Modeling of the Orbital Debris Environment Risks in the Past, Present, and Future

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Orbital Debris Types

- **Intact objects, > 1 m**
  - **Old rocket bodies**
  - **Spacecraft**
  - **"Operational" debris – shrouds, mounts, lens caps, etc**

- **Fragmentation debris, 1 mm – 1 m**
  - **Deliberate or accidental explosions from on-board energy sources**
    - Unvented rocket fuel
    - Active batteries
    - Self-destruct mechanisms
  - **Deliberate or accidental collisions**
    - Weapons tests
    - Random collisions
  - **Solid rocket motor slag**

- **Degradation debris, < 1 mm**
  - **Deterioration of satellite surfaces in space environment**
    - Micrometeoroid and small debris impact ejecta
    - Paint deterioration in harsh space environment

Modeling

- **NASA and the U.S. Dept. of Defense dedicate a tremendous amount of resources to measuring and monitoring the debris environment, but measurements do not always provide all the information we need**
  - **Radars provide radar cross section (RCS), not size, material, shape, or mass**
  - **Similarly, optical telescopes provide brightness of reflected sunlight**
  - **NASA uses a number of telescopes and radars to statistically sample only a subset of the environment**
    - Statistical sampling is the only way to measure objects <10 cm too small to track
  - **No matter how good or complete are our measurements, the orbital debris environment is dynamic. We cannot know with certainty what the environment will look like in the future**

- **The solution to these limitations is modeling**
  - **Modeling is the use of mathematical and compute tools to use the incomplete data we do have and determine the information we truly need**

LEGEND

- **One of NASA's "workhorse" models is LEGEND**

- **LEGEND, a <u>LE</u>O-to-<u>G</u>EO <u>en</u>vironment <u>d</u>ebris model**
  - **Is a high fidelity, three-dimensional numerical simulation model for long-term orbital debris evolutionary studies**
  - **Replaces the previous one-dimensional, LEO only model, EVOLVE**
  - **Includes intacts (R/Bs and S/C), mission-related debris (payload fairings, caps, *etc.*), and explosion/collision fragments**
  - **Handles objects <u>individually</u>**
  - **Is capable of simulating objects down to 1 mm in size, but the focus has been on ≥10 cm objects**
  - **Covers altitudes up to 40,000 km**
  - **Can project the environment several hundred years into the future**
  - **Uses a deterministic approach to "recreate" the historical debris environment based on recorded launches and breakups**
  - **Uses a Monte Carlo approach and a pair-wise collision probability evaluation algorithm to simulate future collision activities**
  - **Analyzes future debris environment based on user-specified launch traffic, post-mission disposal, and active debris removal options**

Similar OD Evolutionary Models

- **ASI's SDM**
  - **Space Debris Mitigation long-term analysis program**
- **ESA's DELTA**
  - **Debris Environment Long-Term Analysis model**
- **ISRO's KSCPROP**
  - **Kustaanheimo and Stiefel Canonical Propagation model**
- **JAXA's LEODEEM**
  - **LEO Debris Environment Evolutionary Model**
- **UKSA's DAMAGE**
  - **Debris Analysis and Monitoring Architecture for the Geosynchronous Environment**

LEGEND Supporting Models

- **LEGEND actually ties in many NASA models to do its calculations**

- **DBS database: a comprehensive record of historical launches and breakup events**
  - **Time, type, orbit, physical properties (mass, area), *etc*.**
  - **The database is updated annually**

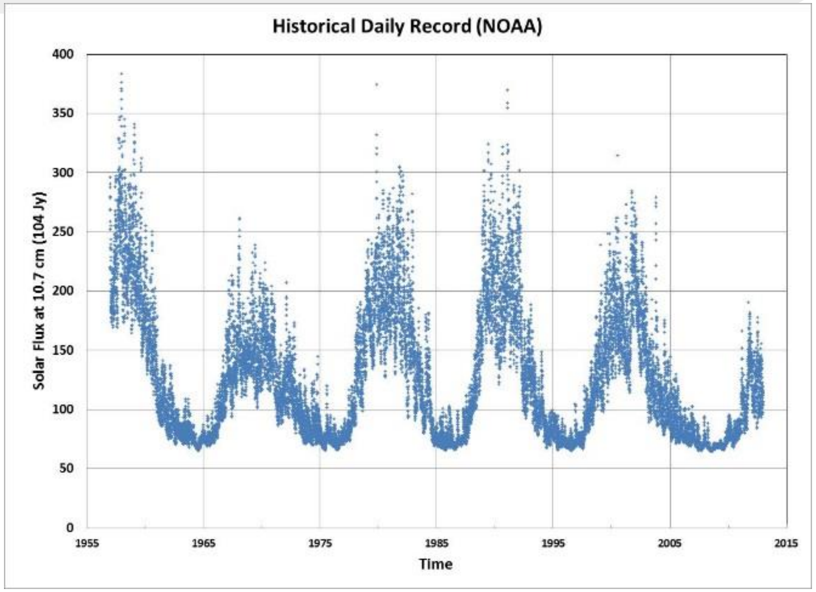
- **U.S. Space Surveillance Network (SSN) catalogs**
  - **Daily records of the historical growth of the ≥10 cm debris population**
  - **Orbit histories are used to derive empirical area-to-mass ratio (A/M) distributions of breakup fragments**
  - **New files are downloaded from "Space Track" website daily**

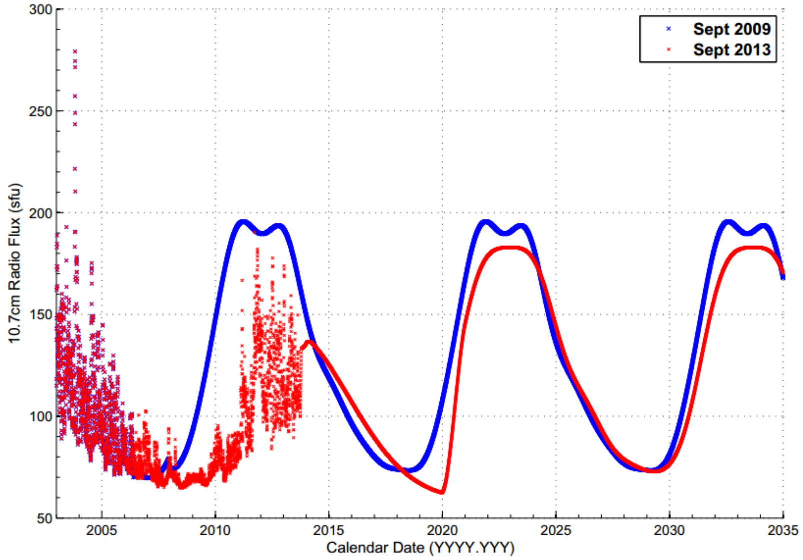
- **Future launch traffic model**
  - **Typically a repeat of the last 8-year cycle, as commonly adopted by the international debris modeling community**

LEGEND Supporting Models

- **Atmospheric drag model**
  - **Jacchia atmospheric density model (1977)**
  - **Drag perturbation equations based on King-Hele (1987)**

- **Solar flux (at 10.7 cm wavelength) model consisting of three components**
  - **Historical daily records available from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC)**
  - **Short-term projection provided by NOAA/SWPC – currently through 2019**
  - **Long-term projection is a repeat of a 13th-order sine and cosine functional fit to Solar Cycles 18 to 24 (1944 – present)**
    - Similar to projections developed for long-term debris evolutionary models by other space agencies (ASI, UKSA, *etc.*)





LEGEND Supporting Models

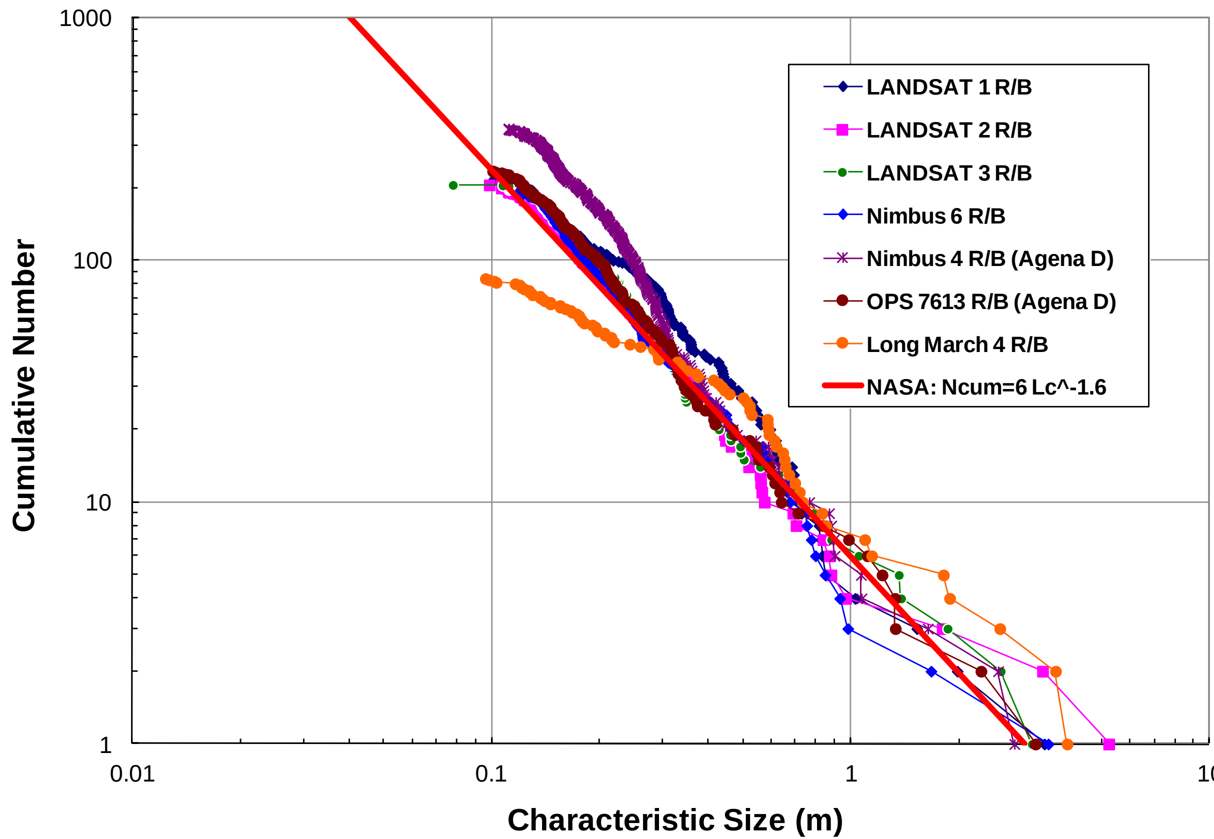
- **GEOprop orbital propagator**
  - Propagates objects near geosynchronous (GEO) region
  - Perturbations include solar and lunar gravitational forces, solar radiation pressure, and Earth's gravity-field zonal (J_2, J_3, and J_4) and tesserral ($J_{2,2}$, $J_{3,1}$, $J_{3,3}$, $J_{4,2}$, and $J_{4,4}$) harmonics

- **Prop3D orbit propagator**
  - Propagates orbits of objects in LEO and GTO regions
  - Perturbations include atmospheric drag, solar and lunar gravitational forces, solar radiation pressure, and Earth's gravity-field zonal harmonics J_2, J_3, and J_4

- **Both propagators compare reasonably well with the evolution of the SSN cataloged objects**

LEGEND Supporting Models

- **NASA Standard Satellite Breakup Model**
  - **Describes the outcome of an explosion or collision**
    - Fragment size, A/M, and ΔV distributions
  - **Based on seven, well-observed on-orbit explosions, several ground-based impact experiments, and one on-orbit collision**



LEGEND Applications

- **LEGEND is the tool the NASA Orbital Debris Program Office uses to**
  - **Provide debris environment projection for the next 200 years**
    - Based on user-specified scenarios (launch traffics, postmission disposal, active debris removal options, etc)
  - **Evaluate the instability of the current debris environment**
  - **Assess the growth of the future debris populations**
  - **Characterize the effectiveness of the NASA, U.S., and international debris mitigation measures**
  - **Quantify the benefits of active debris removal (ADR)**

