Active Experiments Motivated by Space Tethers

Brian Gilchrist

Professor, Electrical Engineering and Space Science

Director, Space Physics Research Laboratory (SPRL)/XTRM Labs

University of Michigan

Special Acknowledgements (Alphabetical, Many More):

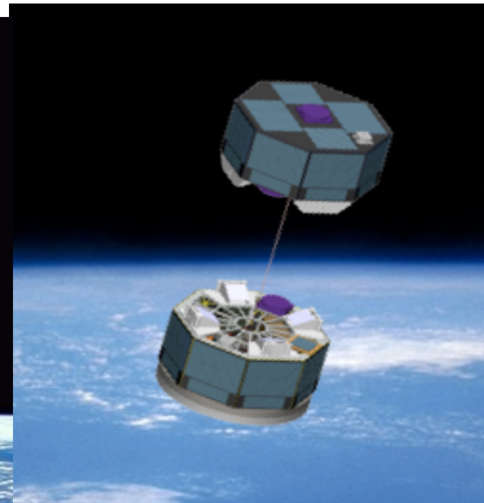
Iverson Bell, Sven Bilén, Craig Elder, Rob Hoyt, Rohini Indiresan, Les Johnson, Linda Krause, David Lee, Omar Leon, Grant Miars, Nobie Stone, Scott Williams

Overview

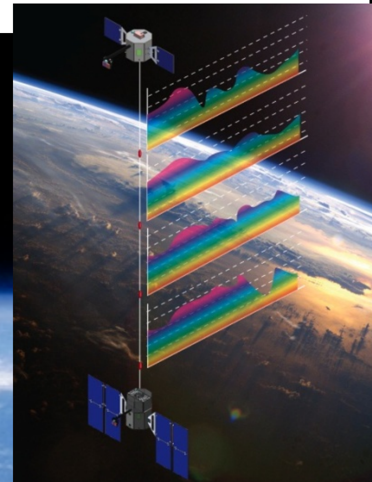
- Space Tethers Short Practical History
- Space Science Measurement Examples
- Electrodynamic ED tethers (Propulsion/Power/Science)
  - TSS-1R Mission
  - Examples (Big and small)

Applications Enabled by *Tethers*

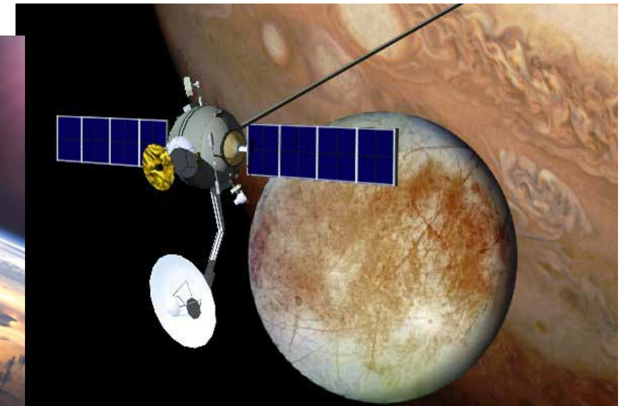
Orbit Transfer Vehicle
(small to large s/c)
boost/deboost/inclination change



