model
  - Improvements to the reentry survivability model and casualty estimation method
  - Improvements to the user interface and documentation
  - Improvements to personal computers, *e.g.*, operating systems and capabilities
  - Recommendations from users of the early versions of DAS

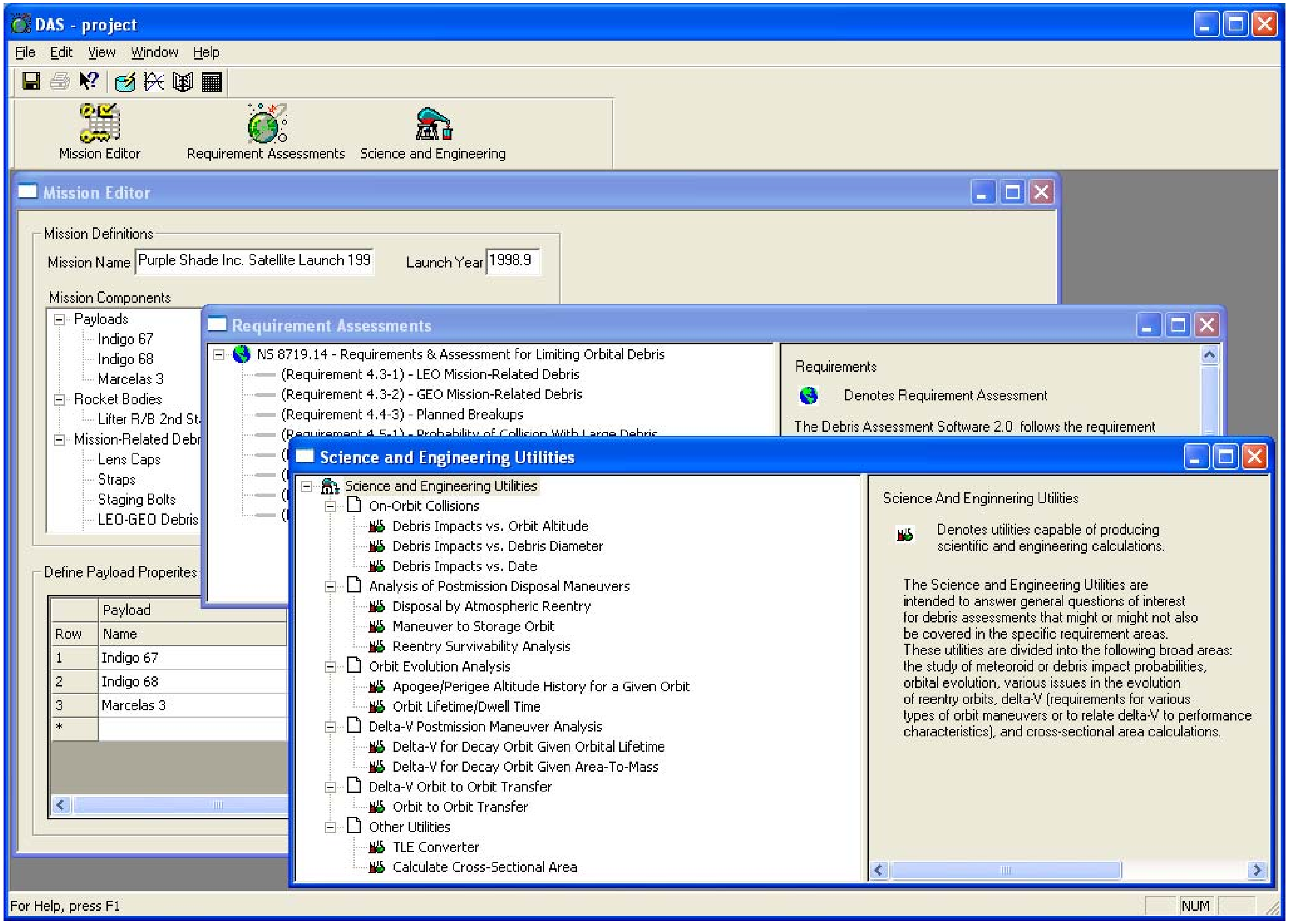
- **Download software and reference materials at:**

http://www.orbitaldebris.jsc.nasa.gov/mitigate/das.html

User Interface

- **Microsoft Windows User Interface**
  - DAS 2.0 uses a “native” Windows graphical user interface (GUI).
  - Runs on Windows 2000, XP, Vista, and Windows 7.
  - The GUI consolidates user input and avoids long chains of menus.
- **“Project” Orientation**
  - DAS 2.0 saves the user’s input and output files as a “project” in a single directory.
  - Other files and directories are not affected by the projects.
  - Moving or sharing a project is as simple as moving or sharing the project directory.
- **Division of Modules**
  - Mission Editor
  - Requirement Assessments
  - Science and Engineering Utilities
  - Supporting features

DAS 2.0 User Interface



Mission Definitions

Mission Name: Purple Shade Inc. Satellite Launch 199

Launch Year: 1998.9

Mission Components
- Payloads
  - Indigo 67
  - Indigo 68
  - Marcelas 3
- Rocket Bodies
  - Lifter R/B 2nd St
- Mission-Related Debr
  - Lens Caps
  - Straps
  - Staging Bolts
  - LEO-GEO Debris

Define Payload Properites

Row	Payload Name
1	Indigo 67
2	Indigo 68
3	Marcelas 3
*	

- NS 8719.14 - Requirements & Assessment for Limiting Orbital Debris
  - (Requirement 4.3-1) - LEO Mission-Related Debris
  - (Requirement 4.3-2) - GEO Mission-Related Debris
  - (Requirement 4.4-3) - Planned Breakups
  - (Requirement 4.5-1) - Probability of Collision With Large Debris

Requirements

Denotes Requirement Assessment

The Debris Assessment Software 2.0 follows the requirement

- Science and Engineering Utilities
  - On-Orbit Collisions
    - Debris Impacts vs. Orbit Altitude
    - Debris Impacts vs. Debris Diameter
    - Debris Impacts vs. Date
  - Analysis of Postmission Disposal Maneuvers
    - Disposal by Atmospheric Reentry
    - Maneuver to Storage Orbit
    - Reentry Survivability Analysis
  - Orbit Evolution Analysis
    - Apogee/Perigee Altitude History for a Given Orbit
    - Orbit Lifetime/Dwell Time
  - Delta-V Postmission Maneuver Analysis
    - Delta-V for Decay Orbit Given Orbital Lifetime
    - Delta-V for Decay Orbit Given Area-To-Mass
  - Delta-V Orbit to Orbit Transfer
    - Orbit to Orbit Transfer
  - Other Utilities
    - TLE Converter
    - Calculate Cross-Sectional Area

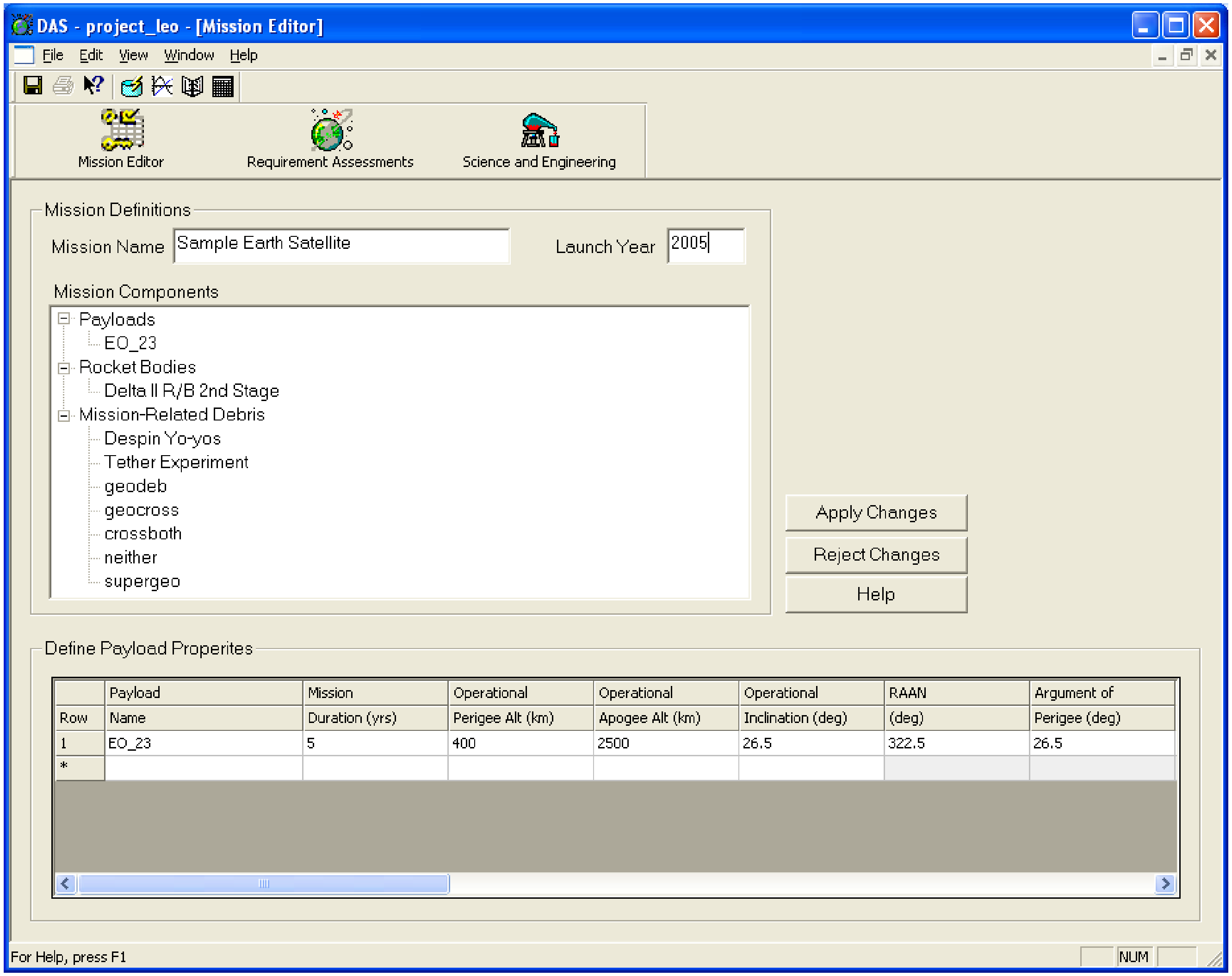
Science And Enginnering Utilities

Denotes utilities capable of producing scientific and engineering calculations.

The Science and Engineering Utilities are intended to answer general questions of interest for debris assessments that might or might not also be covered in the specific requirement areas. These utilities are divided into the following broad areas: the study of meteoroid or debris impact probabilities, orbital evolution, various issues in the evolution of reentry orbits, delta-V (requirements for various types of orbit maneuvers or to relate delta-V to performance characteristics), and cross-sectional area calculations.

The DAS 2.0 top-level window, and three main dialog windows.

