Orbital Debris Modeling

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Outline

- **The NASA OD Engineering Model**
  - A mathematical model capable of predicting OD impact risks for the ISS and other critical space assets
- **The NASA OD Evolutionary Model**
  - A physical model capable of predicting future debris environment based on user-specified scenarios
- **The NASA Standard Satellite Breakup Model**
  - A model describing the outcome of a satellite breakup (explosion or collision)

Orbital Debris Engineering Models

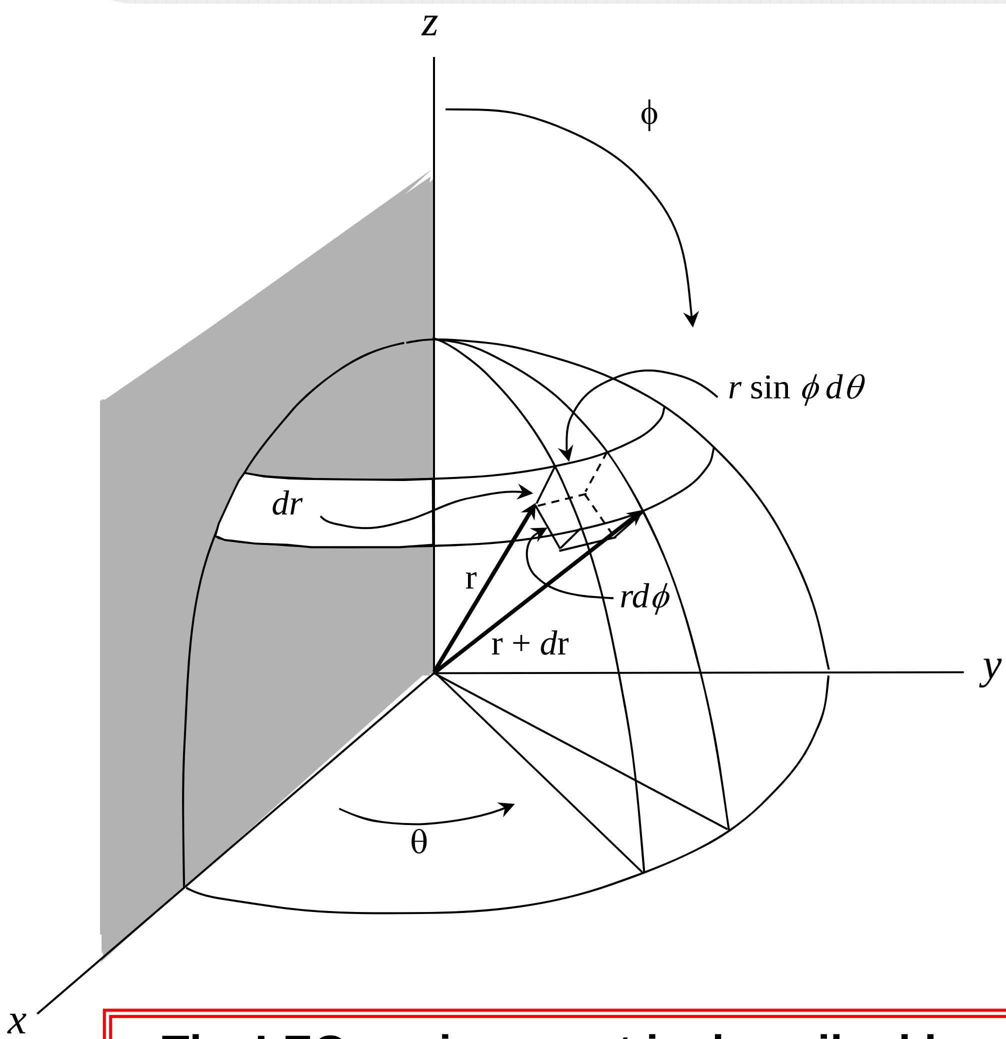
What Is an Engineering Model?

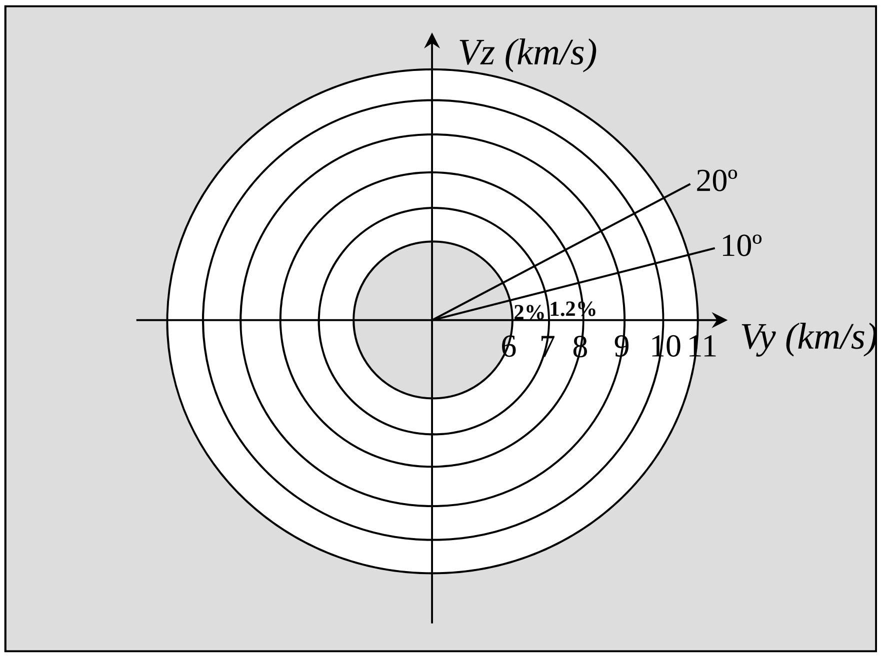
- **An OD engineering model is a mathematical tool**
  - Designed to describe the current and near-future OD flux in the environment
  - Created primarily for spacecraft designers/operators to reliably assess spacecraft risk due to OD impacts
  - Has been used to estimate sensor flux for radar/telescope observers
- **There is a need to update the mode on a regular basis**
  - New data
  - Better techniques
  - Changes in the environment
  - Need for expanded capabilities

History of the NASA OD Engineering Models

- **Pre-1990 – used a simple flux curve based mostly on model results**
- **1994 Space Station Freedom model and ORDEM96 – obtained Haystack radar data for debris in the 1 cm to 10 cm regime**
  - Used simple equations to describe debris populations in 6 inclination and 2 eccentricity groups
- **ORDEM2000 – used new techniques and improved computer capabilities to describe the LEO environment**
  - Populations were derived from data and then processed to generate the model environment

