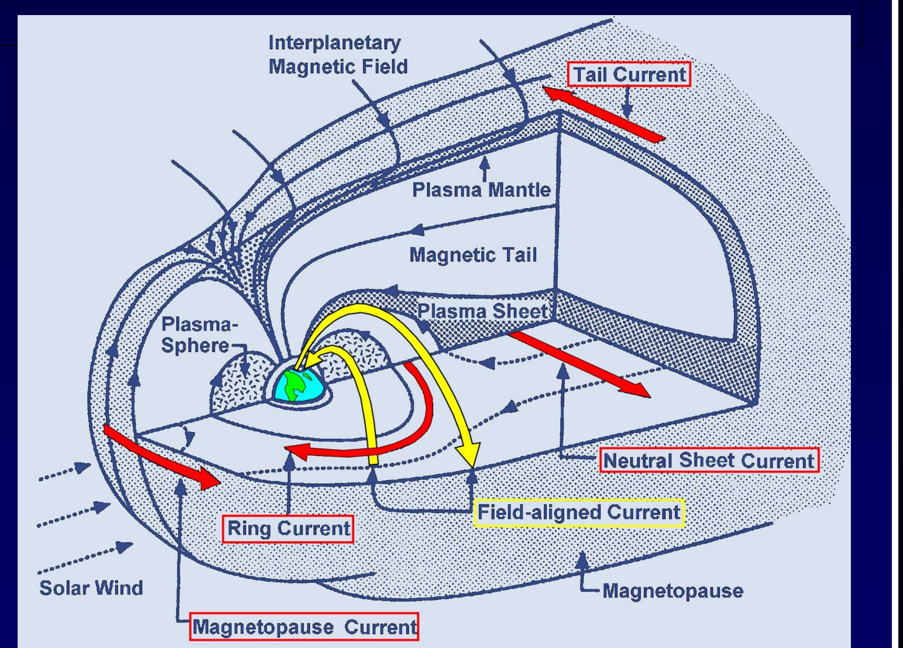
Tethered Satellites as an Enabling Platform for Operational Space Weather Monitoring Systems

Brian E. Gilchrist[1], Linda Habash Krause[2], Dennis Lee Gallagher[2], Sven Gunnar Bilen[3], Keith Fuhrhop[4], Walt R. Hoegy[1], Rohini Inderesan[1], Charles Johnson[2], Jerry Keith Owens[2], Joseph Powers[2], Nestor Voronka[5], Scott Williams[6]

1. University of Michigan, Ann Arbor, MI
2. NASA Marshall Space Flight Center, Huntsville, AL.
3. Pennsylvania State University, University Park, PA.
4. Northop-Grumman, Redondo Beach, CA.
5. Tethers Unlimited, Inc., Bothell, WA.
6. SRI International, Menlo Park, CA.

ABSTRACT – Tethered satellites offer the potential to be an important enabling technology to support operational space weather monitoring systems. Space weather "nowcasting" and forecasting models rely on assimilation of near-real-time (NRT) space environment data to provide warnings for storm events and deleterious effects on the global societal infrastructure. Typically, these models are initialized by a climatological model to provide "most probable distributions" of environmental parameters as a function of time and space. The process of NRT data assimilation gently pulls the climate model closer toward the observed state (e.g., via Kalman smoothing) for nowcasting, and forecasting is achieved through a set of iterative semi-empirical physics-based forward-prediction calculations. Many challenges are associated with the development of an operational system, from the top-level architecture (e.g., the required space weather observatories to meet the spatial and temporal requirements of these models) down to the individual instruments capable of making the NRT measurements. This study focuses on the latter challenge: we present some examples of how tethered satellites (from 100s of m to 20 km) are uniquely suited to address certain shortfalls in our ability to measure critical environmental parameters necessary to drive these space weather models. Examples include long baseline electric field measurements, magnetized ionospheric conductivity measurements, and the ability to separate temporal from spatial irregularities in environmental parameters. Tethered satellite functional requirements are presented for two examples of space environment observables.



