Early Results from the Multi-Application Survivable Tether (MAST) Experiment

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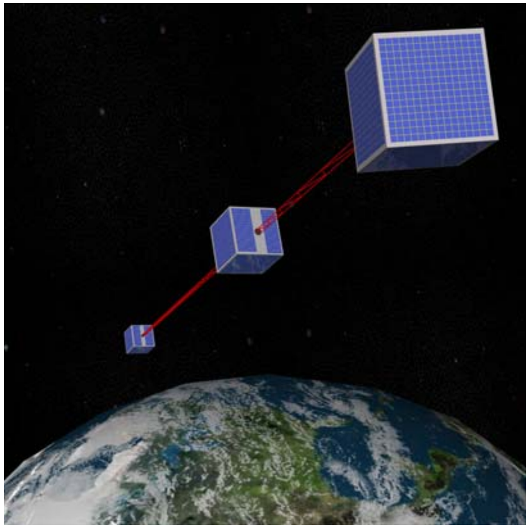
MAST Mission Objectives & Approach

- **MAST - Multi-Application Survivable Tether Experiment**
- **Mission Objectives:**
  - **Deploy a multi-line 'space-survivable' tether structure on orbit**
  - **Inspect tether over a period of several months for micrometeorite & orbital debris impact damage and degradation due to atomic oxygen**
  - **Collect data on tethered satellite dynamics for validation of tether dynamics models**
    - **Measure relative position of tether endpoints, and attitude dynamics of tethered spacecraft**
- **Approach**
  - **Use CubeSat platform to conduct low-cost demonstration space flight**
    - **Use 3 picosats – Deployer (*Ted*), Inspector (*Gadget*), Endmass (*Ralph*)**
  - **Deploy 1-kilometer multi-strand tether between the end picosats (*Ted* and *Ralph*)**
  - ***Gadget* will continually traverse the tether and image it to observe effects of the space environment on the tether, nominally for 6 months**
  - **Collect data on dynamics of tethered spacecraft**
    - **GPS on picosats**
    - **Magnetometer & solar cell data for attitude estimations**

System Architecture

- **Three independent Spacecraft**
  - Tether Deployment Cube (TED)
  - Inspector Cube (GADGET)
  - Instrumented End-mass Cube (RALPH)



- **Design Requirements and Philosophy**
  - Class D mission – single-string failures permitted
    - "Medium or significant risk of not achieving mission success permitted."
    - "Minimum assurance standards are permitted."
    - *ONE EXCEPTION – mechanism to initiate tether deployment may be self-initiated with a watchdog timer (CSM/nano Release Mechanism)*
  - COTS components used in system
    - Reasonable to use in space environment and applications as determined through test, heritage, or analysis
  - Maximal reuse of components and modules throughout MAST