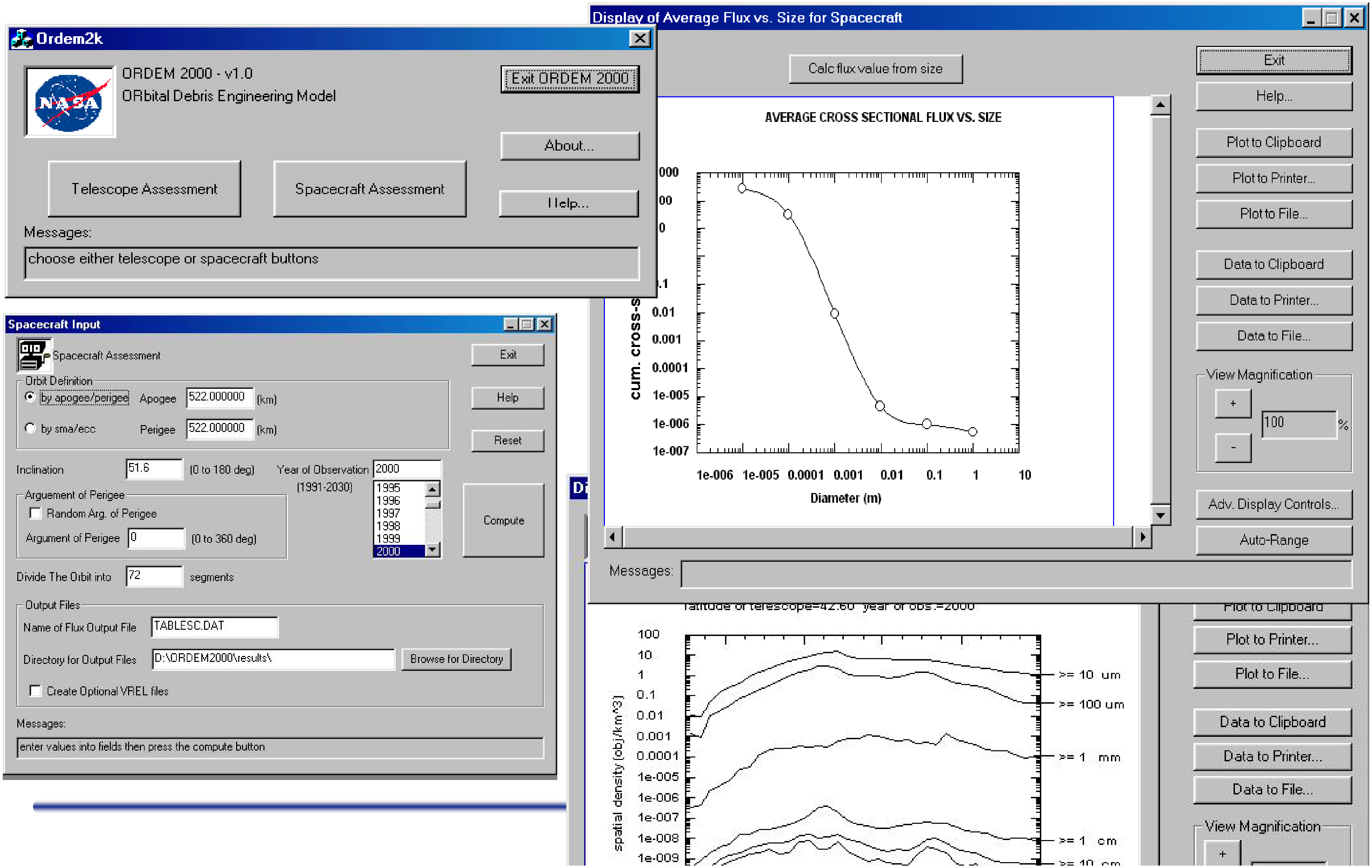
ORDEM2000 Debris Environment





- **The LEO environment is described by a finite element model (5° × 5° × 50 km) with spatial density and velocity distributions of debris of 6 different sizes**

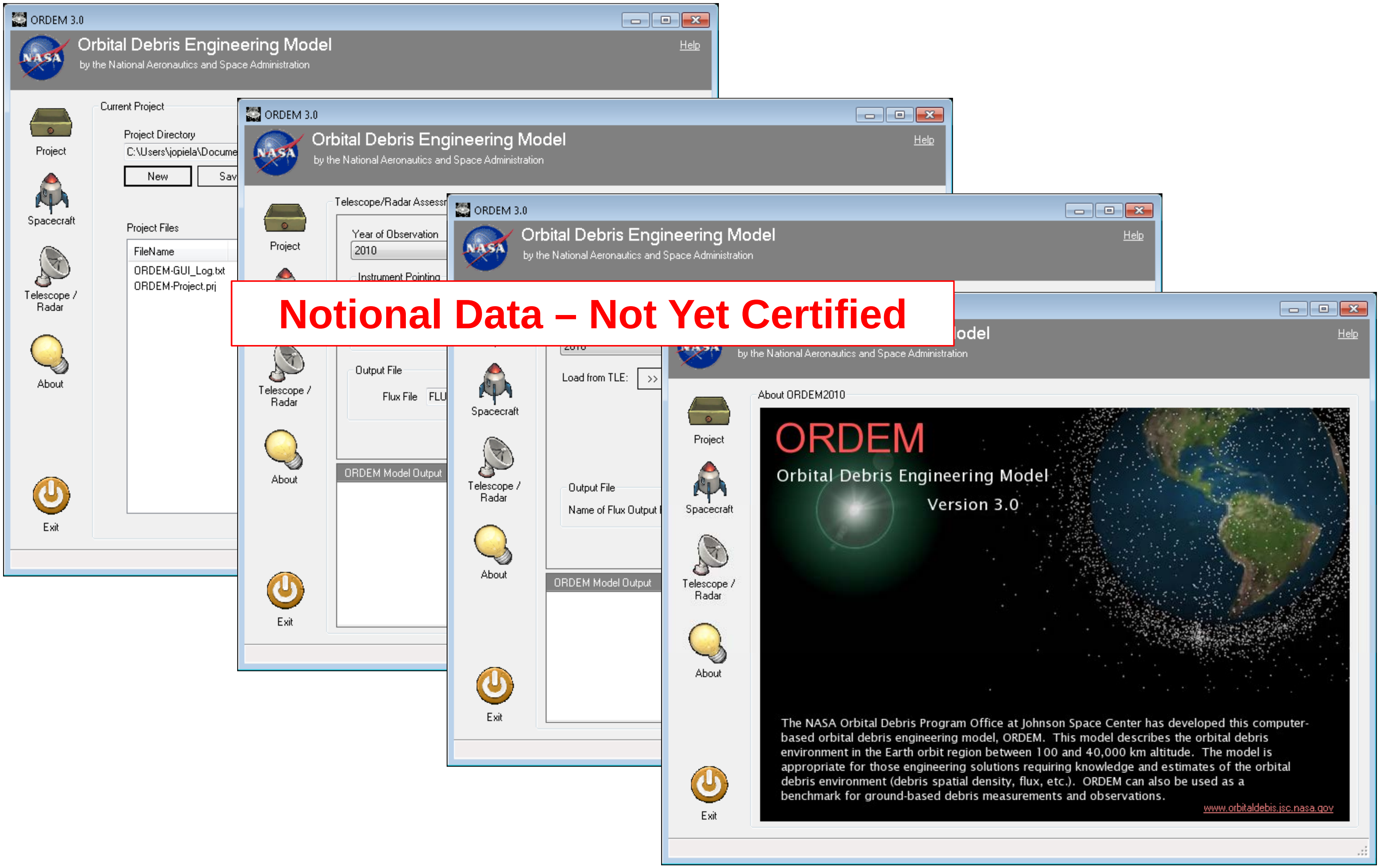
ORDEM2000 Graphical User Interface (GUI)



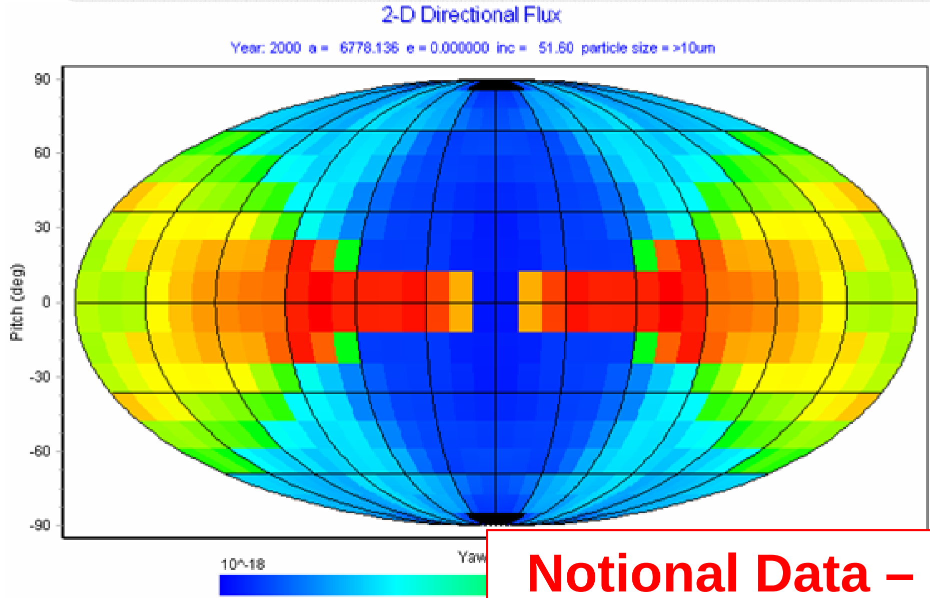
Highlights of the New Model – ORDEM 3.0

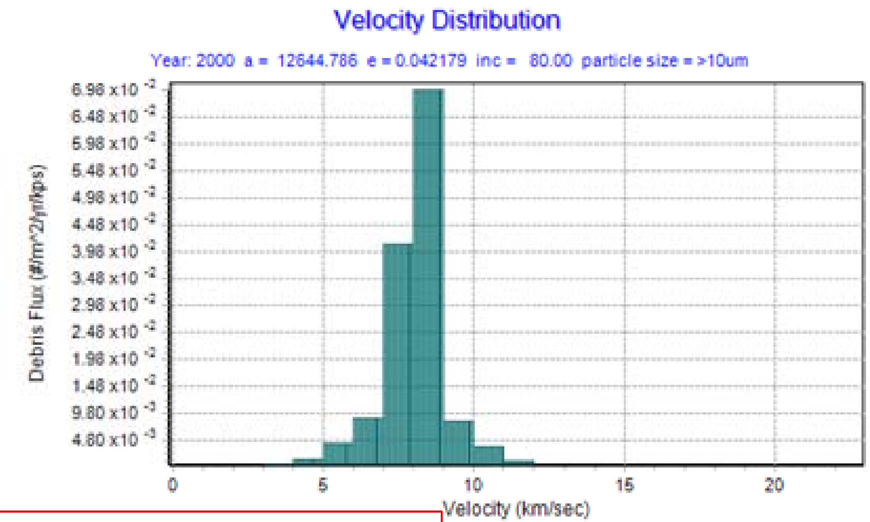
- **Expand data sources in time, altitude, and particle size**
  - Altitude: 100 to 40,000 km (LEO through GEO)
  - LEO-GTO: Use SSN catalog, Haystack, HAX, Goldstone, STS windows/radiators to develop OD populations
  - GEO: use the MODEST GEO survey data to develop ≥10 cm populations
- **Utilize higher fidelity supporting environmental models**
  - LEGEND replaces EVOLVE 4.0
  - Material density breakdown included
  - NaK droplet and degradation/ejecta product models added
- **Use Bayesian statistics to derive debris populations from data**
  - Model uncertainties are included in the output
- **Maintain two analysis modes: spacecraft and telescope/radar**
  - Debris fluxes through 'igloo' in pitch, yaw, impact velocity elements (in spacecraft mode) and through cylinder in range elements (in telescope/radar mode)
- **Update Graphical User Interface (GUI)**

