Two Space Debris Issues:
➢Long-Term Cost of Satellite Operations
➢Refining Reentry Disposal Hazards

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Outline

Space debris and costs

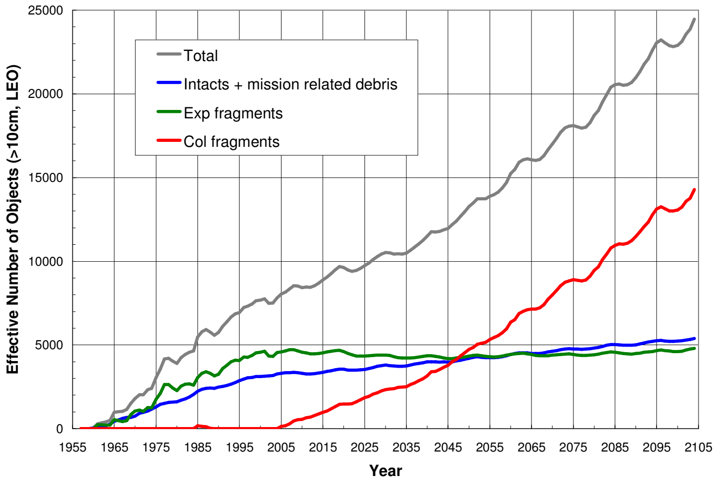
- How debris might affect costs of operating satellites

Refining reentry disposal hazards

- New device designed to refine understanding of reentry hazards

Space Debris and Costs

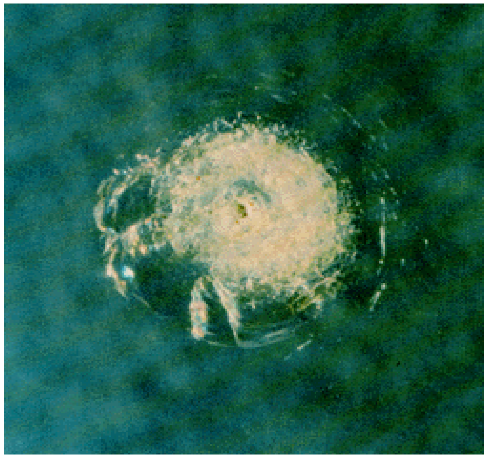
The Problem with Space Debris



J.-C. Liou, "A statistical analysis of the future debris environment," *Acta Astronautica* 62 (2008) , p264 – 271.

Assumes

- **200 to 2000 km altitude orbits**
- **No mitigation (no post-mission maneuvers to dispose of hardware)**
- **1997-2004 launch cycle**



4-mm-diameter crater on windshield of Space Shuttle Orbiter made by 0.2 mm fleck of white paint; relative velocity at impact: 3-6 km/sec (NASA photo)