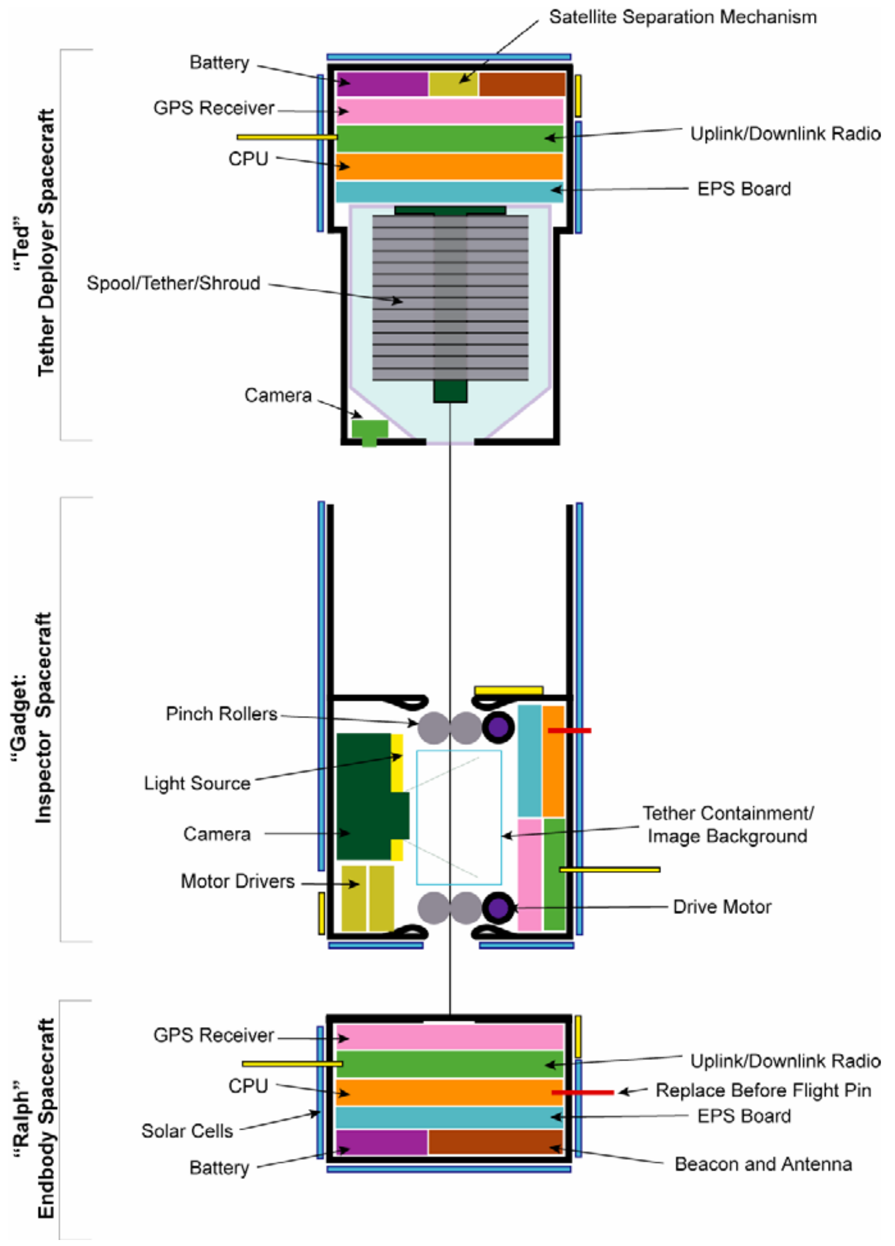
MAST Block Diagram

TUI Engineering the Future

TED

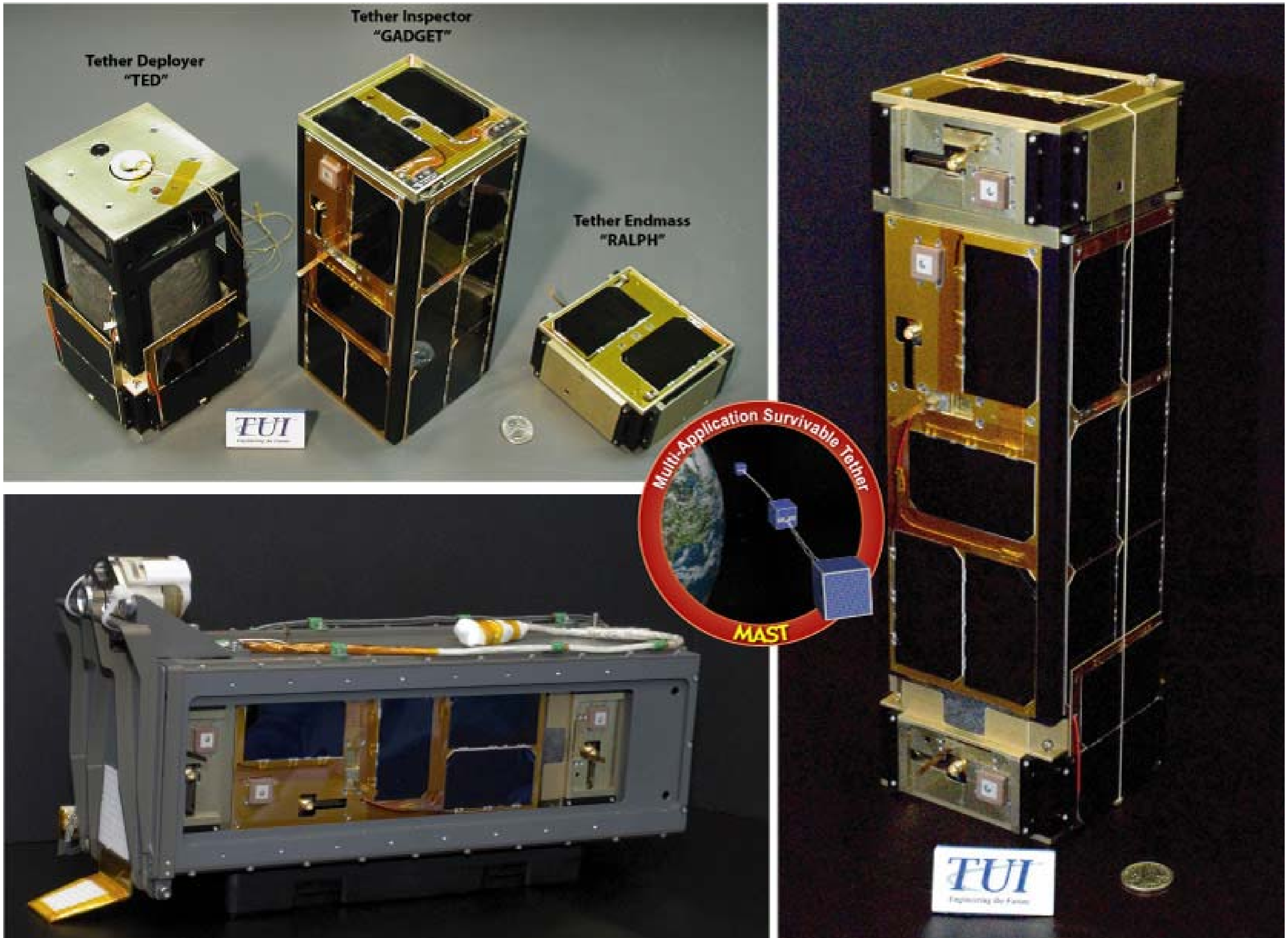
Gadget

Ralph



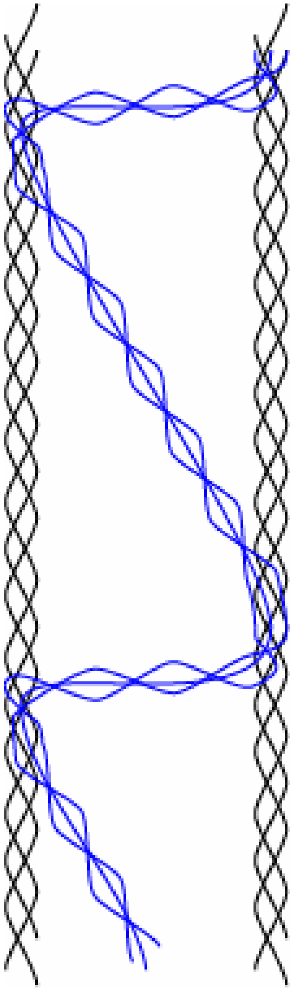
MAST Flight Hardware

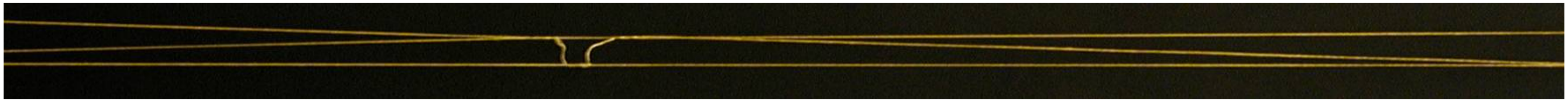
TUI
Engineering the Future



MAST Tether Design

- Minimum mass and volume Hoytether™
  – 250 g/km
- Non-conductive tether
- MAST Tether has 2 primaries, 1 secondary
  – Nominal Primary Line separation distance - 25mm
  – Primary/Secondary tie point separation distance – 250mm
  – Secondary has additional length to permit slack
- MAST Hoytether™ constructed of 250 denier 2% TOR coated Zylon® (PBO)
  – Primary & Secondary Line Diameter ≈ 0.5 mm
- MAST Tether Survivability
  – Expect to see 3.3 to 9.3 cuts/month
  – Probability of survival > 99.7% for 6 months