Motivation

- ➢ The Near-Earth Space Environment varies over spatial and temporal scale sizes covering many orders of magnitude
- ➢ Cross-scale coupling between physics processes often plays an important role in the instigation, evolution, and extinction of each other
- ➢ Plasma waves and instabilities imply spatiotemporal complexity, which presents a challenge to separate temporal evolution from spatial propagation and deformation

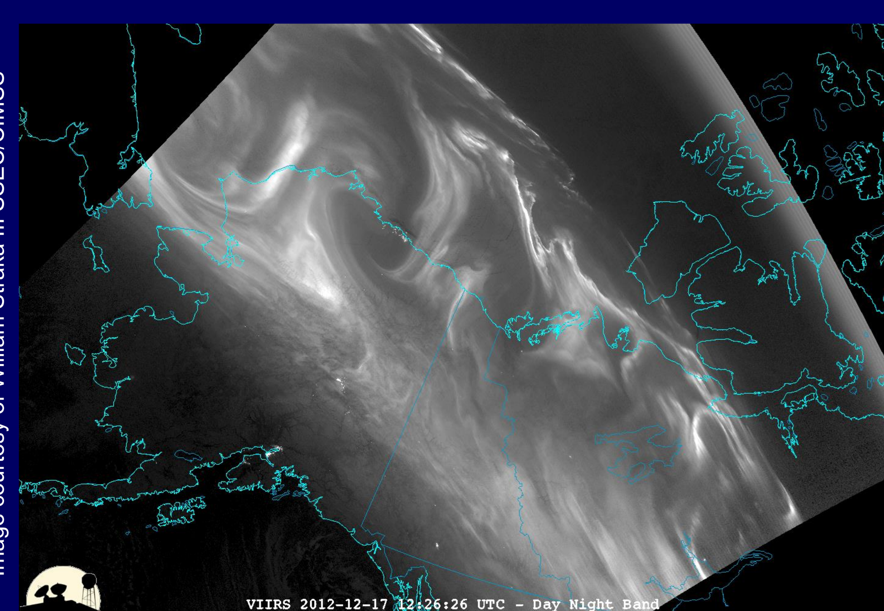
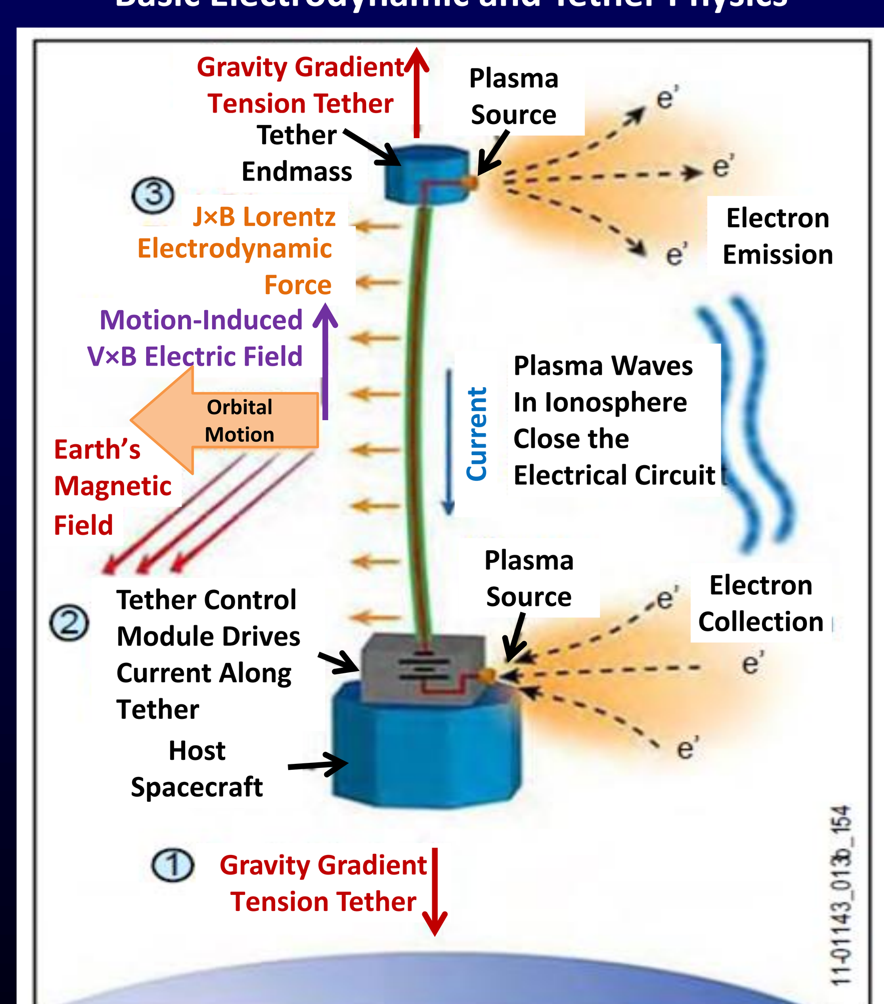