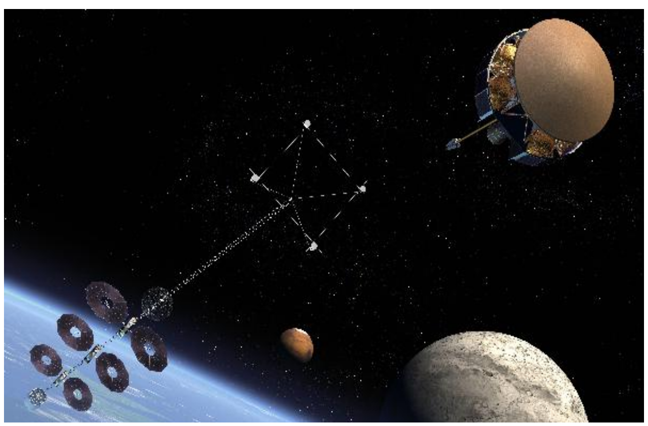
Formation Flying



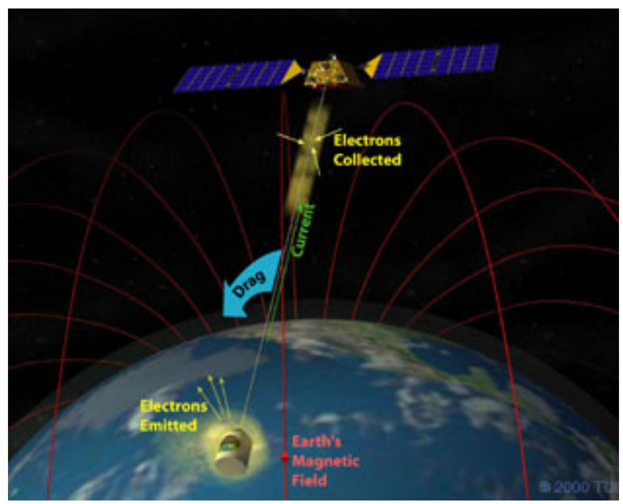
Multipoint
Ionospheric Science



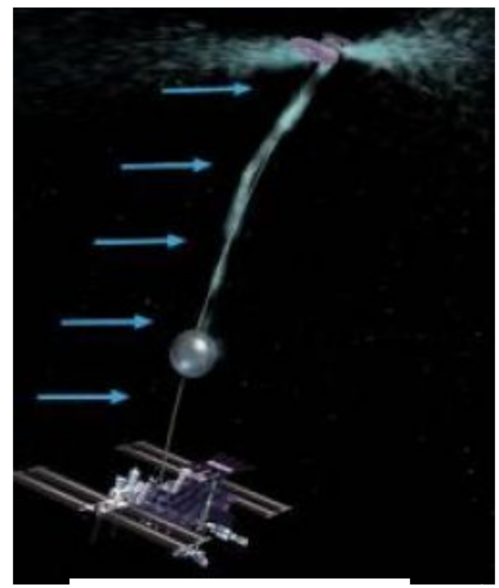
Up to 1 MW Power Generation/
Propulsion at Gas Giants



Reusable Launch Assist and
LEO-to-GTO Transfers



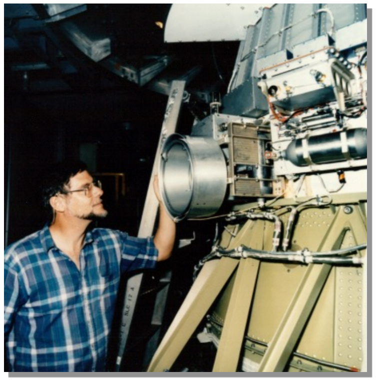
End-Of-Life Deorbit and
Active Orbital Debris Removal



Reboost Large
Space Platforms

Selected Prior Tether Missions

- Small Expendable Deployer System (SEDS) (1993 -1994)
  - SEDS 1: de-orbited small payload using 20 km tether
  - SEDS 2: controlled deployment of a 20 km tether
  - Plasma Motor Generator: EDT physics using 500 m conducting wire, 2 HCPCs
- Shuttle Tethered Satellite System (TSS) (1992, 1996)
  - TSS-1: 256 m deployed, demonstrated stable dynamics
    - Last-minute S&MA design change resulted in bolt jam in deployer (configuration control process failure)
  - TSS-1R: 19.9 km deployed, >5 hours of excellent data validating models of ED tether-ionosphere current flow
    - Arc caused tether to fail (tether fabrication/design/handling flaw)
- TiPS - Survivability & Dynamics investigation (1996 -2006)
  - 4 km nonconducting tether, ~1000 km alt
  - Survived over 10 years on orbit
- T-Rex – Bare Anode Tape Tether deployment (2010)



Past missions demonstrated stable tether deployment & fundamental feasibility of electrodynamic propulsion.

Most tether missions HAVE been successful.
Mission failures were due to design process errors,
<u>not</u> due to fundamental physics.