GUI: Mission Editor



Mission Definitions

Mission Name: Sample Earth Satellite

Launch Year: 2005

Mission Components

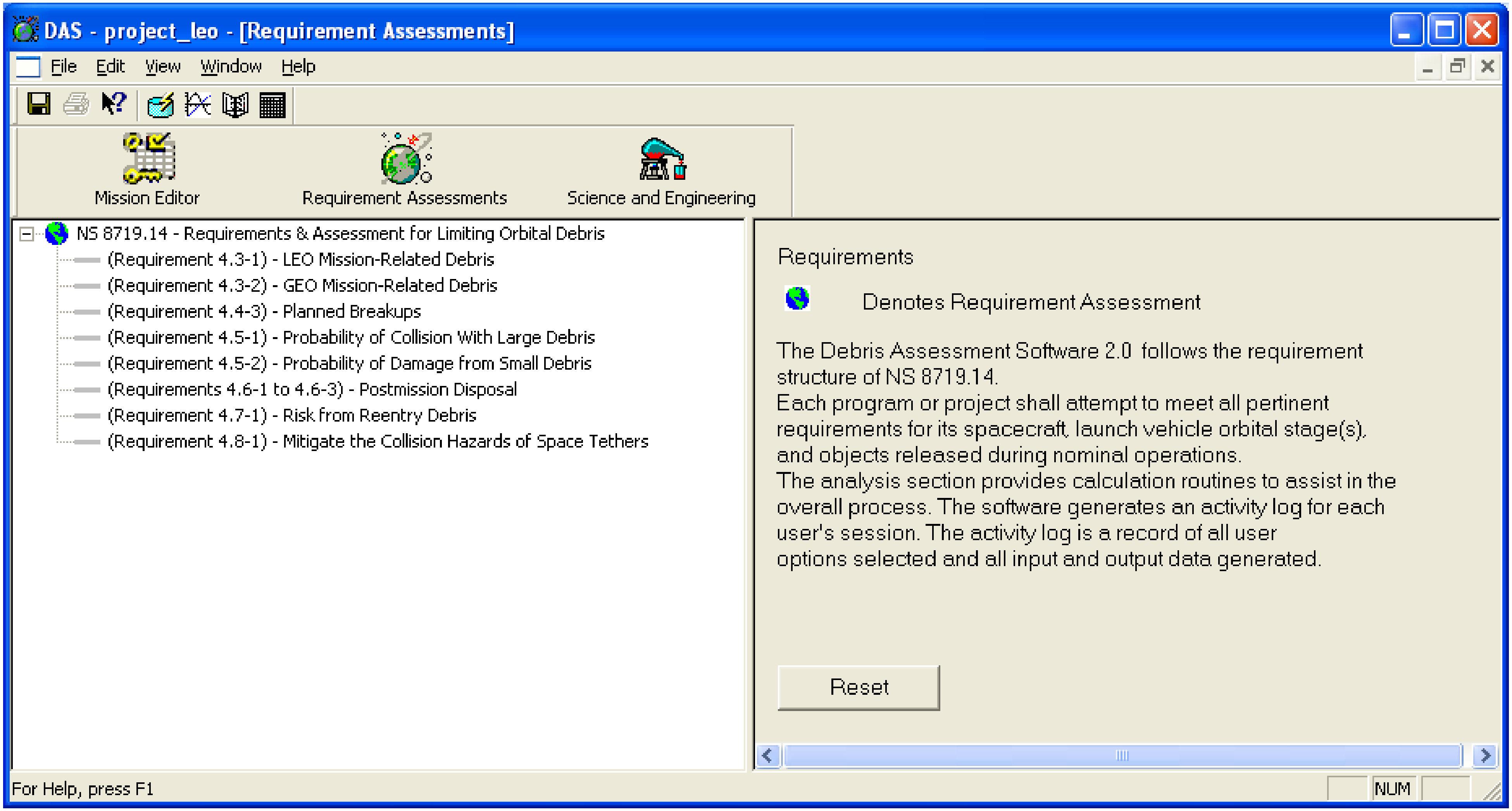
- Payloads
  - EO_23
- Rocket Bodies
  - Delta II R/B 2nd Stage
- Mission-Related Debris
  - Despin Yo-yos
  - Tether Experiment
  - geodeb
  - geocross
  - crossboth
  - neither
  - supergeo

Define Payload Properites

Row	Payload Name	Mission Duration (yrs)	Operational Perigee Alt (km)	Operational Apogee Alt (km)	Operational Inclination (deg)	RAAN (deg)	Argument of Perigee (deg)
1	EO_23	5	400	2500	26.5	322.5	26.5
*							

- **The user enters most of the mission information into the Mission Editor.**
- **Most assessments are complete using only the information in the Mission Editor.**

GUI: Requirement Assessments



NS 8719.14 - Requirements & Assessment for Limiting Orbital Debris

- (Requirement 4.3-1) - LEO Mission-Related Debris
- (Requirement 4.3-2) - GEO Mission-Related Debris
- (Requirement 4.4-3) - Planned Breakups
- (Requirement 4.5-1) - Probability of Collision With Large Debris
- (Requirement 4.5-2) - Probability of Damage from Small Debris
- (Requirements 4.6-1 to 4.6-3) - Postmission Disposal
- (Requirement 4.7-1) - Risk from Reentry Debris
- (Requirement 4.8-1) - Mitigate the Collision Hazards of Space Tethers

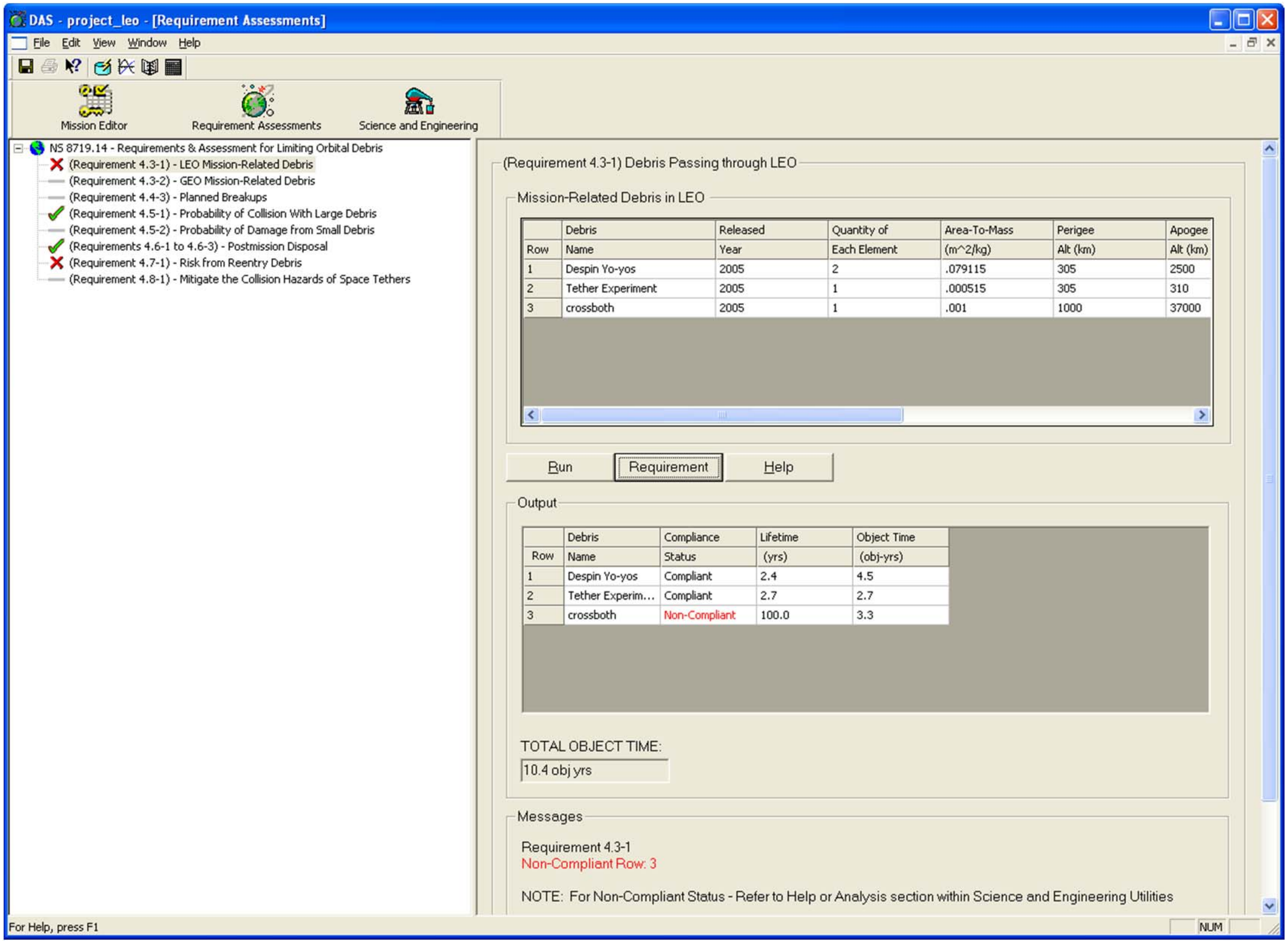
Requirements

Denotes Requirement Assessment

The Debris Assessment Software 2.0 follows the requirement structure of NS 8719.14.
Each program or project shall attempt to meet all pertinent requirements for its spacecraft, launch vehicle orbital stage(s), and objects released during nominal operations.
The analysis section provides calculation routines to assist in the overall process. The software generates an activity log for each user's session. The activity log is a record of all user options selected and all input and output data generated.

The user may assess the mission's compliance with each requirement.

GUI: Sample Requirement Assessment



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- ✗ (Requirement 4.7-1) - Risk from Reentry Debris
- — (Requirement 4.8-1) - Mitigate the Collision Hazards of Space Tethers

(Requirement 4.3-1) Debris Passing through LEO

Mission-Related Debris in LEO

Row	Debris Name	Released Year	Quantity of Each Element	Area-To-Mass (m^2/kg)	Perigee Alt (km)	Apogee Alt (km)
1	Despin Yo-yos	2005	2	.079115	305	2500
2	Tether Experiment	2005	1	.000515	305	310
3	crossboth	2005	1	.001	1000	37000

Output

Row	Debris Name	Compliance Status	Lifetime (yrs)	Object Time (obj-yrs)
1	Despin Yo-yos	Compliant	2.4	4.5
2	Tether Experim...	Compliant	2.7	2.7
3	crossboth	Non-Compliant	100.0	3.3

TOTAL OBJECT TIME:
10.4 obj yrs

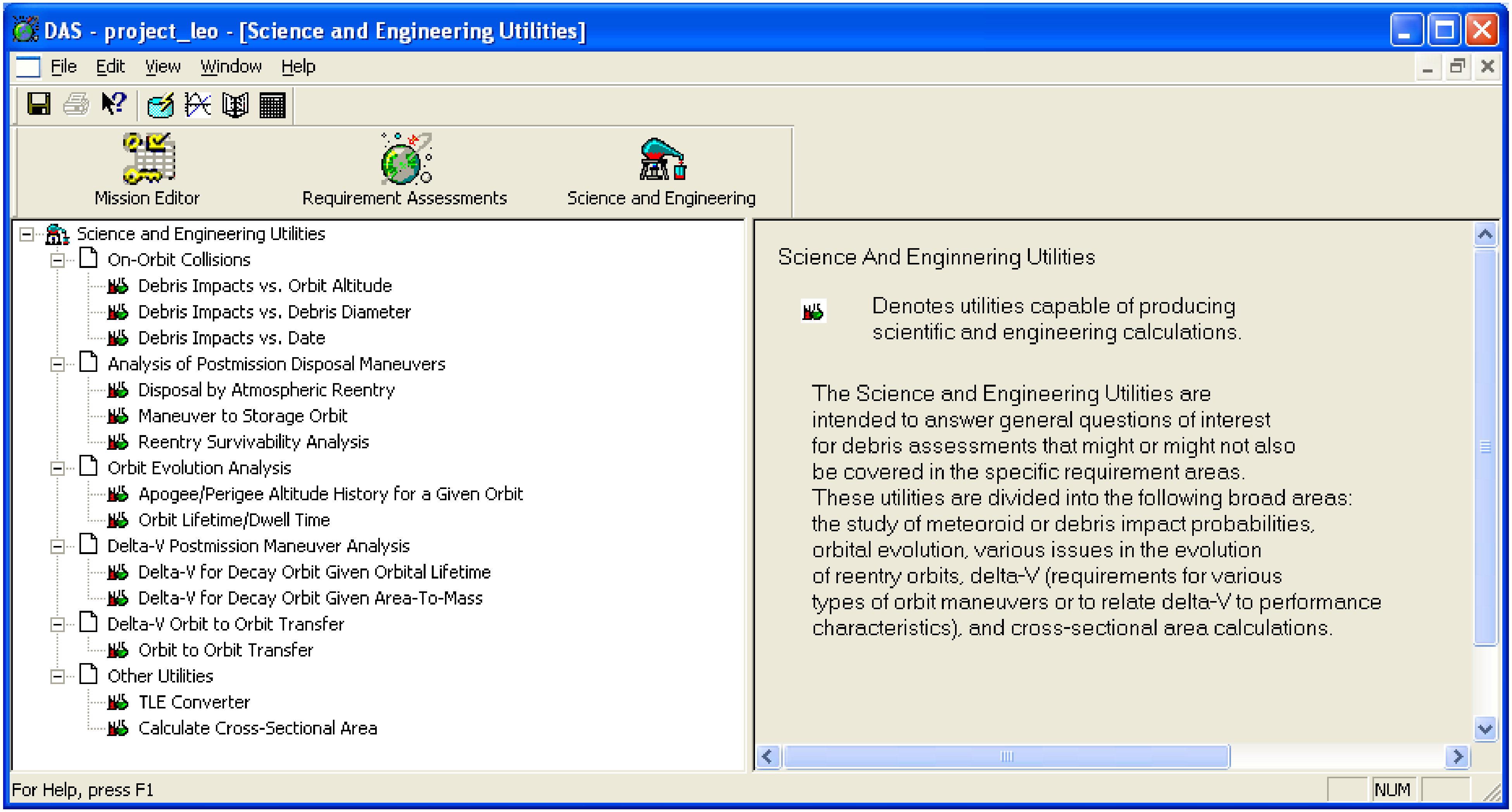
Messages

Requirement 4.3-1
Non-Compliant Row: 3

NOTE: For Non-Compliant Status - Refer to Help or Analysis section within Science and Engineering Utilities

The right-hand pane shows inputs, outputs, and compliance status.