ORDEM 3.0 GUI Interface

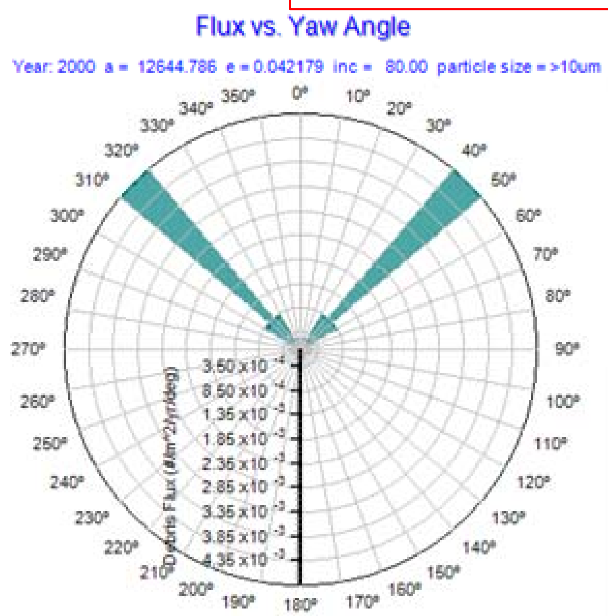


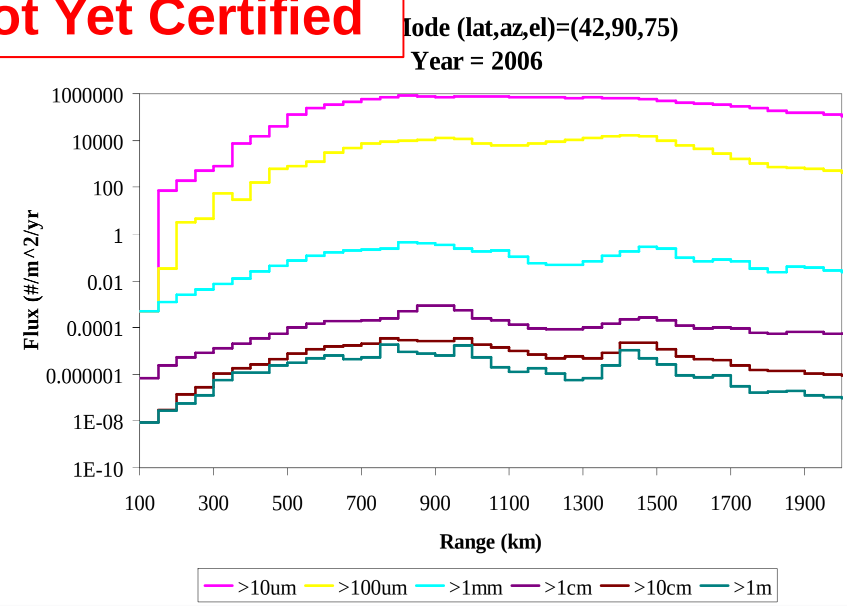
Sample ORDEM 3.0 Model Output





Notional Data – Not Yet Certified





ORDEM2000 versus ORDEM 3.0

Parameter	ORDEM2000	ORDEM 3.0
Spacecraft and 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)	100 to 2000 km(>10 μm) 2000 to 33,000 (>1 cm) 33,000 to 40,000 km (>10 cm)
Model population breakdown	No	Intacts and mission related debris Fragments RORSAT NaK coolant droplets Degradation/ejecta
Material density breakdown	No	Low-density(<2 g/cm^3) : fragments Medium-density(2-6 g/cm^3): fragments, degrad/ejecta High-density(>6 g/cm^3): fragments, degrad/ejecta RORSAT NaK coolant droplets (0.9 g/cm^3)
Model cumulative size thresholds	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
Population uncertainties	No	Yes
File size	16 MB	1.4 GB
Run time	Seconds	Minutes to hours

Status of ORDEM 3.0

- **Model in final validation and verification process**

- **Official release is scheduled for later this year**
  - Will be available for download from the NASA Orbital Debris Program Office website

NASA Orbital Debris Evolutionary Model

LEGEND Overview (1/2)

- **LEGEND, A LEO-to-GEO environment debris 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 (rocket bodies and spacecraft), mission-related debris (rings, caps, *etc.*), and explosion/collision fragments
  - Handles objects individually
  - 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

LEGEND Overview (2/2)

- **LEGEND, an orbital debris evolutionary model**
  - Uses a deterministic approach to mimic the historical debris environment based on recorded launches and breakups
  - Uses a Monte Carlo approach and an innovative, pair-wise collision probability evaluation algorithm to simulate future collision activities
  - Analyzes future debris environment based on user-specified launch traffics, postmission disposal, and active debris removal options
  - Ten peer-reviewed journal papers have been published about LEGEND and its applications since 2004

Peer-Reviewed Journal Publications
(LEGEND and LEGEND Applications)

1. **Liou, J.-C. *et al*., LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res*. 34, 5, 981-986, 2004.**
2. **Liou, J.-C. and Johnson, N.L., A LEO satellite postmission disposal study using LEGEND, *Acta Astronautica* 57, 324-329, 2005.**
3. **Liou, J.-C., Collision activities in the future orbital debris environment, *Adv. Space Res*. 38, 9, 2102-2106, 2006.**
4. **Liou, J.-C. and Johnson, N.L., Risks in space from orbiting debris, *Science* 311, 340-341, 2006.**
5. **Liou, J.-C., A statistic analysis of the future debris environment, *Acta Astronautica* 62, 264-271, 2008.**
6. **Liou, J.-C. and Johnson, N.L., Instability of the present LEO satellite population, *Adv. Space Res*. 41, 1046-1053, 2008.**
7. **Liou, J.-C. and Johnson, N.L., Characterization of the cataloged Fengyun-1C fragments and their long-term effect on the LEO environment, *Adv. Space Res*. 43, 1407-1415, 2009.**
8. **Liou, J.-C. and Johnson, N.L., A sensitivity study of the effectiveness of active debris removal in LEO, *Acta Astronautica* 64, 236-243, 2009.**
9. **Liou, J.-C. *et al*., Controlling the growth of future LEO debris populations with active debris removal, *Acta Astronautica* 66, 648-653, 2010.**
10. **Liou, J.-C., An active debris removal parametric study for LEO environment remediation, *Adv. Space Res*. 47, 1865-1876, 2011.**

