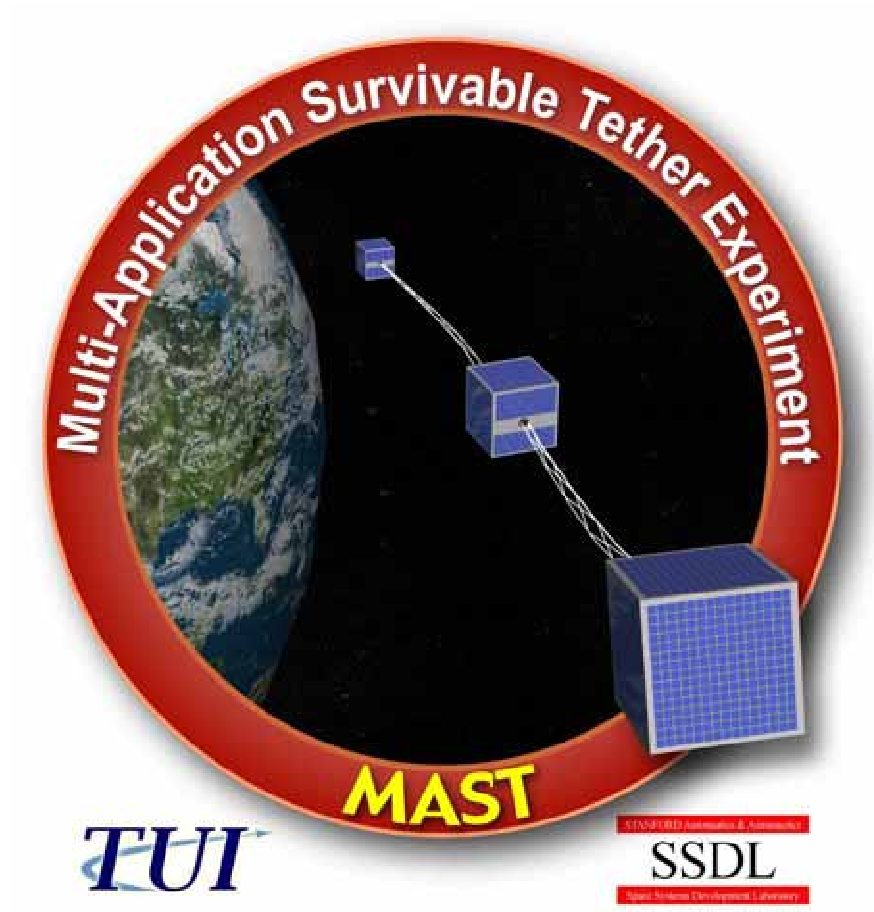
MAST: A Low-Cost Investigation of Space Tether Survivability and Dynamics



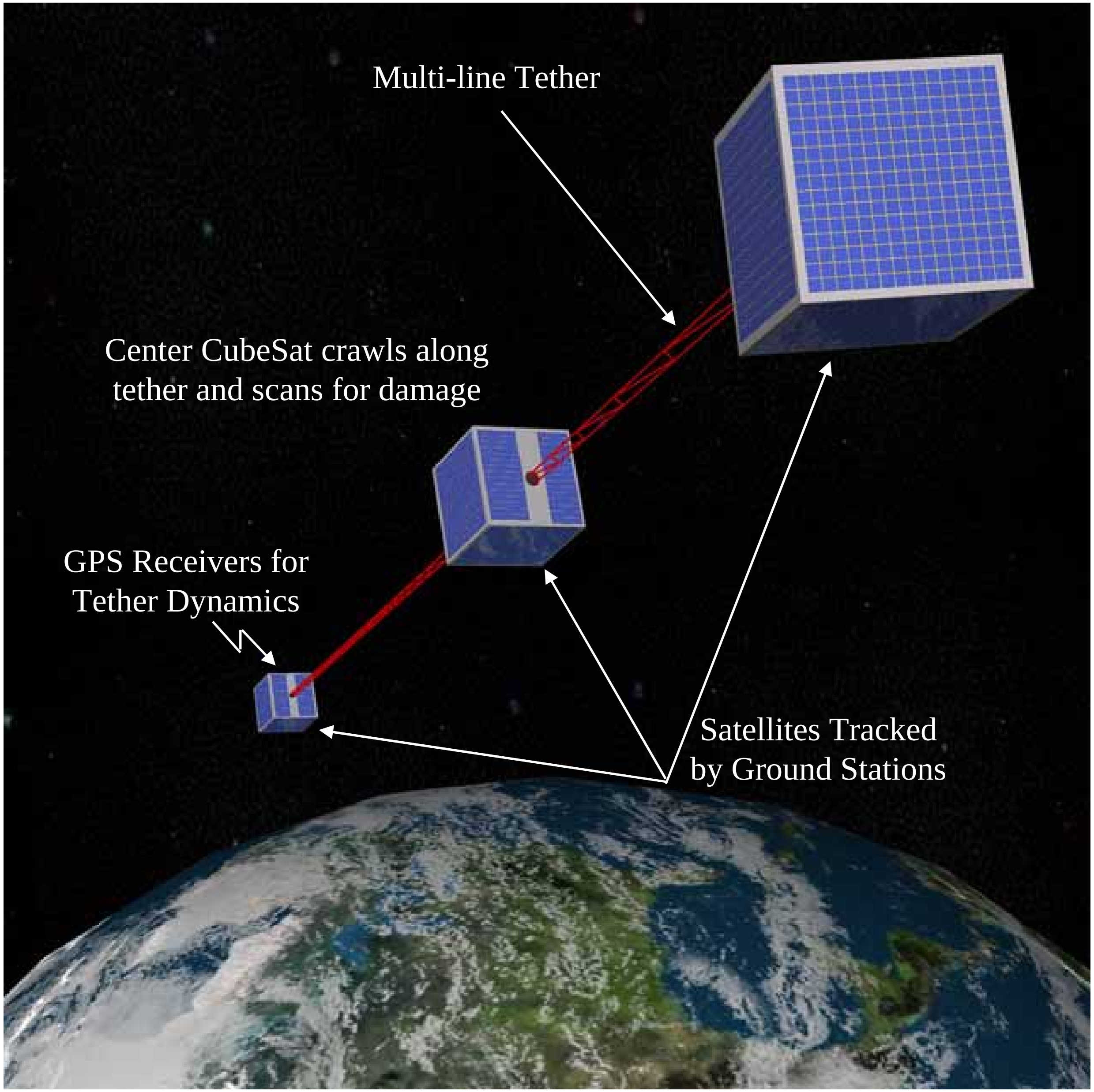
TETHERS UNLIMITED, INC.
11711 N. Creek Pkwy S, Suite D-113
Bothell, WA 98011
(425) 486-0100 Fax:2-9670