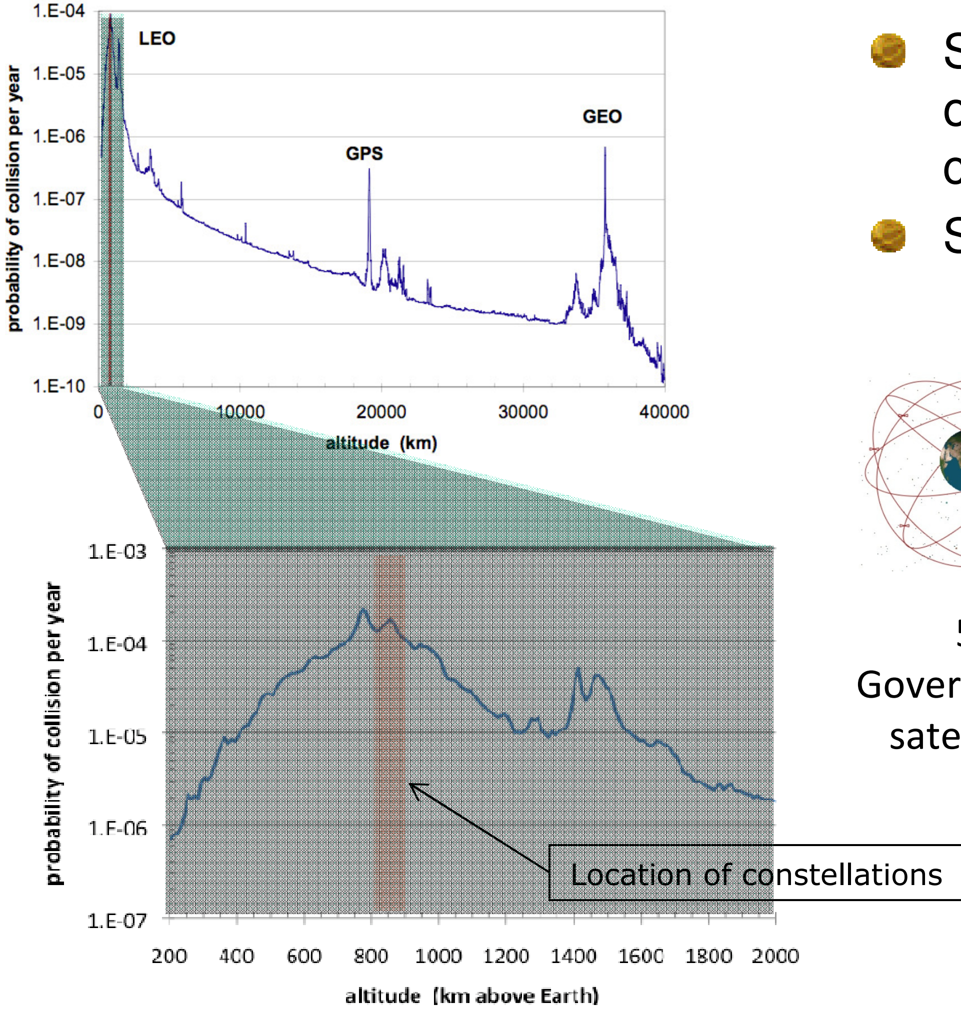
- Tracked objects
  - Objects larger that ~10 cm
  - >20000 objects, ~1000 operating satellites
  - Operating satellites with maneuver capability can move
  - Predict ~2 collisions per 10 years among tracked objects
  - Collision ends satellite's mission, creates more debris
- Untracked objects
  - ~600000 objects larger than 1 cm (impacts can damage or end mission)
  - Millions larger that 1 mm (impacts degrade solar panels)
  - Collisions much more common

How will Debris Environment Affect Costs of Maintaining Satellites?

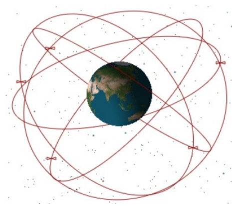
Analysis Approach

- Look at worst-case altitude range (~850 km altitude)
- Define three generic satellite types
- Define critical areas for each satellite type and size of impacting object
- Project populations of orbiting objects for 50 years (1 mm, 1 cm, >10 cm size ranges)
- Estimate changes in satellite operational lifetime due to debris environment
- Estimate increased cost to maintain constellation at full strength for 20 years; constellations fully constituted in 2010, 2020, 2030

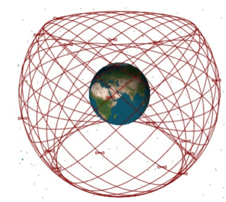
Location of Constellations



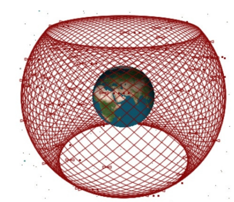
- Satellites placed in region where flux of objects (and probability of collision) is highest
- Sun-synchronous orbits at 850 km