GUI: Science and Engineering Utilities



- Science and Engineering Utilities
  - On-Orbit Collisions
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  - Analysis of Postmission Disposal Maneuvers
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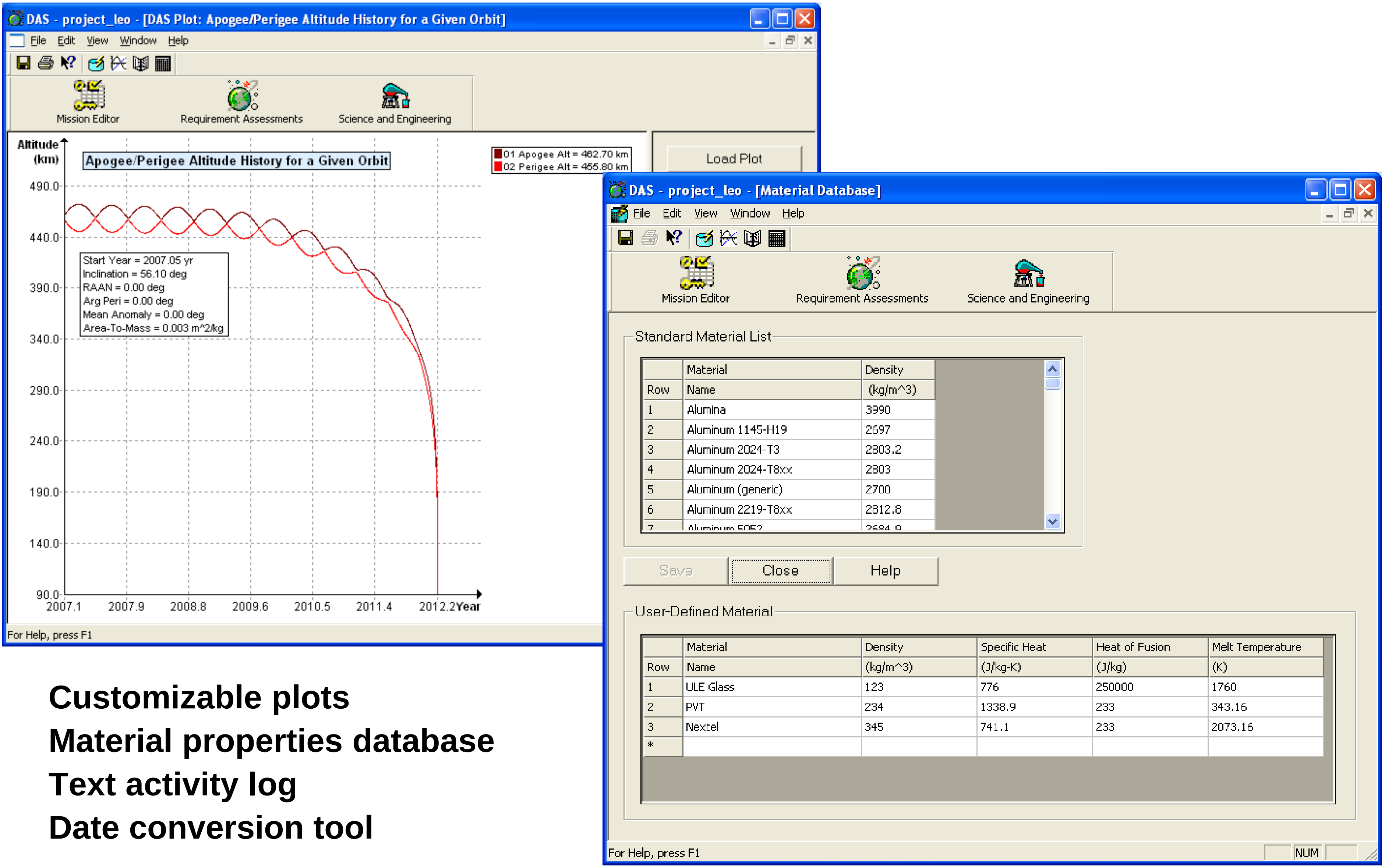
These utilities allow the user to explore options in mission design and to perform other supporting calculations.

GUI: Other Supporting Features



🟥 01 Apogee Alt = 462.70 km
🟥 02 Perigee Alt = 455.80 km

Start Year = 2007.05 yr
Inclination = 56.10 deg
RAAN = 0.00 deg
Arg Peri = 0.00 deg
Mean Anomaly = 0.00 deg
Area-To-Mass = 0.003 m^2/kg

Standard Material List

	Material	Density
Row	Name	(kg/m^3)
1	Alumina	3990
2	Aluminum 1145-H19	2697
3	Aluminum 2024-T3	2803.2
4	Aluminum 2024-T8xx	2803
5	Aluminum (generic)	2700
6	Aluminum 2219-T8xx	2812.8
7	Aluminum 5052	2684.9

User-Defined Material

	Material	Density	Specific Heat	Heat of Fusion	Melt Temperature
Row	Name	(kg/m^3)	(J/kg-K)	(J/kg)	(K)
1	ULE Glass	123	776	250000	1760
2	PVT	234	1338.9	233	343.16
3	Nextel	345	741.1	233	2073.16
*					

- **Customizable plots**
- **Material properties database**
- **Text activity log**
- **Date conversion tool**

Summary

- **DAS is the standard method of assessing compliance with NASA's space debris mitigation requirements (NS 8719.14A).**
  - DAS provides point-by-point assessment of a mission's compliance with NASA's requirements.
  - Results from DAS may be included in reports to NASA.
  - DAS provides additional tools for mission-planning and input conversion.
- **The modular internal structure of the software allows for easy updates (such as to the debris environment model or the human population density) in the future. Solar activity forecasts are updated quarterly.**
- **Software and documentation are available on the NASA Orbital Debris Program Office's internet site:**

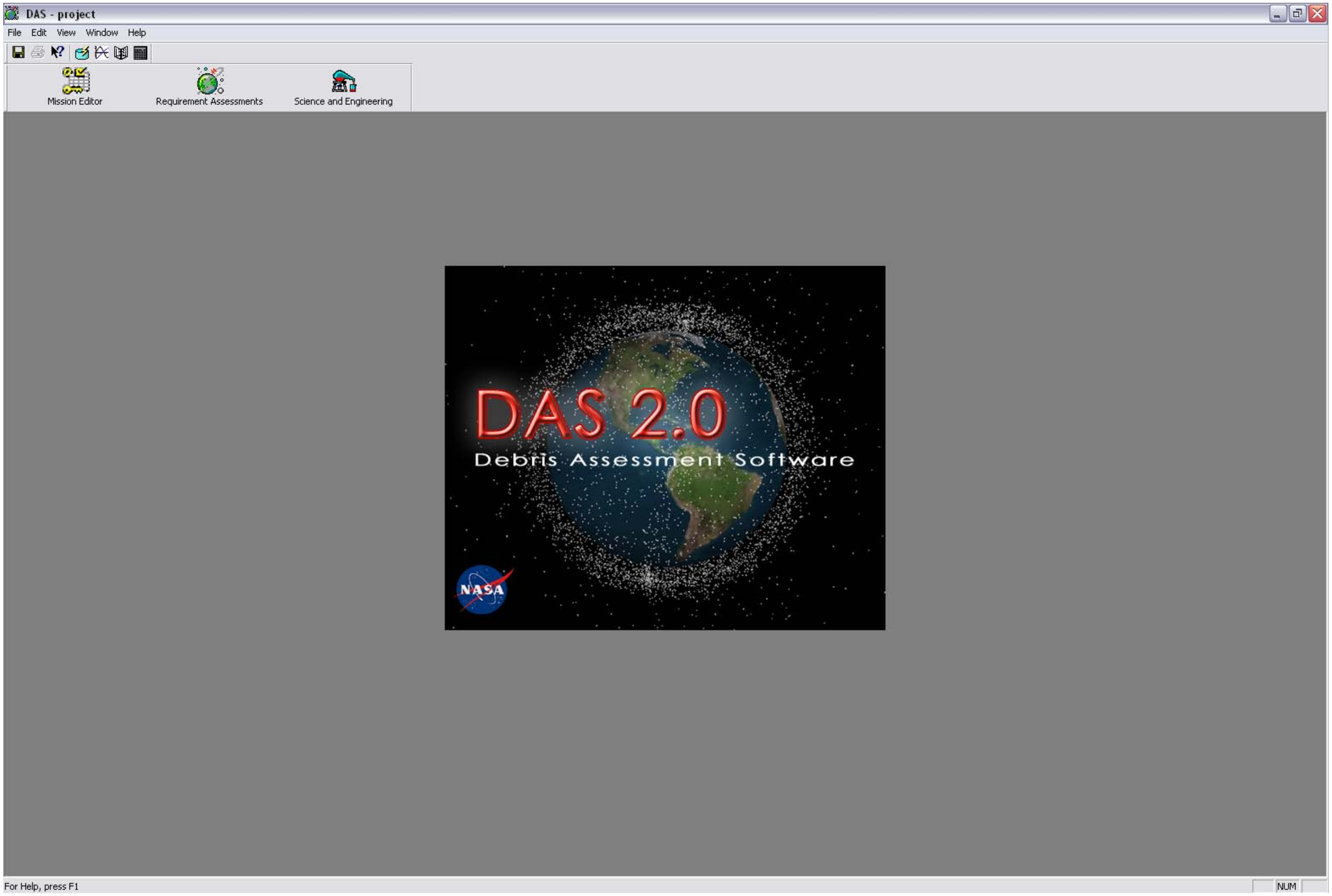
http://www.orbitaldebris.jsc.nasa.gov/mitigate/das.html


Broom Hilda
By Russell Myers
YAHOO!! WHOOPEE!
OOPS!
THUD
SPACE JUNK!
RUSSELL MYERS

DAS Reentry Risk Assessment

Orbital Debris Program Office
NASA Johnson Space Center

DAS Reentry Survivability Analysis



DAS Reentry Survivability Analysis

- **JSC Debris Assessment Software (DAS)**
  - Developed to assist NASA programs in performing orbital debris assessments
  - Able to evaluate compliance with many of the requirements in NS 8719.14A

- **Reentry Survivability Analysis in DAS can be accessed in 2 ways**
  1. As one item in an overall assessment of a project’s compliance with NS 8719.14A
     - Provides Debris Casualty Area (DCA) and Risk
     - Inclination and Parent Objects flow down from Mission Editor
  2. As a separate routine under the Science and Engineering menu
     - Provides DCA only
     - Runs separate from Mission Editor
     - All data provided by user at run time

- **DAS can only asses the risk associated with <u>uncontrolled</u> reentry**

- **DAS’s Reentry Survivability Tool is intended as “1st Cut” Assessment Tool**
  - Provides somewhat conservative results
    - Will classify all missions which clearly do not satisfy the requirement non-compliant
    - May also classify some mission which are borderline non-compliant

DAS Reentry Survivability Analysis

- **Assumptions:**

Uses temperature dependent material properties for 77 common materials

- Allows user to define additional materials as needed

Includes aerodynamic and heating equations for 4 simple shapes

- Sphere
- Flat Plate
- Cylinder
- Box

Parent Object is assumed to break apart at 78 km, exposing 1st level of fragments

- DAS permits 3 levels of fragmentation after the 78 km Parent body break up

Fragments always begin with a temperature of 300 K

- Only inherits trajectory state vectors from the parents

Uses lumped mass thermal model

- No partial ablation means the DCA for an object is either 0 (demised) or the usual product of initial dimensions

DCA for each object is calculated as follows:

- DCA = $(0.6 + \sqrt{A})^2$
  - Additional area accounts for presence of person in proximity to reentering object
  - Area defined for each shape as:

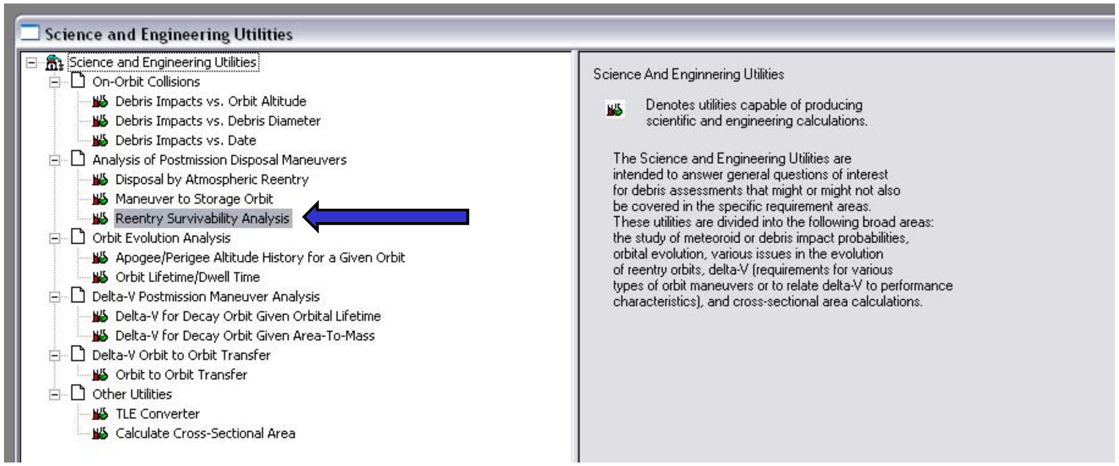
Spheres → $A = \pi * r^2$ Cylinders → $A = L*D$

Flat Plates → $A = L*W$ Boxes → $A = ½*(W*L+L*H)$

DAS Reentry Survivability Analysis

- **Getting Started**

Select Science and Engineering



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Select Reentry Survivability Analysis

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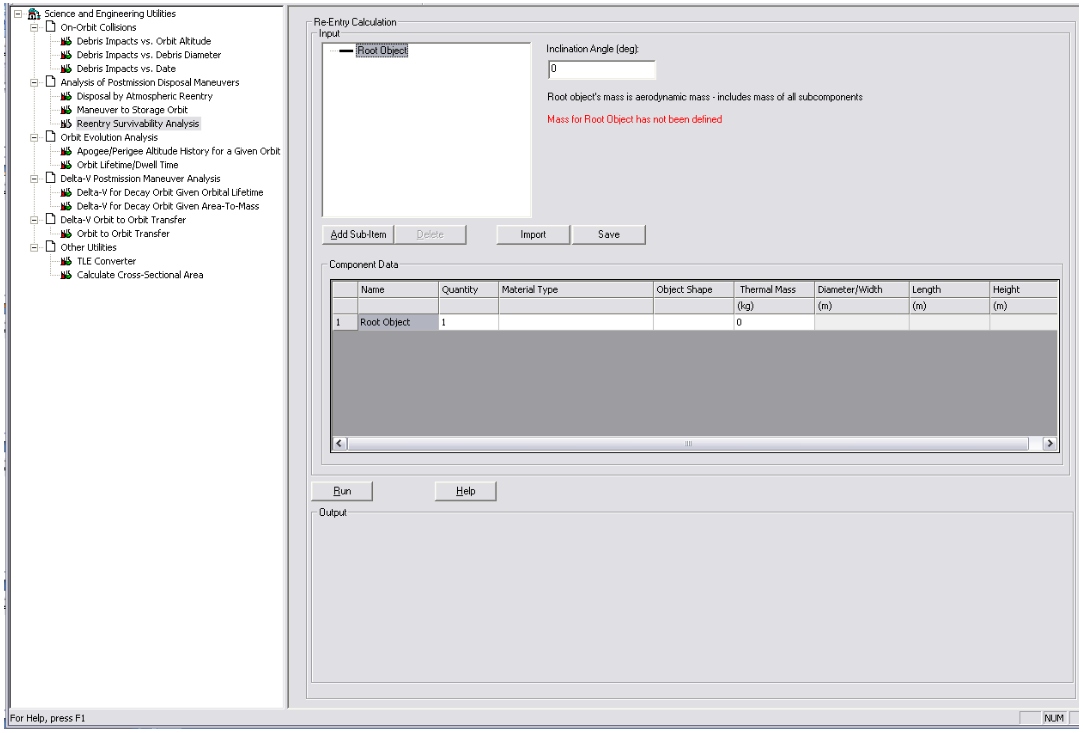
DAS Reentry Survivability Analysis

- **Object Modeling**



Inclination Angle (deg): 0

Root object's mass is aerodynamic mass - includes mass of all subcomponents

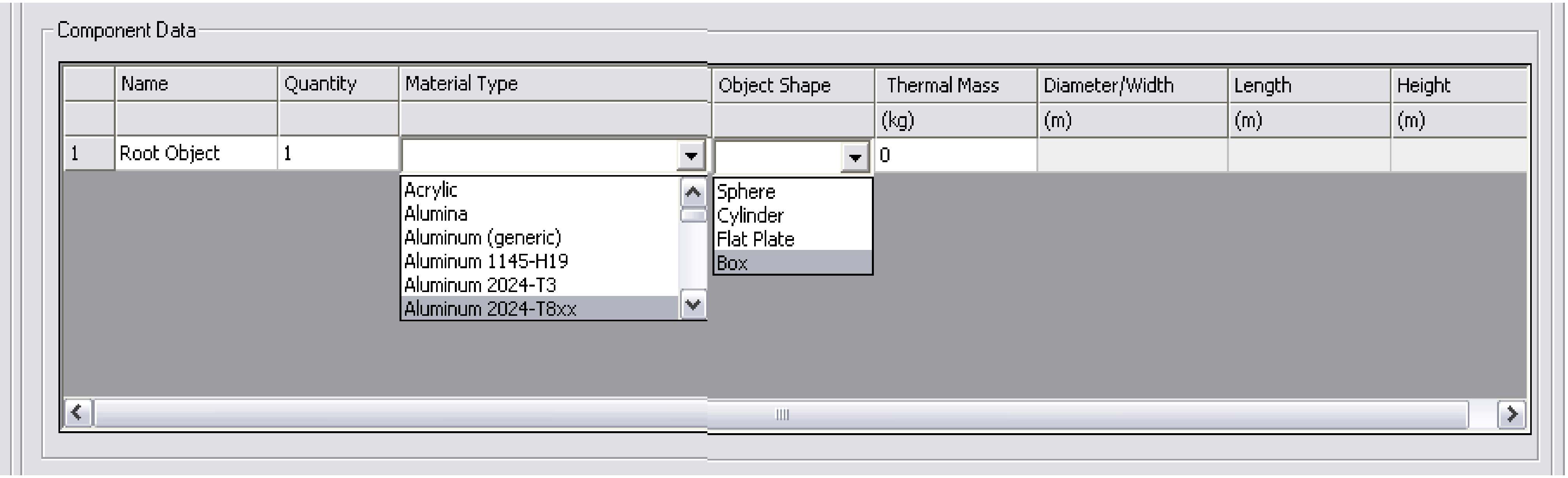
Mass for Root Object has not been defined

	Name	Quantity	Material Type	Object Shape	Thermal Mass	Diameter/Width	Length	Height
					(kg)	(m)	(m)	(m)
1	Root Object	1			0			

- The “Root Object” is the overall vehicle being analyzed.
  - The mass of this object is the total mass of the entire vehicle
  - This object is used only to propagate the trajectory from 122 km to 78 km altitude
- Here the inclination is entered for the vehicle, under Requirements Assessment the inclination would have been populated using the Mission Editor value.

DAS Reentry Survivability Analysis

- **Object Modeling (cont.)**



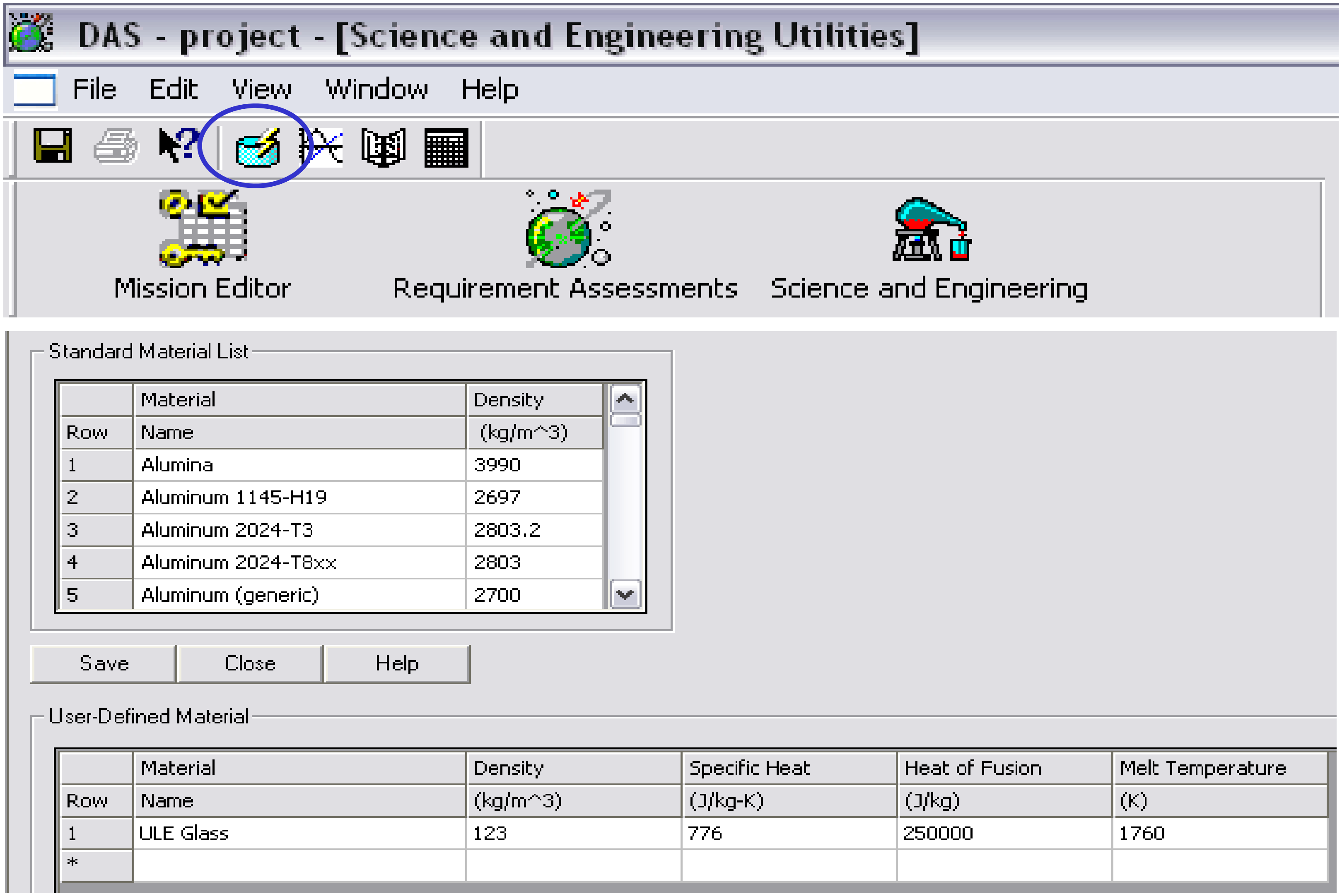
Component Data

	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
1	Root Object	1			0			

- Both the Material Type and Object Shape are drop down menus.
    - Material Type includes all 77 built in materials representing some of the most commonly used materials
    - Object Shape lists the 4 object types used in DAS
- What if the proper material is not included?