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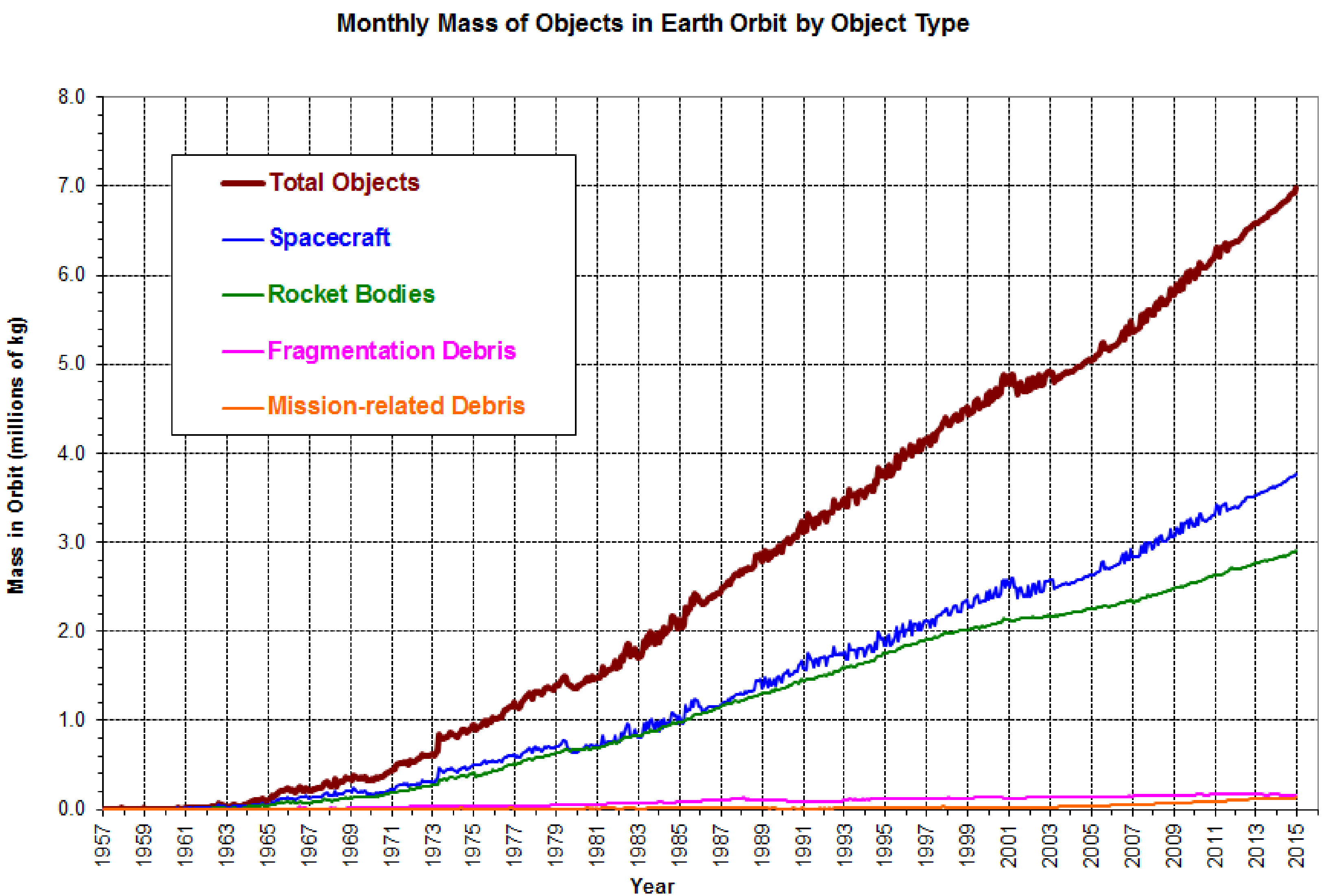
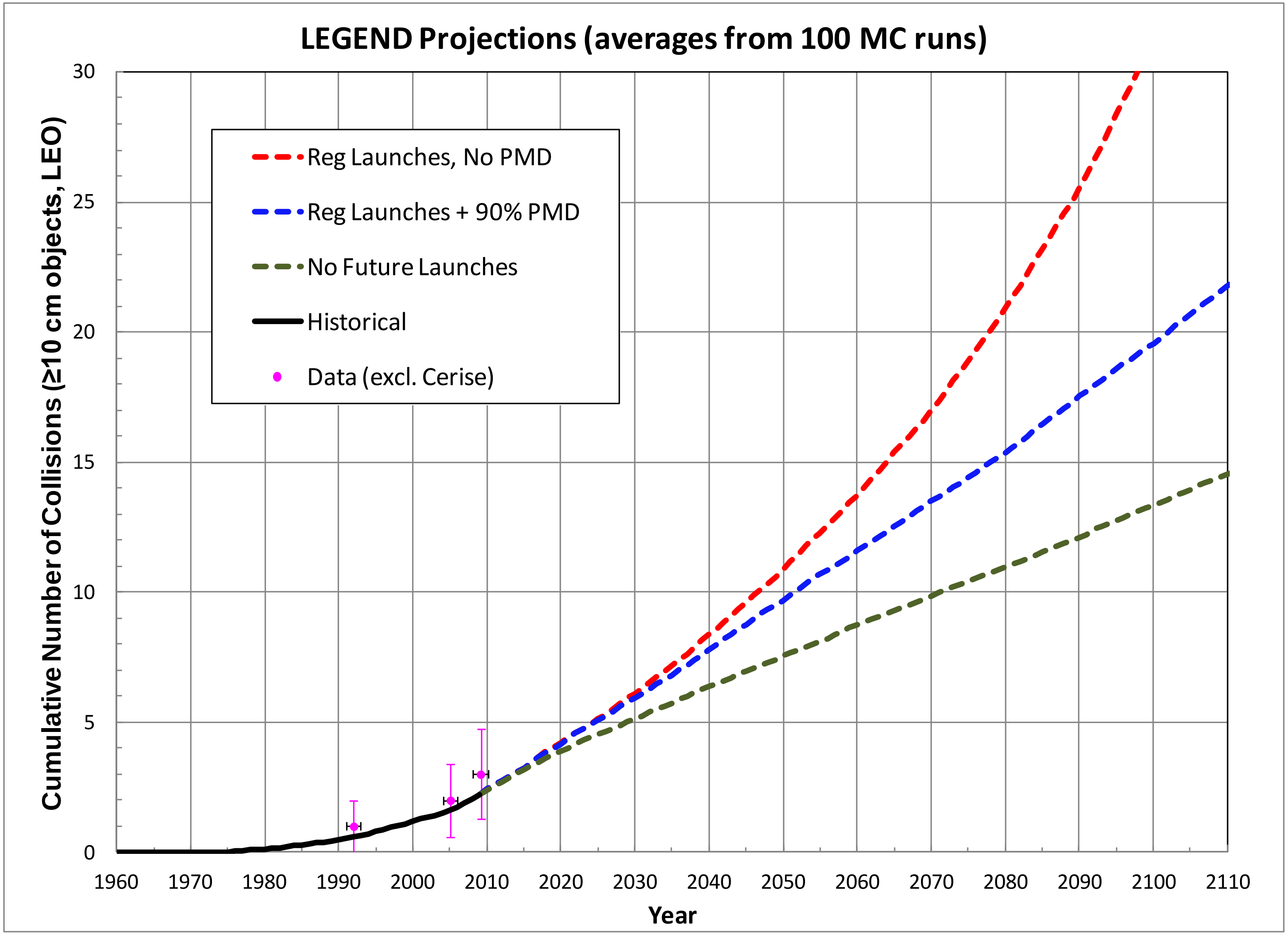
Mass Accumulation in Orbit – Based on DBS



Sample LEGEND Output – Collisions in LEO



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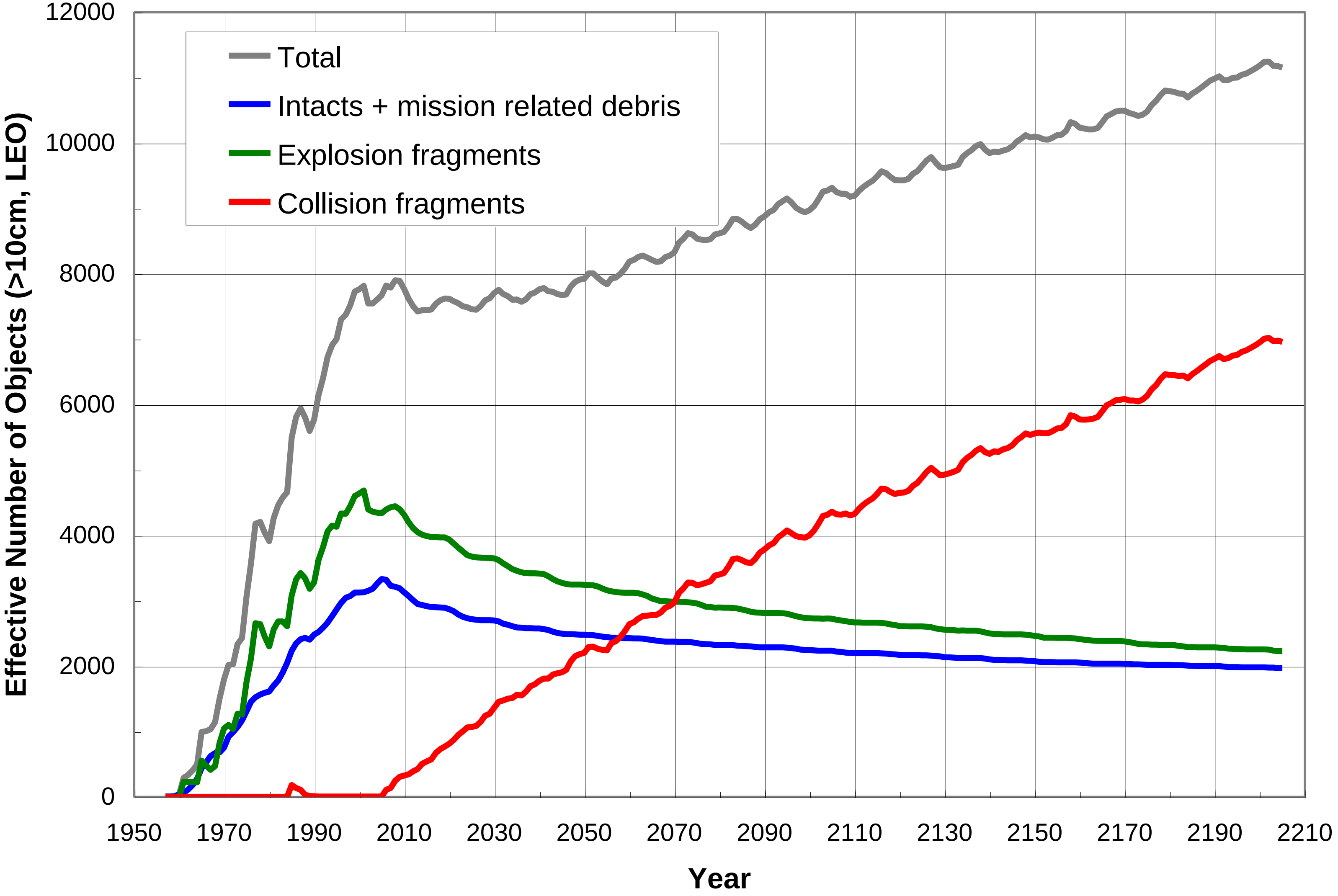
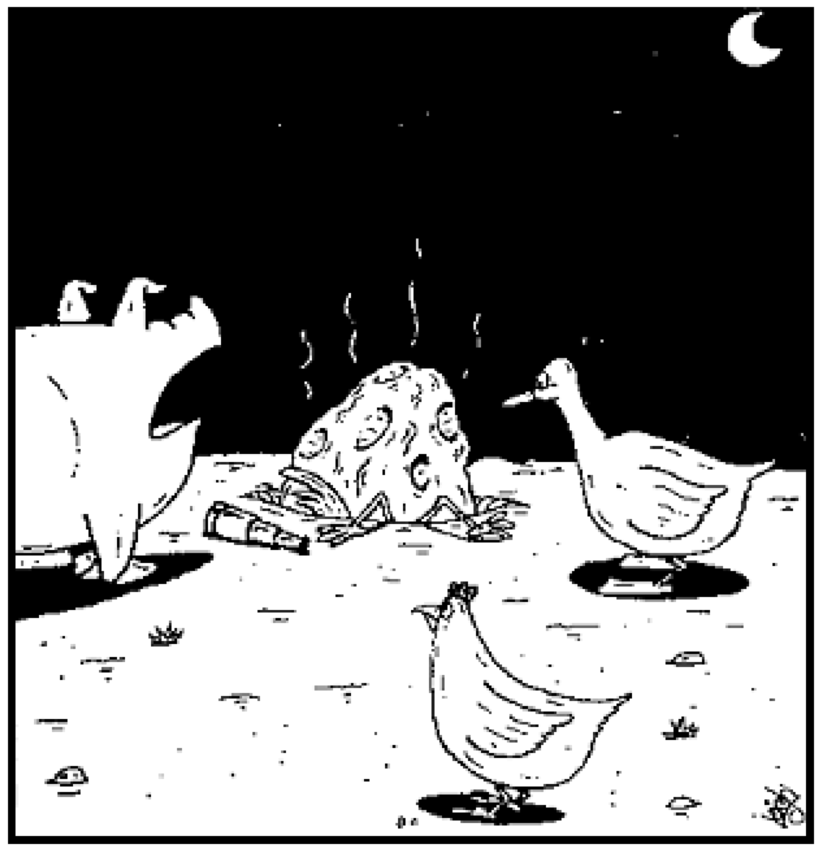
Growth with no future launches
Kessler Syndrome

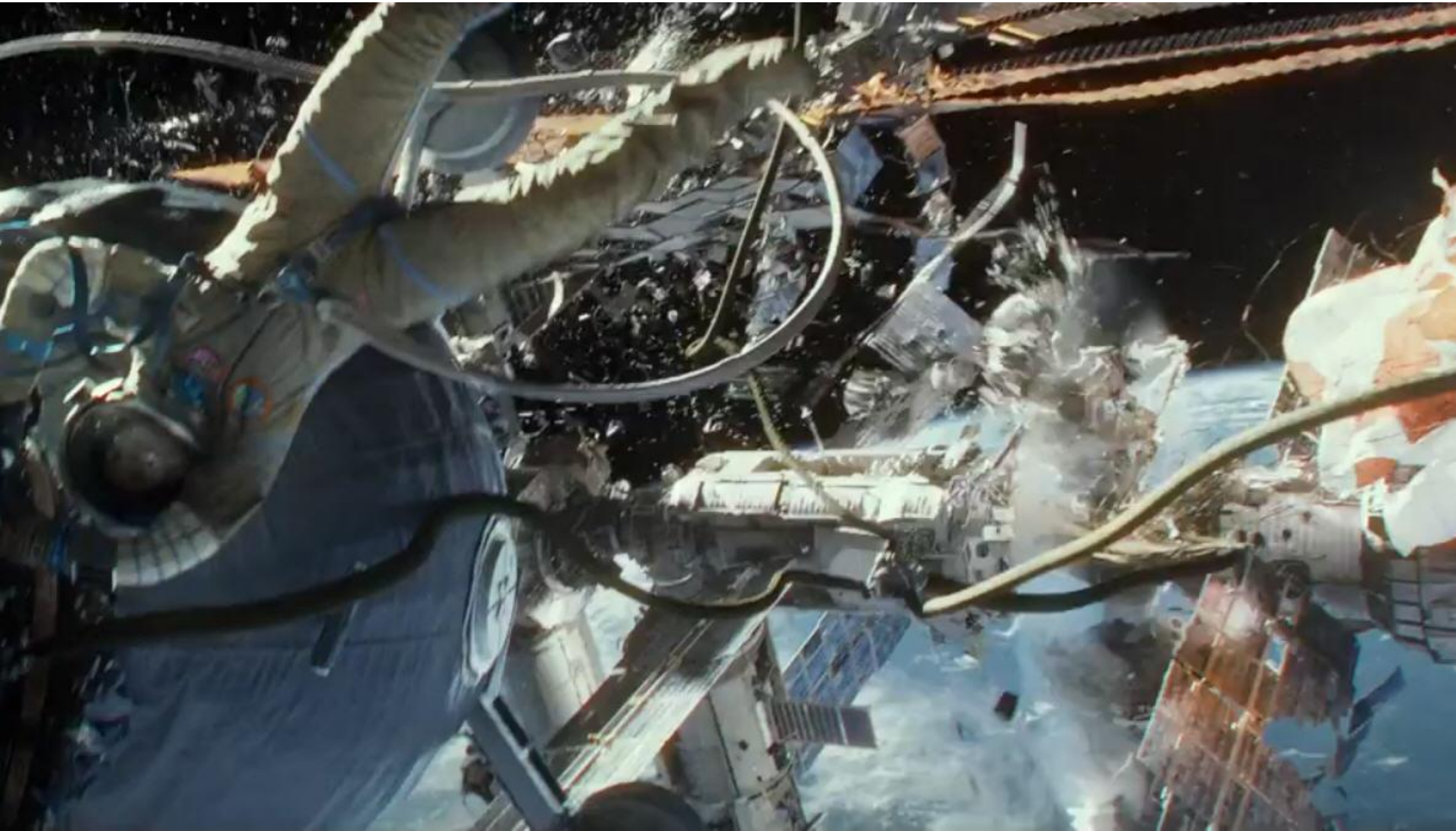


Rubes



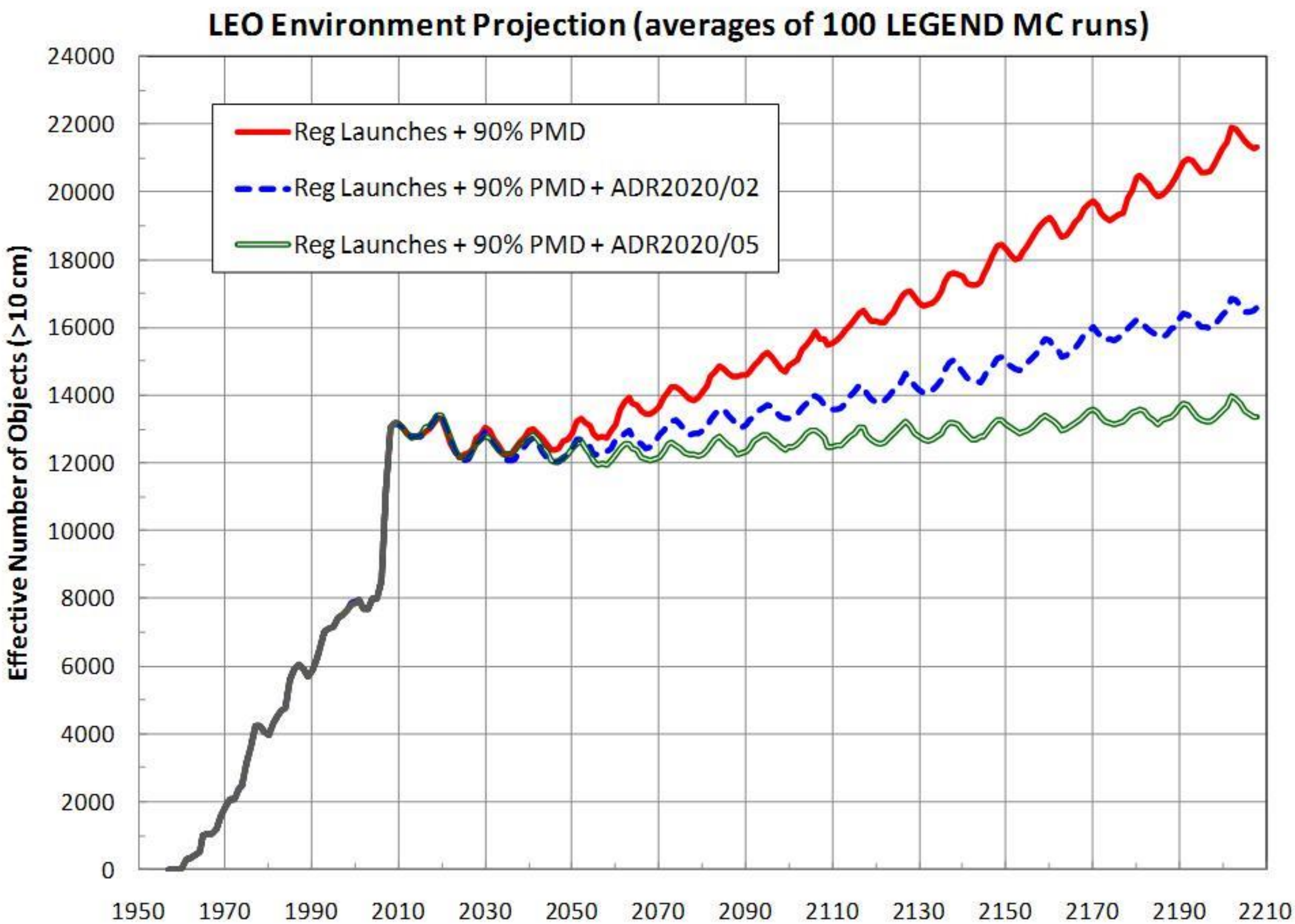
"Well, I'll be ... I guess the little chicken was right."