5 Government satellites



20 Commercial Satellites #1

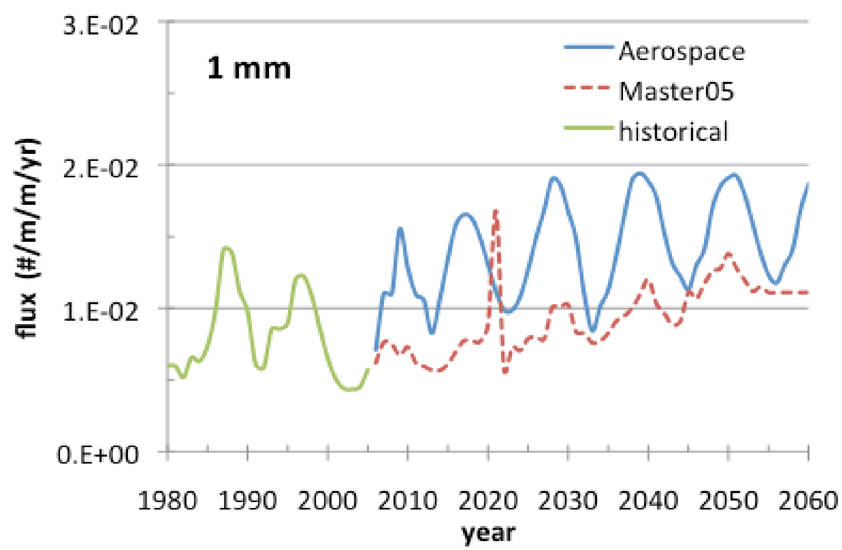


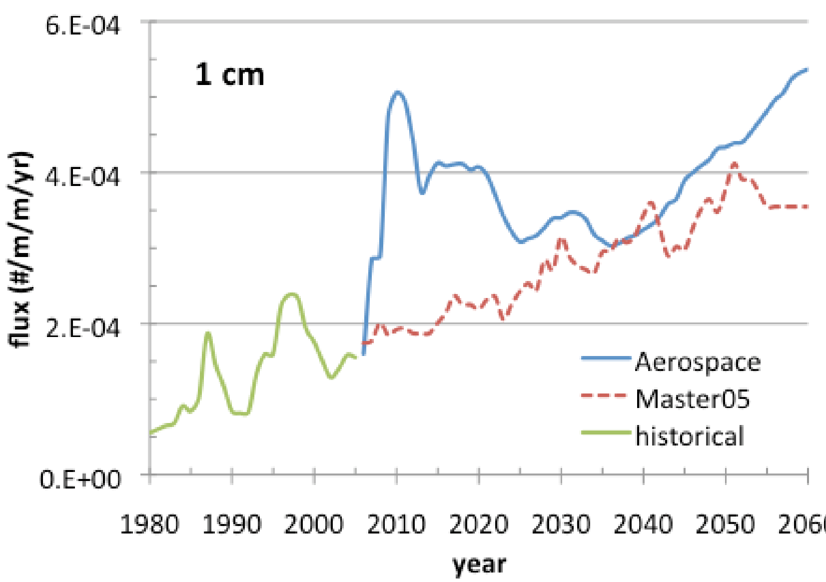
70 Commercial Satellites #2

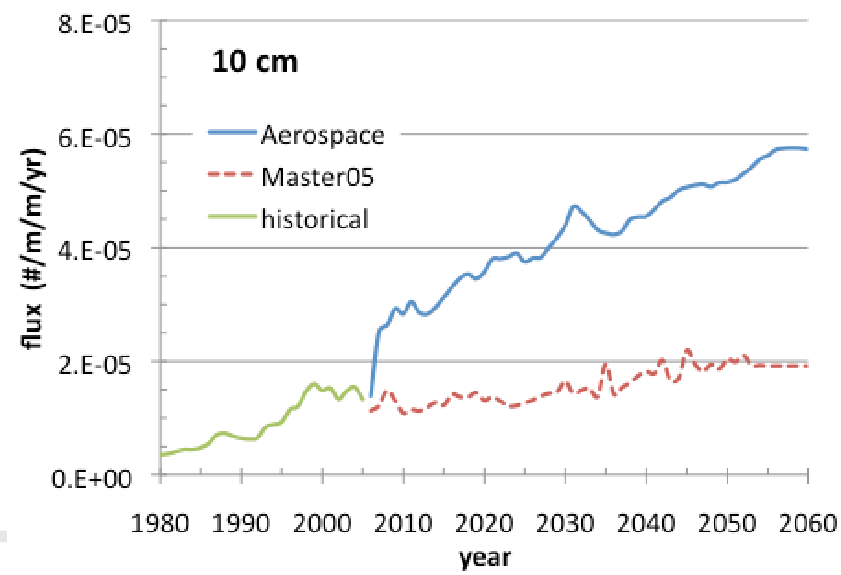
Results from Flux Model

Plots show the annual particle flux for a sample satellite in LEO Sun-synch orbit for 3 particles sizes