DAS Reentry Survivability Analysis

- **Material Database**



Standard Material List

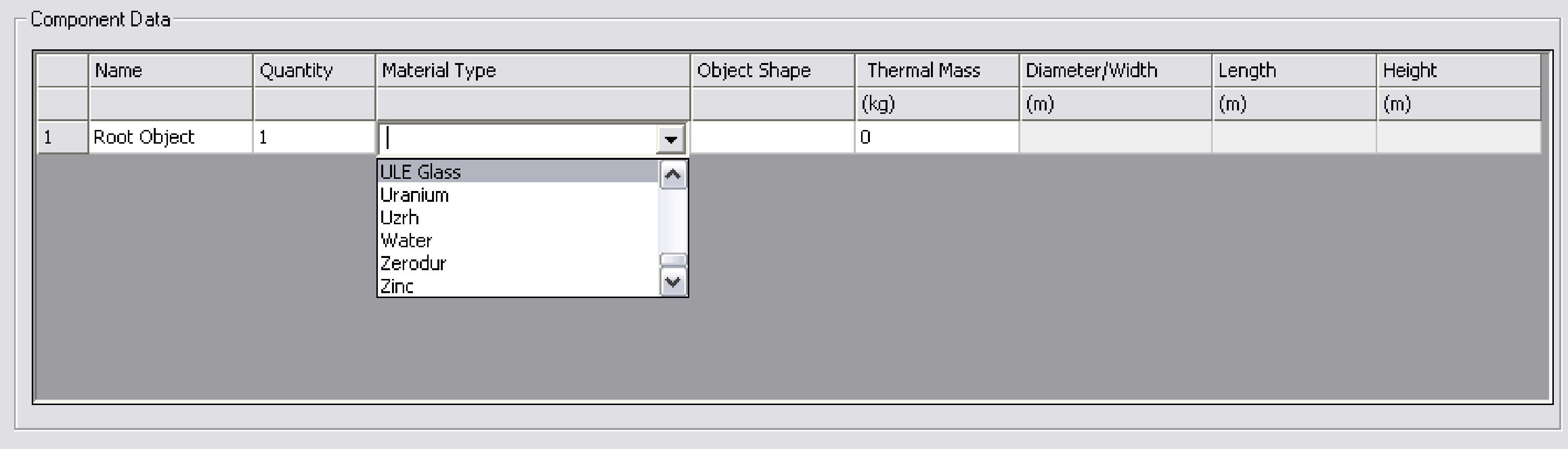
Row	Material Name	Density (kg/m^3)
1	Alumina	3990
2	Aluminum 1145-H19	2697
3	Aluminum 2024-T3	2803.2
4	Aluminum 2024-T8xx	2803
5	Aluminum (generic)	2700

User-Defined Material

Row	Material Name	Density (kg/m^3)	Specific Heat (J/kg-K)	Heat of Fusion (J/kg)	Melt Temperature (K)
1	ULE Glass	123	776	250000	1760
*					

DAS Reentry Survivability Analysis

- **Material Database (cont.)**
  - Allows the user to input additional materials not included in the standard list
  - Requires non-temperature dependent values for material properties
  - Saves materials to “matprops.csv” in the current working directory
  - Adds custom material to the drop down menu in alphabetical order



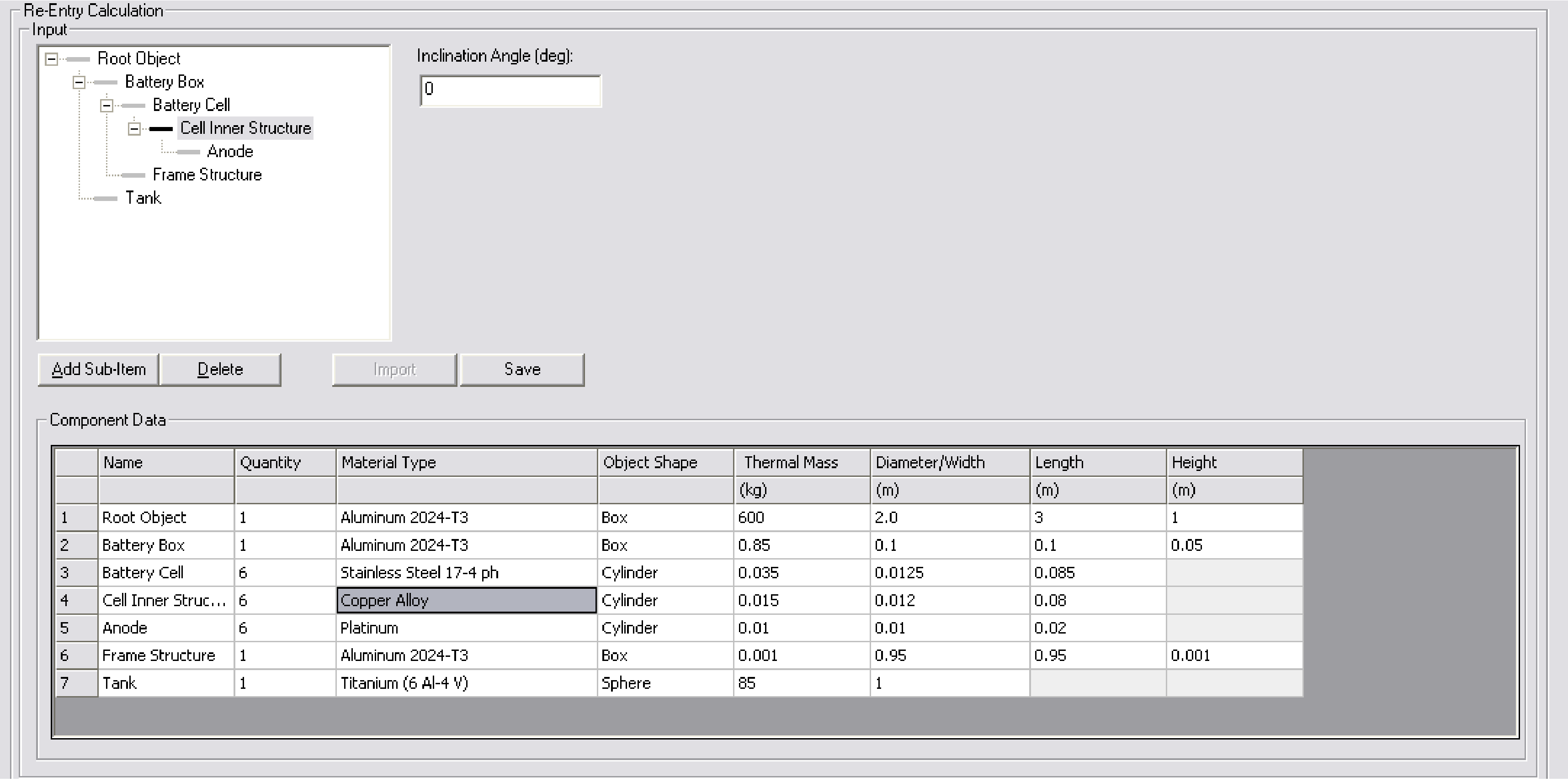
Component Data

	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
1	Root Object	1			0			

  - It is important to note that the composite materials built into DAS (i.e. Graphite Epoxy) are sometimes best defined using the Material Database, as the properties of these materials can vary significantly depending on the manufacturer.

DAS Reentry Survivability Analysis

- **Object Nesting**
  - Each fragment of the vehicle can have up to 3 layers of internal fragments.



- Root Object
  - Battery Box
    - Battery Cell
      - Cell Inner Structure
        - Anode
    - Frame Structure
  - Tank

Inclination Angle (deg): 0

	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
1	Root Object	1	Aluminum 2024-T3	Box	600	2.0	3	1
2	Battery Box	1	Aluminum 2024-T3	Box	0.85	0.1	0.1	0.05
3	Battery Cell	6	Stainless Steel 17-4 ph	Cylinder	0.035	0.0125	0.085	
4	Cell Inner Struc...	6	Copper Alloy	Cylinder	0.015	0.012	0.08	
5	Anode	6	Platinum	Cylinder	0.01	0.01	0.02	
6	Frame Structure	1	Aluminum 2024-T3	Box	0.001	0.95	0.95	0.001
7	Tank	1	Titanium (6 Al-4 V)	Sphere	85	1		

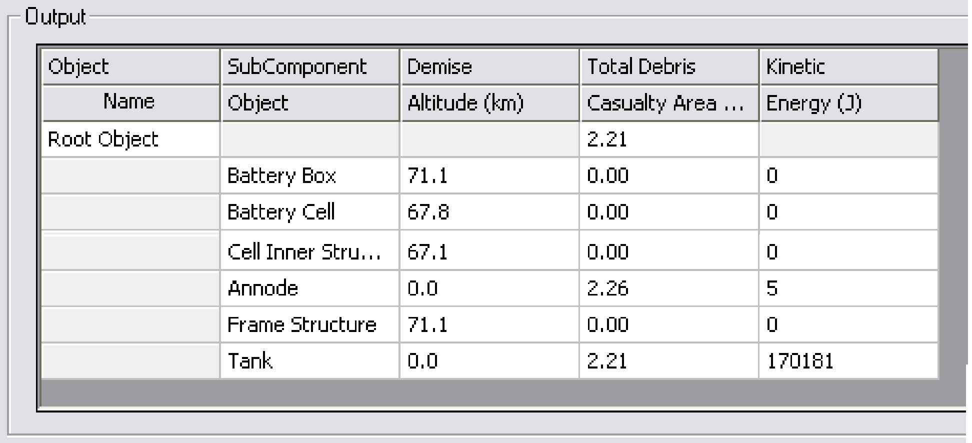
  - Fragment masses should be thermal masses which do not account for the mass of any contents.

DAS Reentry Survivability Analysis

- **After entering in all component information, hit “Run” to get results.**
  - At this point DAS will verify the following:
    - All required fields are filled for each object
    - The entered mass does not exceed a limit defined by an object’s dimensions and its material density
      - For flat plates the computed density is based on an assumed height of 1/10 the width
      - Plates that do not pass input validation or are thicker, should be modeled as boxes
    - For boxes, the values must be entered such that Length ≥ Width ≥ Height
    - A cylinder must have a length of at least 30% of its diameter
      - If its length is less than 10% of its diameter then model it as a flat square plate of equivalent area
      - If its length is between 10% and 30% of its area than it should be modeled as a box of equivalent area
  - If any of the data is not valid, the assessment ceases and the data must be corrected before continuing

DAS Reentry Survivability Analysis

- **Results**



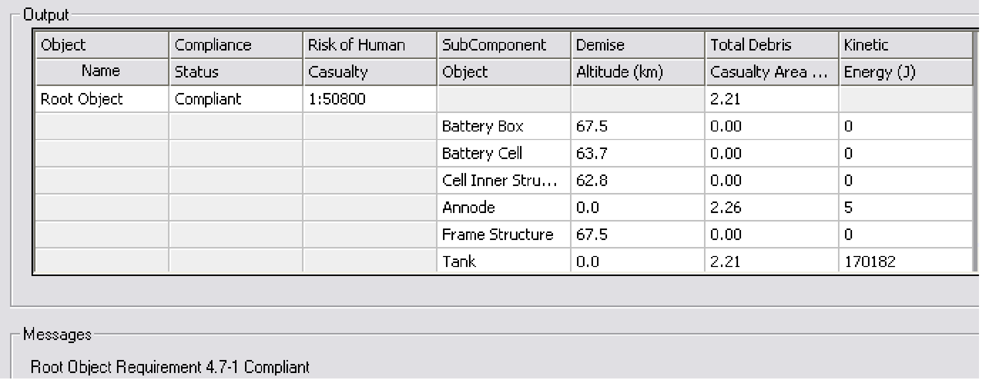
Object Name	SubComponent Object	Demise Altitude (km)	Total Debris Casualty Area ...	Kinetic Energy (J)
Root Object			2.21	
	Battery Box	71.1	0.00	0
	Battery Cell	67.8	0.00	0
	Cell Inner Stru...	67.1	0.00	0
	Annode	0.0	2.26	5
	Frame Structure	71.1	0.00	0
	Tank	0.0	2.21	170181

Results from Science and Engineering Routine

- Gives DCA and impact Kinetic Energy for each object
- Gives total DCA of all objects which impact with a Kinetic Energy greater than 15 J

Results from Requirements Assessment Routine

- Reports total risk for the calculated reentry year
- States whether or not compliant



Object Name	Compliance Status	Risk of Human Casualty	SubComponent Object	Demise Altitude (km)	Total Debris Casualty Area ...	Kinetic Energy (J)
Root Object	Compliant	1:50800			2.21	
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Root Object Requirement 4.7-1 Compliant

DAS Reentry Survivability Analysis

- **Saving**
  - Modeling data and results are saved to .csv files able to be opened by Excel.
  - Clicking Save in the Science and Engineering Routine allows the user to define file name and save location.
  - The Requirements Assessment Routine saves the data and results to “reentry.csv” in the project directory.
- **Importing**
  - Data can be entered into a .csv file and imported into DAS using Excel using the following format.

Reentry Data									
Row Num	Name	Parent	Qty	Material	Body Type	Thermal Mass	Diameter/Width	Length	Height
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  - Note if importing into the Requirements Assessment Routine, omit the first row.