Space Tethers: Prior Missions

■ = Met All Mission Goals ■ = Did Not Meet All Mission Goals

Year	Mission	Type	Description	Lessons Learned
1966	**Gemini-11**	Dynamics	• 15-m tether between capsules • Tethered capsules set in rotation	+ Successful deployment and stable rotation
1966	**Gemini-12**	Dynamics	• 30-m tether between capsules • Tethered capsules set in rotation	+ Successful deployment and stable rotation
1989	**OEDIPUS-A**	ED/Plasma Physics	• Sounding rocket experiment • 958-m conducting tether, spinning	+ Successfully demonstrated strong EM coupling between the ends of conducting tether t + Obtained data on behavior of tethered system as large double electrostatic probe
1992	**TSS-1**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	– Too-long bolt added without proper review caused jam in tether deployer + Demonstrated stable dynamics of short tethered system + Demonstrated controlled retrieval of tether
1993	**SEDS-1**	Momentum Exchange	• Deployed payload on 20-km nonconducting tether and released it into suborbital trajectory	+ Demonstrated successful, stable deployment of tether + Demonstrated deorbit of payload
1993	**PMG**	ED	• 500-m insulated conducting tether • Hollow cathode contactors at both ends	+ Demonstrated ED boost and generator mode operation • Did **not** measure thrust
1994	**SEDS-2**	Dynamics	• Deployed 20-km tether to study dynamics and survivability	+ Demonstrated successful, controlled deployment of tether with minimal swing
1995	**OEDIPUS-C**	ED/Plasma Physics	• Sounding rocket experiment • 1174-m conducting tether, spinning	+ Successfully obtained data on plane and sheath waves in ionospheric plasma
1996	**TSS-1R**	ED/Plasma Physics	• 20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics	+ Demonstrated electrodynamic efficiency exceeding existing theories + Demonstrated ampere-level current – Flaw in insulation allowed high-voltage arc to cut tether • Tether was not tested prior to flight