Image courtesy of William Straka III SSEC/CIMSS

Unique Capabilities of Space Tethers

- ➢ Multipoint In Situ Measurements
- ➢ Long Baseline (up to 20 km) electric field measurements
- ➢ A more efficient VLF antenna for remote sensing (VLF probe of magnetosphere)
- ➢ Fixed-distance transmitter/ receiver for radio wave probing of ionospheric layers between the two s/c (e.g. via Faraday rotation, phase shift irregularities indicating changes in TEC, etc)
- ➢ Fixed-distance electron gun/imagers for probing ionospheric E-region electric fields (e.g. if deployed downward by space plane at 110km, can image auroral emissions stimulated by downward propagating beam to map zonal electric fields)

Basic Electrodynamic and Tether Physics



EXAMPLE 1 Auroral E||B

The Science Question

What mechanisms are involved in control of E||B?

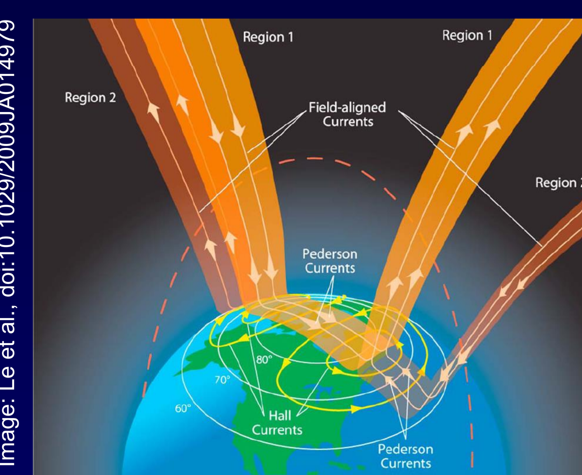
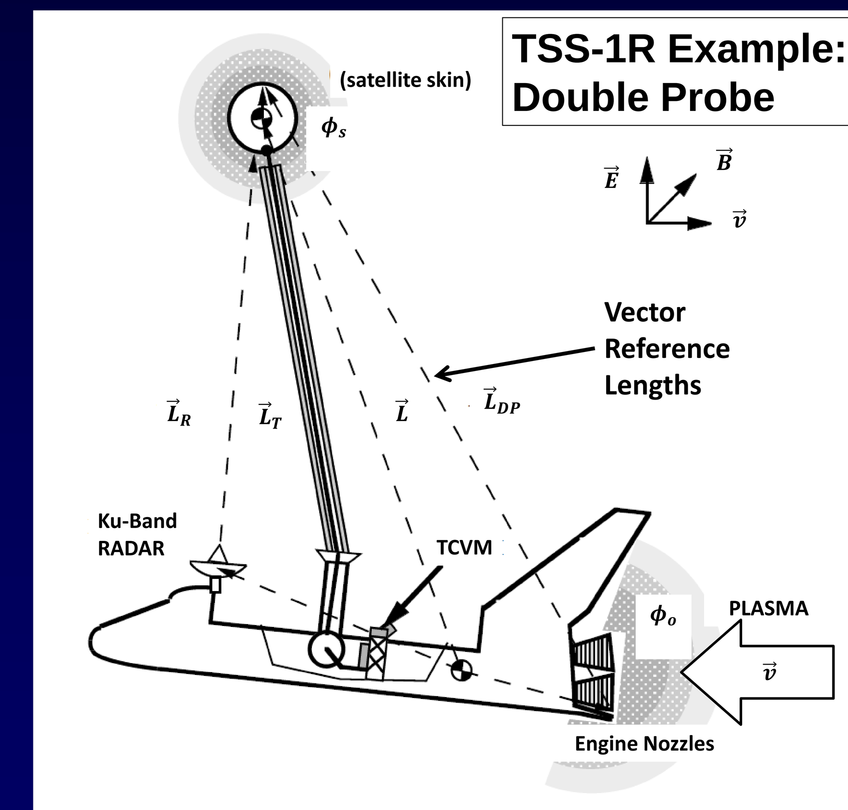