DAS Reentry Survivability Analysis

- **Known Limitations**
  - Honeycomb Panels
    - Typically these panels consist of a layer of aluminum honeycomb sandwiched between two aluminum or composite face sheets.
    - Due to the limitation of the thermal model these objects often survive a DAS reentry analysis and require ORSAT analysis.
  - Objects with complex shapes
    - Items in this category constructed of a single material can be modeled using equivalent area simplified shapes.
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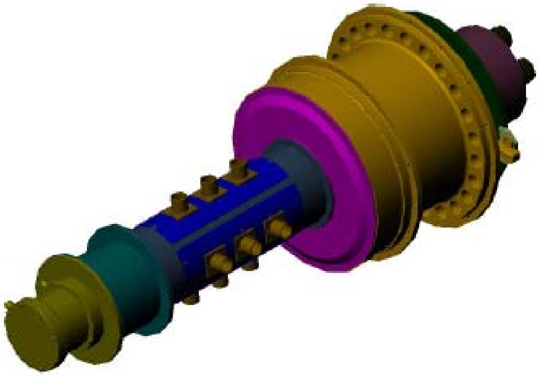

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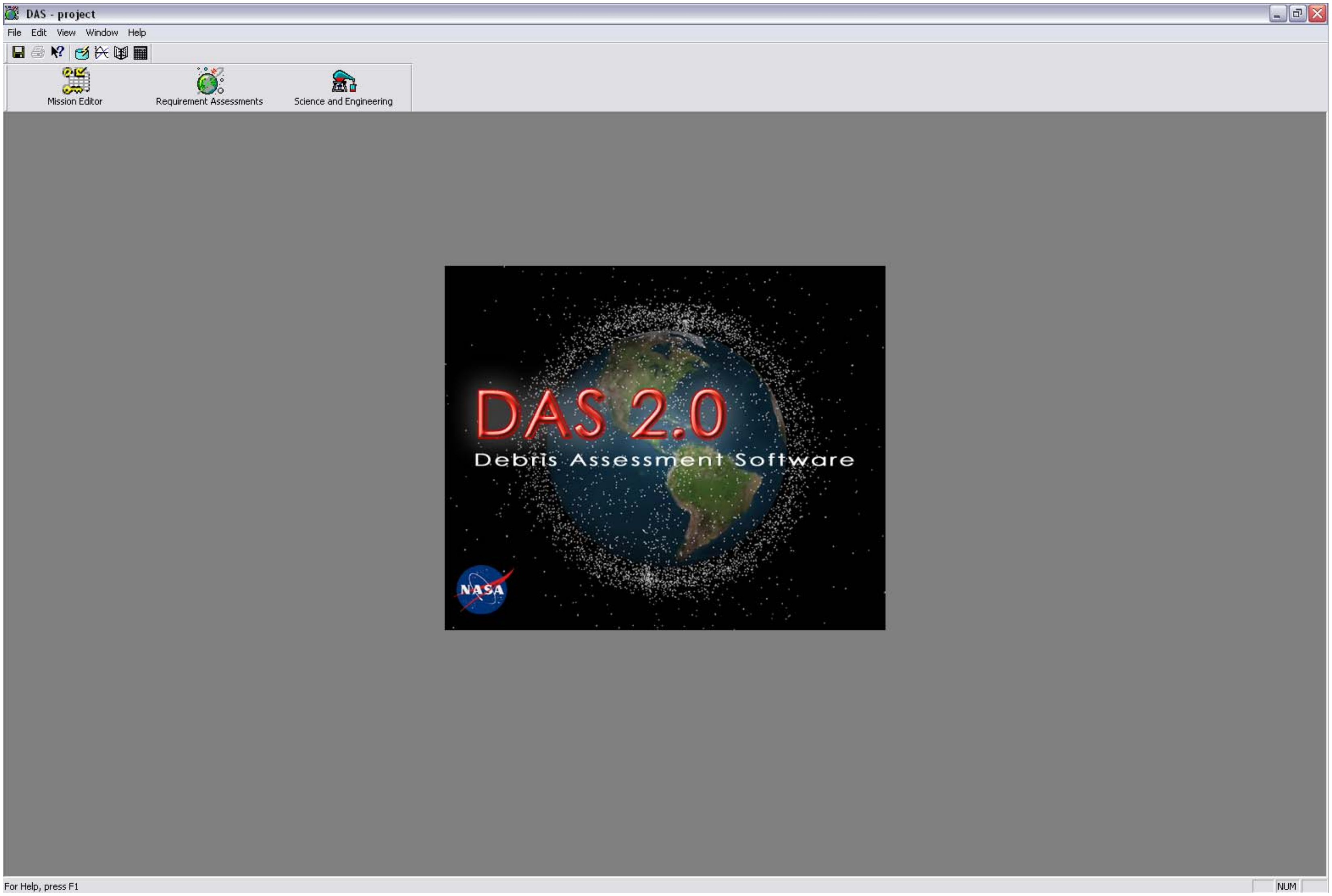

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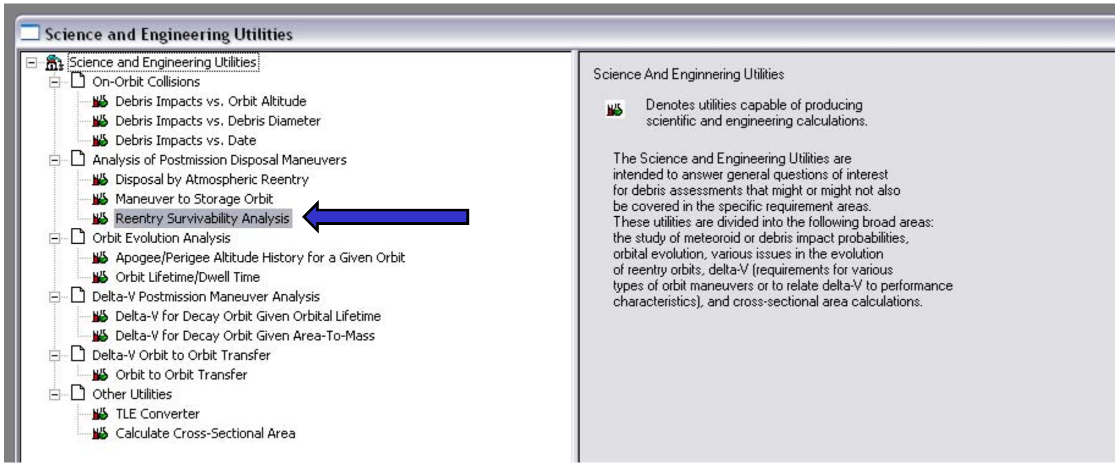

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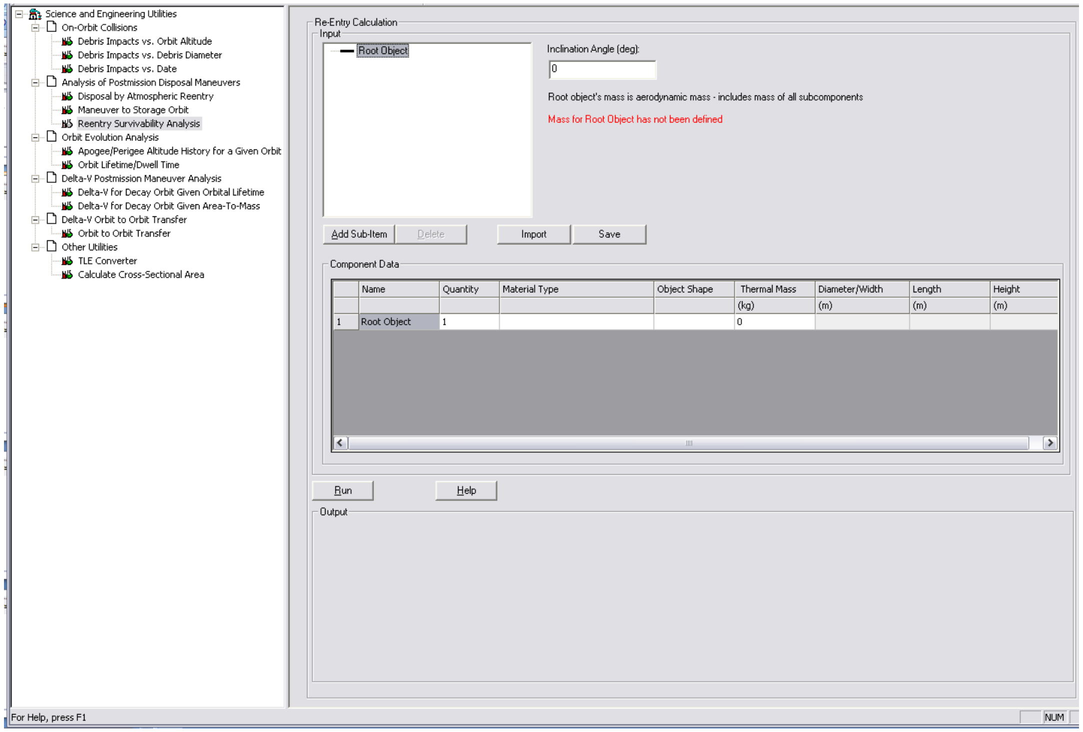

Inclination Angle (deg): 0

Root object's mass is aerodynamic mass - includes mass of all subcomponents

Mass for Root Object has not been defined

	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
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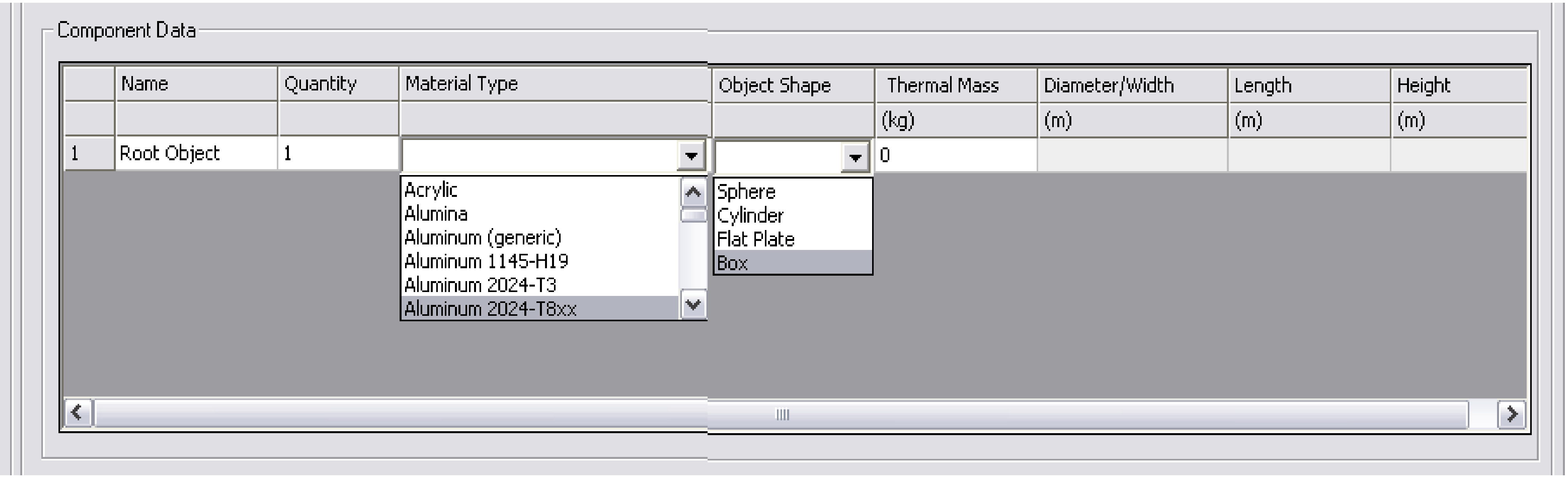