1996	**TiPS**	Dynamics	• Deployed 4-km nonconducting tether to study dynamics and survivability	+ Successful deployment + Tether survived over 10 years on orbit
1999	**ATEx**	Dynamics	• Tape tether deployed with pinch rollers	– "Pushing on a rope" deployment method resulted in unexpected dynamics, experiment terminated early
2000	**Picosats 21/23**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2001	**Picosats 7/8**	Formation	• 2 picosats connected by 30-m tether	+ Demonstrated tethered formation flight
2002	**MEPSI-1**	Formation	• 2 picosats connected by 50-ft tether • Deployed from Shuttle	+ Tethered formation flight
2006	**MEPSI-2**	Formation	• 2 picosats connected by 15-m tether • Deployed from Shuttle	+ Tethered formation flight of nanosats with propulsion and control wheels
2009	**AeroCube-3**	Formation	• 2 picosats connected by 61-m tether • Deployed from Minotaur on TacSat-3 launch	+ Tethered formation flight with tether reel and tether cutter
2007	**MAST**	Dynamics	• 3 tethered picosats to study tether survivability in orbital debris environment	– Problem with release mechanism resulted in minimal tether deployment; + Obtained data on tethered satellite dynamics
2007	**YES-2**	Momentum Exchange	• Deployed payload on 30-km nonconducting tether and released it into suborbital trajectory	+ Tether did deploy, but: – Controlling computer experienced resets during tether deployment, preventing proper control of tether deployment
2010	**T-REX**	ED/Plasma Physics	• Sounding rocket experiment • 300-m bare tape tether	+ Successfully deployment of tape and fast ignition of hollow cathode

>70% of Tether Missions Have Been Fully Successful

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- Electrodynamic ED tethers (Propulsion/Power/Science)
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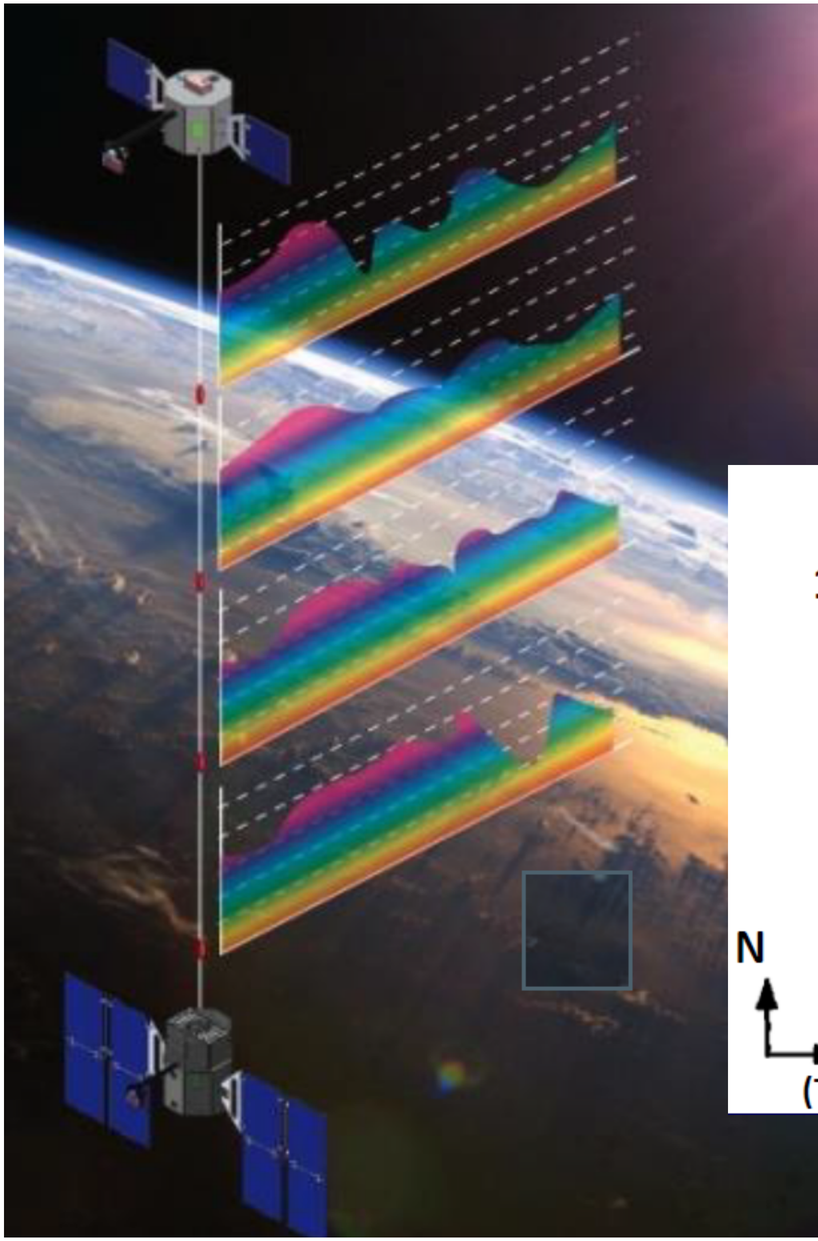
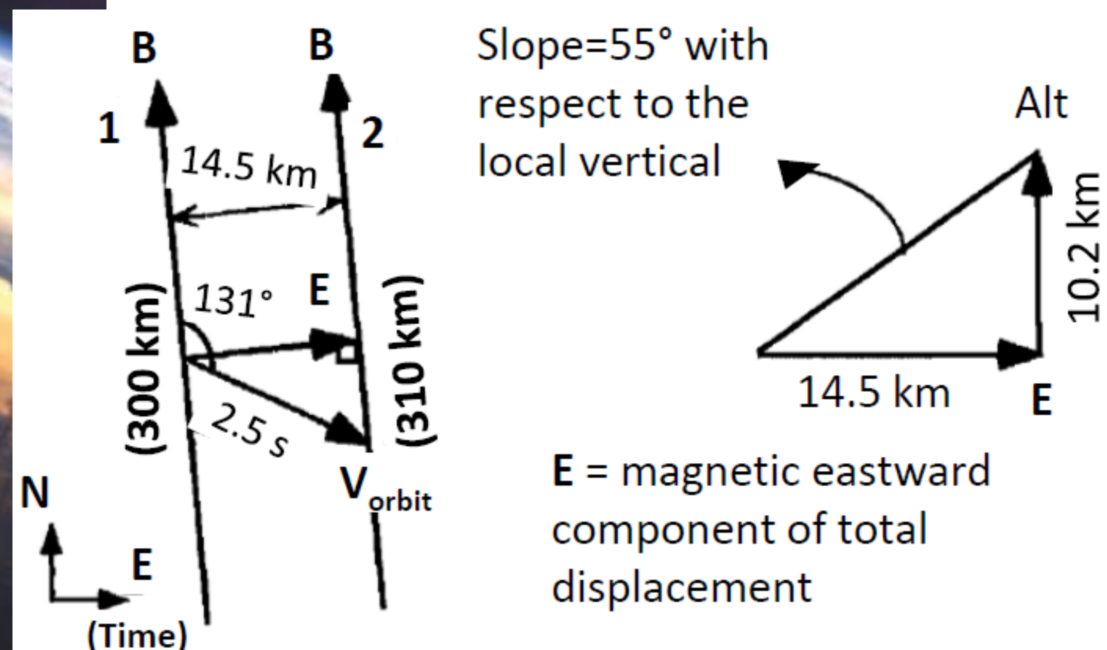
  - Examples (Big and small)