For more info contact:
Nestor Voronka
voronka@tethers.com
(425) 486-0100 x678

MAST Mission Objectives

- MAST - Multi-Application Survivable Tether Experiment
- PRIMARY Mission Objective
  - Inspect multi-strand for micrometeorite impact damage and degradation due to atomic oxygen (AO)
    - Image tether which is a multi-strand 1 kilometer Hoytether™ constructed of MXER tether prototype material
- SECONDARY Mission Objective
  - Collect data on passive tether dynamics for study of formation dynamics and validation of tether dynamics models
    - Measure relative position of tether endpoints, and crawling body
- GOAL
  - Use CubeSat platform to conduct low-cost demonstration space flight
    - Use a 3 CubeSat platform – Deployer (TED), Inspector (GADGET), Other Endbody (RALPH)
      - Utilize an entire P-Pod Deployer with 3 x 1kg, and 3 x 10cm^3 cubes
  - Image Tether for 6 months

Mission Concept

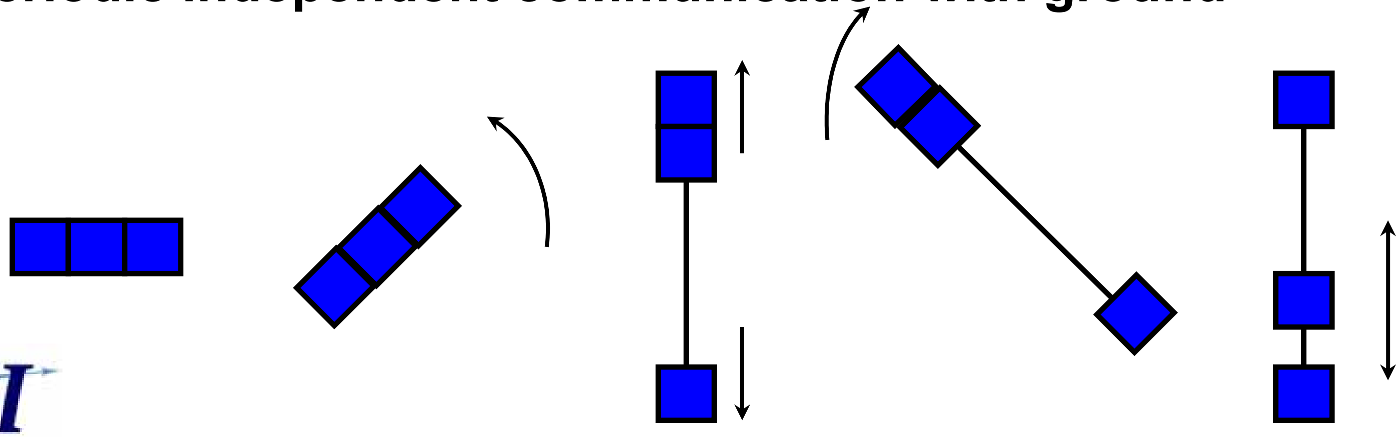


Mission Description

- MAST will consist of 3 tethered CubeSats in Low Earth Orbit (LEO)
- A 1 kilometer multi-strand HoyTether™ will be deployed between the end CubeSats (*Ted* and *Ralph*)
- An Inspector Cube (*Gadget*) will traverse the tether to observed the effects of the space environment on the tether
- Tether Dynamics Data will be gathered throughout the mission and transmitted to the ground
  - Position, Velocity and body attitude will be sampled at a higher rate during tether deployment
  - Position, Velocity and body attitude will be sampled at a reduced rate periodically throughout the mission

Mission Phases

- **Pre-Deployment**
  - Orbit insertion from P-POD
  - Wait for increased separation from other CubeSats
- **Deployment**
  - Tether deployment initiated by an impulsive separation
- **Inspection**
  - Formation Flying/Gravity Gradient Stabilization
  - Inspector cube will traverse tether multiple times
  - Images of entire tether will be sent to ground for analysis
  - Selectable flight dynamic information sampling
  - Periodic independent communication with ground