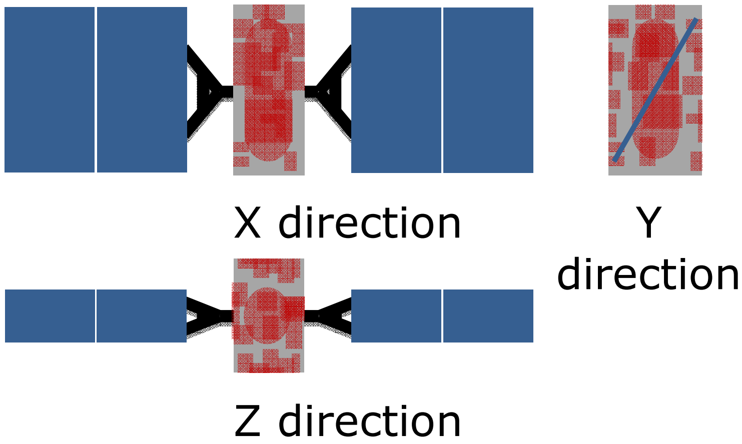
- The smaller particles will decay more rapidly than larger ones
  - Decay is a function of the 11-year solar cycle's effect on the atmosphere
  - For purposes of comparison, flux predictions for ESA's Master05 model are shown
- Master05 does not contain the recent FY1C or Iridium/Cosmos events



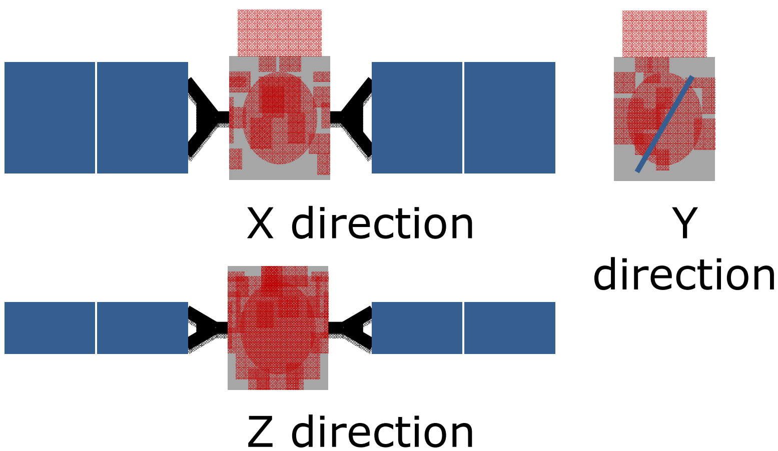




Three Satellite Types & Sizes



Generic Government Satellite



Generic Commercial Satellite

- Government satellite (5 in constellation)
  - Multiple missions
  - High reliability
  - High cost
  - 6-year design life
  - Exposed areas 5.5/15.5 m^2 (Min/Max)
  - 50-60 solar panel strings
- Commercial #1 (20 in constellation)
  - Medium cost
  - 9-year design life
  - Exposed area 8/25 m^2 (Min/Max)
  - 30-40 solar panel strings
- Commercial #2 (70 in constellation)
  - Single mission
  - Low cost “factory built”
  - 12-year design life
  - Exposed area 6.5/22.5 m^2 (Min/Max)
  - 20 solar panel strings

Replenishment Costs due to Debris

Cost Assumptions

Constellation	Satellite Unit Cost ($M)*	Launch Cost ($M)*	Notes
Government	750	250	Heavy lift ELV
Commercial #1	250	80	Medium lift ELV
Commercial #2	50	80	Medium lift ELV, 5 satellites co-manifested per launch

Results

Constellation	Year Constellation Constituted	Replenishment Cost ($B)*		
		No debris	Fatal only	All impacts
Government	2010 2020 2030	20.1 20.1 20.1	20.4 (1% increase) 20.5 (2% increase) 20.5 (2% increase)	20.8 (3% increase) 20.8 (3% increase) 20.9 (3% increase)
Commercial #1	2010 2020 2030	17.0 17.0 17.0	17.7 (5% increase) 17.8 (5% increase) 17.9 (5%	18.4 (9% increase) 18.4 (9% increase) 18.5 (9% increase)
Commercial #2	2010 2020 2030	7.9 7.9 7.9	8.5 (8% increase) 8.5 (8% increase) 8.6 (9% increase)	9.1 (14% increase) 9.2 (16% increase) 9.4 (18% increase)