Tethered Multipoint Measurement

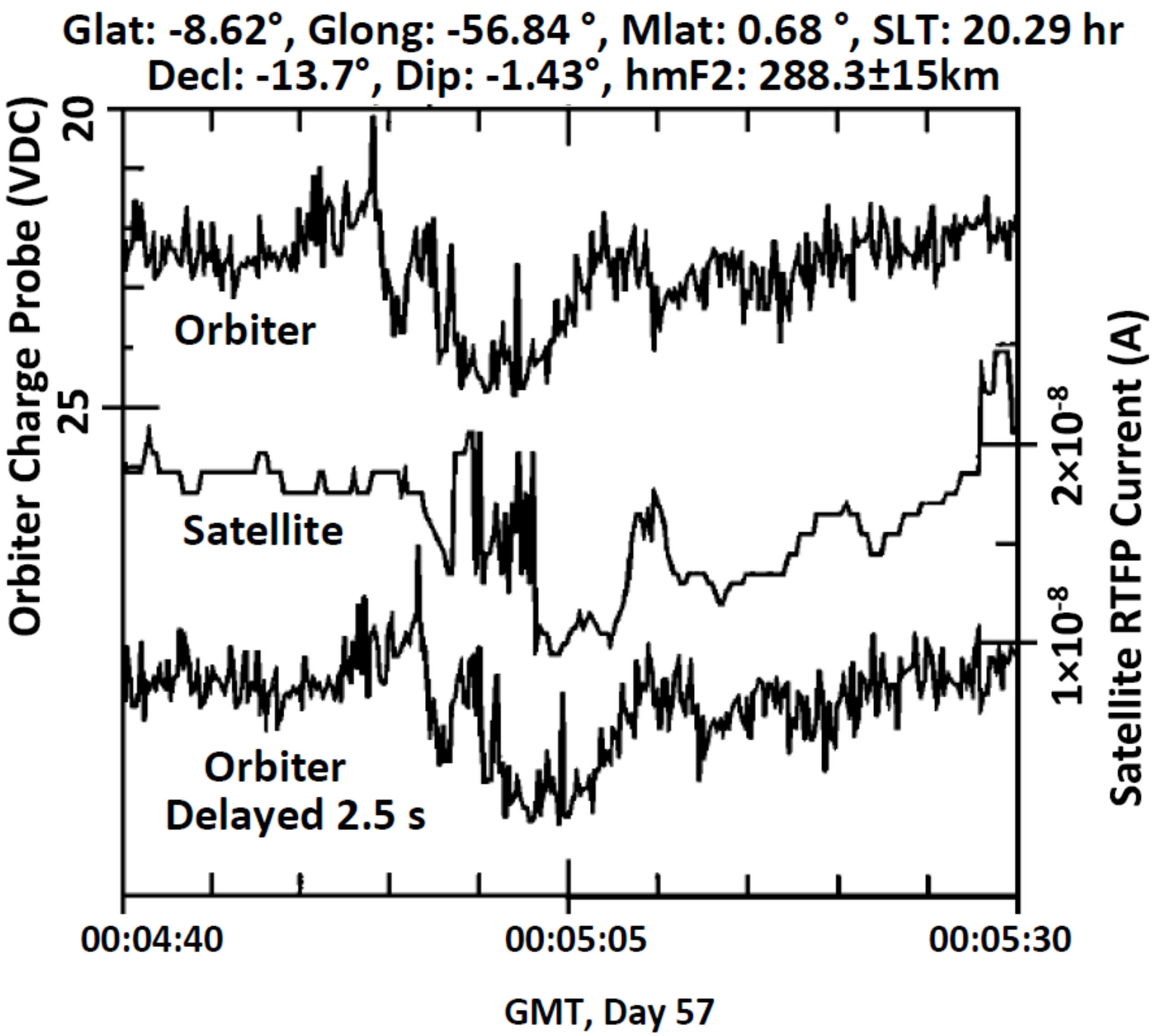


- Proven during TSS-1R
- Found asymmetries in density gradients within a large plasma bubble. Important for scintillation.



TSS-1R tether and magnetic field geometry.