Gravity



Gravity

Fix the Problem? – Remove Mass



(Liou, *Adv. Space Res*, 2011)

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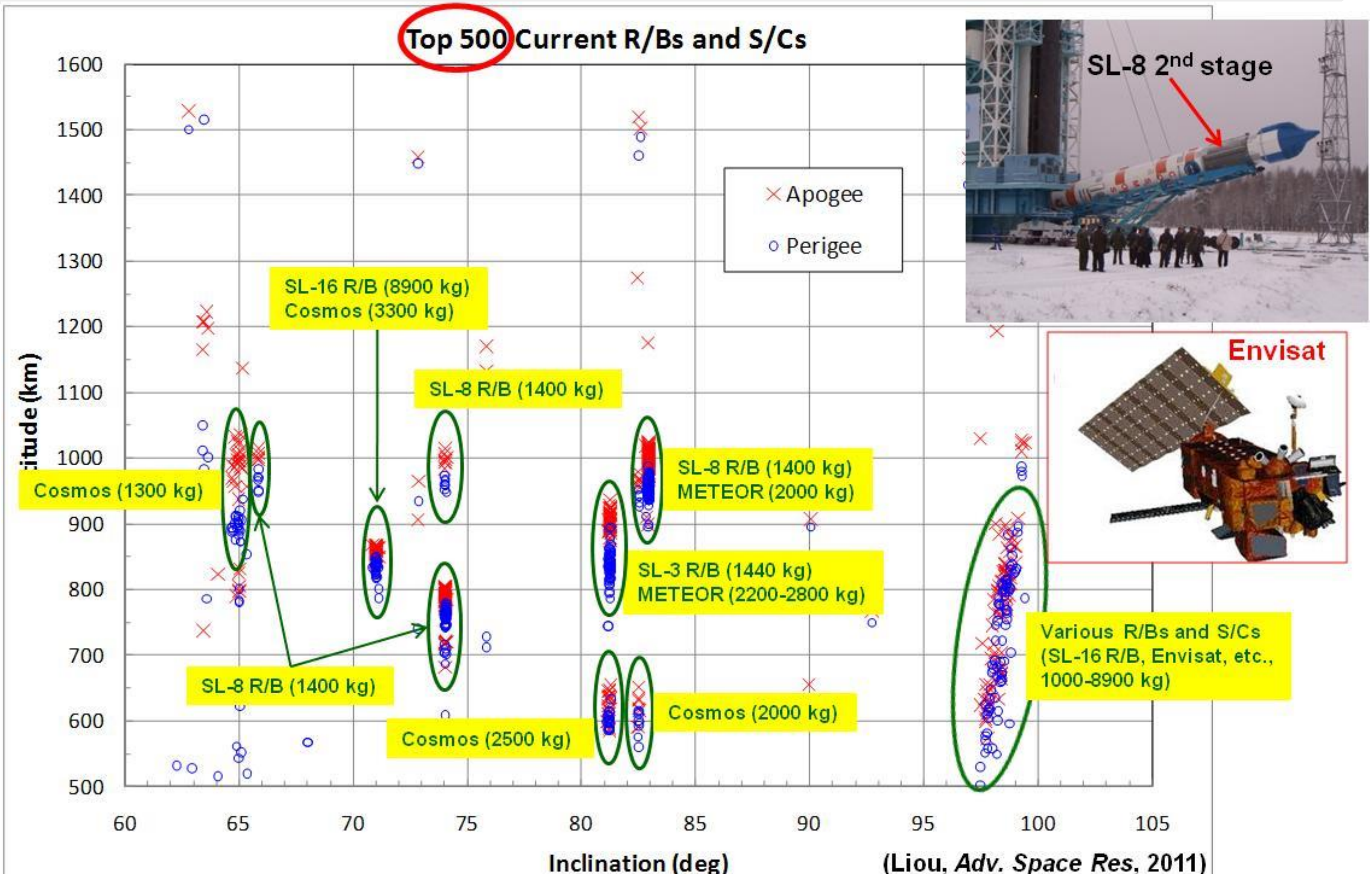
Highest Mass Objects



Active Debris Removal Cartoon, 1965 (!)

ORDEM 3.0

- An Engineering Model is a tool (primarily) for spacecraft designers and users to understand the long-term risks of debris collisions with their spacecraft

- NASA's Orbital Debris Engineering Model ORDEM 3.0 represents NASA's best estimate of the current and near future orbital debris environment.
  - The environment is dynamic and must be updated periodically

- ORDEM 3.0 has significant new capabilities over past ORDEM models
  - Uncertainties
  - Material density categories
  - Model extended to GEO
  - Can easily calculate flux for satellites in highly elliptical orbit

ORDEM 3.0 vs. ORDEM2000

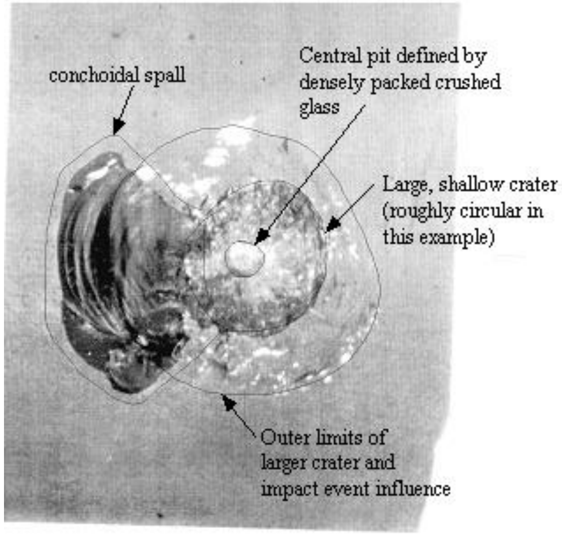
Parameter	ORDEM2000	ORDEM 3.0
Spacecraft & telescope/radar analysis modes	Yes	Yes
Time range	1991 to 2030	2010 to 2035
Altitude range with minimum debris size	200 to 2000 km (>10 μm) (LEO)	200 to 38,000 km (>10 μm) (LEO to GTO) 34,000 to 38,000 km (>10 cm) (GEO)
Orbit types	Circular (radial velocity ignored)	Circular to highly elliptical
Model populations divided by type & material density	No	Intacts Low-density (<2 g/cc) – e.g., plastic Medium-density (2-6 g/cc) – e.g., aluminum High-density (>6 g/cc) – e.g., steel RORSAT NaK coolant droplets (0.9 g/cc)
Special model populations	No	Yes (ASAT, Iridium/Cosmos, Snapshot, Transit)
Model cumulative size thresholds (*fiducial points*)	10 μm, 100 μm, 1 mm, 1 cm , 10 cm, 1 m	10 μm, 31.6 μm, 100 μm, 316 μm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, 1 m
Flux uncertainties	No	Yes
Meteoroids	No	No*

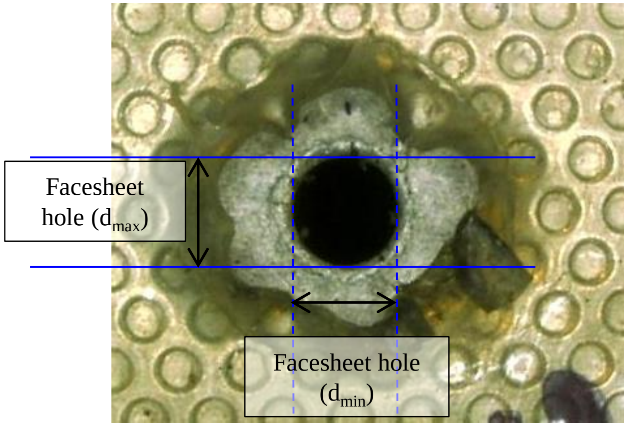
*** a separate meteoroid environment model (MEM) is available from NASA's Meteoroid Environment Office**

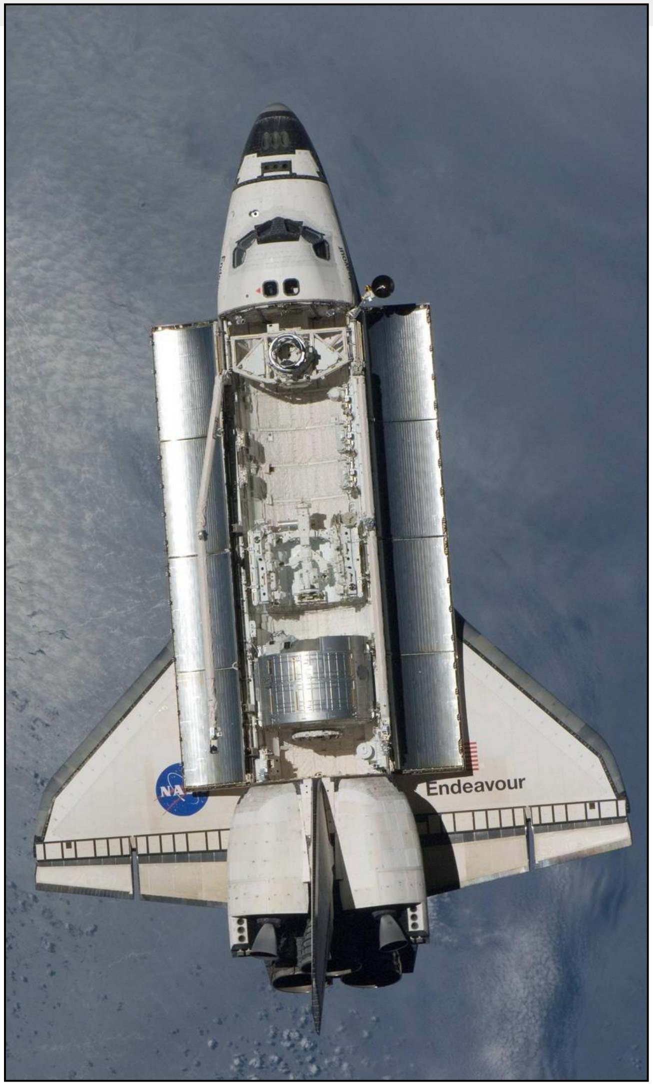
ORDEM Process
Creating the Current Environment

- **Initial environment created by using database of known space activity and tools such as the NASA Standard Breakup Model (to model breakup clouds) & PROP3D (to model long-term orbit evolution)**
- **Environment-dominating events such as the Chinese ASAT (~850 km) and the Iridium/COSMOS collision (~775 km) were modeled separately as were a few unique non-breakup populations**
- **Debris material densities**
  - **For sub-mm debris - determined from analysis of residue in impact features from returned spacecraft surfaces (specifically, Shuttle windows and radiators)**
  - **For larger debris - directly measured from ground impact tests**
- **Maximum Likelihood Estimator used to empirically fit the environment to measurement data, creating a final "Current" debris environment**
  - **This resulted in adjusting model populations to fit data using size-dependent "weighting factors"**
  - **Size-dependent weighting factors derived from these data-fitting processes are used to project into the future**
  - **Uncertainties computed using Bayesian and other techniques**

Shuttle *In Situ* Data





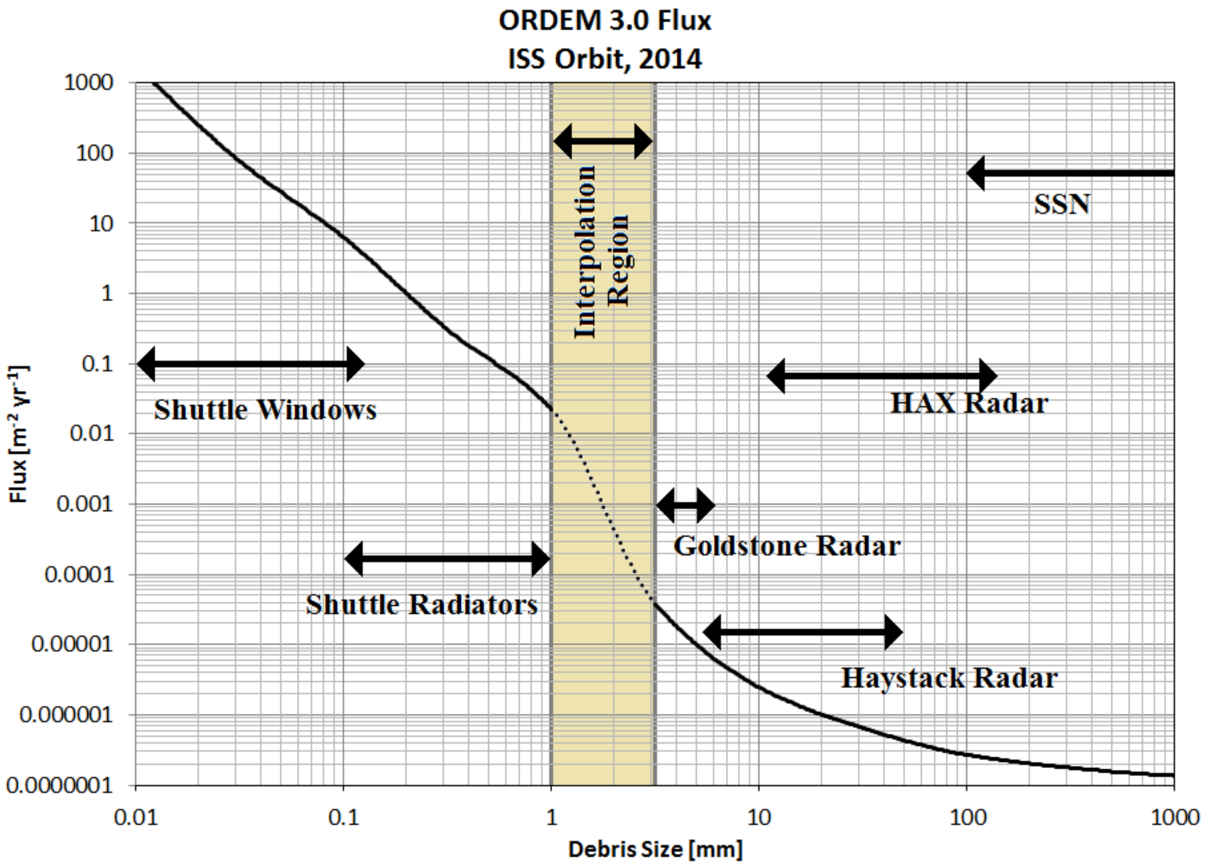


ORDEM 3.0 Datasets and Supporting Models

Observational Data	**Role**	**Region/Size**
SSN catalog (radars, telescopes)	Intacts & large fragments	LEO > 10 cm, GEO > 70 cm
HAX (radar)	Statistical populations	LEO > 3 cm
Haystack (radar)	Statistical populations	LEO > 5.5 mm
Goldstone (radar)	Statistical populations	LEO > 3 mm
STS windows & radiators (returned surfaces)	Statistical populations	10 μm <LEO ≤ 1 mm
MODEST (telescope)	GEO data set	GEO > 30 cm