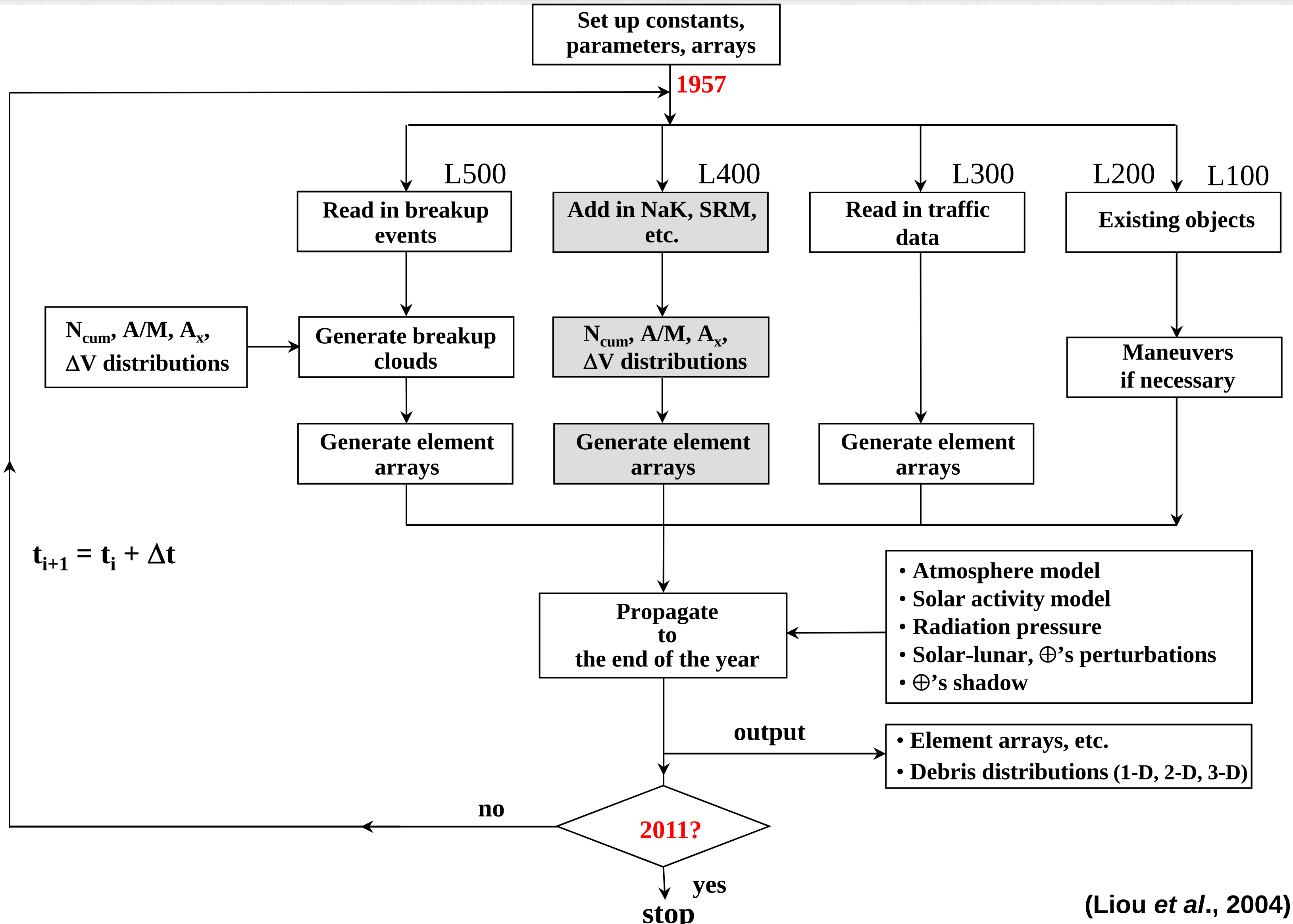
Development History

- **History**
  - 2003: Completed the historical component
  - 2005: Developed the “Cube” collision probability evaluation algorithm
  - 2006: Completed the future projection component
  - 2006: Added the postmission disposal mitigation options
  - 2007: Added the new capabilities to evaluate and identify individual objects for removal
  - 2008: Added additional options and output information for debris removal
- **Future Improvements**
  - Increase the computational speed of the two orbit propagators
  - Validate model predictions for sub-10 cm populations

The LEGEND Code

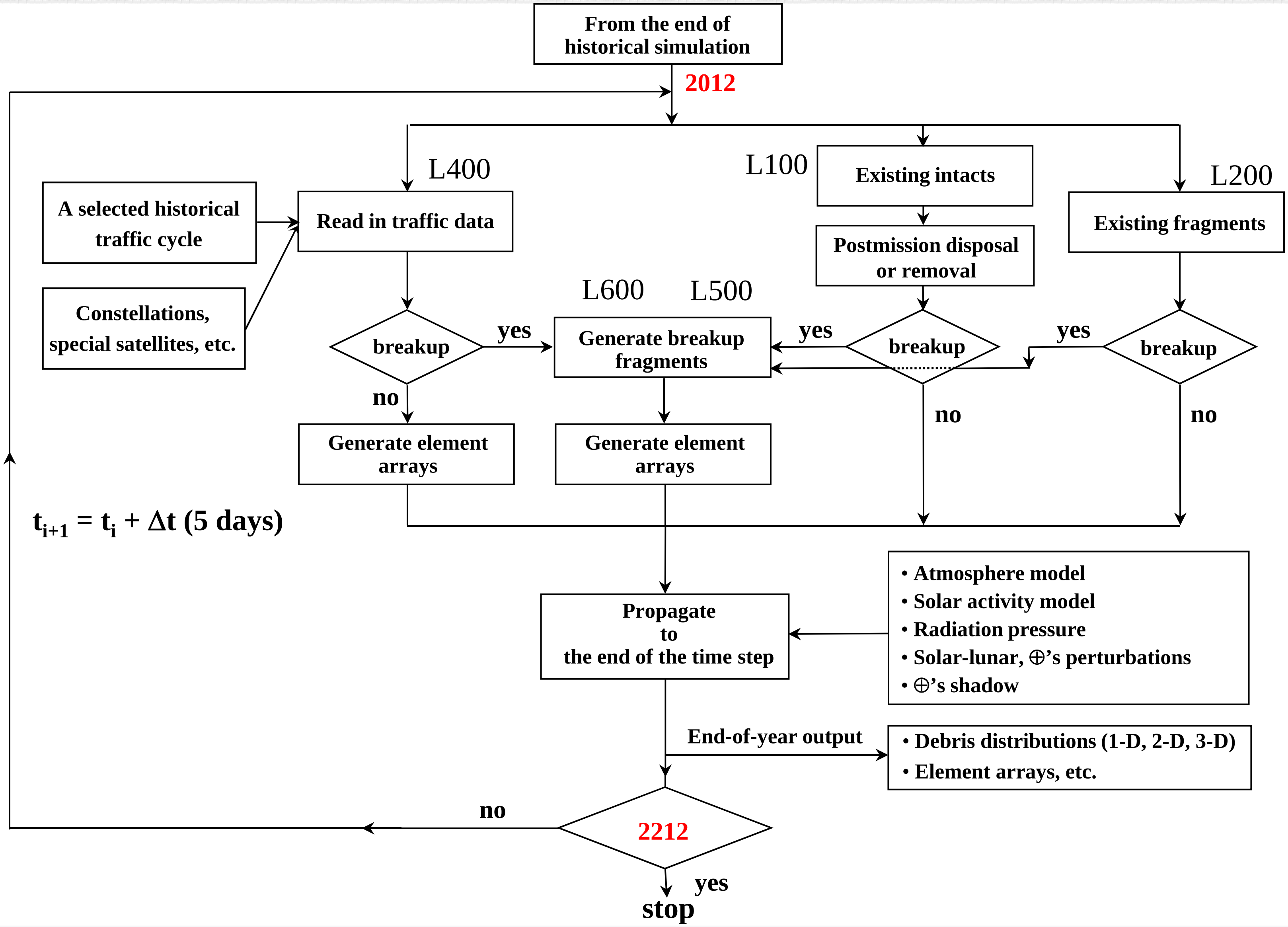
- **LEGEND is written in Fortran**
  - Includes ~18,000 lines of Fortran code
- **LEGEND runs on Unix/Linux-based workstations**
  - Typical runtime: ~days to weeks
- **LEGEND is only available to a few well-trained Orbital Debris Program Office scientists**

LEGEND Architecture (1/2)



(Liou *et al.*, 2004)

LEGEND Architecture (2/2)



LEGEND Supporting Models (1/4)

- **DBS database: a comprehensive record of historical launches and breakup events**
  - Time, type, orbit, physical properties (mass, area), *etc*.
  - The database is updated annually
- **Space Surveillance Network (SSN) catalogs**
  - Daily records of the historical growth of the ≥10 cm debris population
  - Basis of empirical area-to-mass ratio (A/M) distributions of large 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 (2/4)

- **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 23 (1944 – 2010)
    - **Similar to projections developed for long-term debris evolutionary models by other space agencies (ASI, UKSA, *etc.*)**

LEGEND Supporting Models (3/4)

- **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 well with similar tools used by other space agencies**