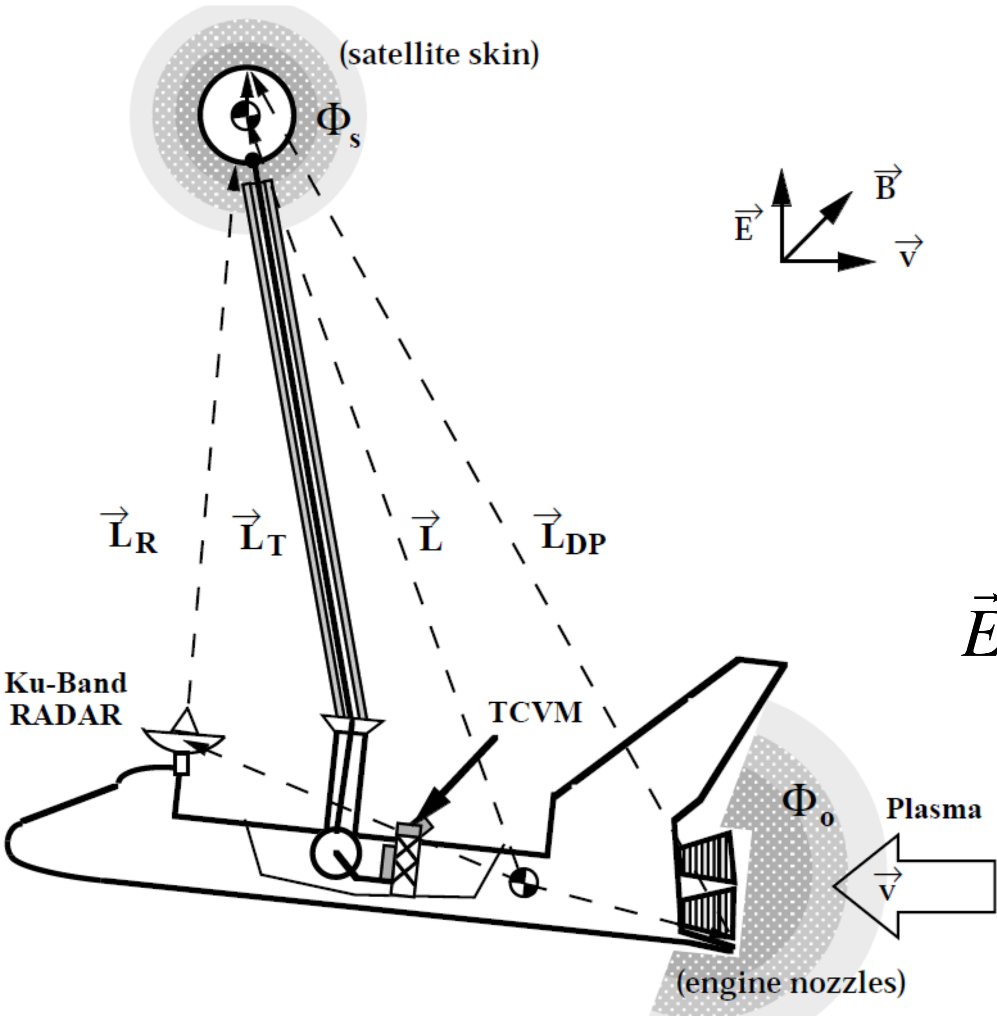
TSS-1R Two-Point Example



- TSS-1R Orbiter and Satellite data
- Prominent density structures seen at both Orbiter and satellite
- Uniform time delay of 2.5 s aligns them

Indiresan, R., B. Gilchrist, S. Basu, J.-P. Lebreton, E. P. Szuszczweicz, Simultaneous, dual-point, in situ measurements of ionospheric structures using space tethers: TSS-1R observations, *Geophys. Res. Lett.*, 25, 3725-3728, Oct. 1, 1998

Space Tether as long-baseline double-probe

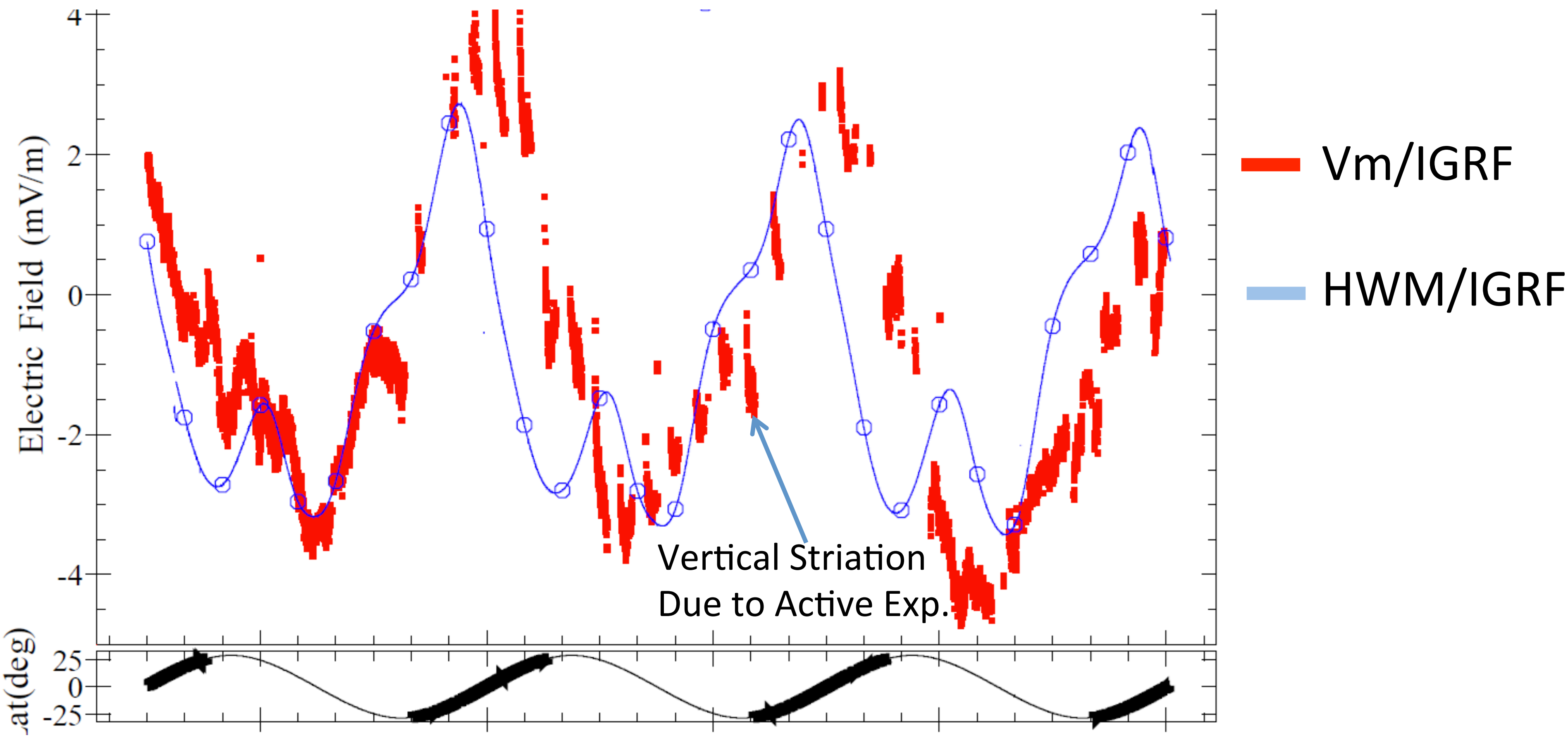


- Proven during TSS-1R
- Ambient Electric field (E_{amb}) deduced after removing tether electromotive force
- E_{amb} parallel to tether length: uncertainty scales as ~ 1/L

$$\vec{E}_{amb} \cdot \hat{L} = \frac{V_m}{L} - \left(\vec{v}_O \times \vec{B} \cdot \vec{L}\right) + \frac{\delta}{L}$$

$$\delta = V_m \left(\frac{R_T + R_{P_O} + R_{P_S} + R_O + R_S}{R_M} \right) + \left(\phi_O - \phi_S\right) + \left(WF_S - WF_O\right)$$