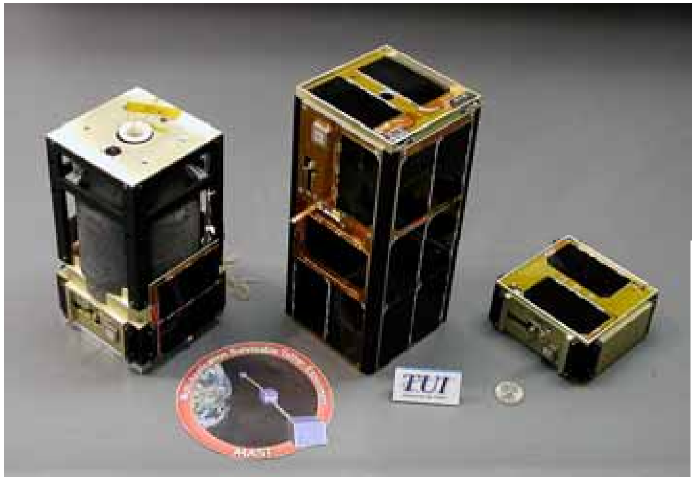


Overall Mission Timeline

- **On-orbit operations**
  - After (P-POD deployment)+3 days, command deployment of tether
  - After (P-POD deployment)+7 days, CSM watchdog timer independently activates cube separation regardless of orientation and status of spacecraft
  - After (Tether deployment+7 days), start crawling along tether
  - Image deployed tether repeatedly, with 7 day nominal crawl time
  - (OPTIONAL) Tether can be (partially) retracted at end-of-mission
    - Will Increase the orbital lifetime
- **Launch Schedule**
  - Currently scheduled launch date is 1 Dec 2006
  - Orbit: 803.0 x 658.5 km, with 98°inclination
  - Predicted Orbital Lifetime: 3.57 years