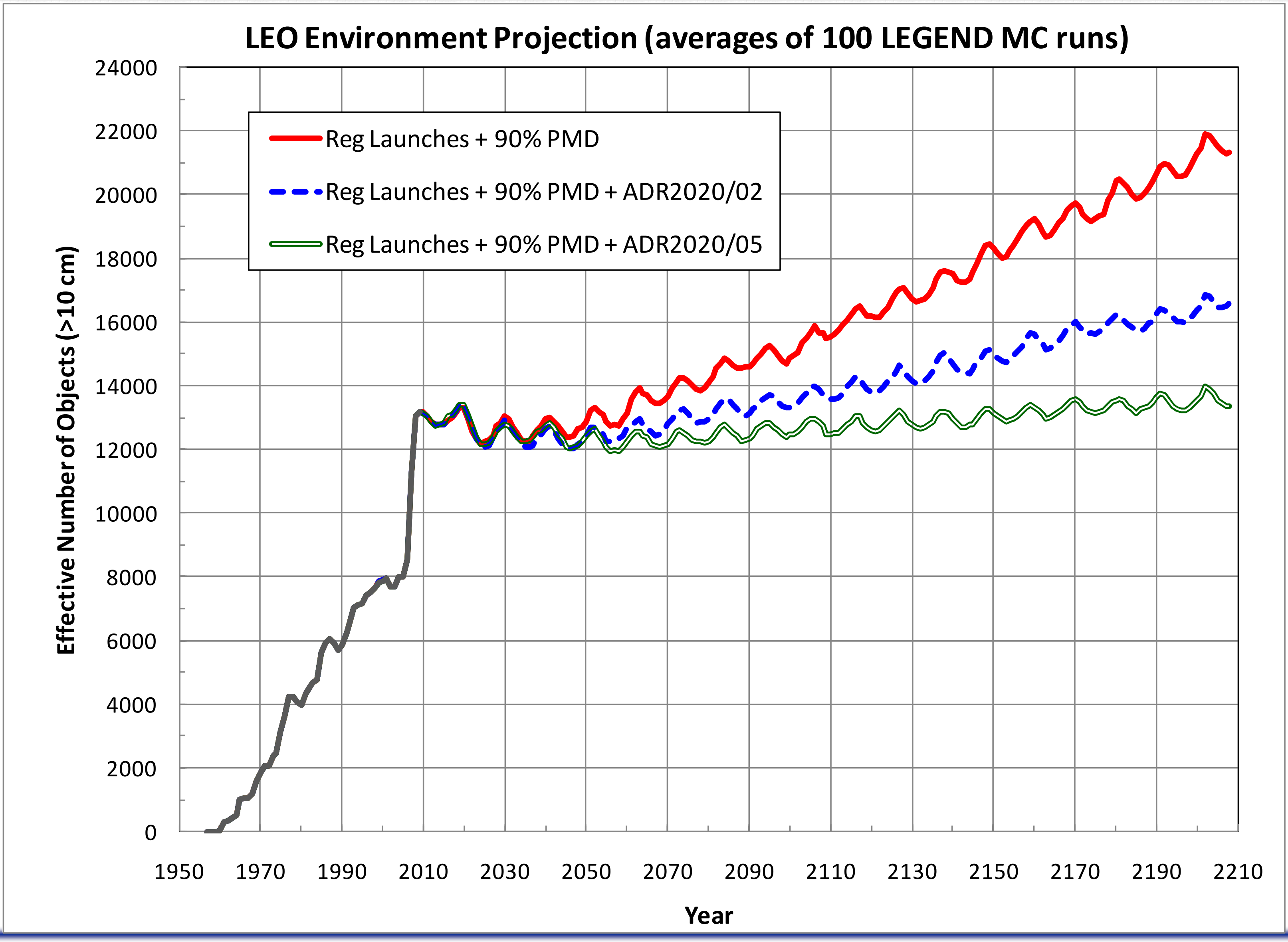
LEGEND Supporting Models (4/4)

- **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)

Sample LEGEND Output



NASA Standard Satellite Breakup Model

What Is a Satellite Breakup Model?

- **A satellite breakup model describes the outcome of a satellite breakup (explosion or collision)**
  – Fragment size, area-to-mass ratio (A/M), and ΔV distributions
- **The key to provide good short- and long-term debris impact risk assessments for critical space assets is the ability to reliably predict the outcome of a satellite breakup**
- **There are two options to develop the model**
  – Theoretical
  – Empirical

NASA Breakup Model for Explosions

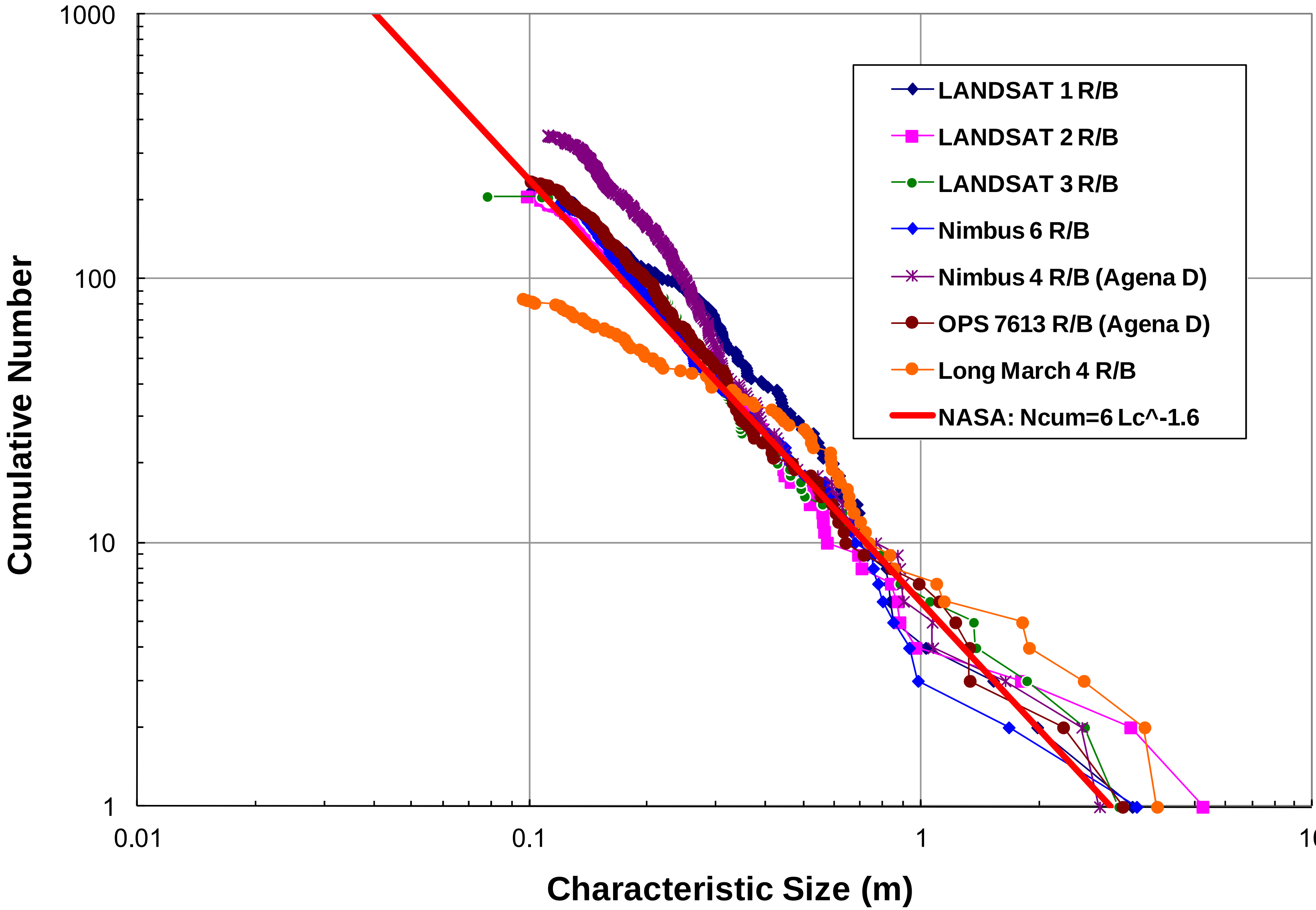
- Based on the fragment distribution of 7 well-observed on-orbit R/B explosions
- Fragments are described by a single power law distribution
- Explosions are classified into 6 different groups with different scaling factors (sf) assigned to their fragment distribution

$$N_{cum} = sf \times 6 \times L_c^{-1.6}$$

N_{cum}: number of fragments $\geq L_c$,

L_c: characteristic length in (m)

Size Distribution of Explosion Fragments



NASA Breakup Model for Collisions

- **Based on ground-based impact experiments and one well observed on-orbit collision (P78/SOLWIND)**
- **A catastrophic collision occurs when the ratio of impact energy to target mass exceeds 40 J/g**
- **Fragments are described by a single power law distribution**