- Note that the US Space Shuttle is no longer an active data source

Data and Size Regimes



- **Small particle populations are fit separately from large particle populations**

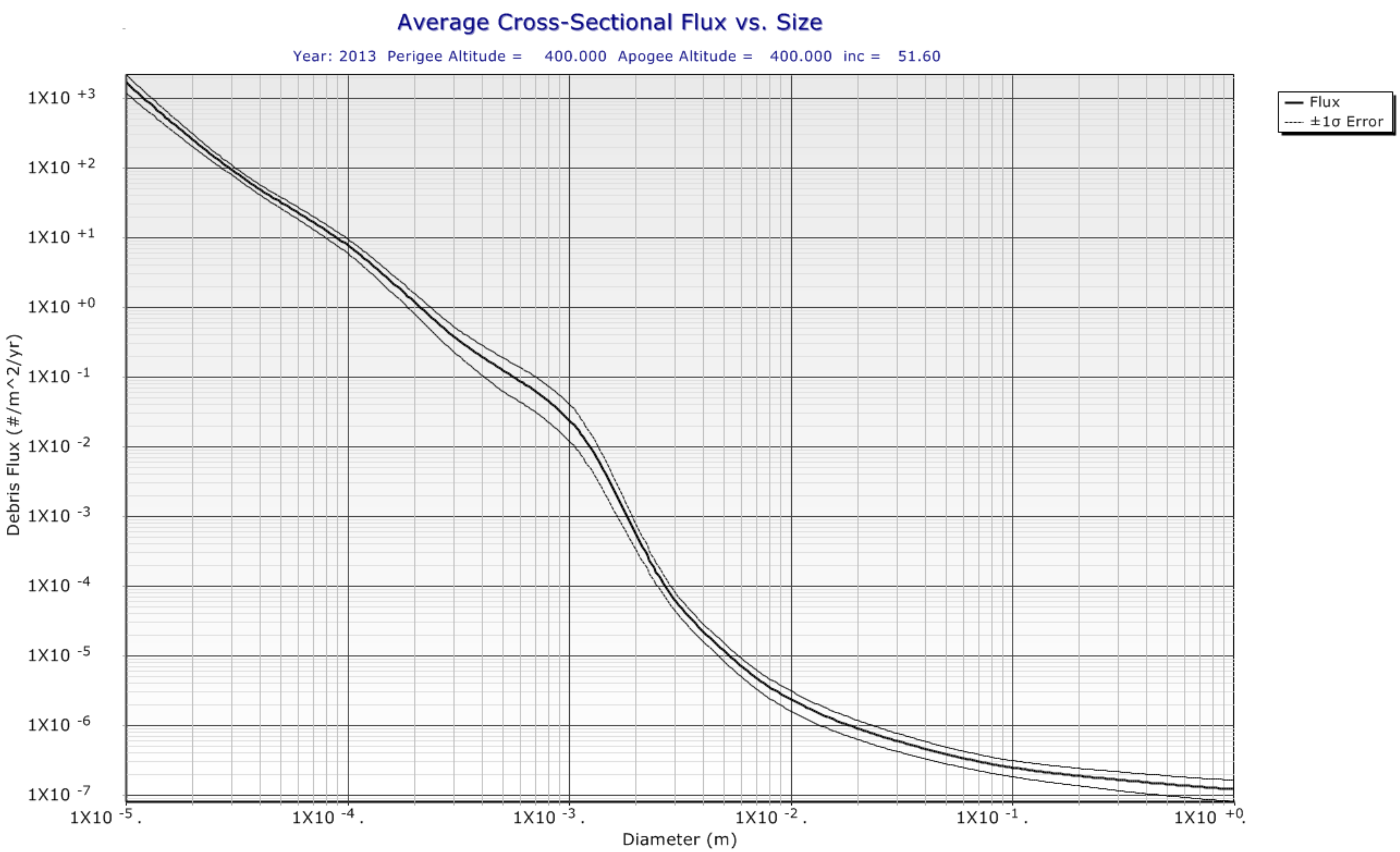
ORDEM
Projecting Into the Future – Debris > 3 mm

- LEGEND used to propagate the "Current" environment into the future
- Populations empirically adjusted to match radar and optical measurement data
- When LEGEND creates new future debris (through future collisions or explosions) the same weighting values that were used to fit historical size distributions are applied to debris production in the future
- Launch rate, solar activity, and explosion rate are independent inputs into the model
- 120 Monte Carlo future environments are created
  - Future collisions simulated stochastically
- Reported future environment is the average of the 120 possible future environments, "spread" of possible futures preserved as population uncertainties

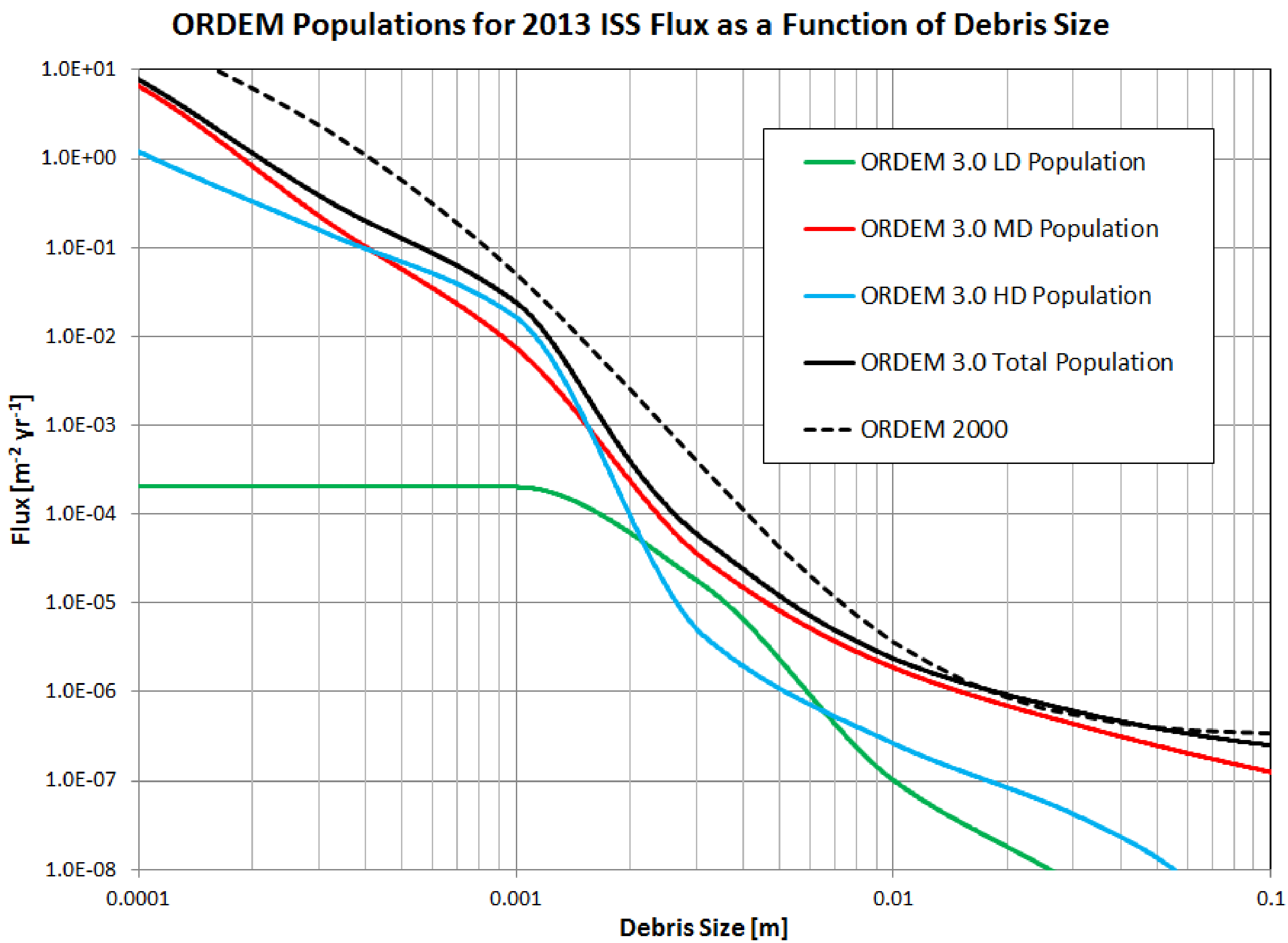
ORDEM
Projecting Into the Future – Debris < 1 mm

- **LEGEND used to characterize the population of intact objects in the future as source objects for small debris**
- **The surface degradation model "creates" particles with zero delta-velocity at different sizes and material types proportional to the area of the parent body**
- **These debris are propagated under solar radiation pressure and atmospheric drag to compute flux on *in situ* surfaces**
- **Damage equations (based on empirical tests) are used to "predict" distribution in feature size (e.g., crater diameter) on the *in situ* surface using reference debris population**
- **Production rates at the parent bodies adjusted to match empirical data**

ORDEM Flux for ISS 400km



Material Distributions - ISS



ORDEM Flux for A-Train 705km

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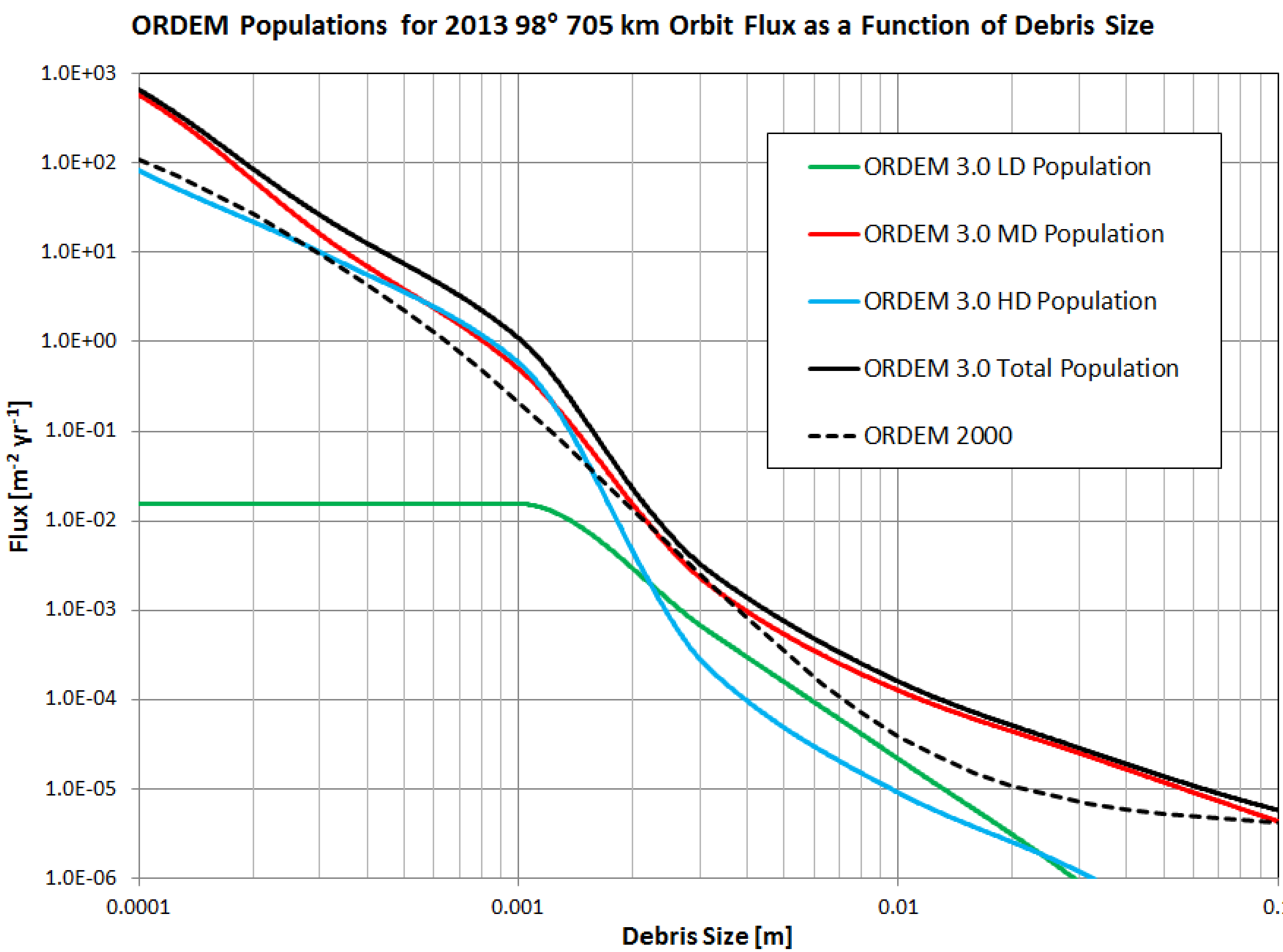
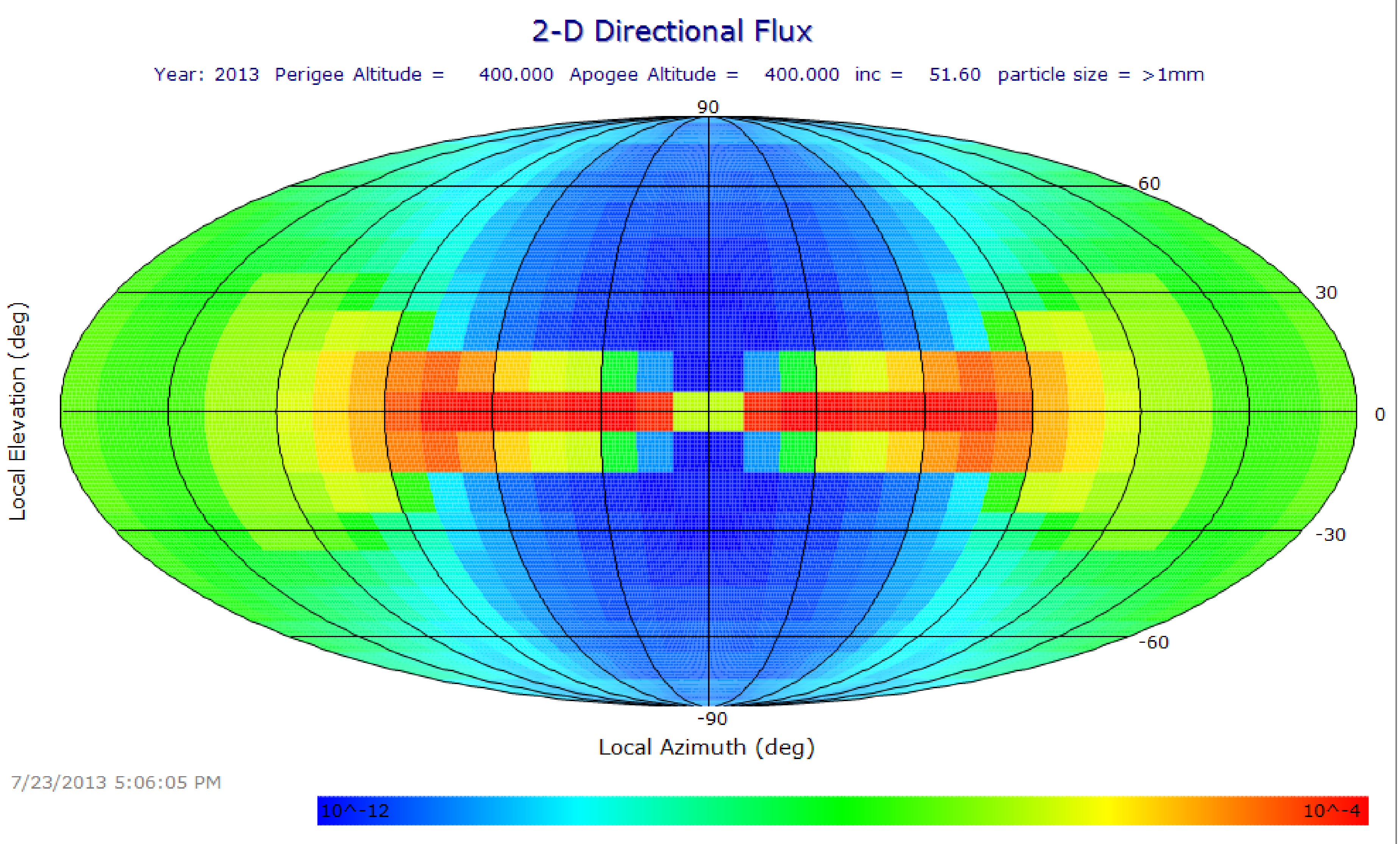
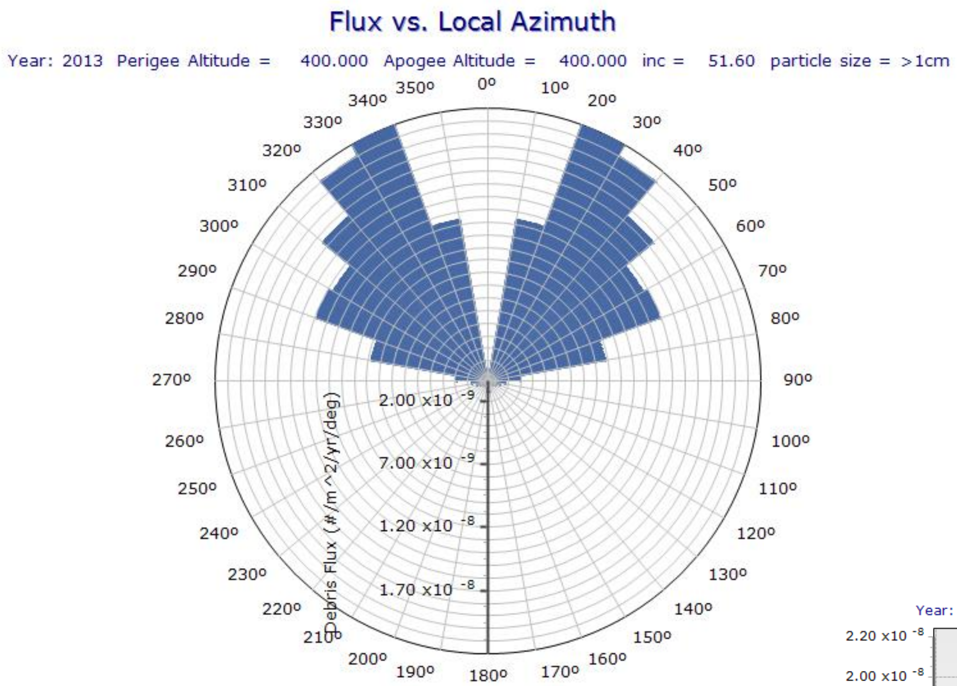
Material Distribution – A-Train