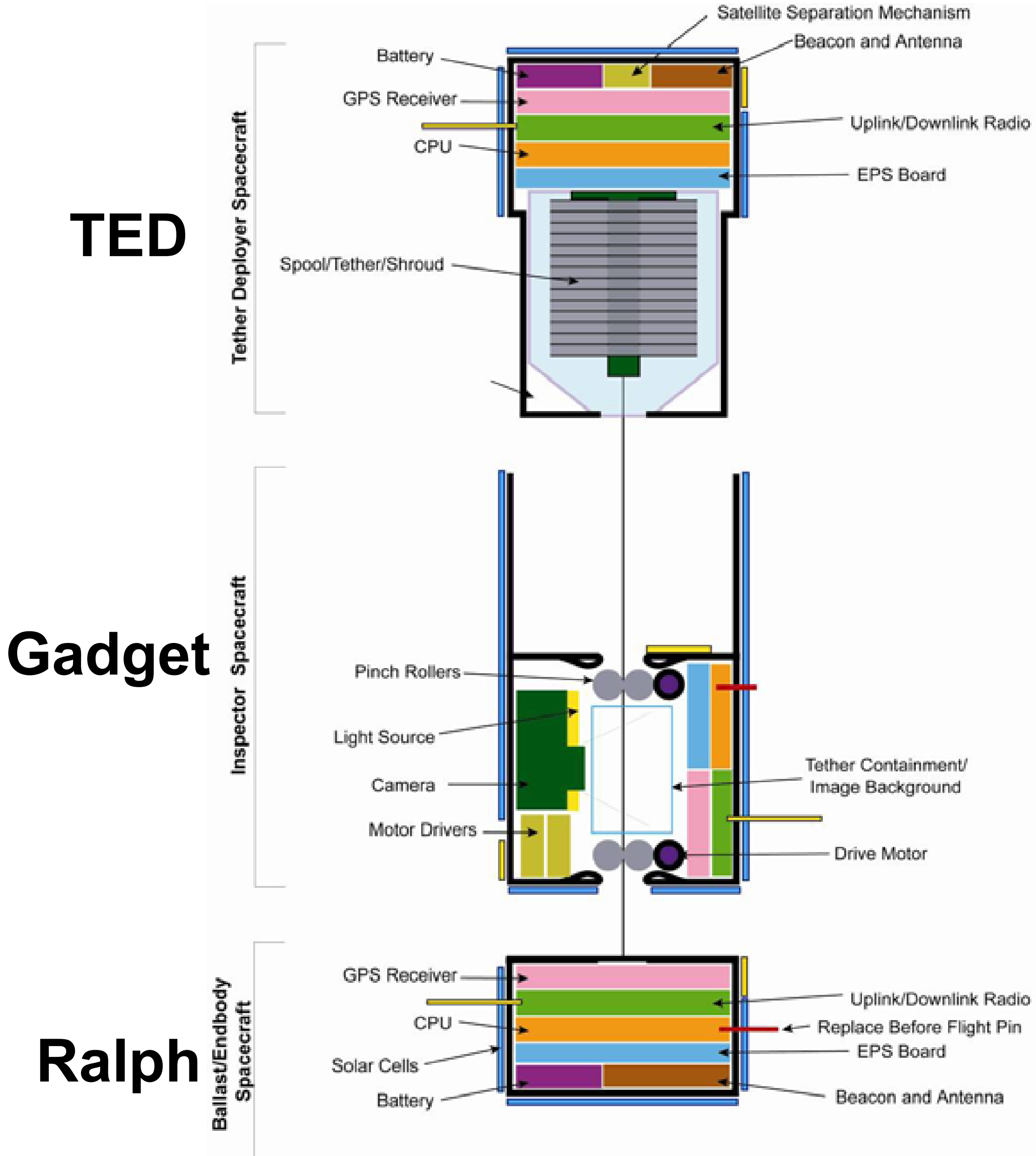
System Architecture

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

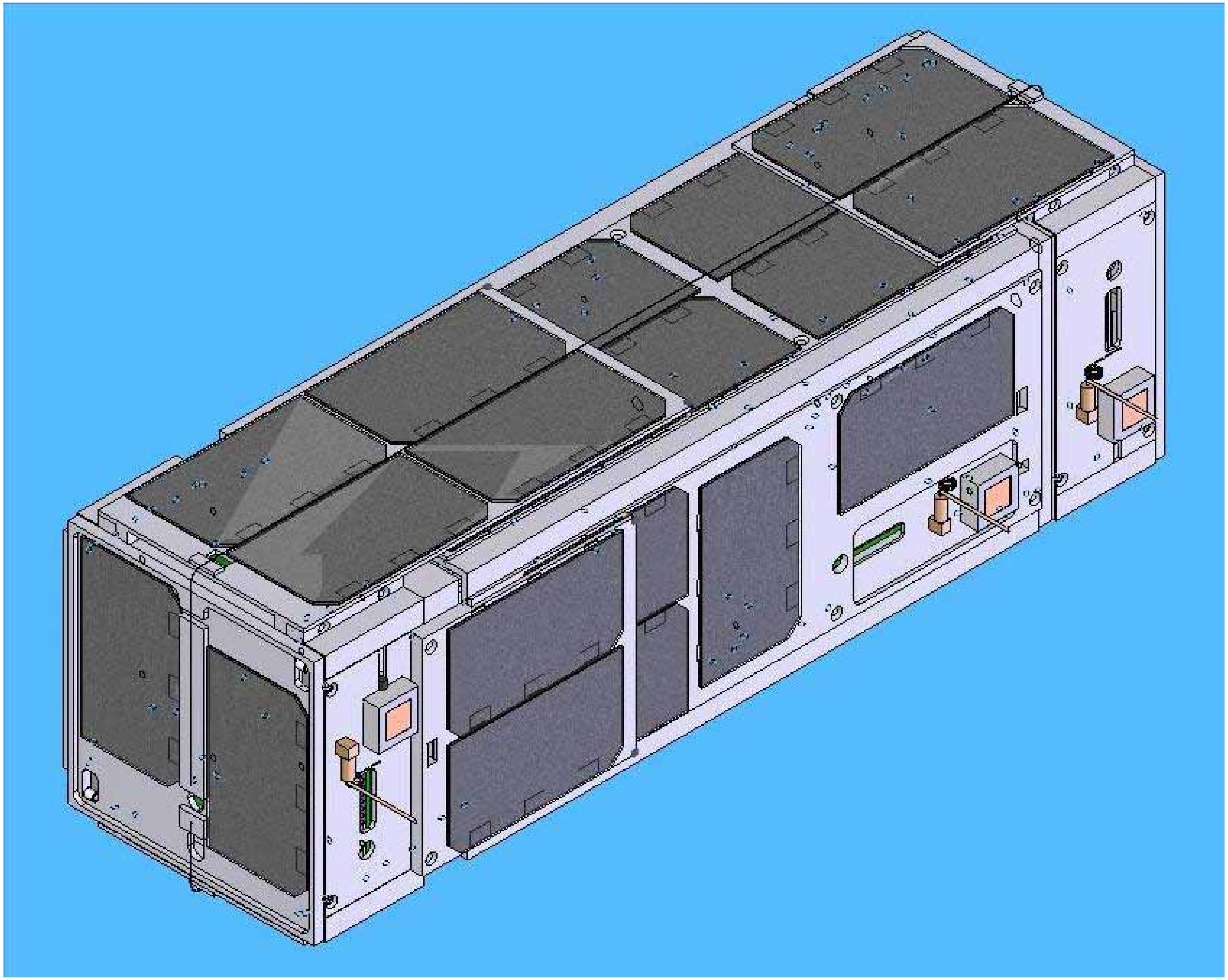


- **Design Requirements and Philosophy**
  - Class D mission – single-string failures permitted
    - "Medium or significant risk of not achieving mission success permitted."
    - "Minimum assurance standards are permitted."
    - *ONE EXCEPTION – mechanism to initiate tether deployment may be self-initiated 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