TSS-1R Measured Vertical E-Field Comparison: Horz Wind Model

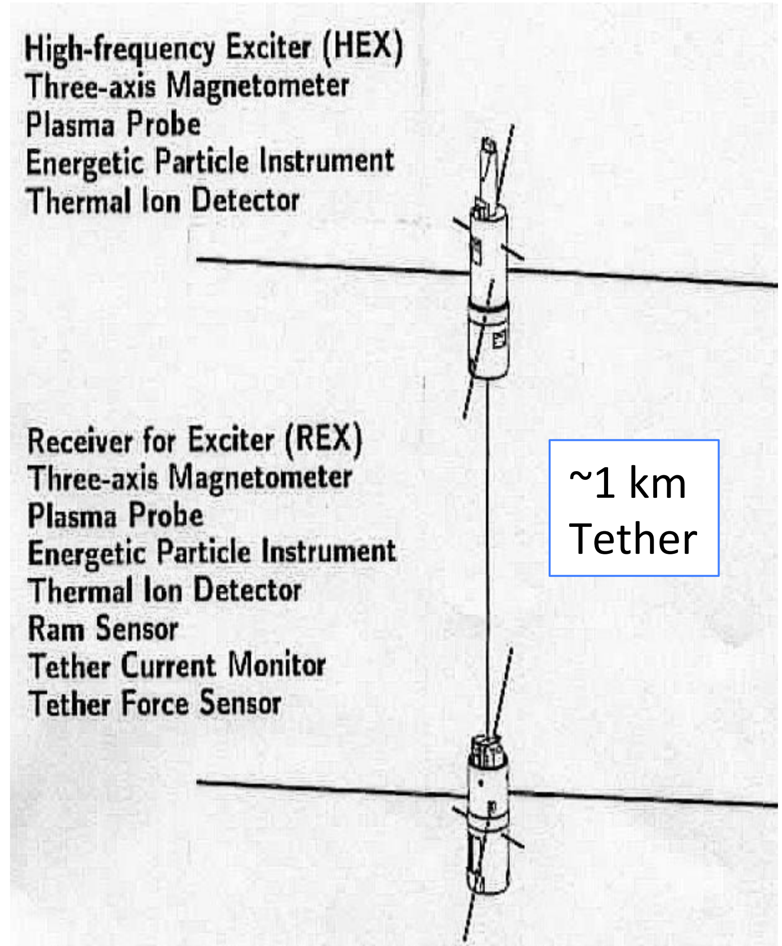


Williams, S. D., B. E. Gilchrist, V. M. Aguero, R. S. Indiresan, D. C. Thompson, and W. J. Raitt, "Measurements of induced potential and natural electric fields using an electrodynamic tether double probe: TSS-1R Results," *Geophys. Res. Lett.*,Vol. 25 , No. 4, p. 445-448, 1998.

OEDIPUS A-C Rocket Results

PI: H. Gordon James

- Detection of radio emissions in whistler and Z modes
- Demonstrated existence of sheath waves.
- Noted effect of geomagnetic field on s/c floating potential via change in ponderomotive-force effect.
- Measured natural electric fields due to auroral processes.



James, H. G., and B. A. Whalen. "OEDIPUS-A: Space research with a new tether." *Eos, Trans AGU* 72.12 (1991): 137-144.
Laframboise, J. G., D. D. Wallis, and H. G. James. "RF effects on Oedipus-C floating voltages." *Spacecraft Charging Technology*. Vol. 476. 2001.
James, H. G. "Ionospheric wave emissions passively detected by the OEDIPUS A tether.JGR: Space Physics 98.A11 (1993): 19099-19109.
Prikryl, P., et al. "OEDIPUS-C topside sounding of a structured auroral E region." JGR: Space Physics 105.A1 (2000): 193-204.