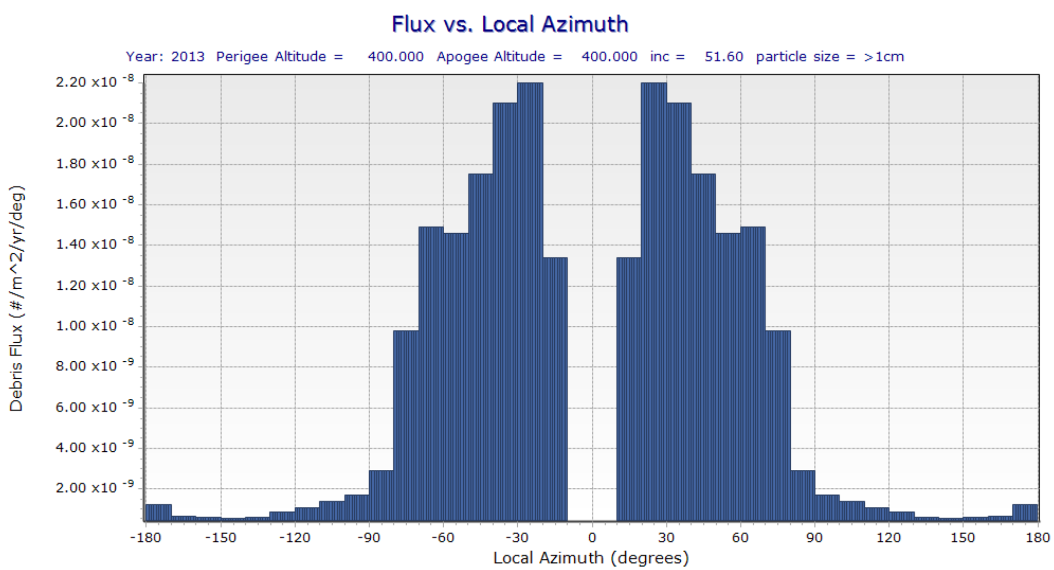


ORDEM 3.0 Outputs



ORDEM 3.0 Outputs



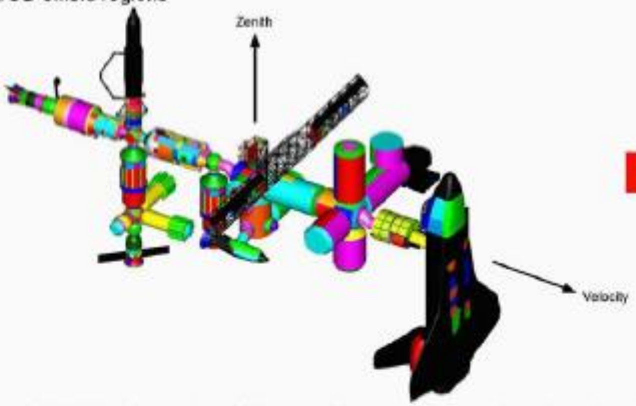


BUMPER

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

Spacecraft Configuration (I-DEAS Finite Element Model)

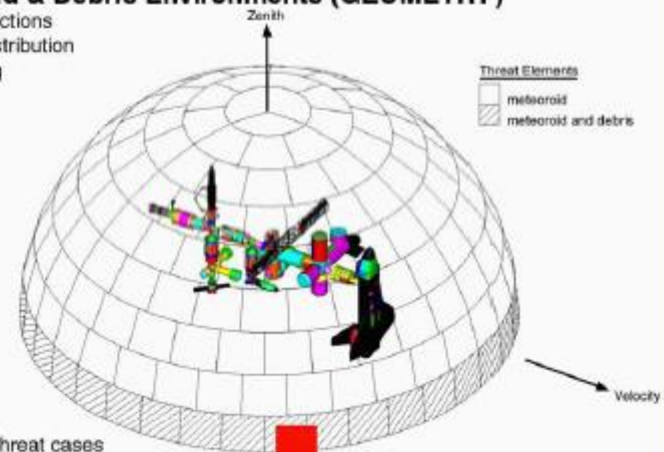
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions



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

Meteoroid & Debris Environments (GEOMETRY)

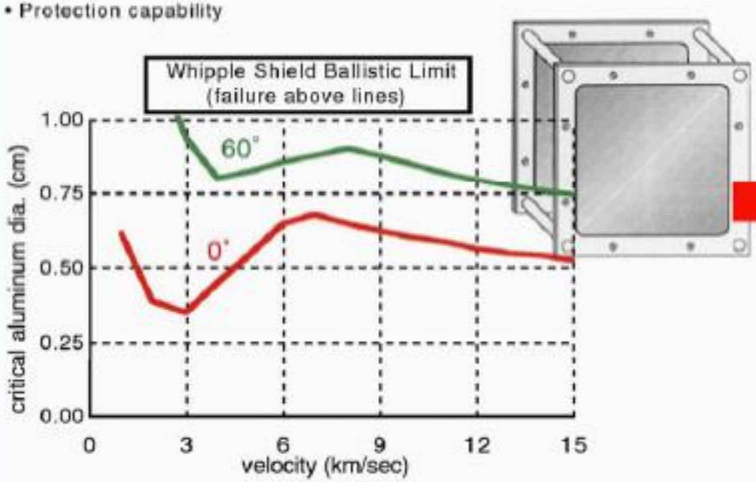
- Threat directions
- Velocity distribution
- Shadowing



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

Critical Particle Diameter Calculation (RESPONSE)

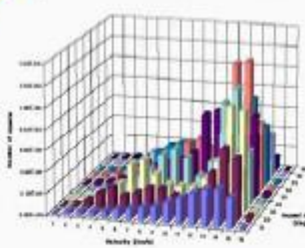
- Protection capability

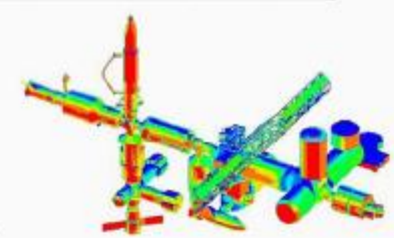


Computation of Penetrating Flux and PNP (SHIELD)
Graphical Interpretation of Results (EXCEL & I-DEAS)

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	0.997448	1/391	0.999839	1/6228
TOTALS	0.934822	1/15	0.993132	1/146





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

Collision Avoidance

- **Orbiting objects larger than about 10 cm are tracked by the U.S. Dept. of Defense (DoD) Space Surveillance Network (SSN)**
- **Current statistical technique was developed as a joint project by the DoD and NASA to ensure the safety of Shuttle and ISS astronauts**
- **Service now provided to any space user**
  - **Possible conjunction warning given to registered user**
  - **Contains the covariance matrix and encounter geometry for each object**
    - Covariance matrix gives uncertainty ellipsoid of the position of each object
    - Information can be used to compute a probability of collision
- **For every object tracked, there are tens to hundreds of objects we cannot track that can still cause serious damage to a spacecraft**
  - **Collision avoidance is prudent, but does not solve the debris problem**
- **Vast majority of objects tracked (~95%) are inert and cannot maneuver**
  - **Not a solution for problem of long-term collisional growth**

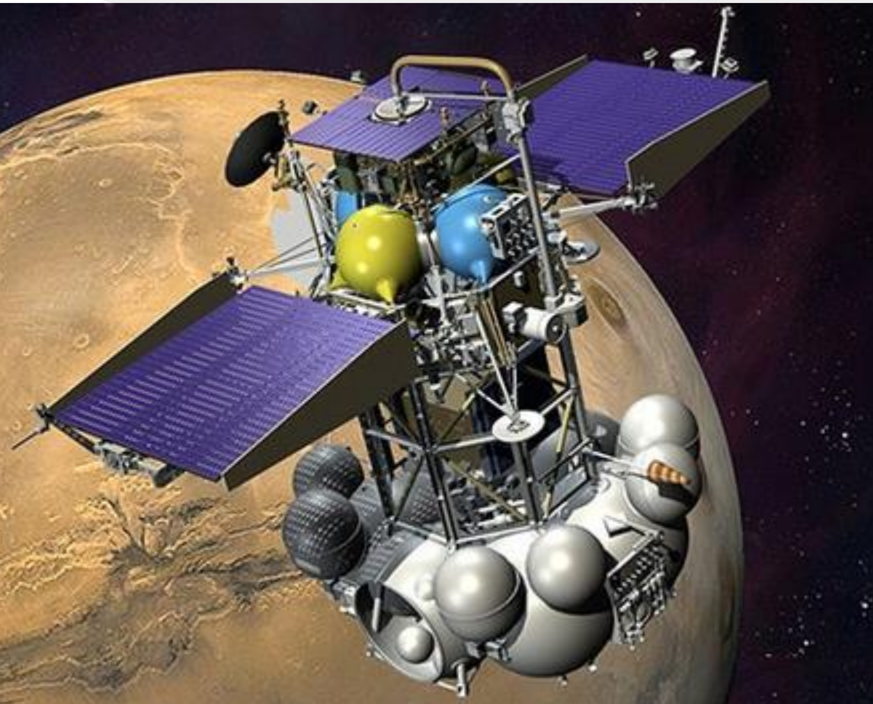
Reentry Modeling

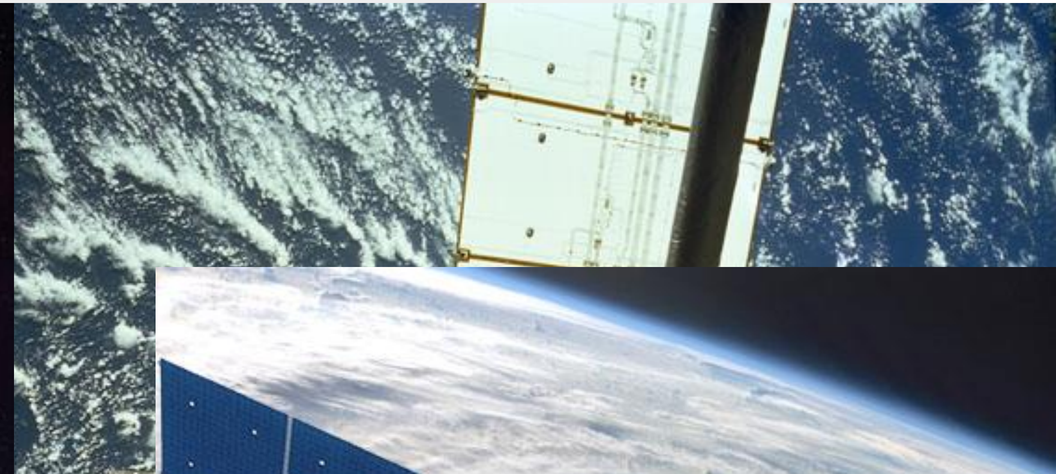
- **NASA's ORSAT code is used to assess the survivability of reentering objects in order to account for risk to ground population**
- **Cases are run in hierarchy beginning with parent body and then moving on to components and sub-components if necessary**
- **User makes decisions on how components are modeled**
  - **Breakup altitude**
  - **Component shape selection**
  - **Component motion**
  - **When component heating begins**
- **Options exist to run parametric study on specific variables:**
  - **oxidation efficiency**
  - **initial wall temperature**
  - **surface emissivity**
  - **breakup altitude**