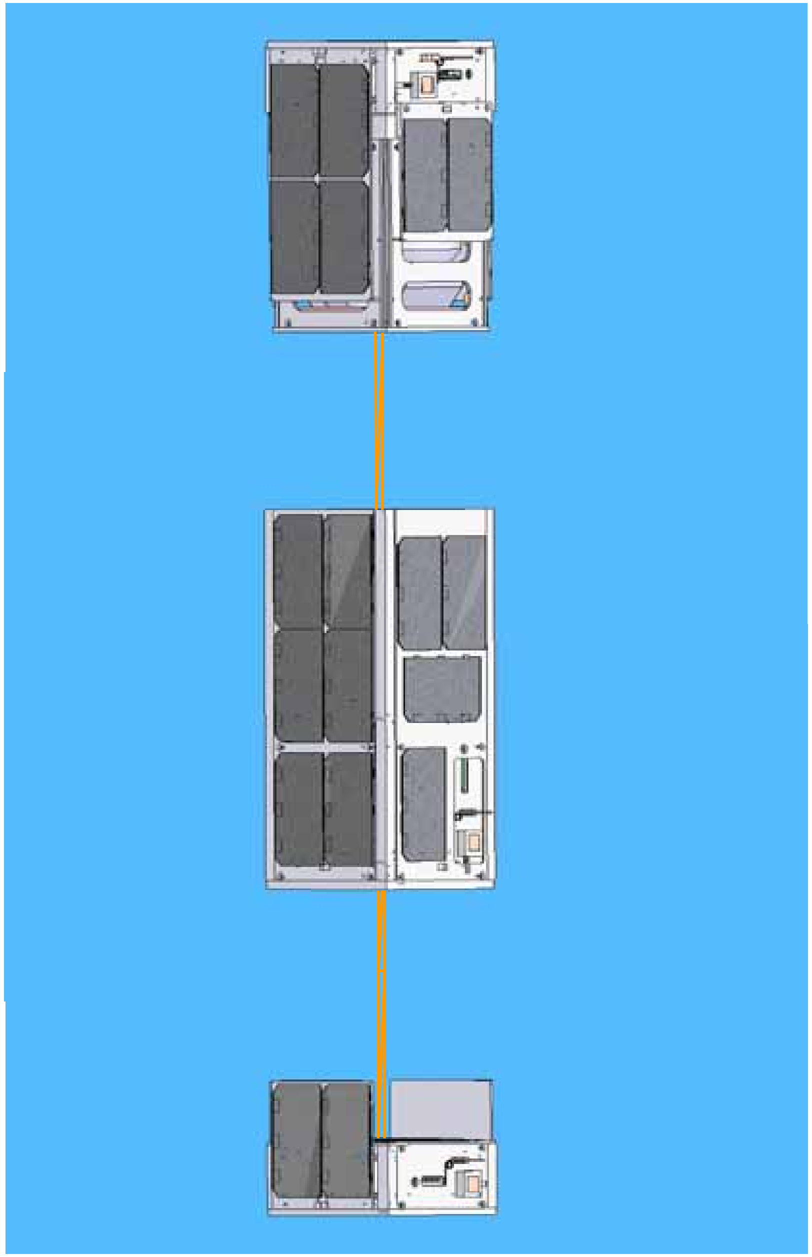
MAST Block Diagram



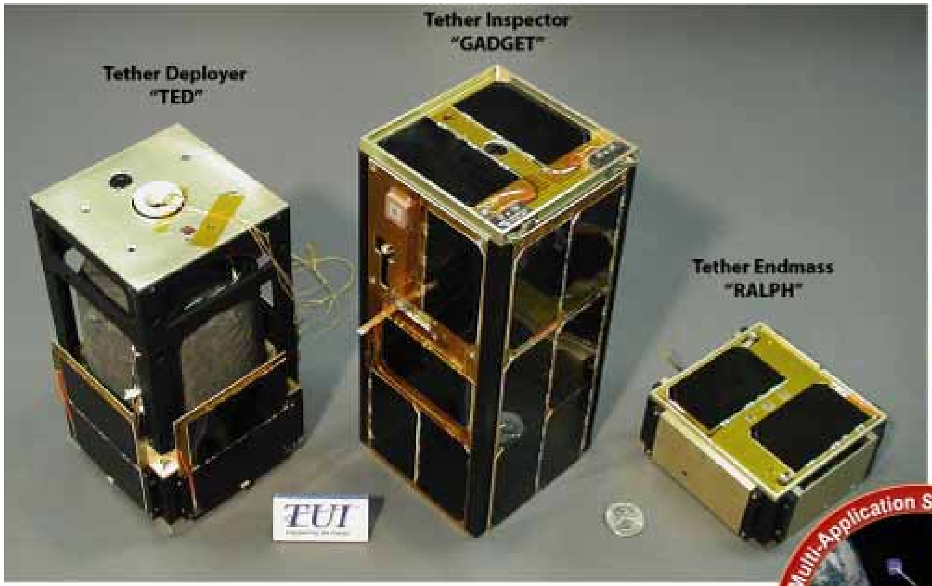
MAST Experiment Before Tether Deployment



MAST Experiment After Tether Deployment

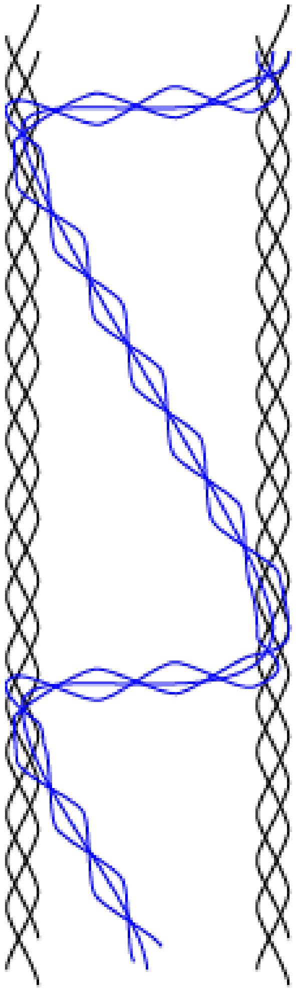


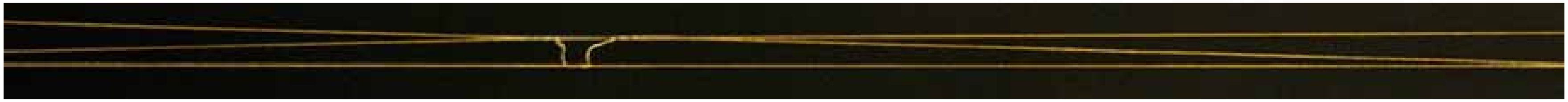
MAST Flight Hardware



MAST Tether Design

- Minimum mass and volume HoyTether™
- 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 > 99.9% for 6 months
- Tether is visually marked every few meters
- Radar reflective element (33cm long conductor) integrated into tether every 200m





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MAST Expected Debris and Meteoroid Flux

- **Orbital Debris and Micrometeoroid Flux**
  - **Use NASA/JSC Orbital Debris Engineering Model**
    - **ORDEM2000 Does not include meteoroid flux**
  - **Since meteoroid flux approximately equal the orbital debris flux in the 0.1 – 1.0 mm range, we double the ORDEM2000 predicted debris flux**