Image: Le et al., doi:10.1029/2009JA014979

NEED Direct Measurements of E||B in auroral acceleration region

The Space Tether Solution



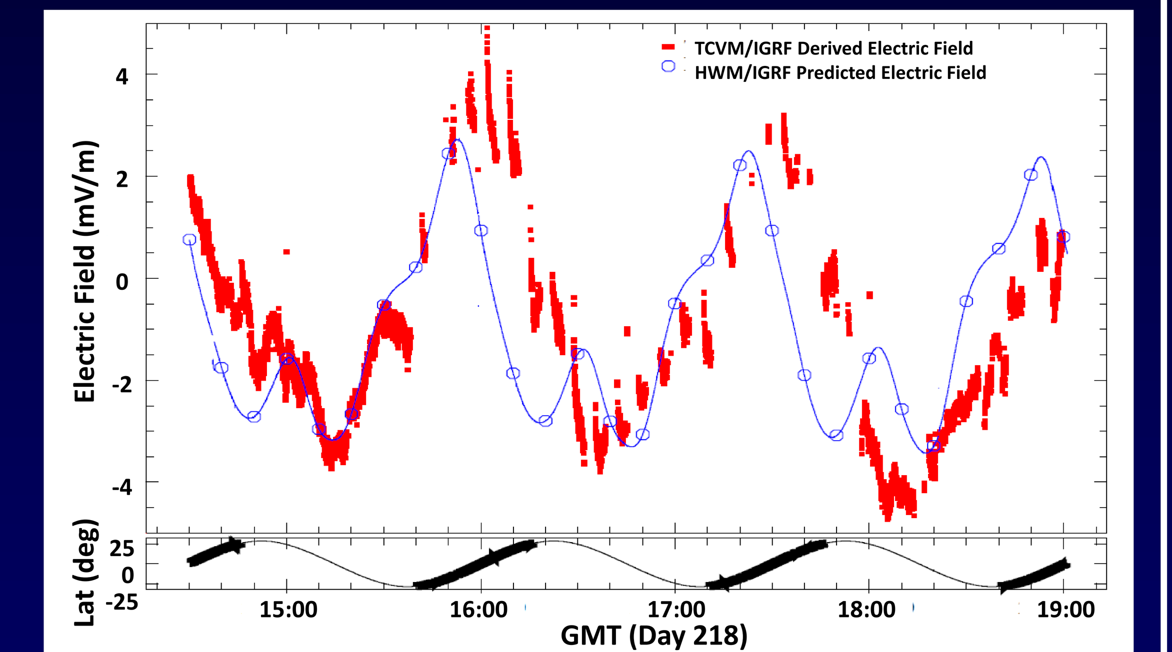
Space tethers can make Long Baseline Electric field measurements via "Double Probe" technique

- Proven during TSS-1R
- Ambient Electric field (E_{amb}) deduced after removing tether electromotive force
- E_{amb} parallel to tether length: uncertainty scales as ~ 1/L

$$\delta = V_m\left(\frac{R_T+R_{Po}+R_{Ps}+R_o+R_s}{R_m}\right) + (\phi_o+\phi_s)+(WF_s-WF_o).$$

$$\vec{E}_{amb}\cdot\hat{L} = \frac{V_m}{L} - \vec{v}_o\times\vec{B}\cdot\hat{L} + \frac{\delta}{L}$$