$$N_{cum} = 0.1 \times (M_{tot})^{0.75} \times L_c^{-1.71}$$

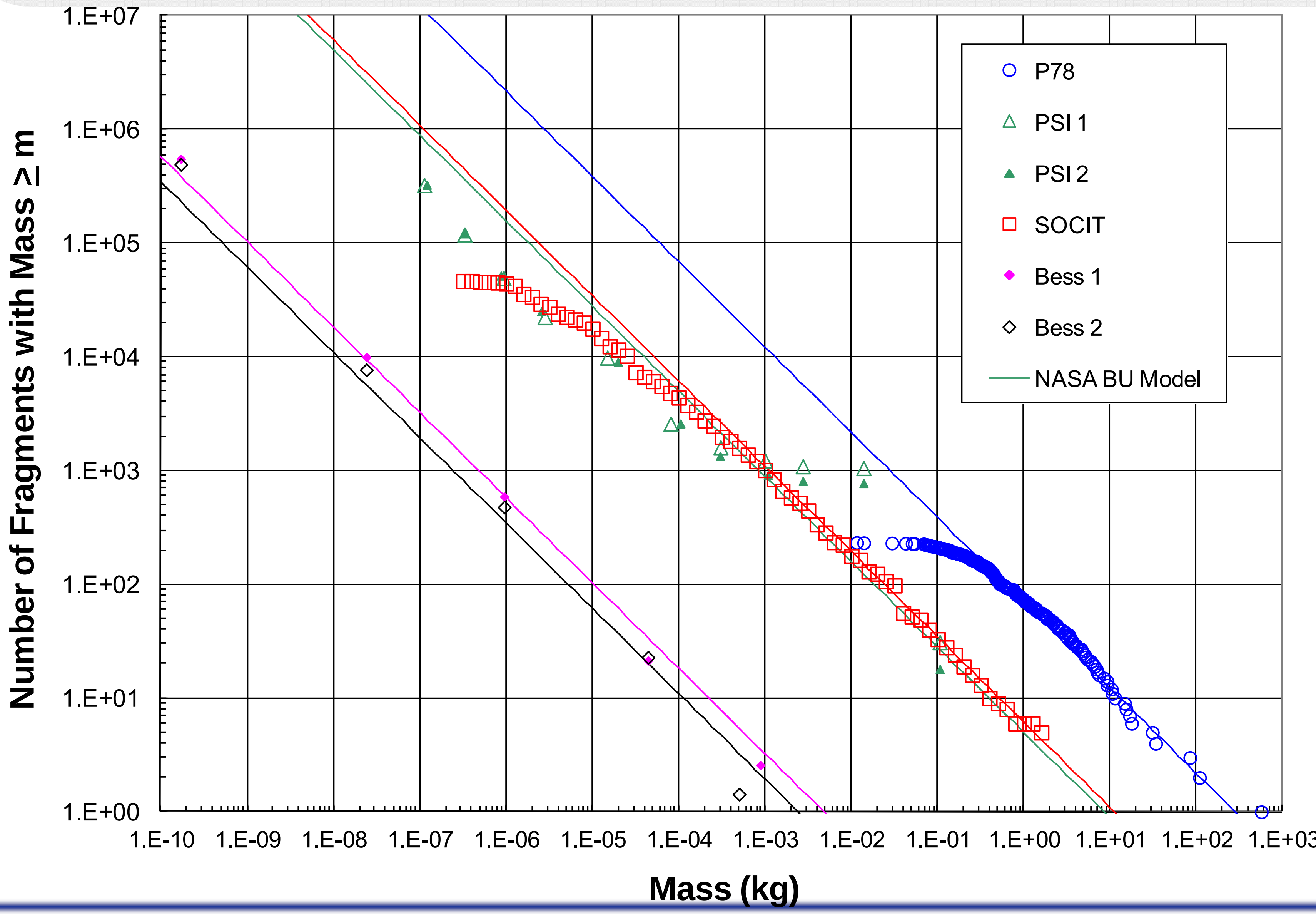
N_{cum}: number of fragments $\geq L_c$

Lc: characteristic length in (m),

$M_{tot} = m_{tar} + m_{proj}$ (catastrophic) or

$M_{tot} = m_{proj} + m_{proj} \times V^2/(km/sec)^2$ (non-catastrophic)

Mass Distribution of Collision Fragments

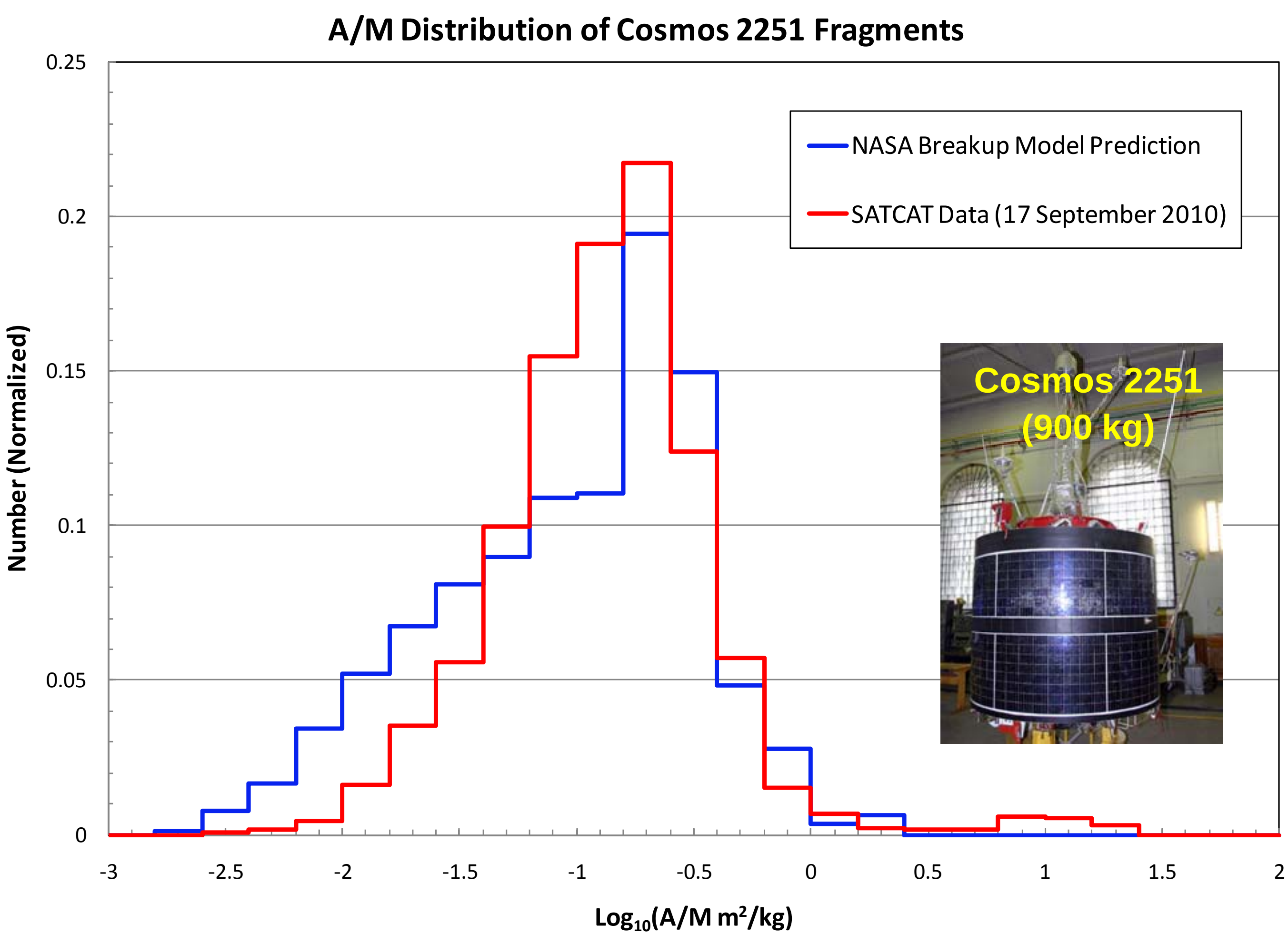


Improving the NASA Breakup Model

- The NASA satellite breakup model has been adopted by major international space agencies for various OD environment studies]

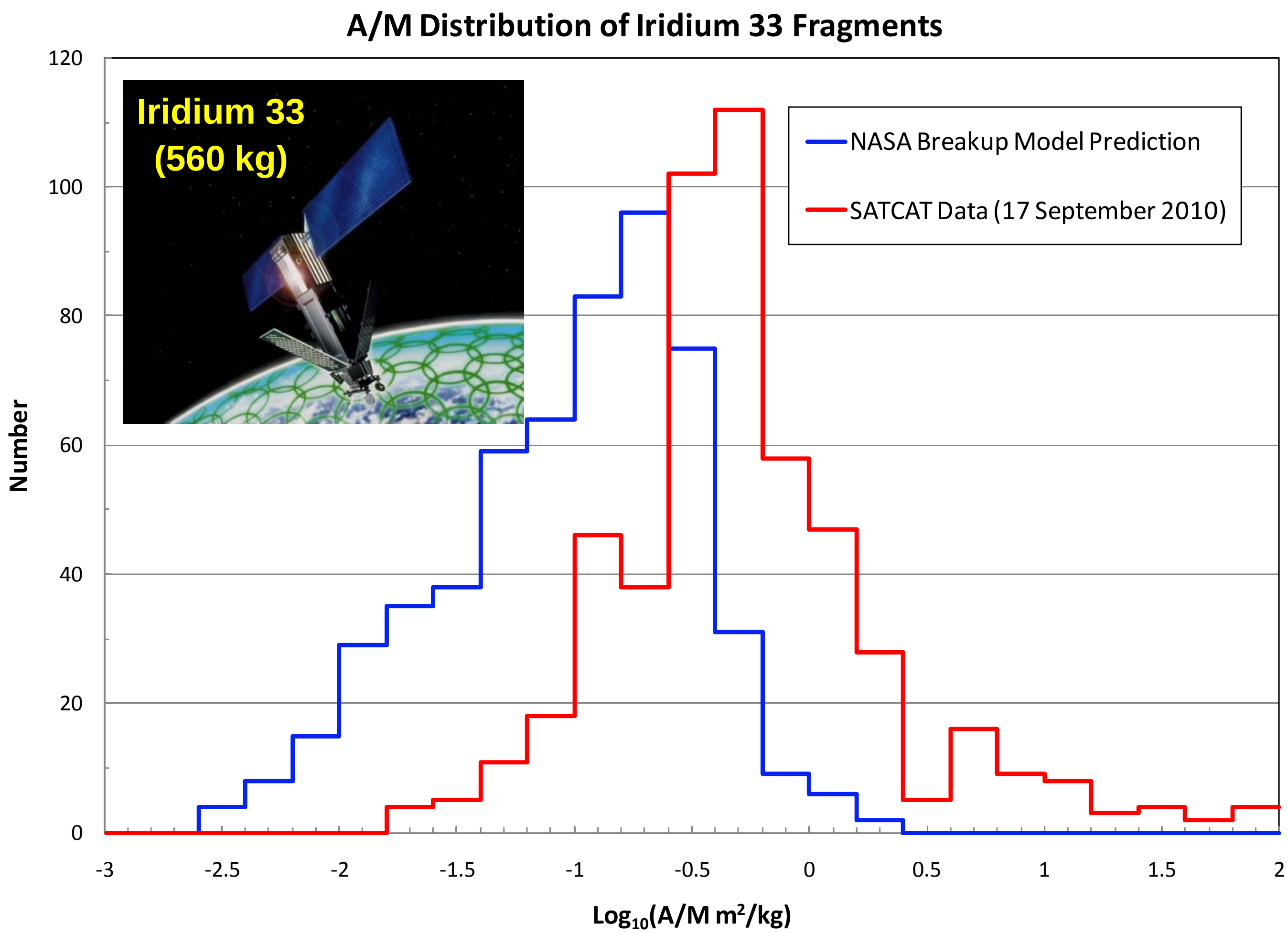
- As new materials and new construction techniques are developed for modern satellites, there is a need to conduct additional ground-based tests and use the data to further enhance the collision model