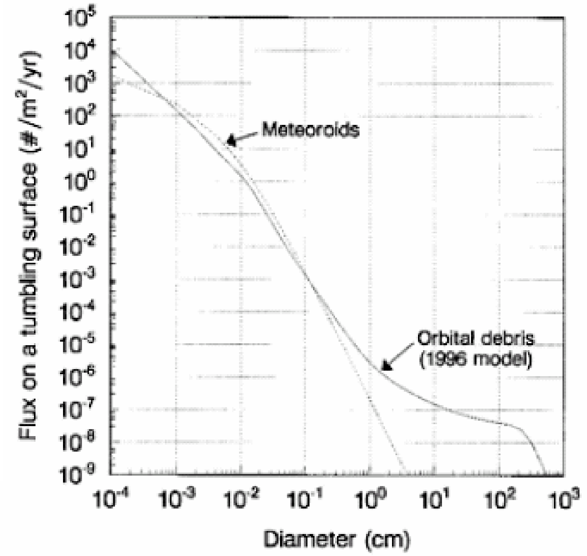
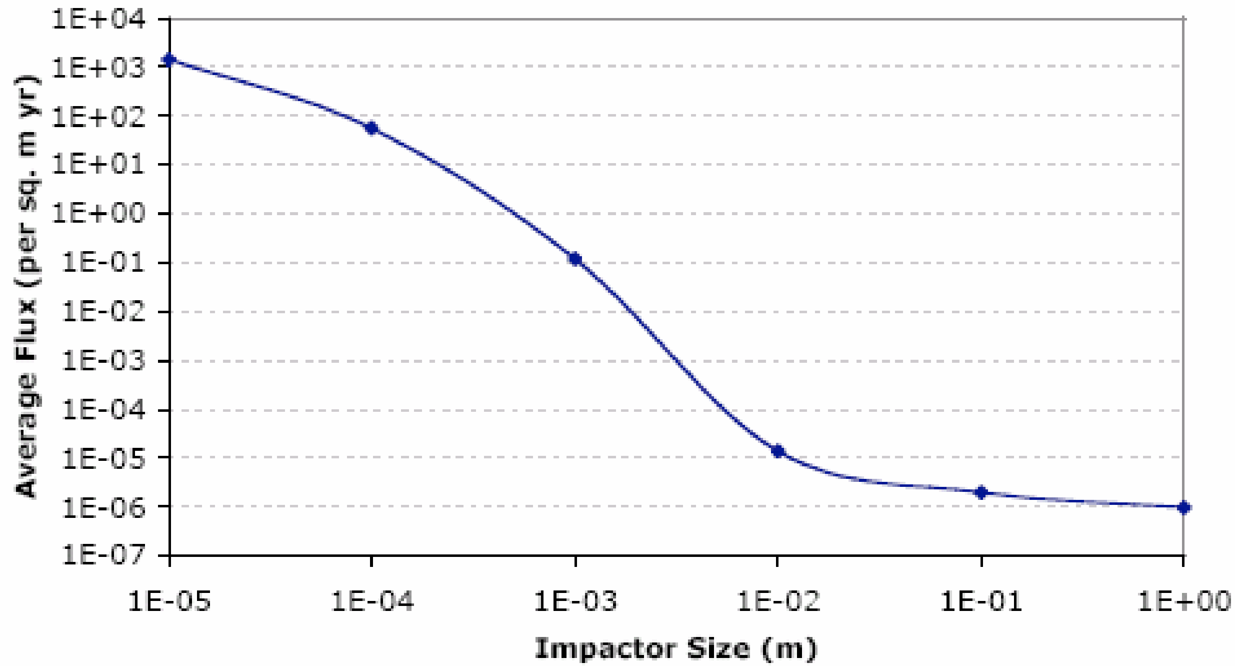


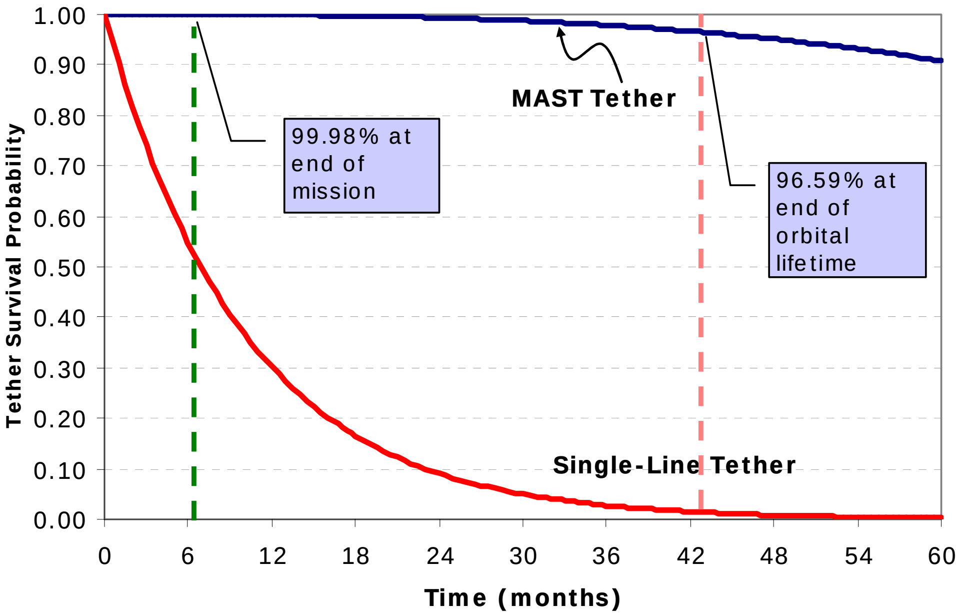
FIGURE 3-1 Comparison of meteoroid and debris flux in ISS orbit. Source: NASA.