Example Technique Proven

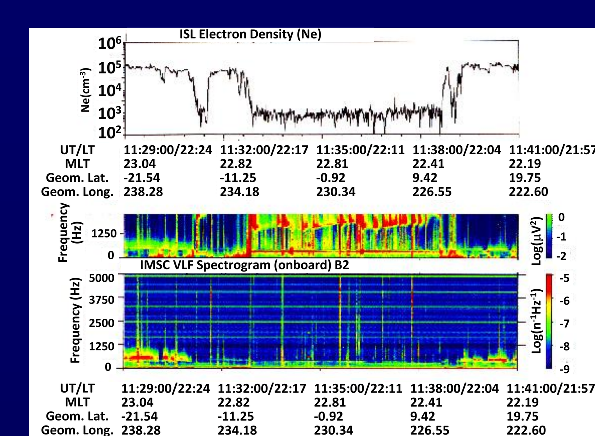


Measurement to enable Science Closure: A polar orbiting 1 km tethered cubesat would provide direct measurements of E||B to within 6 mV/m

EXAMPLE 2 Plasma Bubbles

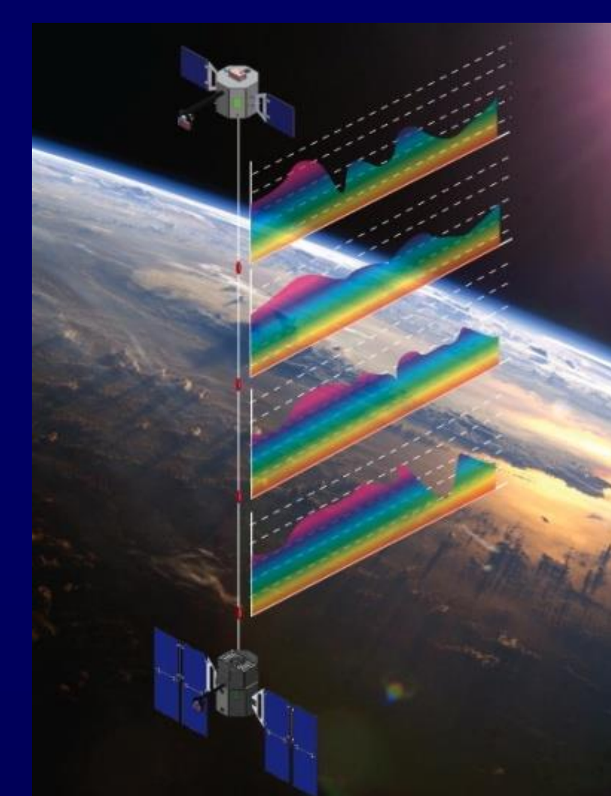
The Science Question

What mechanisms are involved in cross-scale coupling of Equatorial Ionospheric plasma bubbles?



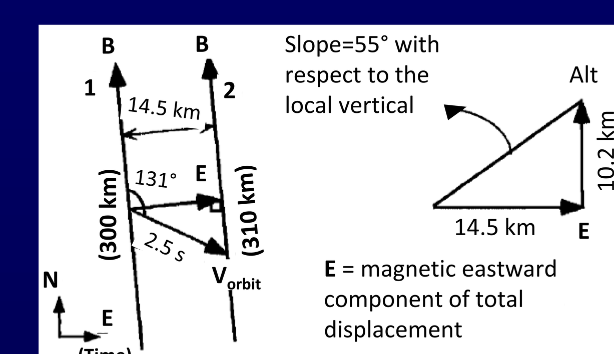
NEED Systematic Multipoint measurements of plasma density