*Costs in 2009 Dollars

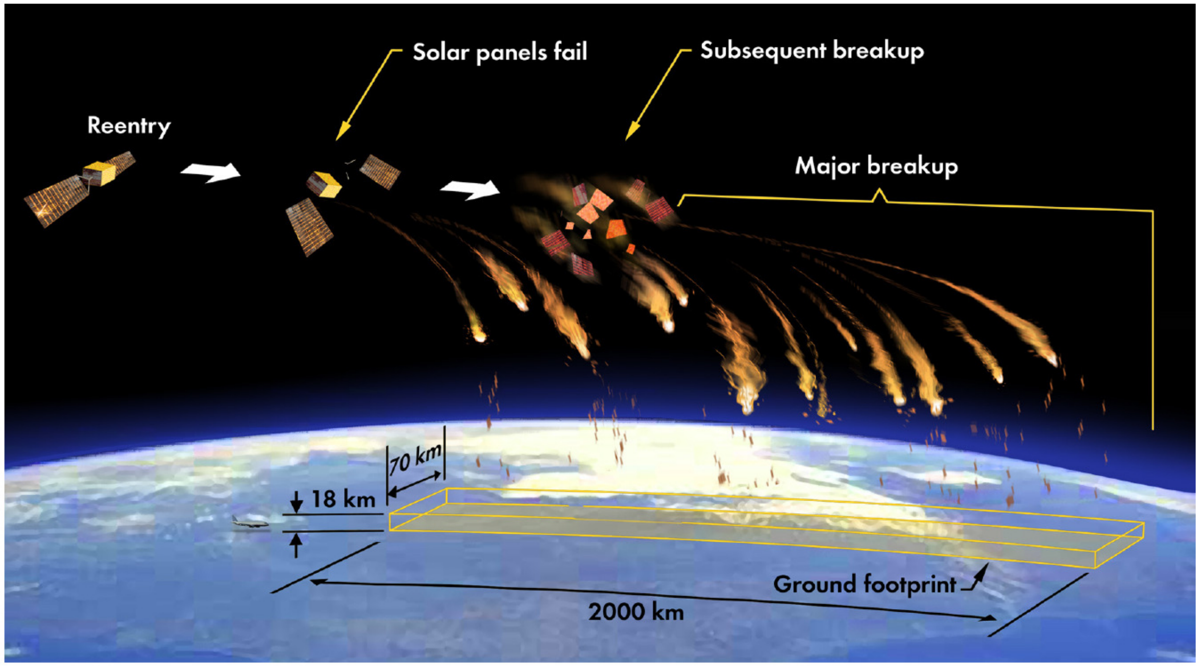
1-9% increase 3-18% increase

Summary

- Degradation of solar panels by small debris increases overall constellation maintenance costs
  - 1-2% for government satellites
  - 4-9% for commercial satellites
- Debris environment increases costs of maintaining constellations over no-debris costs by as much as
  - 3% today and 3% in 2030 for government constellation (i.e., no major change)
  - 14% today and as much as 18% in 2030 for large commercial constellation (increasing solar panel robustness reduces cost increase by ~50%)
- Results indicate slow growth cost due to debris environment at worst-case altitude over next 50 years
  - Less than 1% growth for government systems
  - As much as 4% growth for commercial systems
- Collision avoidance service reduces cost increase by ~10% (does not account for loss-of-service costs, etc.)
- Design-based debris mitigation (e.g., increasing solar panel robustness) may be acceptable strategy for significant period

Refining Reentry Disposal Hazards

Reentry Breakup Basics



Illustration, not to scale

- Space hardware reenters at very shallow angle (<1 degree)
- ~50 objects weighing more than 1 ton reenter randomly per year
- Major breakup at ~78 km (42 nmi)
- 10 to 40% of dry mass on orbit survives and impacts the Earth's surface; poses hazard to people and property
- Debris spread over long, thin ground footprint

Recovered Debris

Texas, 1997 (NASA photo)

Oklahoma, 1997 (World Staff Photo by Brandi Stafford)

South Africa, 2000 (Photo: Die Burger/Johann van Tonder)

Saudi Arabia, 2001 (NASA Photo)