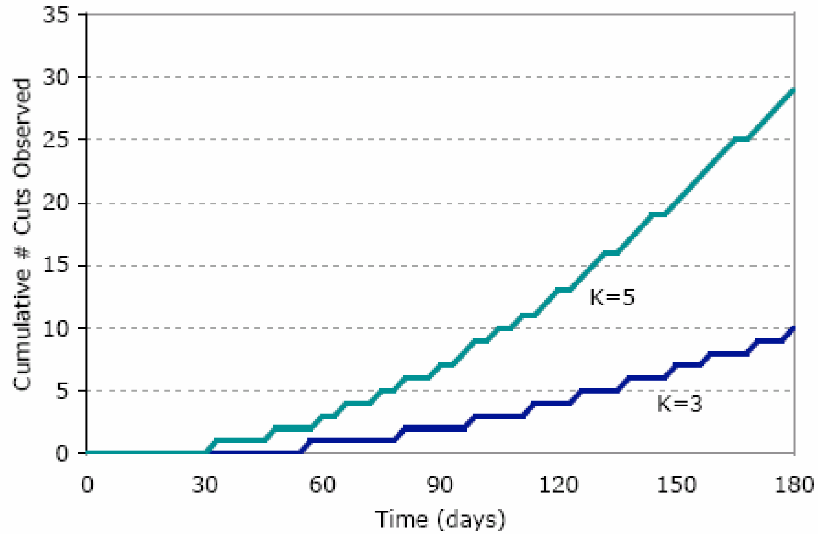


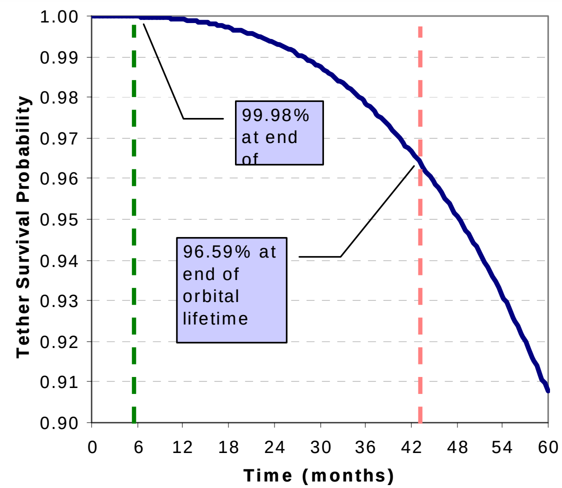
MAST Tether Cut Rate & Survivability

- **Prior experiments and analyses indicate a tether can be cut by an object 3-5 times its diameter**
  - **<u>MAST experiment will measure K</u>**
- **Inspector will traverse and image the 1 km tether nominally over 7 days**

Lethality Coeff.: Dia. (mm)	3 Impactor Dia. (mm)	OD Flux (#/m^2 yr)	# Cuts/month	5 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

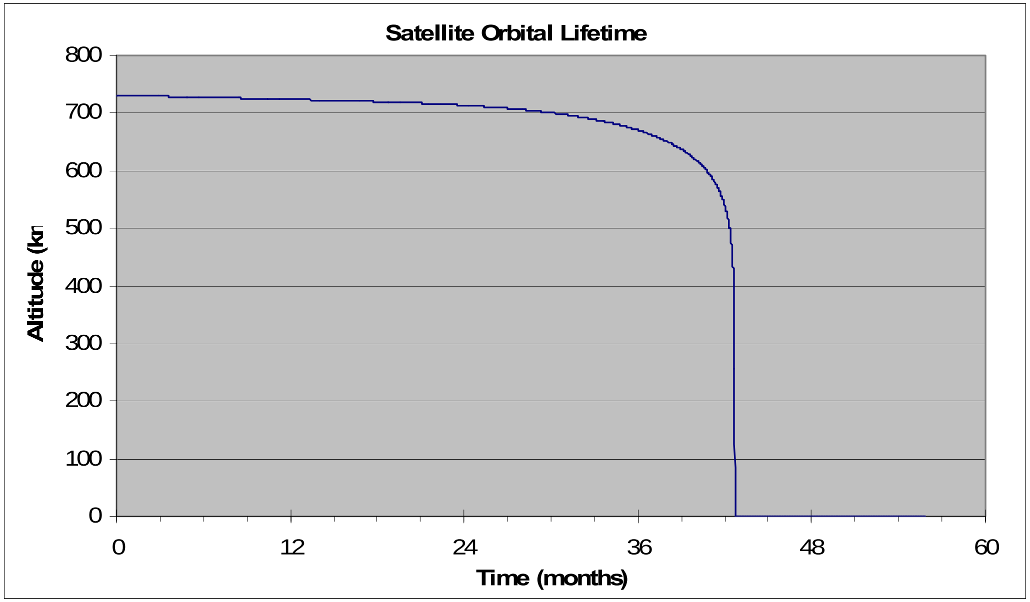






MAST Orbital Lifetime

- **MAST experiment with 1km of tether**
  - System Mass: 3.21 kg
  - Cross-sectional area after tether deployment:
    - 0.034 m^2 (spacecraft) + 1.5 m^2 (tether) = 1.53 m^2
  - Ballistic Coefficient: 1.044 kg/m^2
- **Simulation Inputs**
  - Initial Orbit: 98º inclination, 803.0 x 658.5 km orbit
  - Orbital Insertion: 01 December 2006
- **Predicted Orbital Lifetime: 3.57 years**



Orbital Debris Assessment

- **Assessment of Orbital Debris Generated by Explosions and Intentional Breakups**
  - – **MAST *<u>DOES NOT</u>* contain the following explosion or breakup hazards:**
    - **Pressurized volumes**
    - **On-board propellants**
    - **Fuel storage or transport systems**
    - **Pyrotechnics**
    - **High capacity batteries**
  - – **MAST DOES contain the following breakup hazard:**
    - **Kinetic Energy Storage Devices**
      - – **There are 4 spring/post units in the Inspector Cube**
        - **Impart a 0.9 m/s relative separation velocity for tether deployment**
        - **Motion of posts and plate constrained**
      - – **Kinetic energy is held in storage by a Vectran cable**
        - **Cable is severed by heat from a nichrome wire**
        - **Cable ends remain attached to Ralph**

MAST Inspector - Gadget

- **Inspector Requirements**
  - Inspector will travel along the 1 kilometer length of the tether with knowledge of its absolute position along the tether
    - Crawler mechanism will minimize the tether dynamics perturbations
    - Crawling velocity and acceleration is limited by tether tension
  - Inspector will inspect the tether with sufficient resolution to determine tether damage due to micrometeoroids, and orbital debris
    - Optical imaging most suitable for evaluating
  - Having sufficient resources (power, image storage space, downlink) Gadget will traverse the tether once every 7 days
- **Additional Design Goals**
  - Gather data on tether and body dynamics
    - Inspector will house GPS receiver in addition to GPS receivers in tether endbodies
    - Integrate magnetoinductive 3-axis magnetometer & compare to IGRF/WMM
    - Measure power produced by solar panels on each face (coarse sun sensor)