The Space Tether Solution



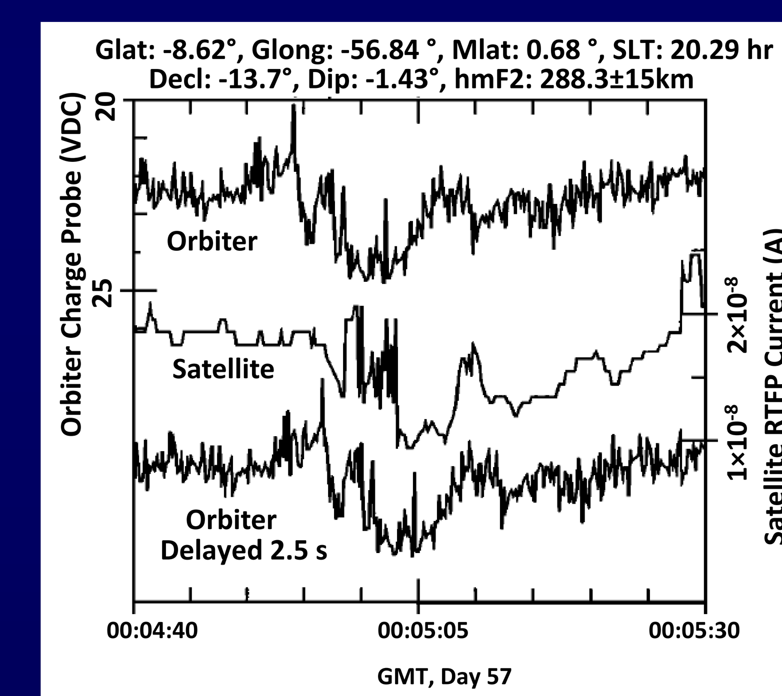
Space tethers can make simultaneous multipoint measurements with a fixed separation in distance

- Proven during TSS-1R
- Found asymmetries in density gradients within a large plasma bubble. Important for scintillation.

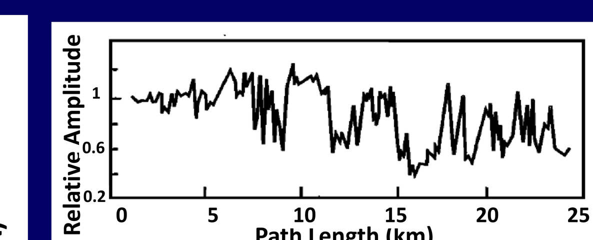


TSS-1R tether and magnetic field geometry.

Example Technique Proven



TSS-1R Orbiter data before and after a uniform time delay of 2.5 s is applied, thus aligning them with most of the prominent density structures at the satellite.