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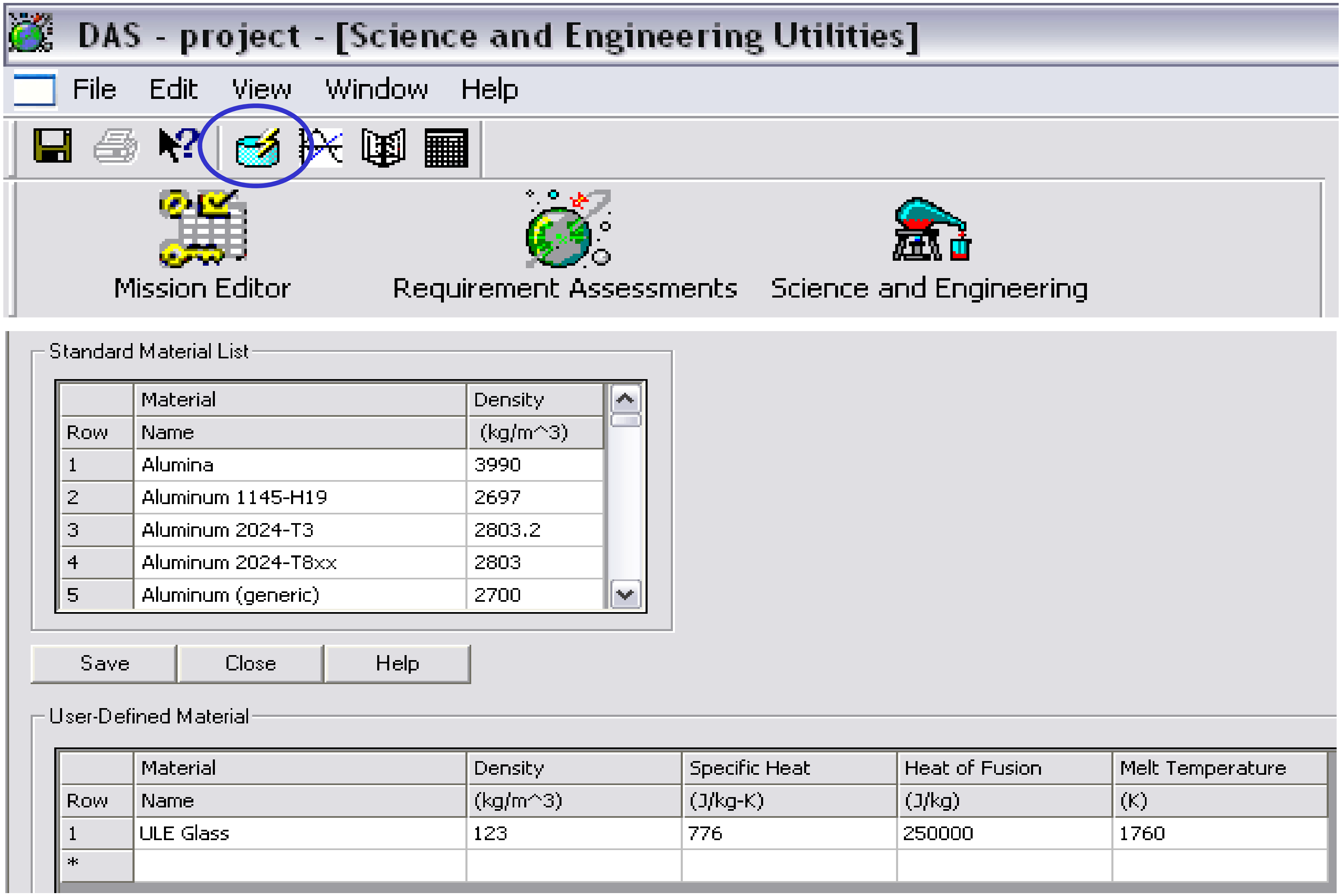

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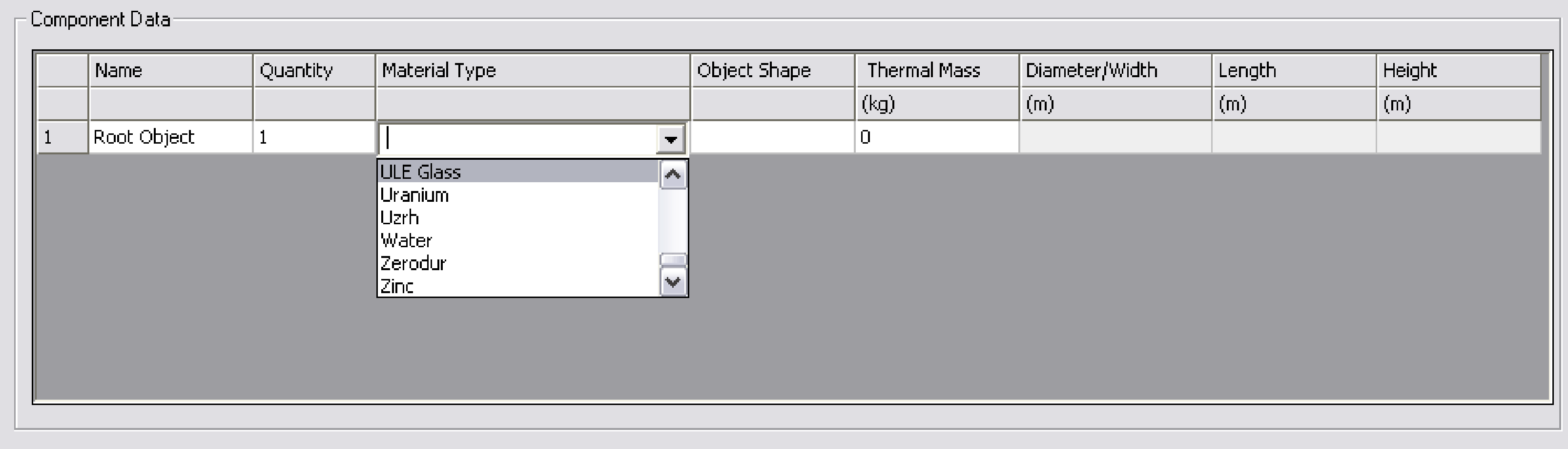

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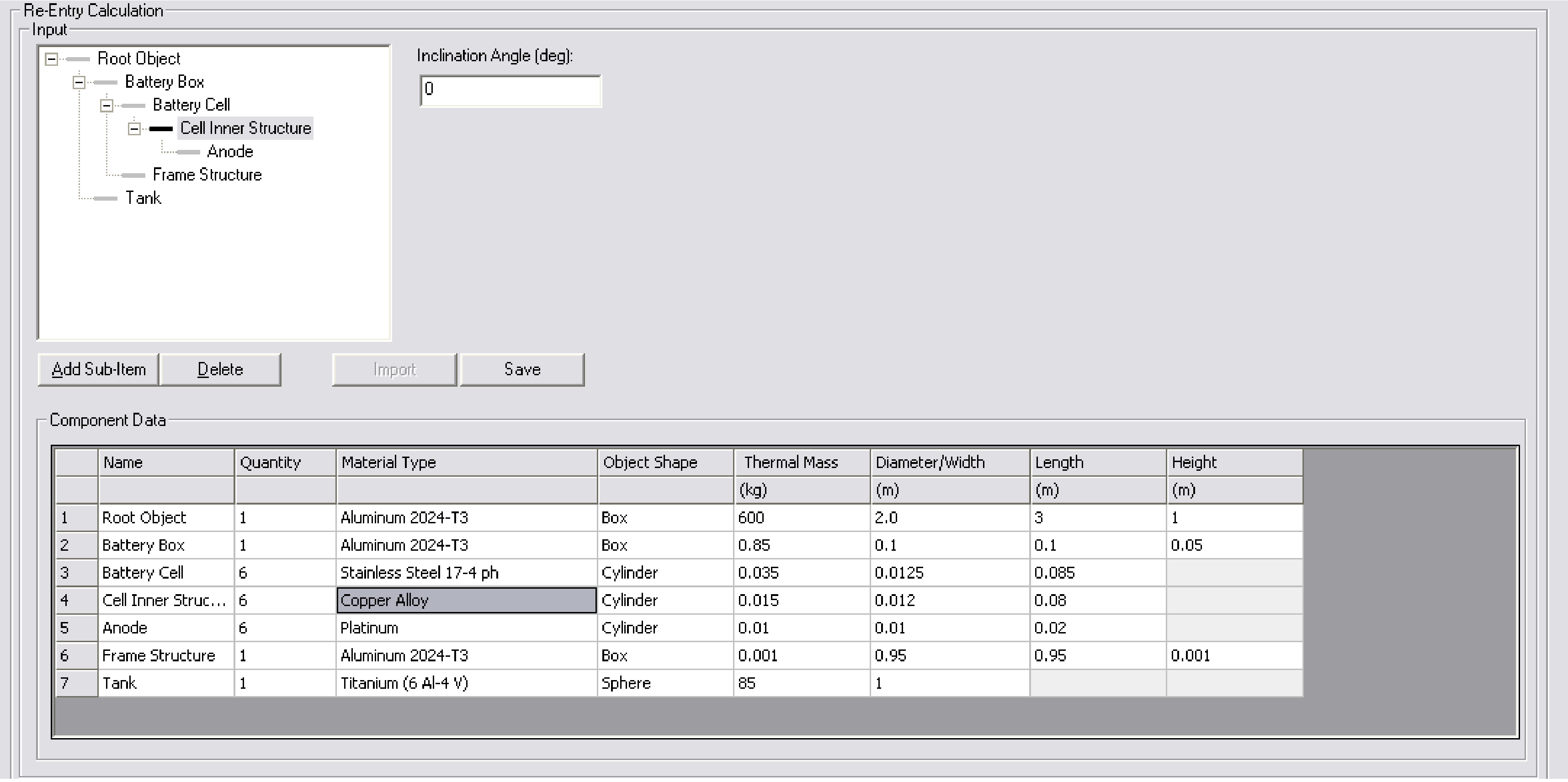

Inclination Angle (deg): 0

	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
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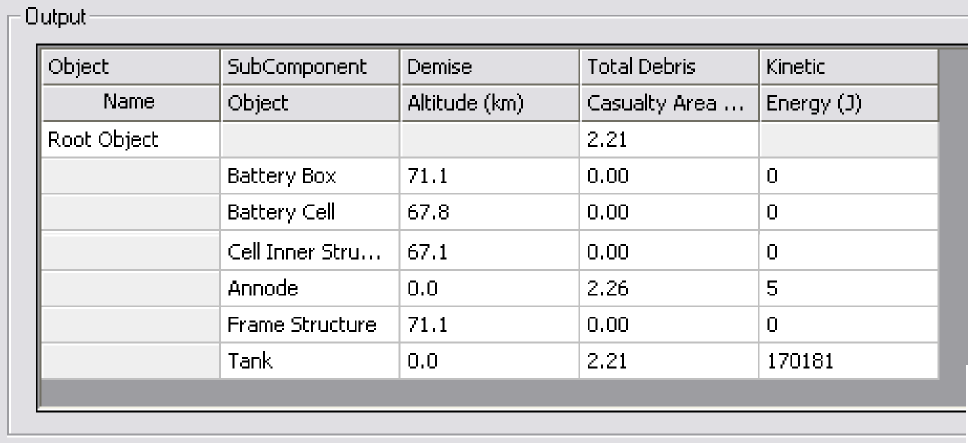
DAS Reentry Survivability Analysis

- **Results**



Output

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	Battery Box	71.1	0.00	0
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Results from Science and Engineering Routine

- Gives DCA and impact Kinetic Energy for each object
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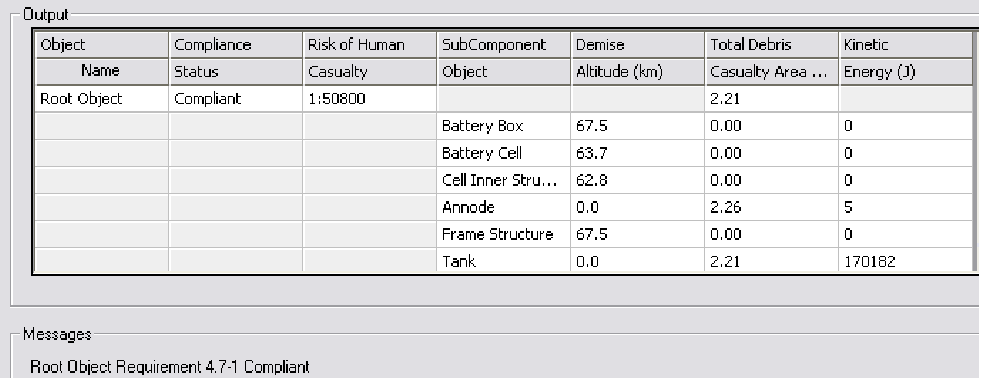
Results from Requirements Assessment Routine

- Reports total risk for the calculated reentry year
- States whether or not compliant



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Messages

Root Object Requirement 4.7-1 Compliant

DAS Reentry Survivability Analysis

- **Saving**
  - Modeling data and results are saved to .csv files able to be opened by Excel
  - Clicking Save in the Science and Engineering Routine allows the user to define file name and save location
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  - Note if importing into the Requirements Assessment Routine, omit the first row