Command and Telemetry Radio

- Telemeter collected images, attitude, and housekeeping data to the ground
- Receive commands to modify MAST operations
- Constraints and Challenges
  - Low average available power
  - Image download requires high data rates
- MAST Comm Radio
  - Microhard MHX-2400 transceiver
    - 2.4 GHz ISM band, 1 Watt output power
    - Frequency Hopping Spread Spectrum
    - 115.2Kbaud Serial Interface
    - Satellite Antenna – monople with ≈ 2 dBi gain

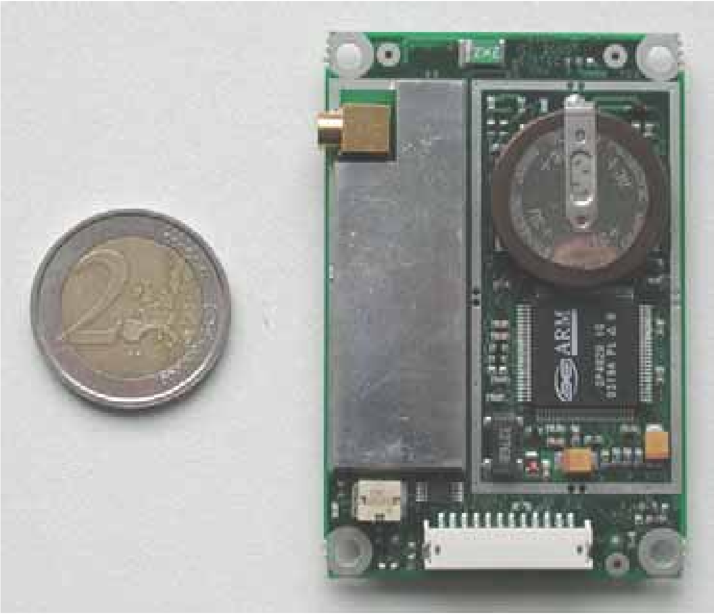
- Access Time: nominally 23 minutes/day
- Effective Throughput:
  - 20 Kbps (Considering packet overhead, round-trip delay, etc.)
- Downlink Capability:
  - 3.45 MegaBytes per day
- Transmission controlled by onboard orbital propagator to minimize power requirements

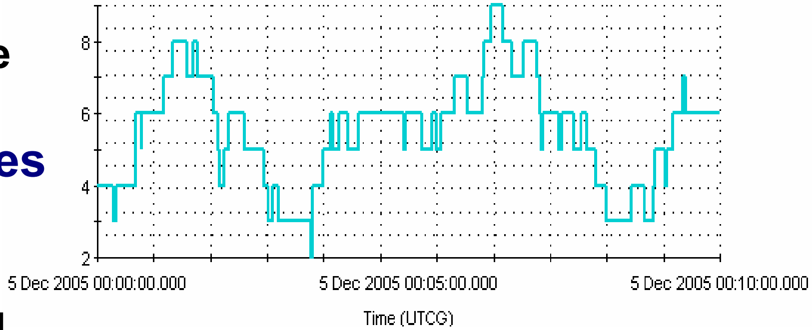
Ground Stations for MAST

- **Primary GS located in Stanford Hills - 6 meter dish**
  - Gain: 41 dBi
  - Beam width: 1.46 degrees
  - Polarization: Right Hand Circular (RHCP)
  - Full-motion Tracking and Control System
  - Microhard MHX-2400 located at feed
- **Internet Enabled Mercury Ground Station Software**
  - Uses two-line elements (TLEs) from Space Command to point dish
  - Allows experimenters and users to access dish via TCP/IP
- **Possible Additional Ground Stations**
  - 4 meter dish at Penn State - State College, PA
  - 21 meter dish at Morehead University - Morehead, KY

GPS Receiver for MAST

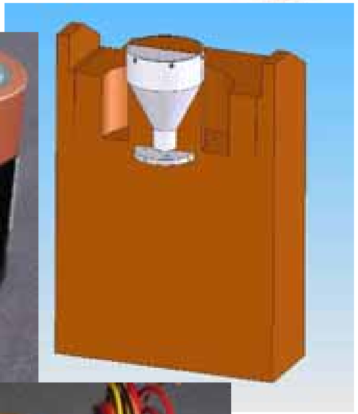
- **Phoenix GPS receiver from Deutsche Zentrum für Luft- und Raumfahrt (DLR)**
  - DLR has successfully flown predecessor Orion receiver
  - Stanford University has cooperative agreement in place with DLR for MAST
  - Low cost COTS hardware (Signav MG5001)
  - Technical expertise/advice available at Stanford
- **Orbital Position information**
  - Available in WGS-84 Cartesian format
- **Measurements for tether dynamics:**
  - During deployment: once every 5 seconds
  - Post-deployment: once every 1 minute
  - Differential post-processing by DLR will improve measurement accuracy
- **GPS Antenna located on 'side' face of satellites due to zenith/nadir ambiguity**
  - $\geq$ 5 satellites in view 95+% when satellite stable
  - Spinning may cause the system to lose lock and resolution due to limited number of sats in view





Follow-on Technologies & Products

- **Products Released in August 2005**
  - **nanoTerminator™** - end-of-mission deorbit module for nanosatellites
    - 100 meters of conductive tether
    - Utilizes ED tether drag to rapidly deorbit a small spacecraft
    - Enables pico- and nano-satellites to comply with orbital debris mitigation guidelines with minimal mass and volume impacts and at a low cost.
  - **nanosat Release Mechanism** – device for mechanism release or nanoTerminator™ deployment
    - Used to initiate mechanism release, spring energized separation, or nanoTerminator™ ejection either upon command or via integral watchdog timer expiration



[Web Link to nanoTerminator Data Sheet]

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