ORSAT Code Structure

- **Six general modules in code:**
  - **Trajectory**
    - Recently updated in ORSAT 6.0 and 6.1 from Miehle method to Vinh
  - **Atmosphere**
    - Chosen from 3 models or input a user-defined model
    - Difference between 3 models is small due to only small changes in density
  - **Aerodynamics**
    - Recent updates to low altitude/Mach number drag coefficients
  - **Aerothermodynamics**
    - Detra-Kemp-Riddell or Fay-Riddell (small variations in results)
    - Stagnation point heating is well developed
    - Averages and 3D distributions over various shapes
  - **Thermal**
    - Different modes can lead to different results
  - **Debris Casualty Area / Risk**

Recent Reentries
UARS, ROSAT, Phobos-Grunt, TRMM





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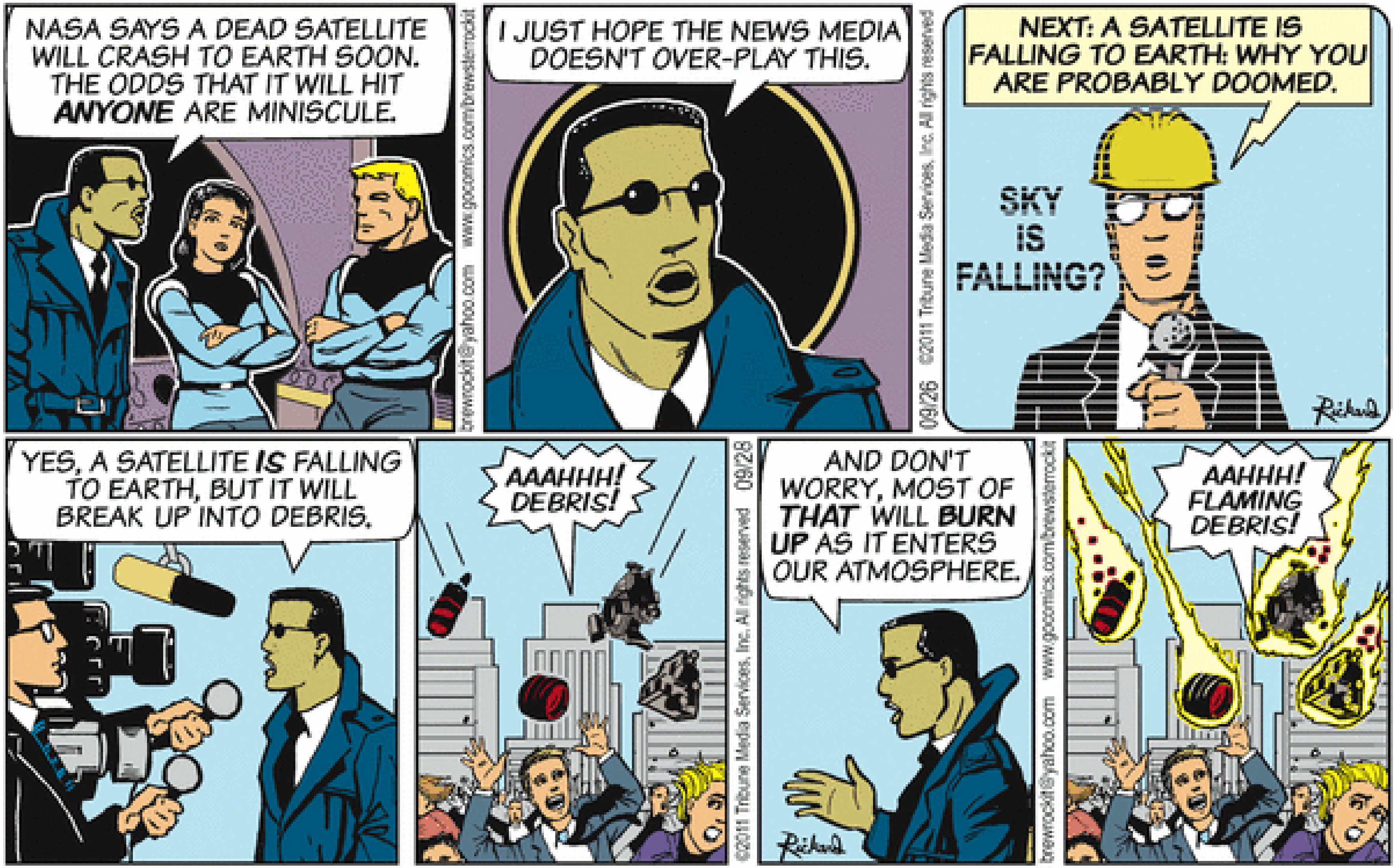
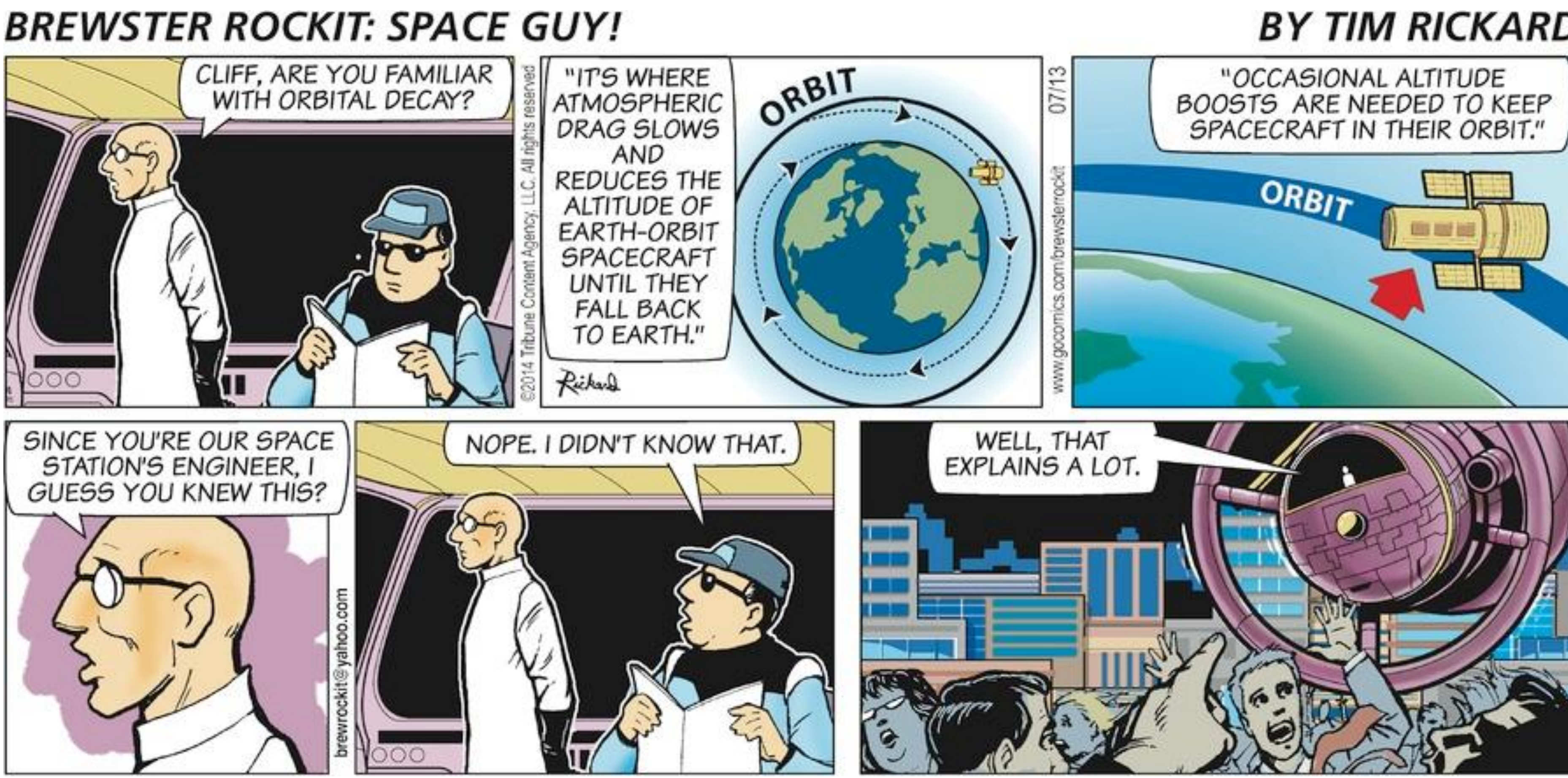
UARS Reentry in the Popular Imagination




BREWSTER ROCKIT: SPACE GUY!
BY TIM RICKARD
CLIFF, ARE YOU FAMILIAR WITH ORBITAL DECAY?
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"IT'S WHERE ATMOSPHERIC DRAG SLOWS AND REDUCES THE ALTITUDE OF EARTH-ORBIT SPACECRAFT UNTIL THEY FALL BACK TO EARTH."
ORBIT
Rickard
07/13
www.gocomics.com/brewsterrockit
"OCCASIONAL ALTITUDE BOOSTS ARE NEEDED TO KEEP SPACECRAFT IN THEIR ORBIT."
ORBIT
SINCE YOU'RE OUR SPACE STATION'S ENGINEER, I GUESS YOU KNEW THIS?
brewrockit@yahoo.com
NOPE. I DIDN'T KNOW THAT.
WELL, THAT EXPLAINS A LOT.

That Which Survives…

Texas, 1997

South Africa, 2000

Zimbabwe, 2013

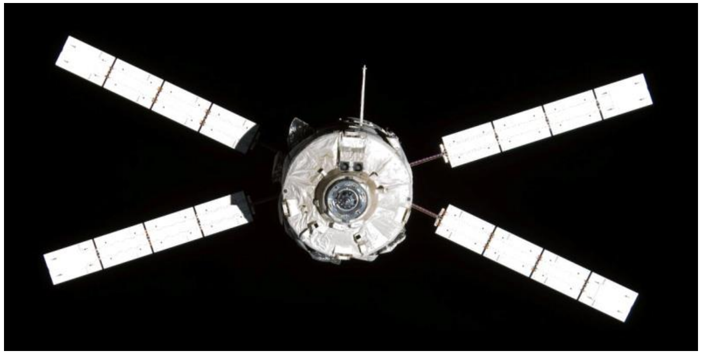
Guatemala, 2003

Argentina, 2004

Saudi Arabia, 2001

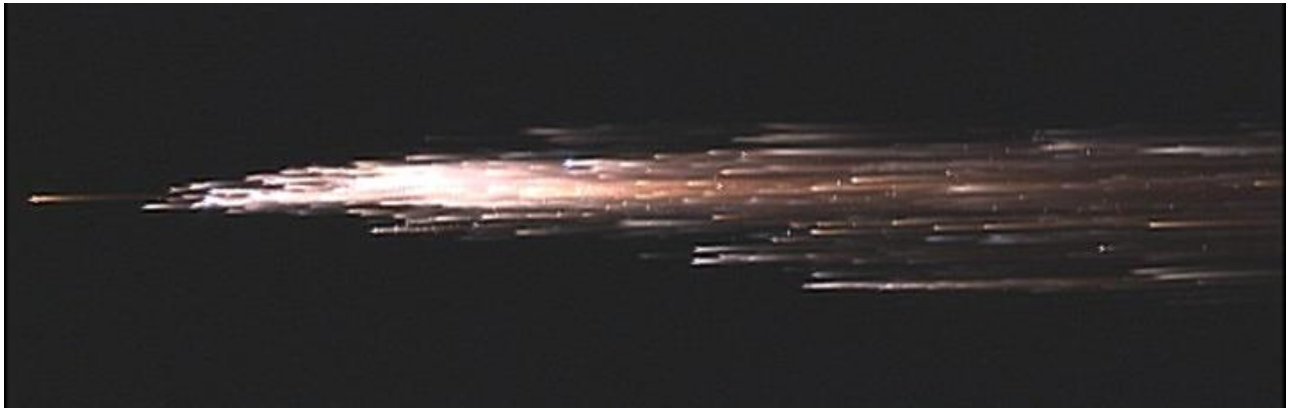
Reentry of the Jules Verne ATV

- **NASA and ESA conducted a joint observation campaign of the reentry of the Jules Verne ATV on 29 September 2008.**
  - **Two aircraft collected a wide variety of data from vantage points over the Pacific Ocean near the reentry path of the Jules Verne.**