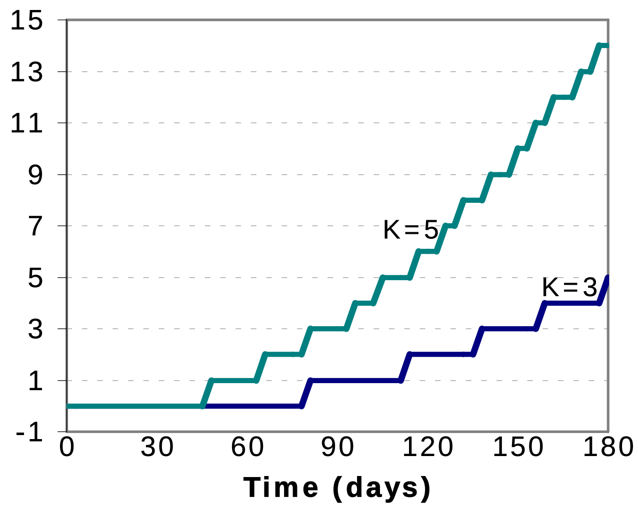


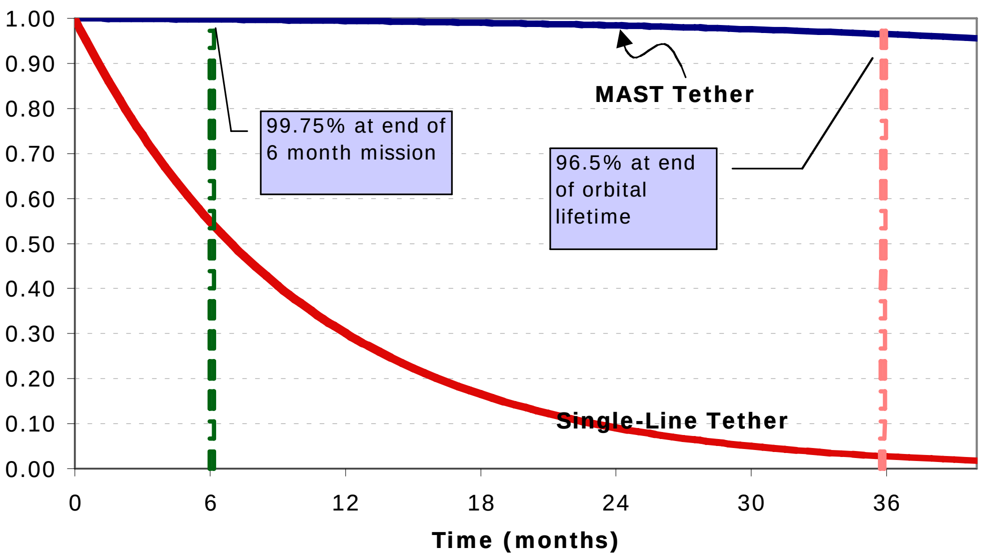


MAST Cut Rate & Survivability

- Prior experiments and analyses indicate a tether can be cut by a M/OD object 3-5 times tether's diameter
  - MAST experiment will measure 'lethality coefficient' *K*
- To obtain data on cut rates, Gadget will slowly crawl along tether and record images of each section of tether
- Nominally 14 days to traverse 1 km of tether

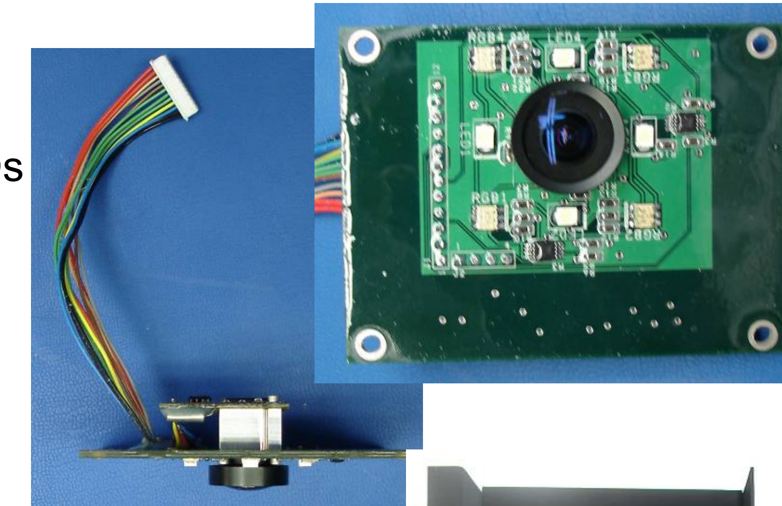
Lethality Coeff.:		3			5		
	Dia. (mm)	Impactor Dia. (mm)	OD Flux (#/m^2 yr)	# Cuts/month	Impactor Dia. (mm)	OD Flux (#/m^2 yr)	# Cuts/month
Primaries	0.5	0.17	19.9	3.3	0.1	55.6	9.3
Secondaries	1	0.33	4.2	0.7	0.2	14.0	2.3