DAS Reentry Survivability Analysis

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    - Typically these panels consist of a layer of aluminum honeycomb sandwiched between two aluminum or composite face sheets
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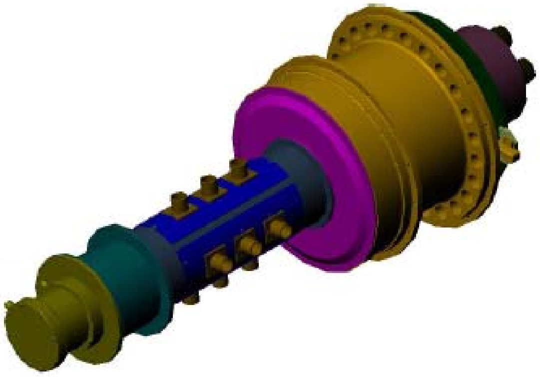
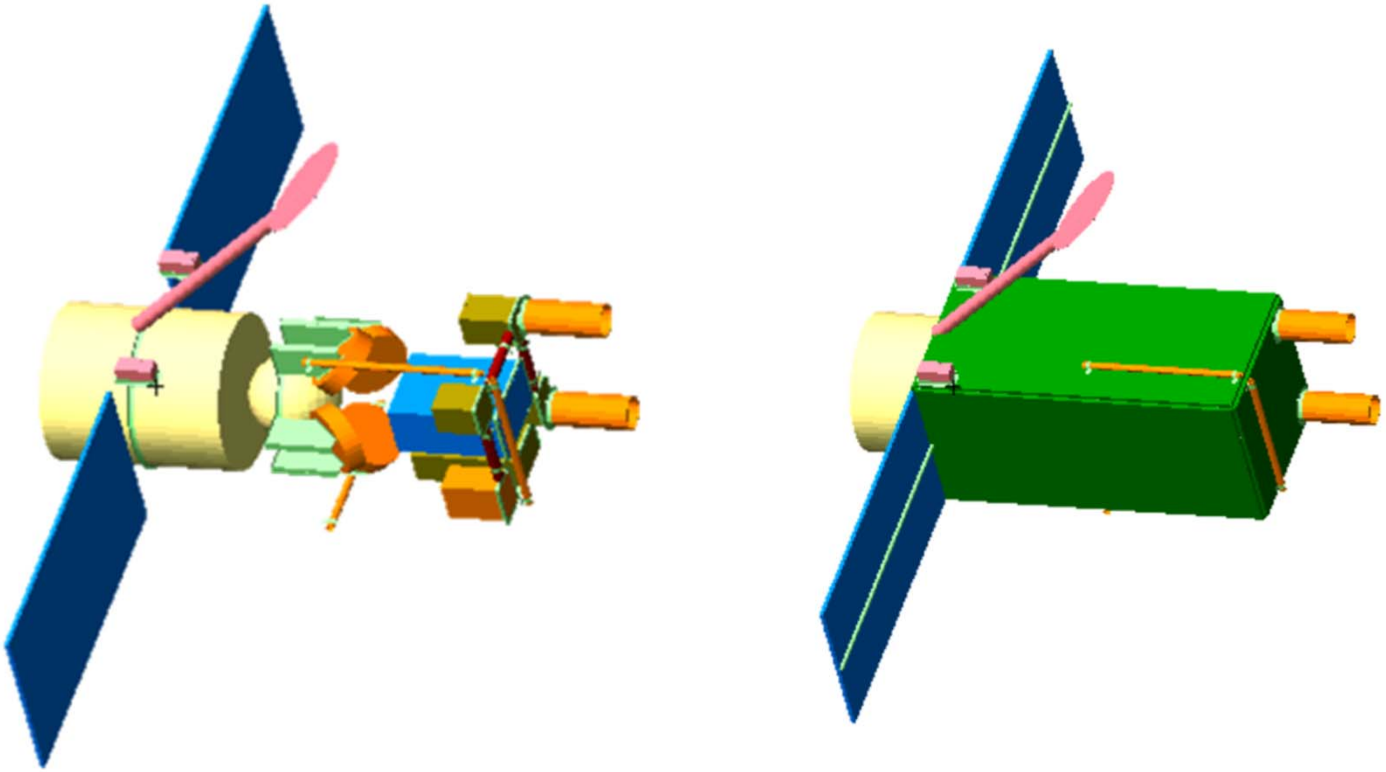


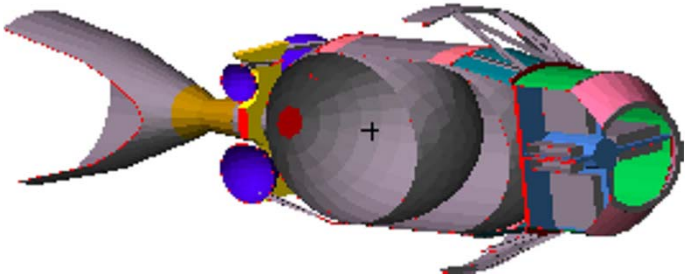
Reentry Example 1 - GenSat

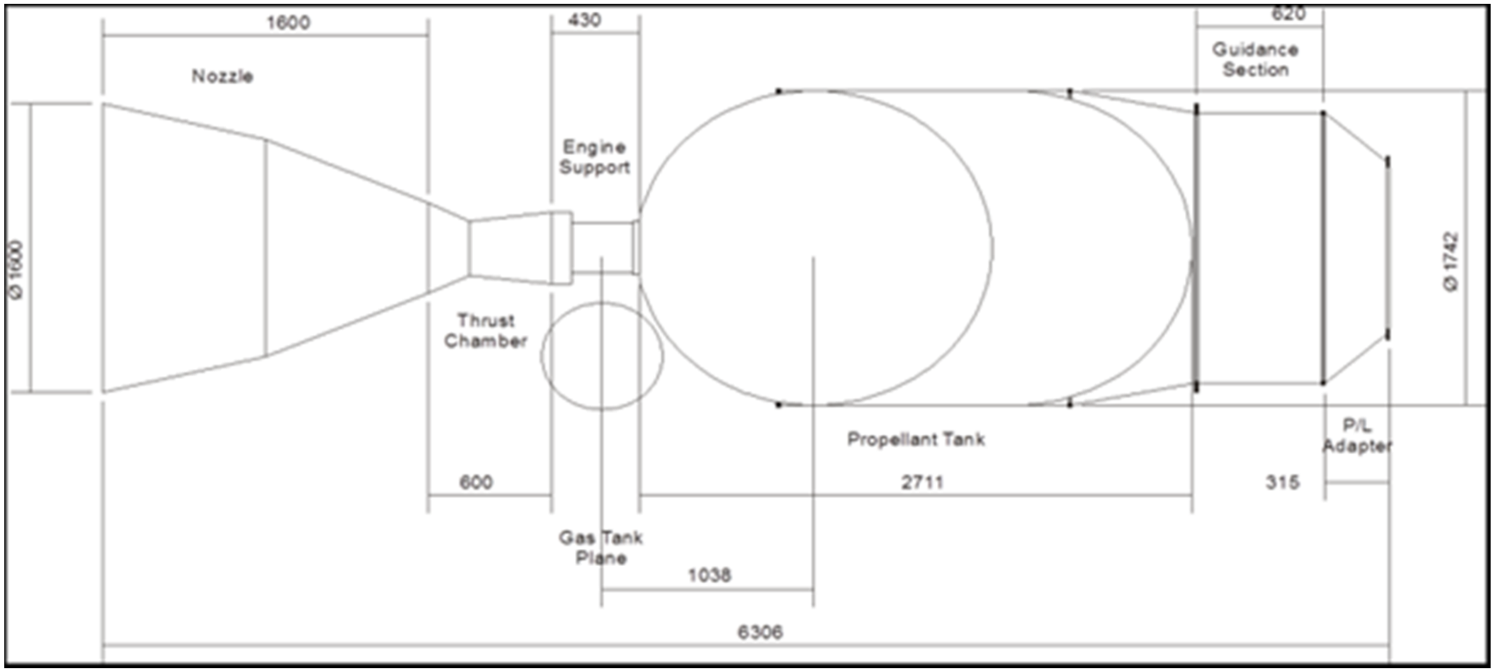


Reentry Example 1 - GenSat

Row Num	Name	Parent	Qty	Material	Body Type	Thermal Mass	Diameter/Width	Length	Height	
1	GenSat	0	1	Aluminum (generic)	Box	391.641	1	2	1	
2	Side Panels	1	3	Aluminum (generic)	Flat Plate	14.239	1	2	0.0254	Honey Comb
3	Side Panels (with cutout)	1	1	Aluminum (generic)	Flat Plate	12.814	1	2	0.0254	Honey Comb
4	Top Panel	1	1	Aluminum (generic)	Flat Plate	7.1196	1	1	0.0254	Honey Comb
5	Mid Panel (with cutout for LH2 tank)	1	1	Aluminum (generic)	Flat Plate	5.7004	1	1	0.0254	Honey Comb
6	Bottom Panel (with cutout for LO2 tank)	1	1	Aluminum (generic)	Flat Plate	2.6134	1	1	0.0254	Honey Comb
7	Solar Array Boom	1	2	Aluminum (generic)	Cylinder	0.71859	0.0254	2.0254	0	
8	Battery Box (outer box)	1	1	Aluminum (generic)	Box	28.655	0.4668	0.6168	0.3168	
9	Battery Box (inner frame, part 1)	8	2	Aluminum (generic)	Flat Plate	3.11	0.295788	0.449984	0.008408	
10	Battery Box (inner frame, part 2)	8	1	Aluminum (generic)	Flat Plate	3.154	0.299984	0.449984	0.008408	
11	Mounting Profiles (Battery Box, part 1)	1	2	Aluminum (generic)	Flat Plate	0.045	0.0254	0.3168	0.0254	
12	Mounting Profiles (Battery Box, part 2)	1	2	Aluminum (generic)	Flat Plate	0.066	0.0254	0.4668	0.0254	
13	Batteries	8	12	Nickel	Cylinder	1.912	0.145788	0.295788	0	
14	Solar Panels	1	2	Aluminum (generic)	Flat Plate	14.239	1	2	0.0254	
15	LH2 Tank	1	1	Titanium (generic)	Sphere	10	0.5	0	0	
16	LO2 Tank	1	1	Aluminum (generic)	Cylinder	38.9	0.8984	1	0	
17	Magnetic Torquer Rod	1	3	Iron	Cylinder	3.3336	0.045	1	0	
18	Star Tracker	1	2	Aluminum (generic)	Cylinder	6.5009	0.2	0.45	0	
19	Reaction Wheel Assy Housing	1	4	Aluminum (generic)	Cylinder	4.36	0.4	0.1	0	
20	Reaction Wheel Flywheel	19	4	Titanium (generic)	Disk	3.1363	0.3	0	0.01	
21	Reaction Wheel Assy Shaft	19	4	Stainless Steel (generic)	Cylinder	0.22734	0.02	0.0910812	0	
22	Gyroscopes	1	1	Aluminum (generic)	Box	9.9036	0.246	0.3295	0.176	
23	X-Band Antenna	1	1	Aluminum (generic)	Disk	1.9813	0.6	0	0.0025	
24	X-Band Boom	1	1	Graphite Epoxy 1	Cylinder	3.1928	0.09	1.7	0	
25	S-Band Transponder	1	2	Aluminum (generic)	Box	3.2711	0.1	0.2	0.1	
26	Computer	1	1	Aluminum (generic)	Box	2.0058	0.3	0.6	0.2	
27	Data Storage	1	1	Aluminum (generic)	Box	16.989	0.2	0.25	0.2	
28	Command	1	1	Aluminum (generic)	Box	24.867	0.25	0.4	0.15	
29	Telemetry	1	1	Aluminum (generic)	Box	10.383	0.2	0.3	0.2	
30	Louvers (Blades)	1	6	Aluminum (generic)	Flat Plate	0.070075	0.05	0.5	0.001	
31	Louvers (Shafts)	1	6	Aluminum (generic)	Cylinder	0.019021	0.005	0.54	0	
32	Louvers (Frame, part 1)	1	2	Aluminum (generic)	Flat Plate	0.057181	0.02	0.34	0.003	
33	Louvers (Frame, part 2)	1	2	Aluminum (generic)	Flat Plate	0.08409	0.02	0.5	0.003	
34	Cold Plate	1	1	Aluminum (generic)	Flat Plate	13.072	0.34	0.54	0.0254	
35	Space Radiator	1	1	Aluminum (generic)	Flat Plate	4.2045	0.3	0.5	0.01	
36	Cable	1	3	Copper Alloy	Cylinder	10.937	0.06	0.5	0	

Reentry Example 2 – Generic Upper Stage





Reentry Example 2 – Generic Upper Stage

Row Num	Name	Parent	Qty	Material	Body Type	Thermal Mass	Diameter/Width	Length	Height
1	Parent	0	1	Aluminum (generic)	Cylinder	924.343	6.3	1.8	0
2	Propellant Tank	1	1	Stainless Steel (gene	Cylinder	267.675	2.7	1.7	0
3	Thrust Chamber	1	1	Inconel	Cylinder	45.8	0.6	0.44	0
4	Gas Tank 1	1	2	Titanium (generic)	Sphere	10.056	0	0.41	0
5	Gas Tank 2	1	2	Titanium (generic)	Sphere	30.548	0	0.59	0
6	Nozzle	1	1	Graphite Epoxy 1	Cylinder	99.594	1.6	1	0
7	Engine Support	1	1	Aluminum (generic)	Cylinder	52.175	0.43	0.3	0
8	Guidance Electronics	1	8	Aluminum (generic)	Box	10.337	0.45	0.5	0.1