South Africa 2000 (Photo: Argus/Enver Essop)

Current Status of Reentry Hazard Modeling

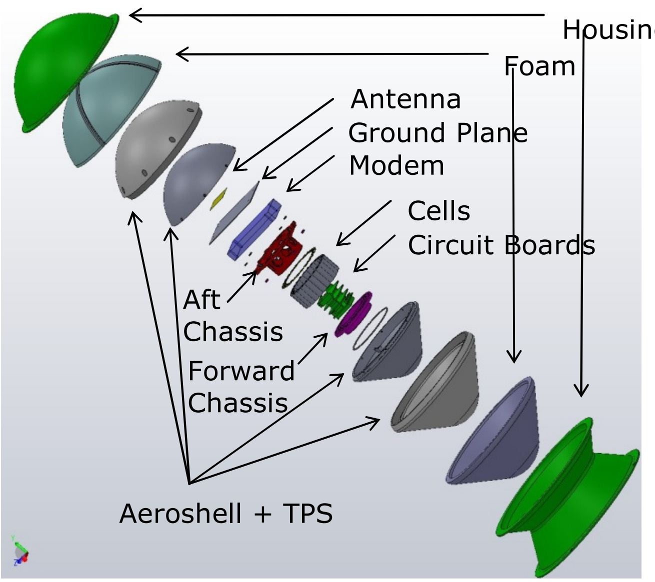
- Emerging requirements state that space hardware must be deorbited into a safe region if casualty expectation for random reentry exceeds a threshold value (1 in 10,000 in U.S.)
- Computer models are used to predict surviving debris and resulting hazards
- Validated reentry survivability models are needed for reliable "design for demise"
- Design for demise for future hardware will help satisfy policy requirements
- Results from reentry observations indicate reentry heating/breakup models at critical altitudes can be improved

Motivation for Reentry Measurement Data

- Quality benchmark data, from relevant flight regimes, needed to validate these models
- Ground facilities don't have capability to match reentry conditions
- Data collected during actual reentry and breakup needed to upgrade prediction models
- Data from multiple reentries would bound uncertainties

New Recording Device

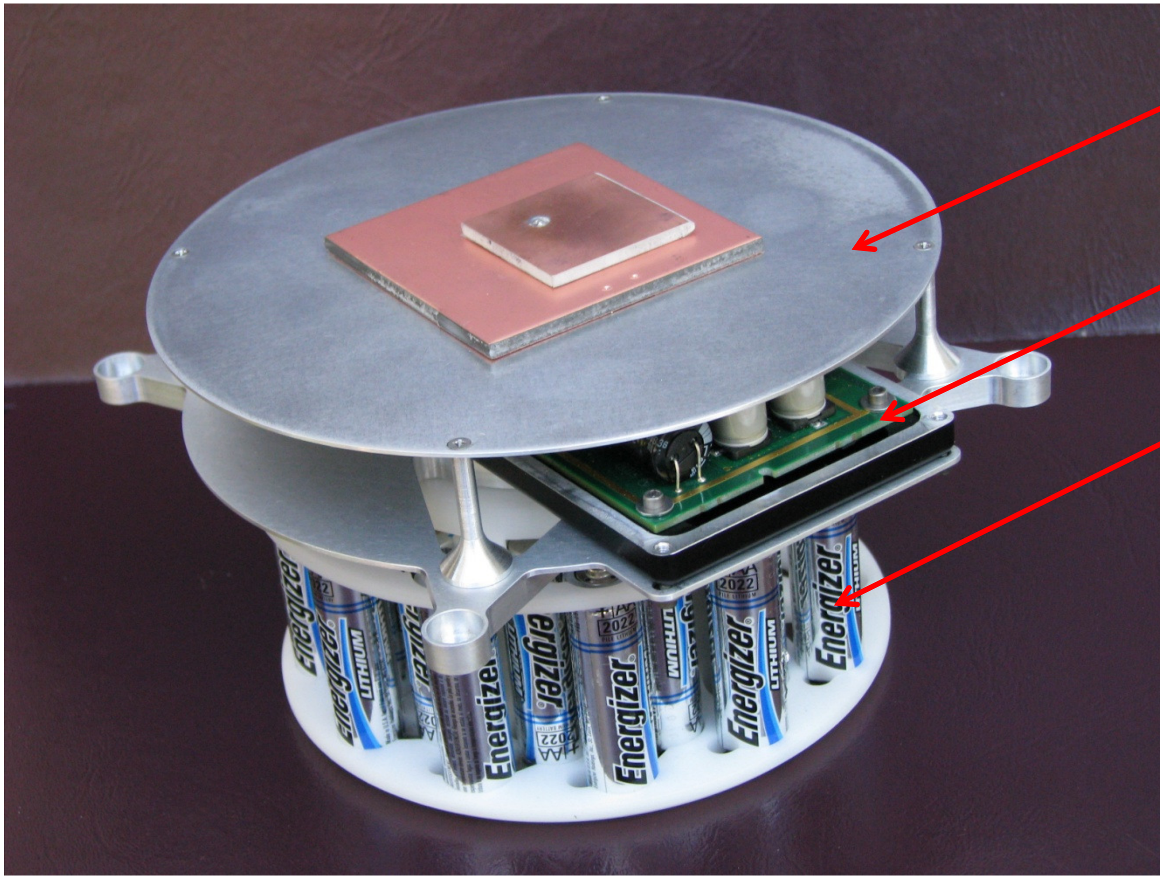
REBR recovered after balloon drop from 86,000 ft in 2006