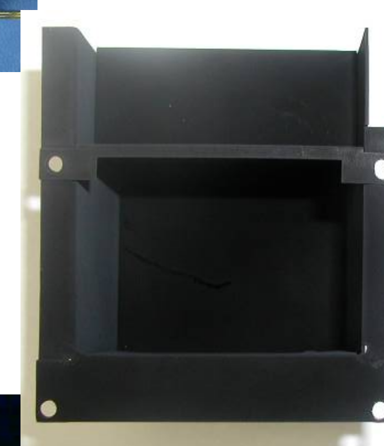




Inspector Flight Imager

- VGA (640x480) Color CMOS Imager with integrated JPEG compression
  - CMOS Imagers more radiation tolerant than CCDs
  - Image Transfer Modes
    - Still – 640x480/320x240/160x128/80x64
    - Video - 160x128 @ 0.75-6 fps
- Affordable COTS Optics
  - 3.66 mm f/2.0 1/3" CCD Lens, M12x0.5 thread
  - Lens consists 4 Glass Elements in Black Anodized Barrel
- Background for image is 'Laser Black'
  - Semi-fragile copper oxide of micro-dendritic structures on the optical surface
- Active illumination
  - Intensity controlled White & RGB LEDs
- Nominal Imaging Operations
  - 160x128/320x240 color image ≈ 2K bytes
  - 640x480 image taken of region of interest





Zero-G Testing

- **MAST Tether Deployment**
  - **Separation of Ted from Gadget+Ralph, and tether deployment initiated by flight-like Nanosat Release Mechanism**

  - **Off-nominal tether deployment tests with fast and slow tumbling deployers performed – all successful**

MAST Flight Timeline

- **MAST experiment was delivered into LEO on 17 April 2007 aboard a Dnepr rocket launched out of Baikonur Cosmodrome, Kazakhstan**
  - Initial Orbit: 782 x 647km, inclined at 98.1º
- **First contact opportunity, late 19 April 2007**
  - Contact immediately established with Gadget
- **Deployment Switch opens 30 minutes into flight**
- **Last contact with Gadget made on 14 May 2007**
- **Last attempted contact: 21 May 2007**