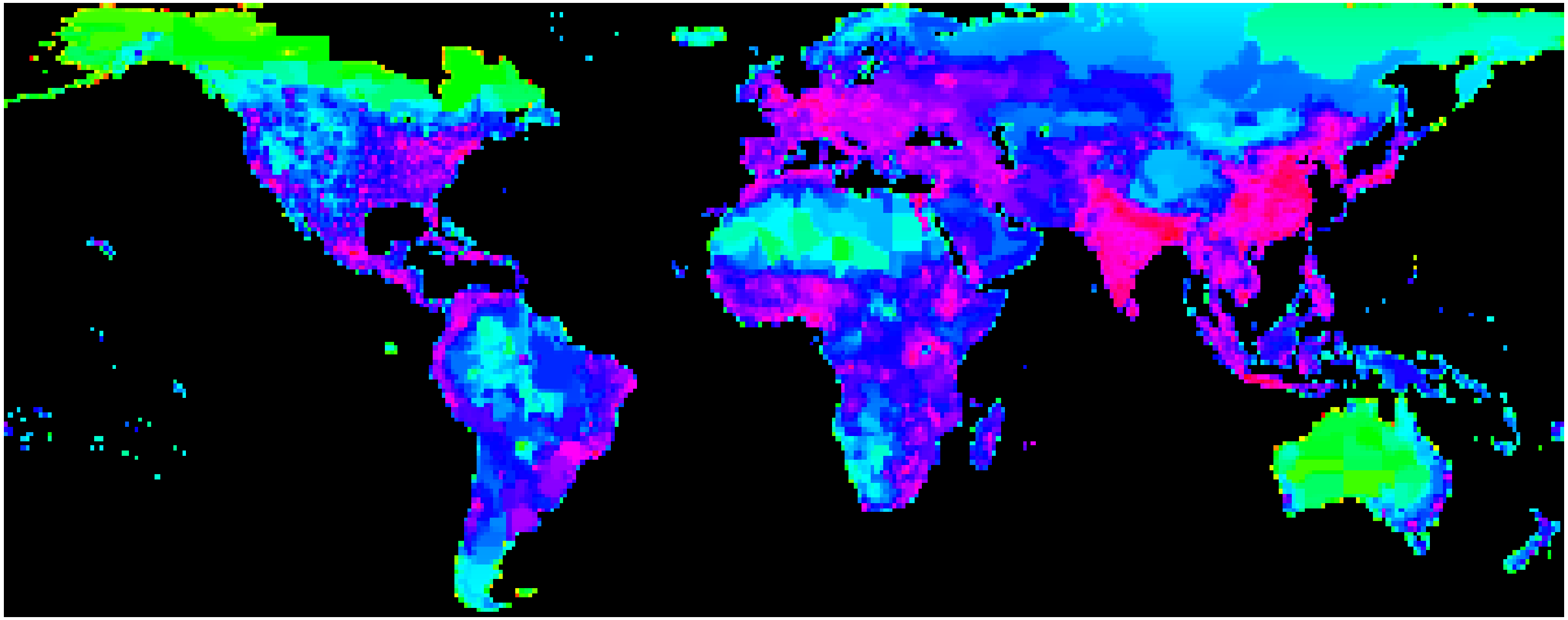


Jules Verne undocking on 5 September 2008

Reentry over Pacific Ocean

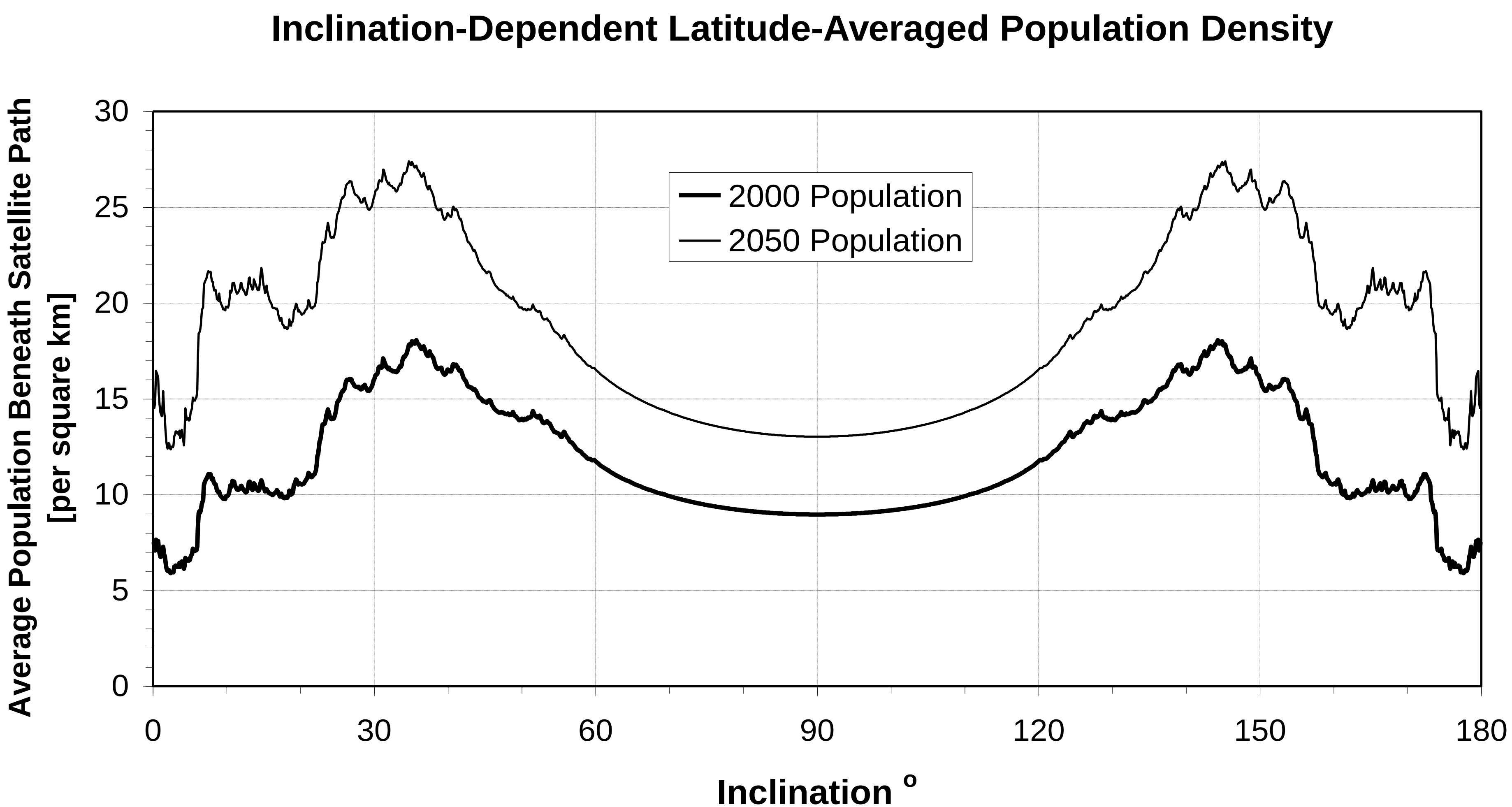


Population Distribution on the Earth

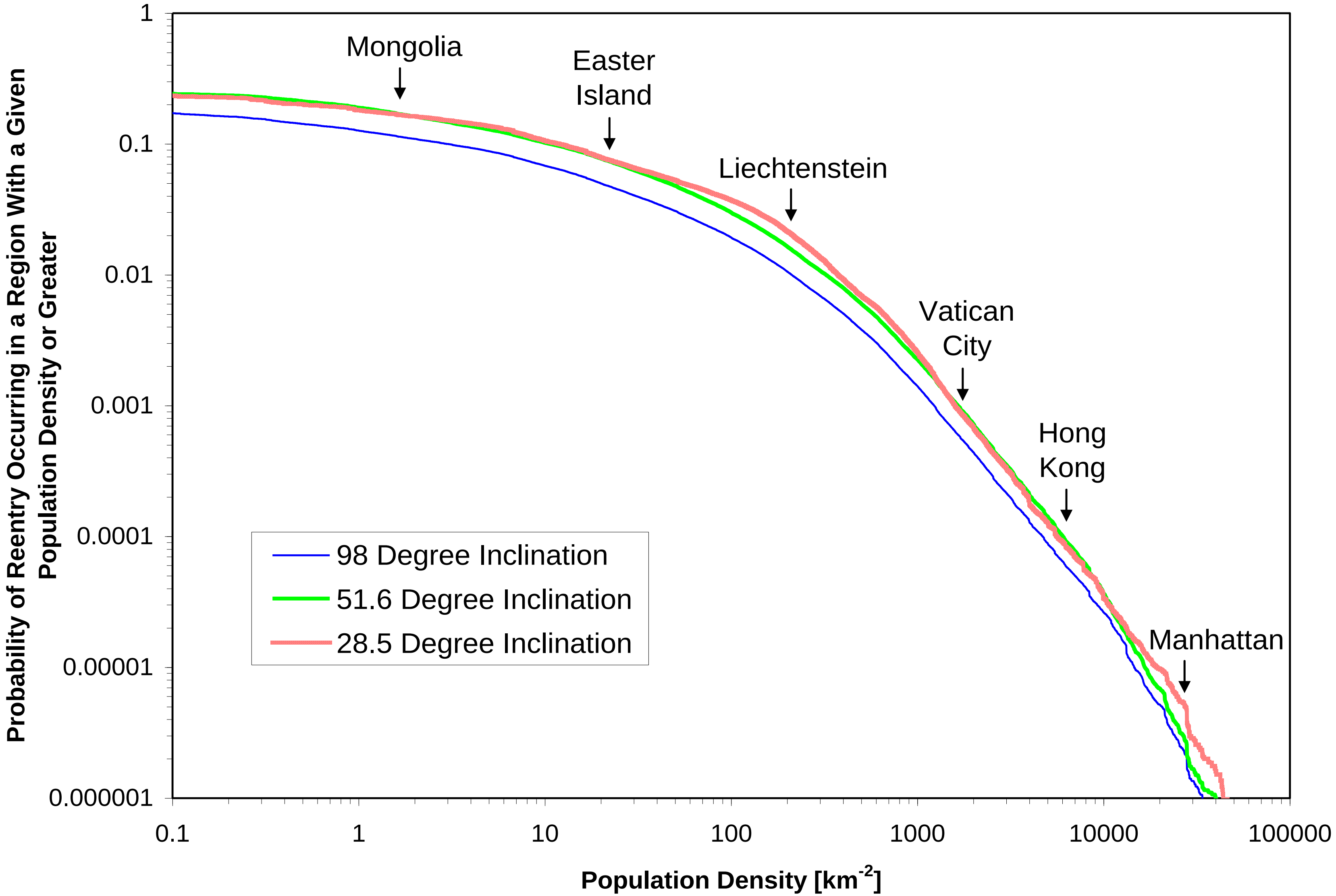


- Gridded Population of the World, version 3 (GPWv3)
- Socioeconomic Data and Applications Center (SEDAC) at Columbia University
- 2.5×2.5 arc minute cells = 4.6 km×4.6 km cells at the Equator
- Reference years 1990-2015 in 5-year intervals

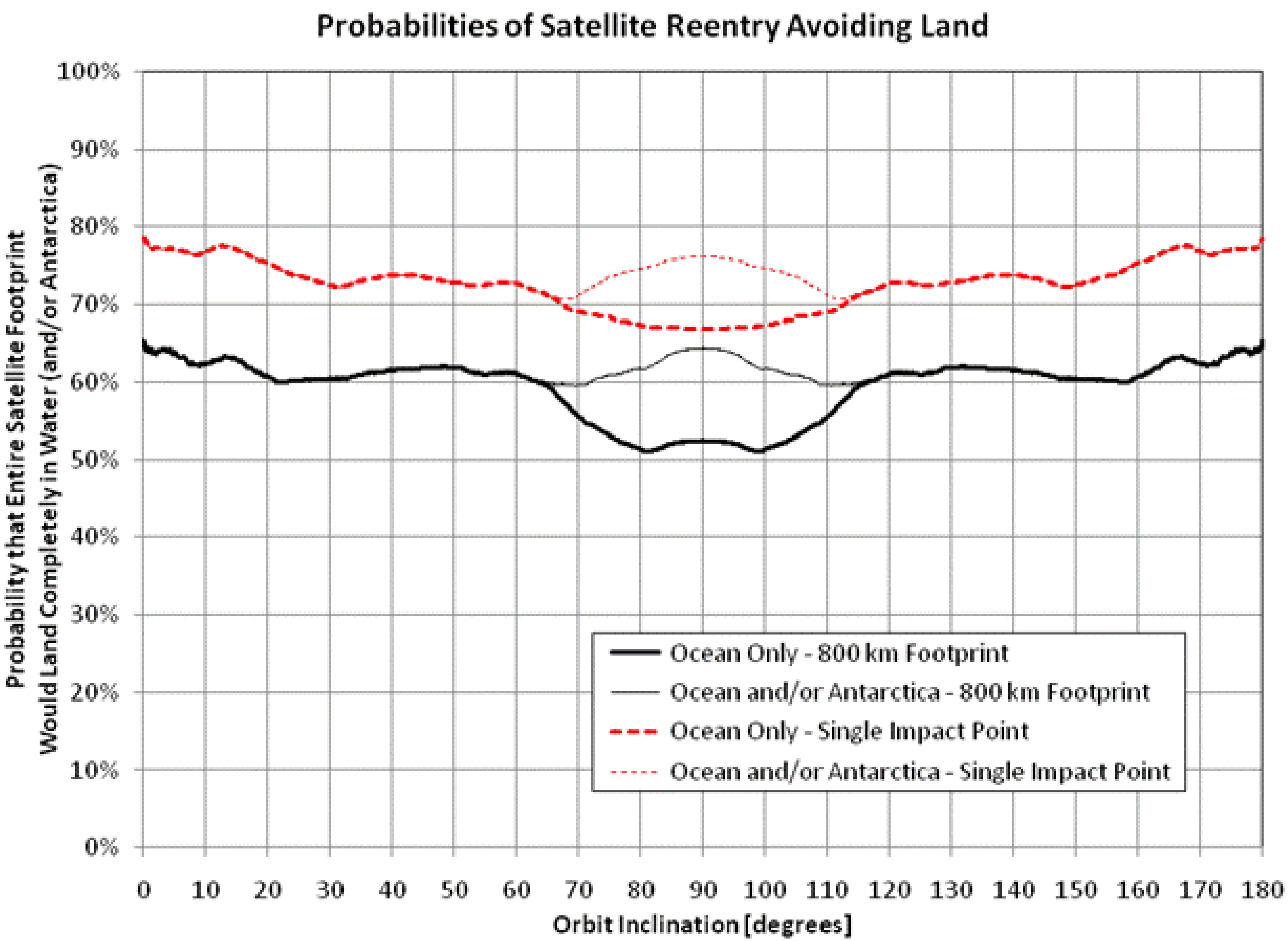
Average Density of People Below Satellite Path



Probability of Falling in Populated Areas



Probability of Ocean Reentry



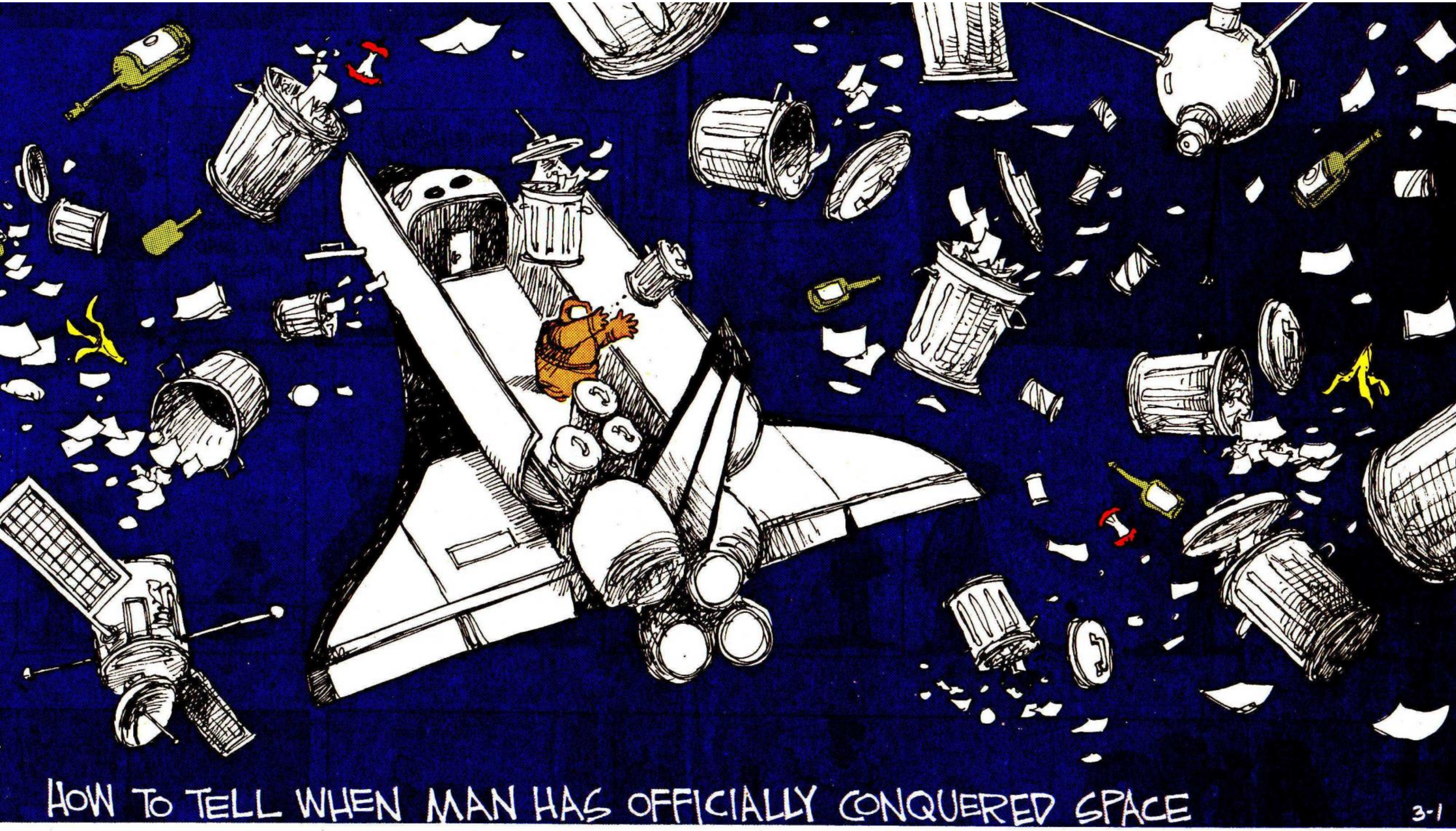
Brewster Rockit on Reentry Risks

Conclusions

- Monitoring the Earth space environment is insufficient to understand the risks posed by debris
  - Never observe all the debris characteristics you need
  - Cannot see the entire environment
  - Must be able to make predictions about the future
- Modeling permeates all aspects of orbital debris studies
- Models provide users with tools to design their spacecraft to survive the debris environment
- Models provide policy makers with tools to be able to make informed decisions about guidelines and regulations concerning space activities
- Models are only as good as the assumptions made and the quality of the data behind them