Reentry Breakup Recorder (REBR) is

- Light-weight (~4 kg), self-contained, autonomous, survivable, locatable
  - Solid state sensors, low-power data recorder to collect data
  - Internal GPS sensor to provide location
  - Light-weight, rugged heat shield material to protect recorded information
  - Satellite-based cell phone (modem) to send recorded information and location near real-time
- Attached to host vehicle, sleeps until atmospheric reentry
- Wakes up and records data on host vehicle leading up to and during breakup
- Transmits recorded data via Iridium satellite system during freefall
- Retrieval not required

REBR Instrument: “Cell Phone with a Heat Shield”



GPS & Iridium Antennas

Iridium Modem & GPS

Batteries & Electronics

•24 AA batteries

•Electronics include

- Command and control
- Accelerometers
- Rate gyro
- Data recorder
- Temperature & pressure sensors
- Data from thermocouples in heat shield

2011 – First Flights

ATV-1 (Jules Verne) (courtesy ESA)

ATV-1 (Jules Verne) Reentry Sept 29, 2008 (courtesy NASA, ESA)

HTV-1 (courtesy JAXA)

- First reentry tests scheduled for 1st Quarter 2011 aboard European Space Agency's Automated Transfer Vehicle ATV-2 and Japanese HTV-2 missions to the International Space Station
  - REBR will record data during reentry breakup of ATV-2 and HTV-2
  - REBR will protect data through reentry
  - Recorded data will be transmitted during post-reentry flight and before ground impact
- Information recorded during breakup
  - First ever collected during breakup of unprotected vehicle
  - Revolutionize study of reentry hazards
    - Enable validation of hazard prediction models
    - Enable spacecraft, launch stages to be designed to minimize risks from surviving debris
    - Maximize spacecraft mission life, assure hazard limits not exceeded
  - Precise information on impact location
- REBR will also be platform for testing new heat shield materials
- REBR paves way for spacecraft "Black Box" system

Summary

- Device developed to collect, protect, and transmit data collected during breakup of space hardware
- Data critical for validating hazard models and designing hardware to minimize hazards after reentry, increase compliance with safety requirements
- First reentry test in 2011

Additional Information

Effect of space debris on long-term costs of space operations

- Ailor, W., Womack, J., Peterson, G., Murrell, E., “Space Debris and the Cost of Space Operations,” Presented at the 4th International Association for the Advancement of Space Safety Conference, Huntsville, Alabama, May 19-21, 2010.
- Ailor, W., Womack, J, Peterson, G., Lao, N., “Effects of Space Debris on the Cost of Space Operations,” IAC-10.A6.2.10, Presented at 61st International Astronautical Congress, Prague, Czech Republic, September 27-October 1, 2010.

Refining reentry disposal hazards

- Ailor, W., Dupzyk, I., Shepard, J., Newfield, M., “REBR: An Innovative, Cost-Effective System for Return of Reentry Data,” Presented at AIAA Space 2007 Conference, Long Beach, CA. August 2007.