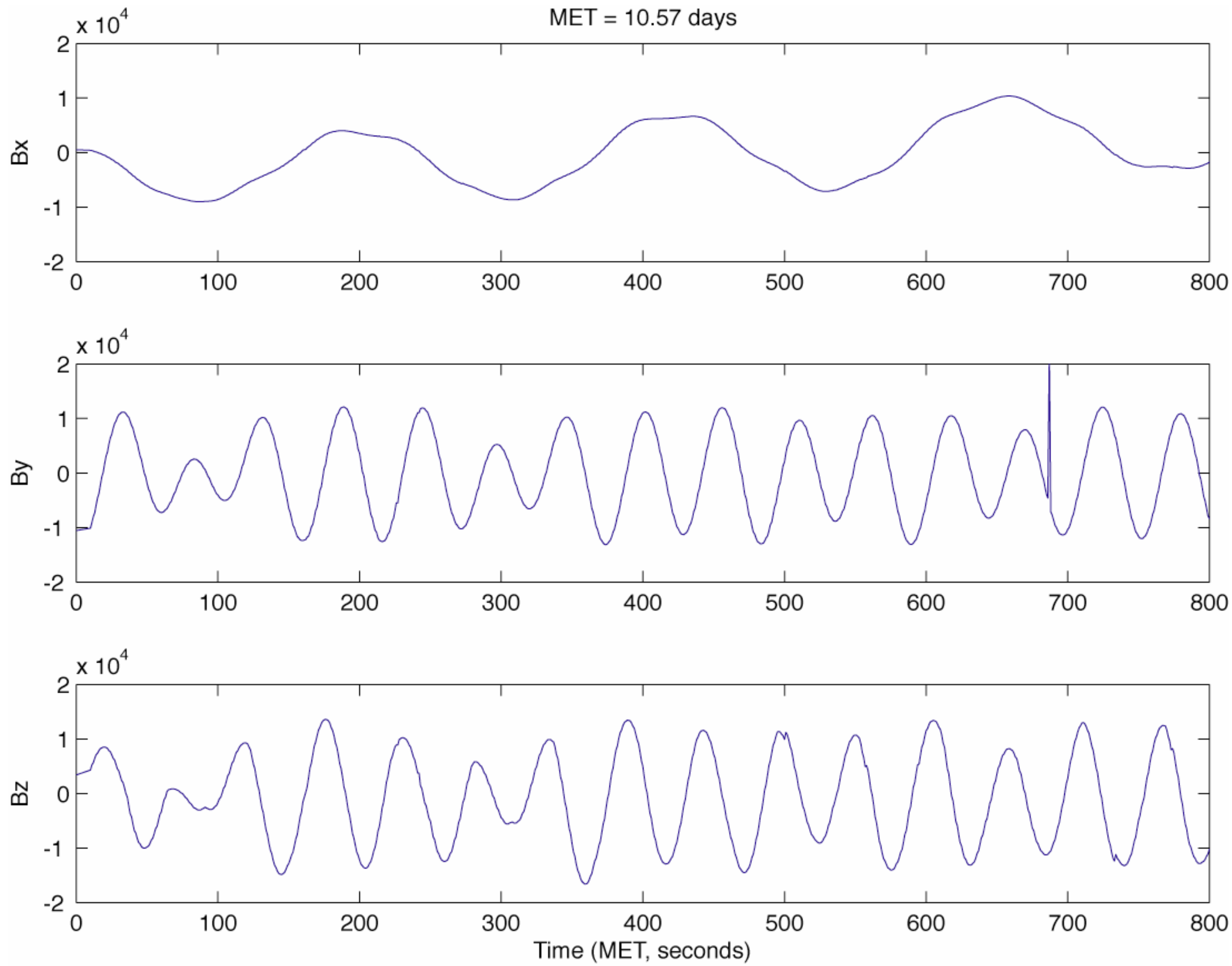
- **Magnetometer & Solar Panel data analysis to estimate Gadget's attitude behavior over time**
- **Postponed planned Gadget crawling operations to let dynamics settle down**

- **Just before contact was lost plans included:**
  - **Test crawling mechanism**
    - **Short crawl (~15 cm) to image exposed tether**

- **Back-up tether deployment option:**
  - **Crawl Gadget towards Ted to pull more tether off of spool**
  - **Plan was not do this due to risks involved until later in the mission**