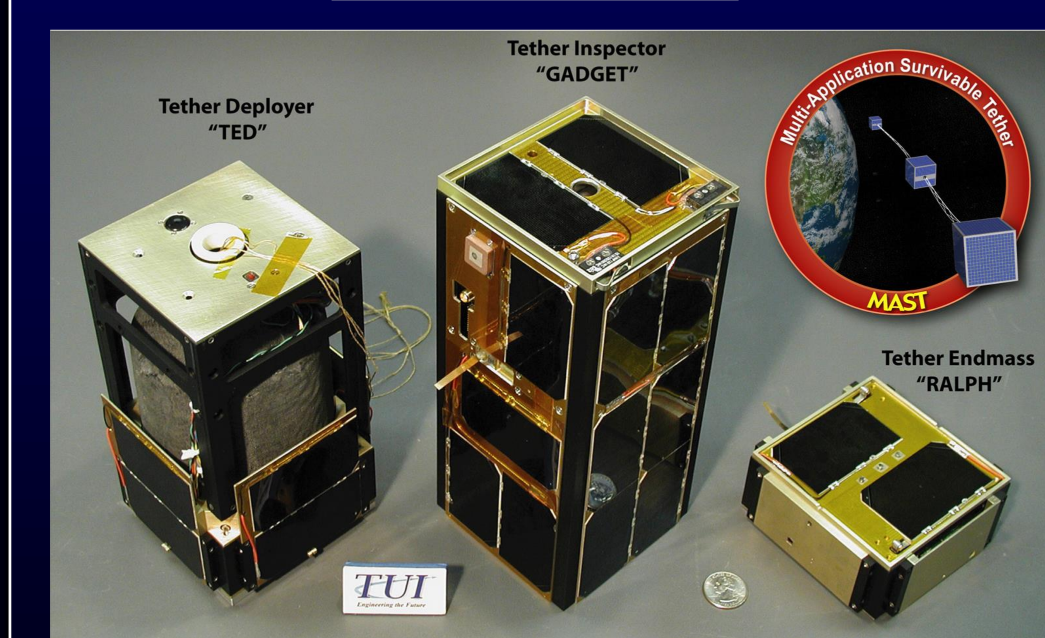


Observations from AE-E RPA data (Basu et al. [1980]) show similar behavior: sharp horizontal gradients in density structures are followed by more shallow ones as the sensor leaves the bubble. Tethers allow separation of spatial versus temporal effects.

Measurement to enable Science Closure: A low altitude (<1000 km) tethered satellite would provide simultaneous multipoint measurements of both large and small plasma structures

Enabling Technology For Space Wx Tethers

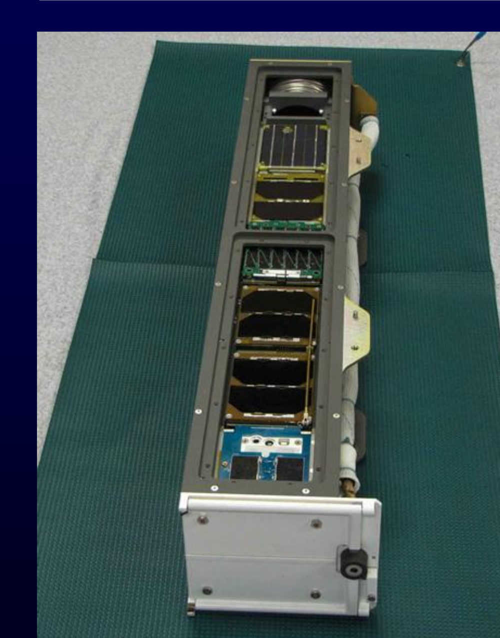
Tethers for CubeSats



Tethers Unlimited (TUI) developed TRL7 CubeSat.

Solution Enables CubeSat with miniature plasma and/or field sensors

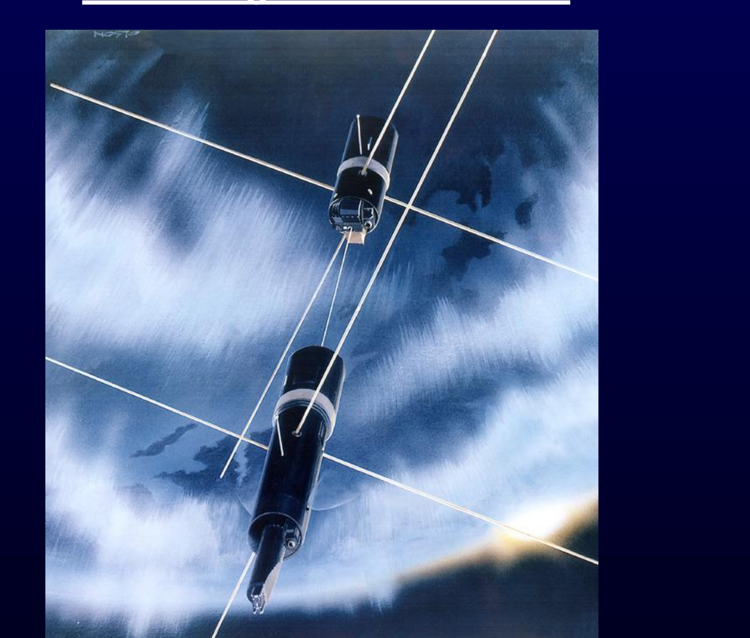
ISS & CubeSat launches



NanoRack launches CubeSats via ISS

Solution Enables launch tethered CubeSat into low altitude orbit

Sounding Rocket Tethers



Tethered Sounding Rocket Sections

Solution Enables unique observations of space environment (e.g., E||B, plasma turbulence)

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