Cosmos 2251 Fragments



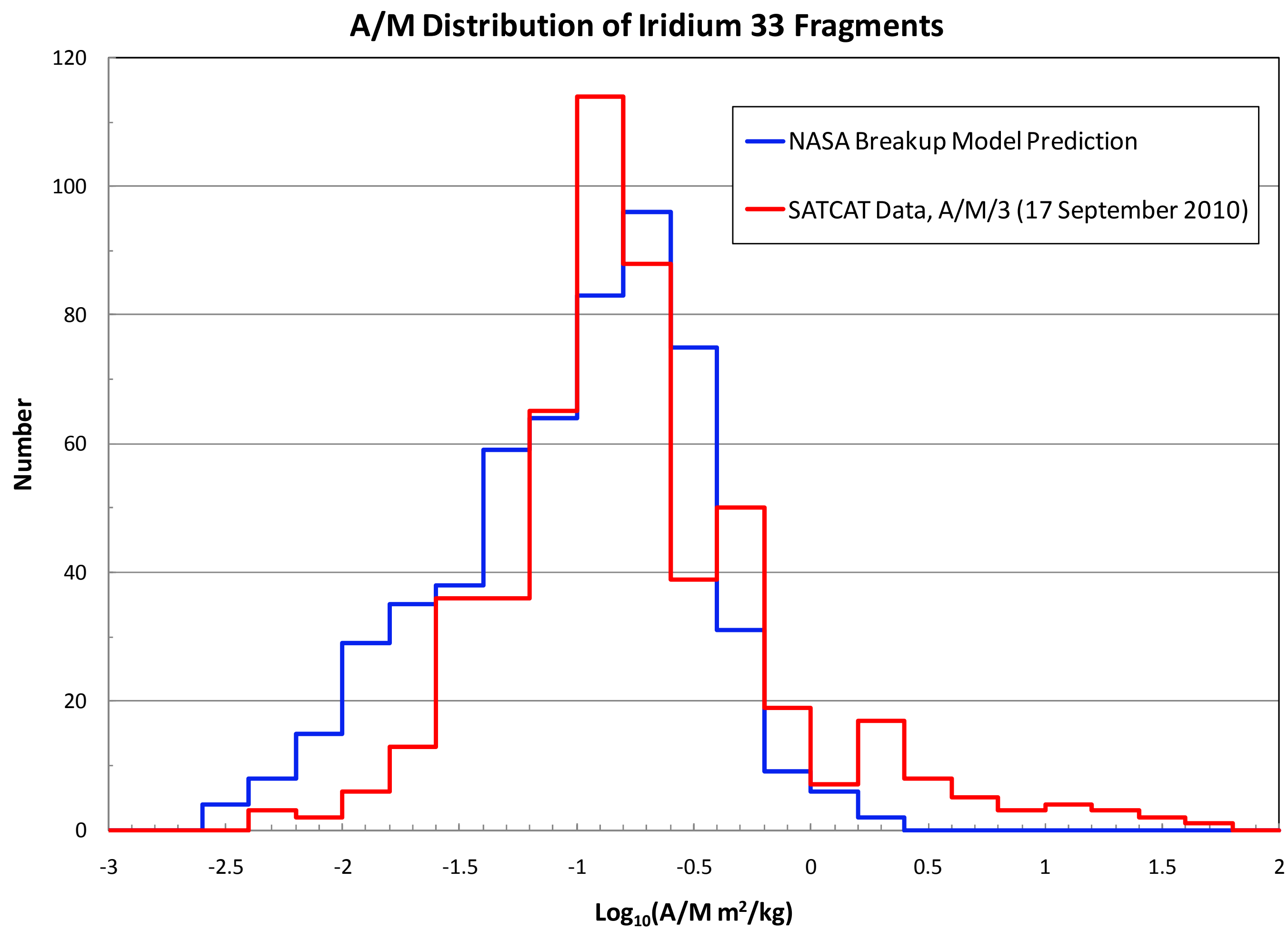
- The A/M distribution of the Cosmos 2251 fragments matches well with the NASA model prediction

Iridium 33 Fragments (1/2)



- **The A/M distribution of the Iridium 33 fragments appears to be systematically higher than the NASA model prediction**
- **Lightweight composite materials were extensively used in the construction of the vehicle**

Iridium 33 Fragments (2/2)



- The A/M distribution of the Iridium 33 fragments is approximately a factor of 3 higher than the NASA model prediction

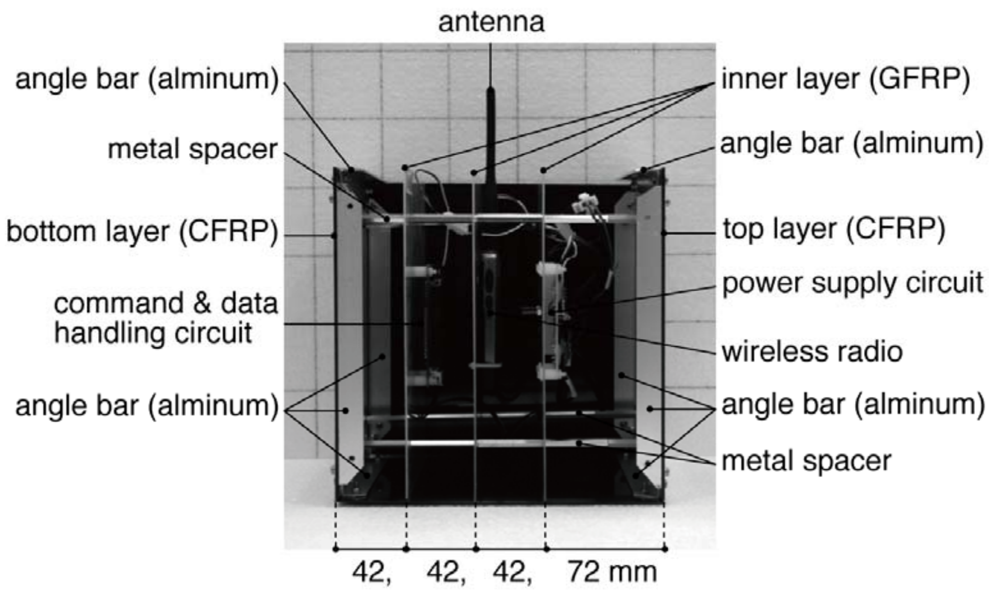
7 Micro Satellite Impact Tests (2005-2008)

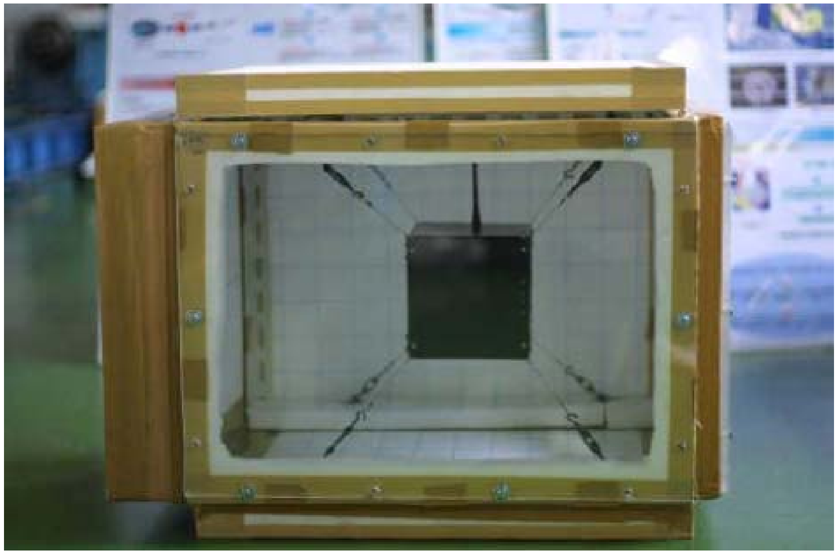
- **The project is a collaboration between NASA ODPO and the Kyushu University in Japan**