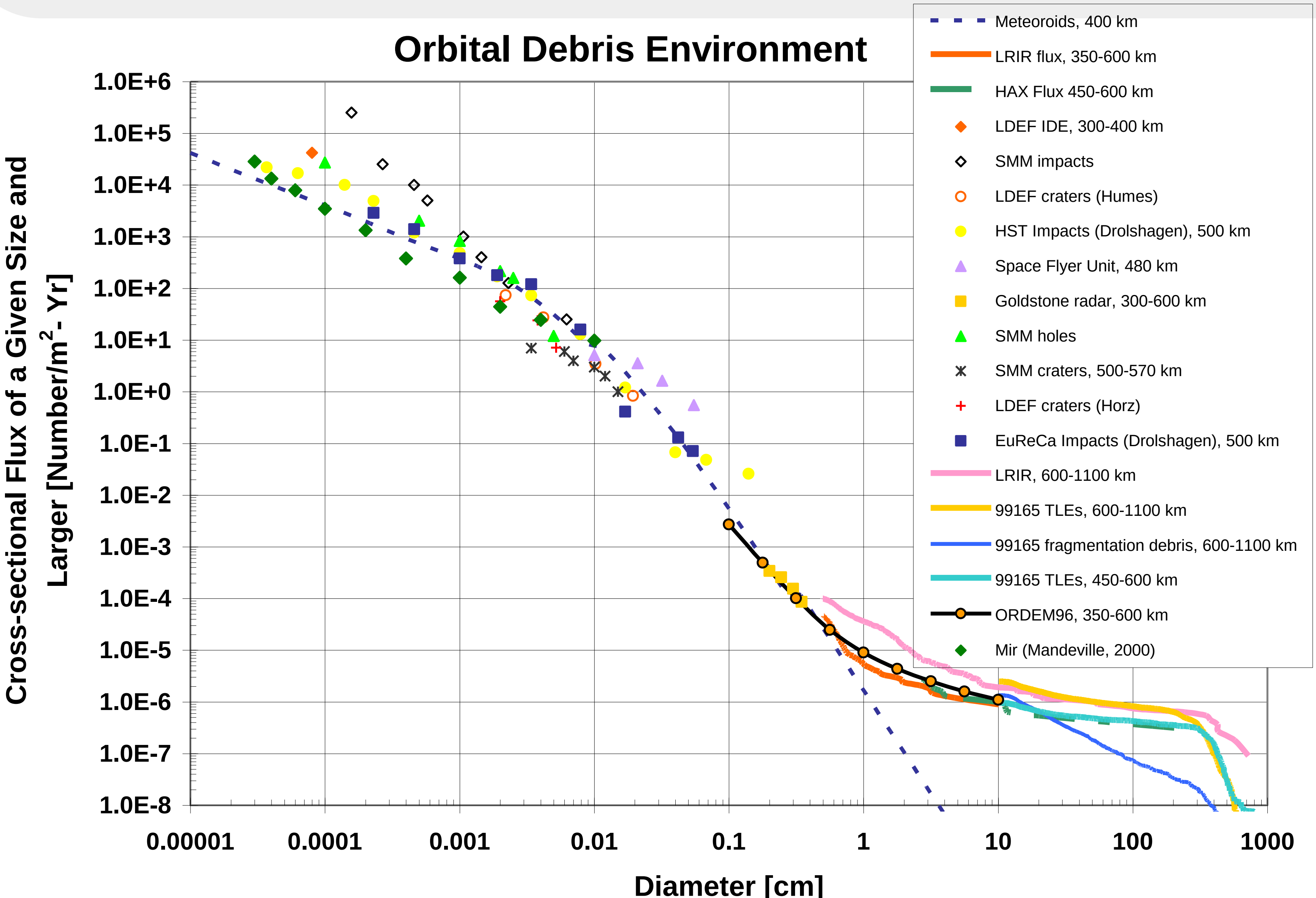
National Aeronautics and Space Administration

Questions?



Backup

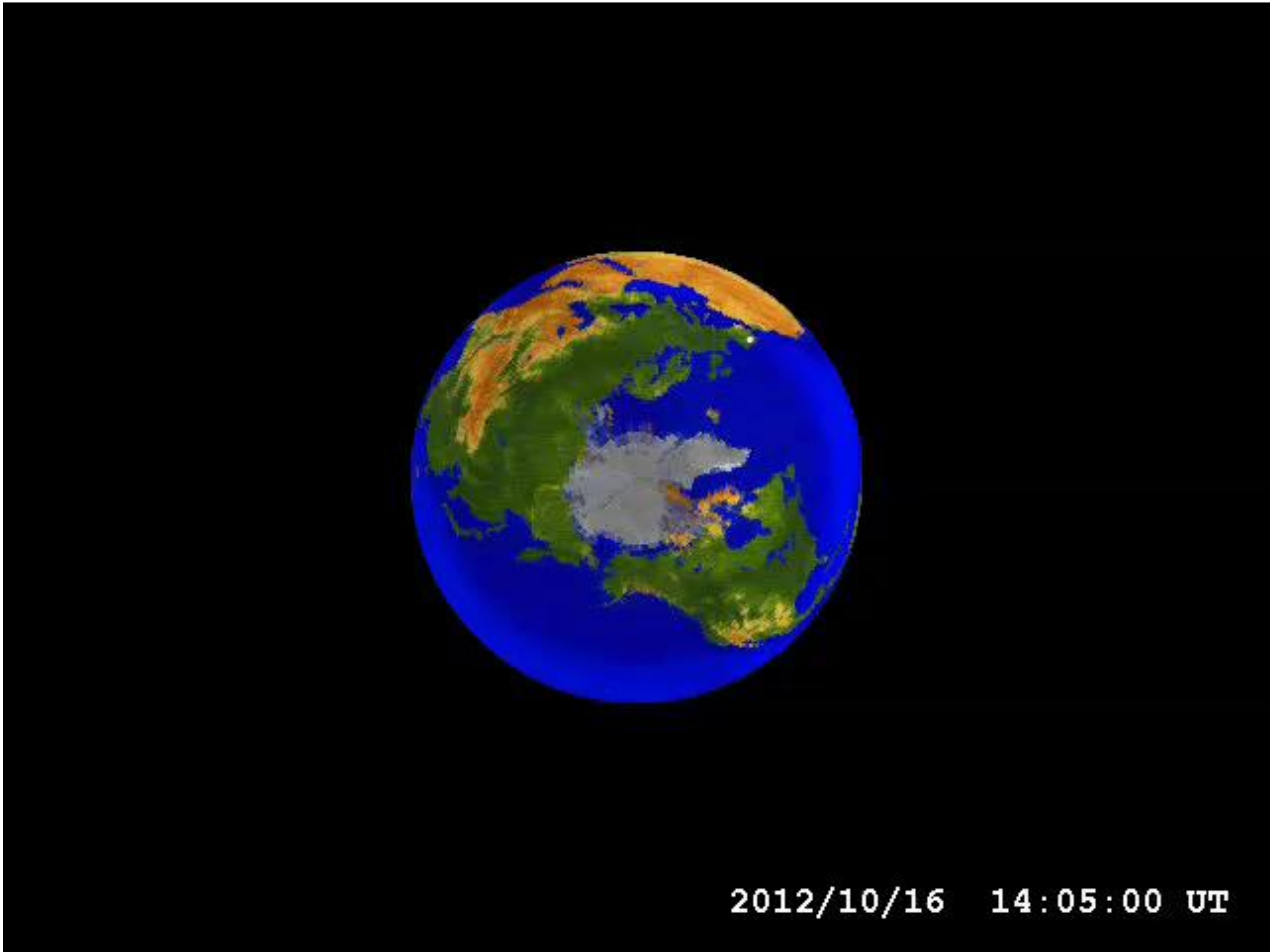
Data Compilation



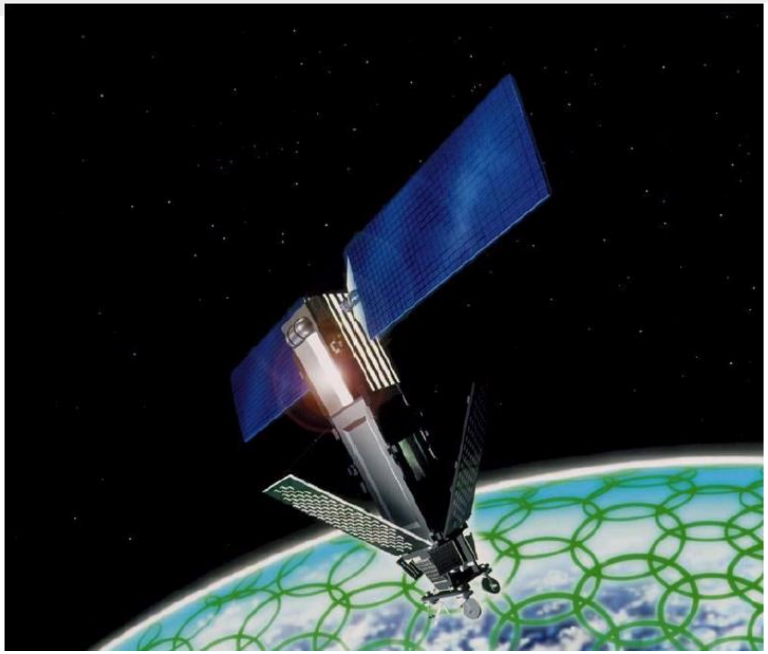
Breakup Model

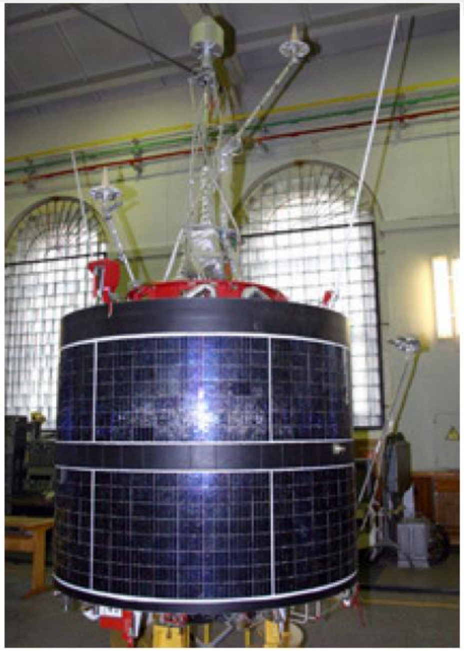
- **NASA's Breakup Model can be used to simulate the evolution of individual breakups**
- **On August 6, 2012, the Russians attempted to launch two communications satellites using a Proton rocket**
- **The BRIZ-M upper stage failed to burn properly, and was left stranded in an elliptical orbit with about 5 metric tons of its propellant still aboard**
- **On October 16, the rocket body exploded, creating at least 700 trackable pieces of debris (and probably many more too small to be tracked) in orbits that cross ISS altitude**
- **Observed by astronomers at the Siding Springs Observatory**

BRIZ-M Explosion



2009 Collision





February 10, 16:56 GMT two satellites collided near 789 km altitude

Iridium 33 (24946, 97051C)

779 x 808 km, 86.4° orbit, 556 kg

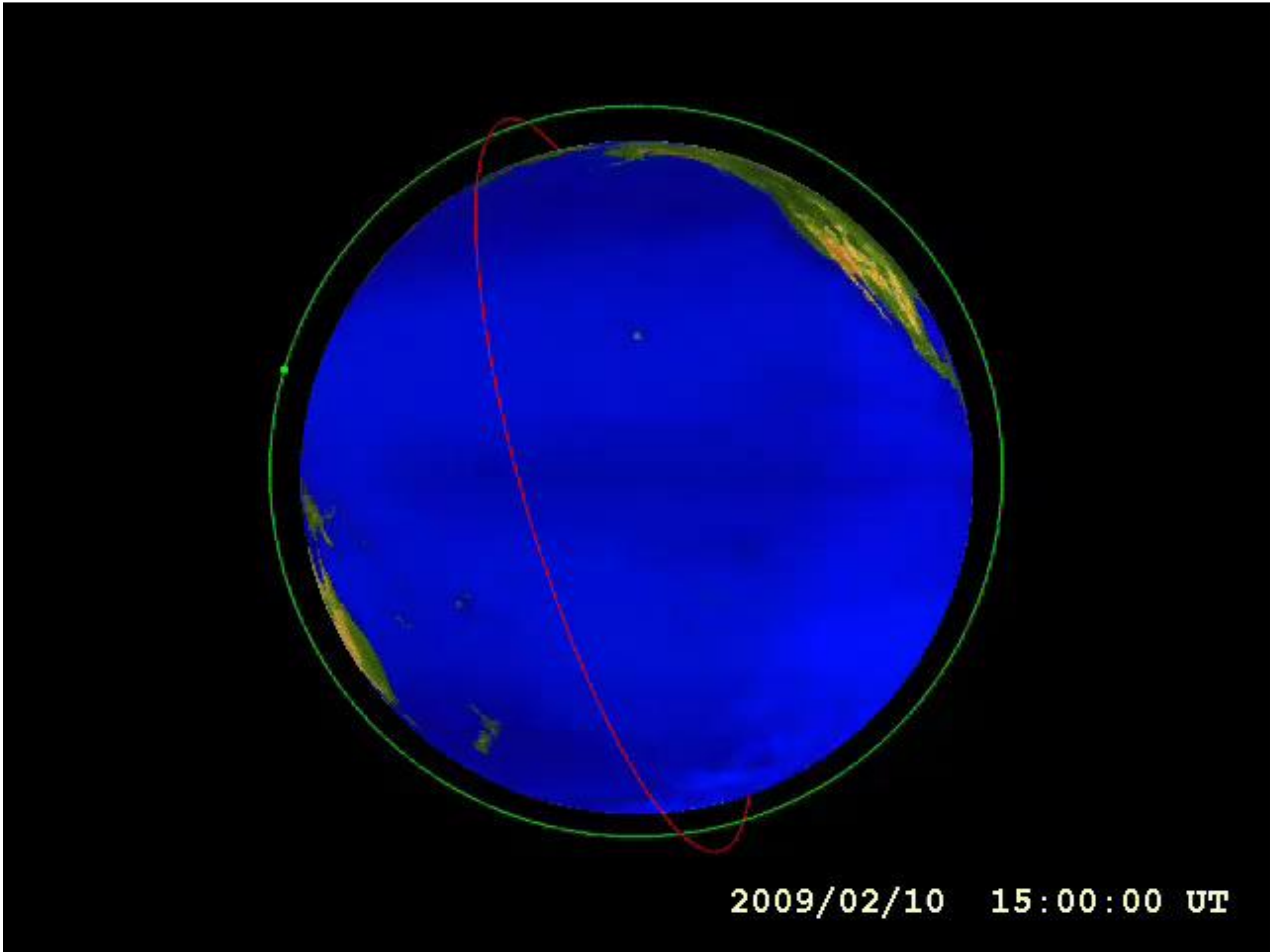
Operational US Commercial Communication Satellite

Kosmos 2251 (22675, 93036A)

786 x 826 km, 74.0° orbit, 900 kg

Non-operational Russian Communication Satellite

2009 Collision



2009 Collision