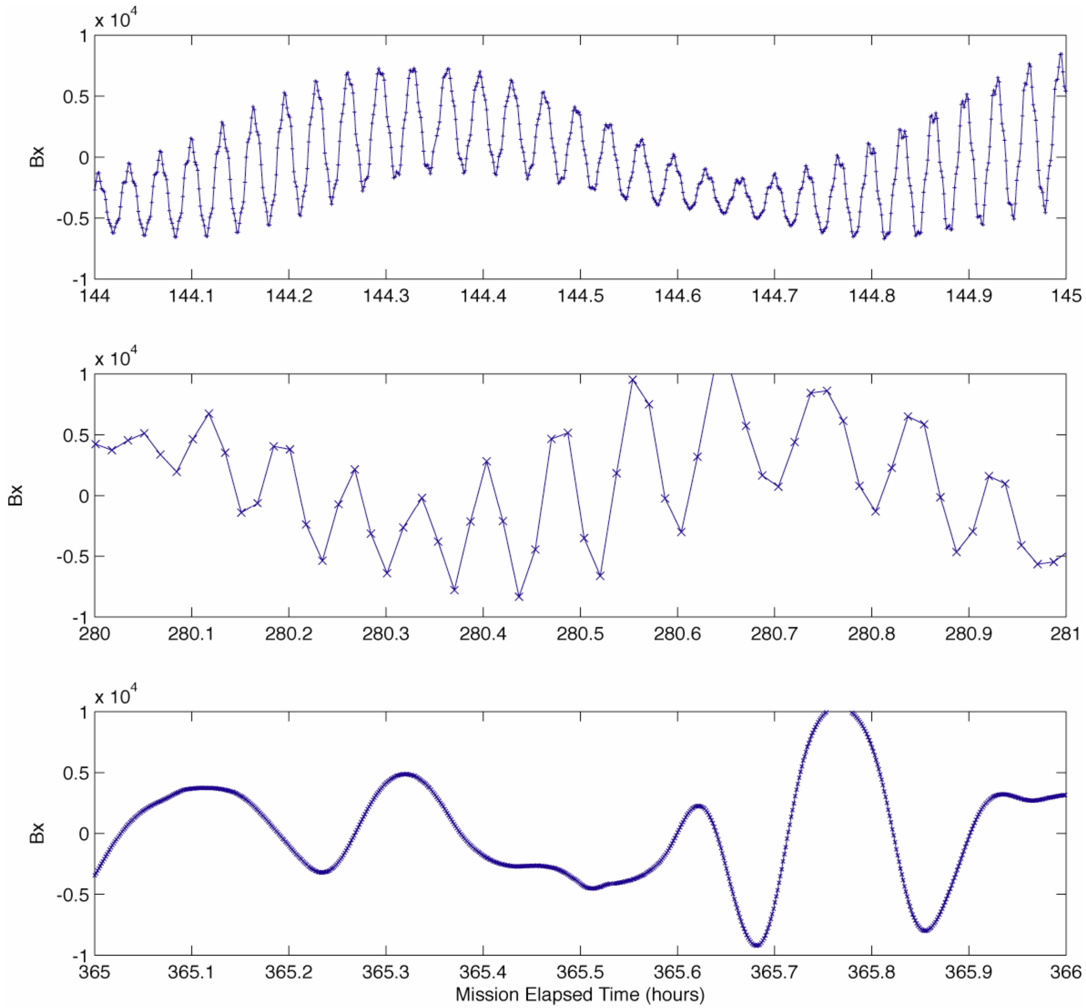
Gadget Magnetometer Data

Gadget's
Long Axis



- **Magnetometer data shows evidence of:**
  - Spin around long axis with period = 50 seconds
  - Rotation around short axis with period = 224 seconds