	Size (cm)	M_t (g)	M_p (g) / D_p (cm)	V_{imp} (km/s)	EMR (J/g)	Impact Angle
0501H	15	740	4.03 / 1.4	4.44	53.7	⊥
0502L	15	740	39.2 / 3.0	1.45	55.7	⊥
0701L	20	1300	39.2 / 3.0	1.66	41.5	⊥
0702L	20	1283	39.2 / 3.0	1.66	42.0	//
0703L	20	1285	39.2 / 3.0	1.72	45.1	⊥
0801F	20	1515	39.2 / 3.0	1.74	39.2	⊥
0801R	20	1525	39.3 / 3.0	1.78	40.8	⊥

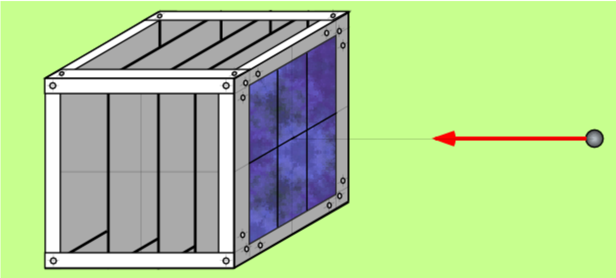
Micro Satellites

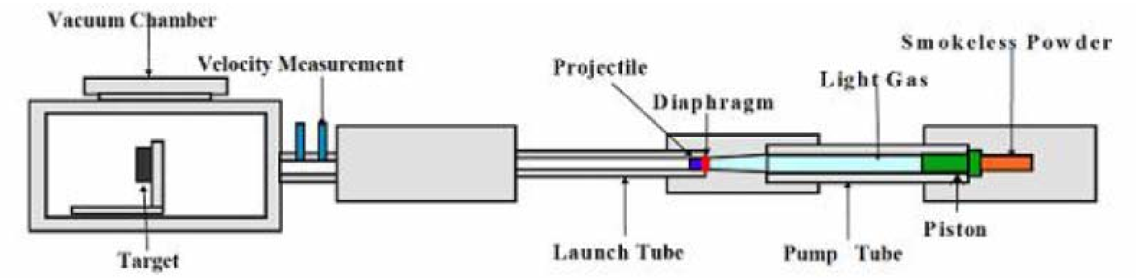
- **Target satellites**
  - Cube-shaped, with 6 Carbon Fiber Reinforced Plastic (CFRP) outer walls and 3 Glass Fiber Reinforced Plastic (GFRP) boards inside
    - **Direction of CFRP fiber: (0°, 90°)**
    - **Thickness of the front and back CFRP walls: 2 mm**
    - **Thickness of other CFRP and GFRP walls: 1 mm**
  - Components: lithium-ion batteries, transmitter, solar cells, power circuit board, communication circuit board, on board computer, antenna

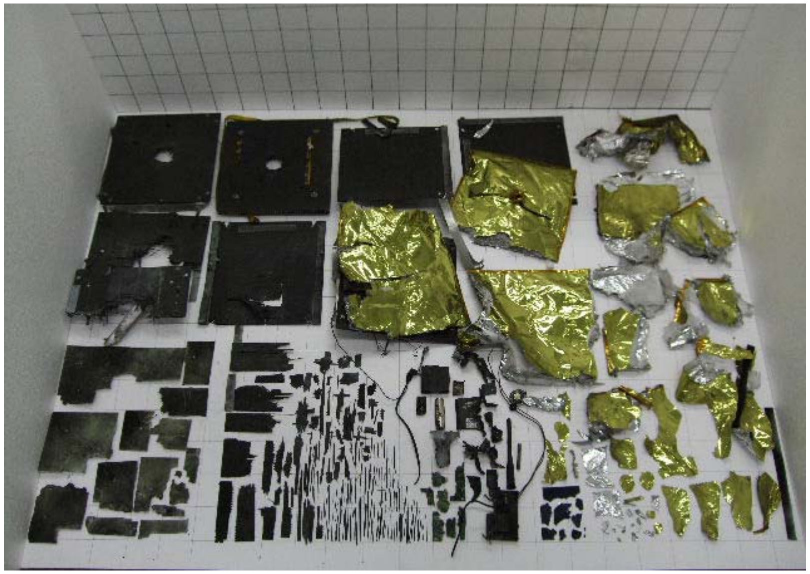




Ground-based Impact Experiments





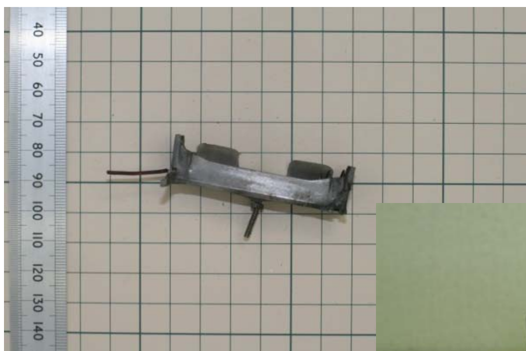


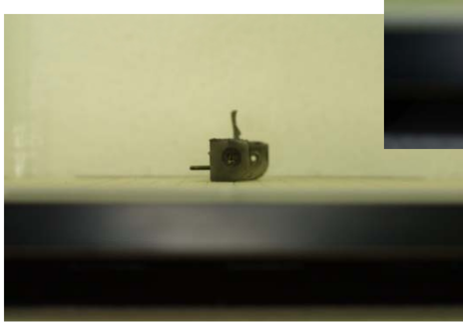
Impact Fragmentation

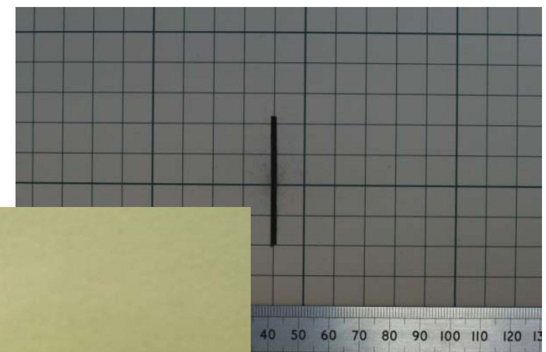
- **Target: Micro satellite covered with Multi-Layer Insulation (MLI) a solar panel on one side**
  - Objective: characterize satellite, MLI, and solar panel fragments

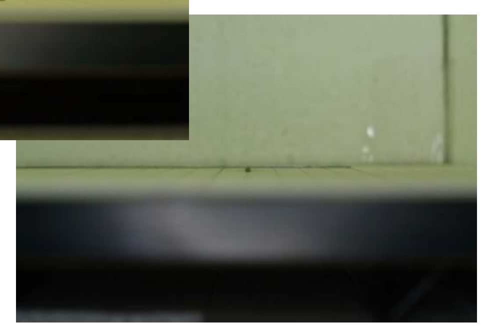
Sample Measurement Data

No	Characteristic	Label	Shape	x[m]	y[m]	z[m]	M[kg]
1	CFRP+Aluminum	Medium	Plate_Square	0.28284	0.28284	0.03031	2.014E-01
2	CFRP+Aluminum	Medium	Plate_Square	0.28284	0.28284	0.02186	8.873E-02
3	CFRP	Low	Plate_Square	0.28284	0.28284	0.00167	6.263E-02
4	CFRP+Aluminum	Medium	Plate_Square	0.28284	0.28284	0.06762	7.567E-02
5	GFRP+Metal	Medium	Plate_Square	0.28230	0.19110	0.08777	5.075E-02
6	CFRP+Aluninum+Metal	Medium	Cube_Complex_Oblong	0.34520	0.14032	0.05755	6.910E-02
7	CFRP	Low	Plate_Square	0.14846	0.13875	0.02689	2.192E-02
8	CFRP	Low	Plate_Square	0.14953	0.14678	0.01391	1.668E-02
9	CFRP	Low	Plate_Oblong	0.20080	0.02619	0.00406	1.234E-03
10	Aluminum	Medium	Cube_Complex_Oblong	0.15790	0.03335	0.02576	1.464E-02









Upcoming Ground-based Impact Test

- **A collaboration of NASA ODPO, AF/SMC, and University of Florida**

	SOCIT	**Proposed Test**
Target dimensions	46 cm (dia) × 30 cm (ht)	50 cm
Target mass	34.5 kg	50 kg
MLI and solar panel	No	Yes
Projectile material	Al sphere	Al sphere
Projectile dimensions/mass	4.7 cm diameter, 150 g	5 cm diameter, 176 g
Impact speed	6.075 km/sec	7 km/sec
Impact Energy to Target Mass ratio (EMR)	78 J/g	86 J/g

Questions?