Evolution of B_x Over Time



Period

121 s

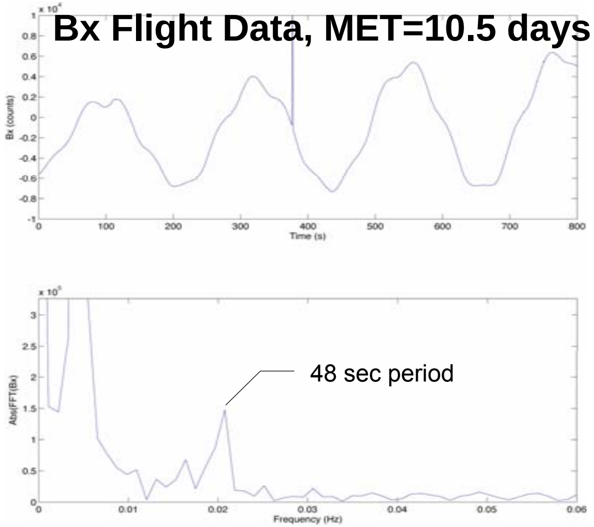
269 s

782 s

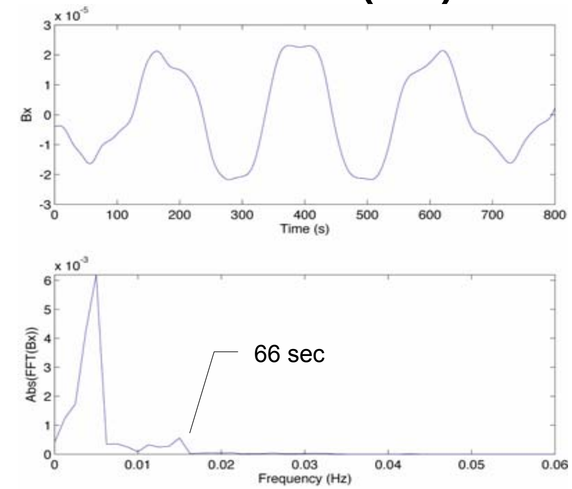
- **Marked rotation rate decrease over time**
  - **Transition from out-of-plane rotation to in-plane libration?**

Rotation Analysis

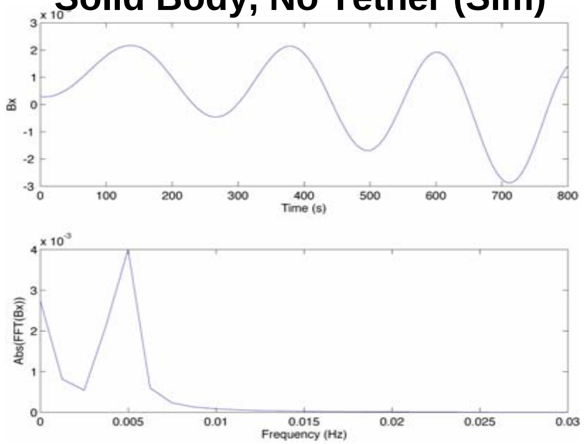
Bx Flight Data, MET=10.5 days



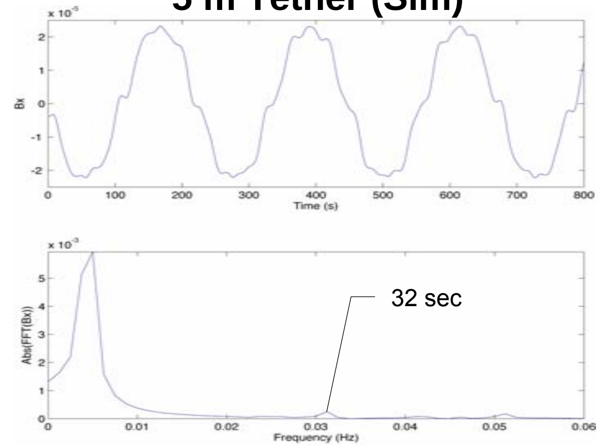
1 m Tether (Sim)



Solid Body, No Tether (Sim)



5 m Tether (Sim)



- B_x signal at MET=10.5 days shows evidence of precession of spin due to short tether
  - Deployed tether length at MET=10.5 days is only on the order of a few meters
- Corroborated by data from Space Command

GPS & Communications Performance

- **GPS:**
  - Almanac acquired, tracked up to 7 satellites
- **Radio: Microhard MHX-2400**
  - Frequency: 2.4 GHz ISM
  - Modulation: frequency hopping spread spectrum
- **Spacecraft Antenna: 1/4 wave monopole**
- **Altitude: 720 km**
- **Transmit Power: 1 Watt**
- **Receiving Antenna: SRI 18 m parabolic mesh dish**
  - SRI and Santa Clara University provided support for dish operations
- **Estimated Performance:**
  - Theoretical Bandwidth: 80-115 kbps
  - Laboratory Throughput Tests: 30 kbps
  - Predicted Link Margin: < 10 dB
- **Limitations:**
  - Synchronization time and Doppler shift vs. frequency hopping period
  - Elevated 2.4 GHz noise floor in Silicon Valley
- **Actual Performance:**
  - Peak bandwidth ~ 15 kbps
  - Optimization of download packet size and ground software increased data download from 10kB to 250kB per pass
  - Total data downloaded in 3 weeks > 2 MB

Summary

- Restraint/release mechanism did not function properly resulting in low separation velocity
- Due to insufficient energy, only a short segment of tether was deployed
  - Unlikely that any tether survivability can be collected
- Highlights the risks of single-string, low-cost class-D missions

- Experiment did collect data on dynamics of tethered spacecraft

- Successful operations of Gadget do demonstrate that science and technology missions can be achieved on a picosatellite scale