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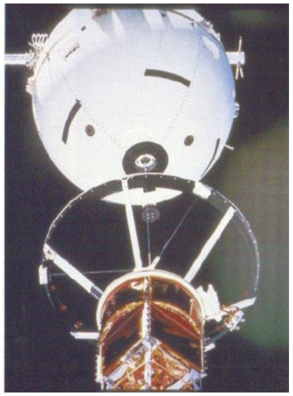
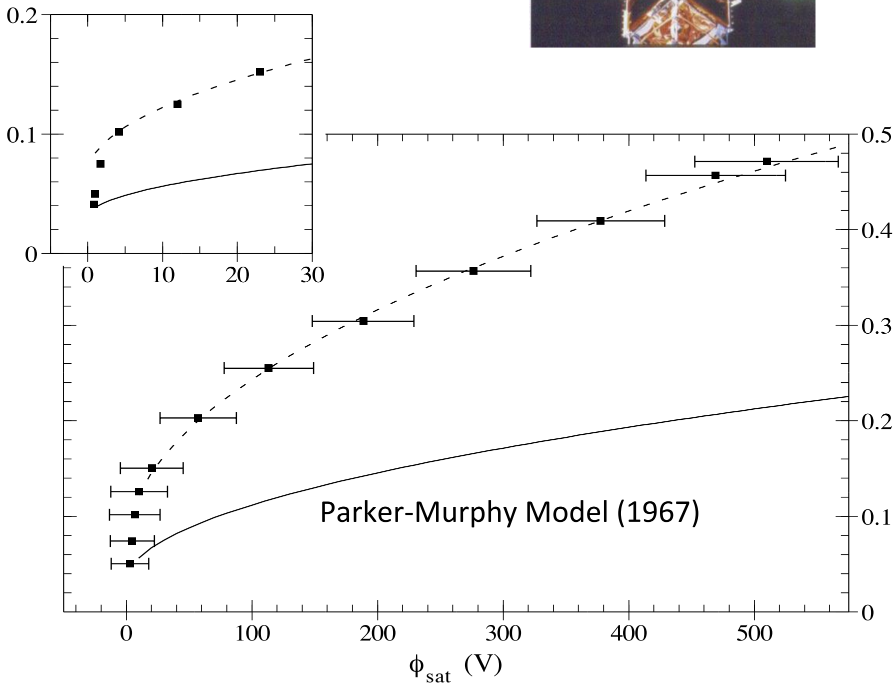
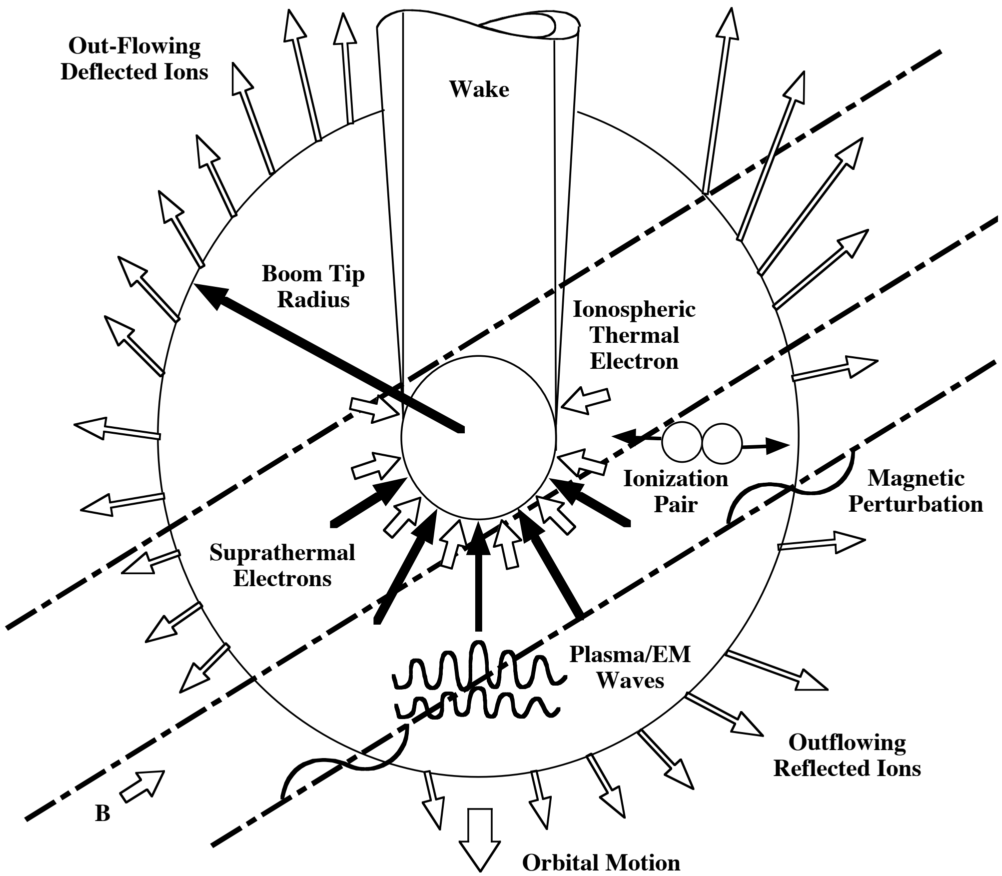
TSS–1R Enhanced Current Collection

TSS–1R Satellite





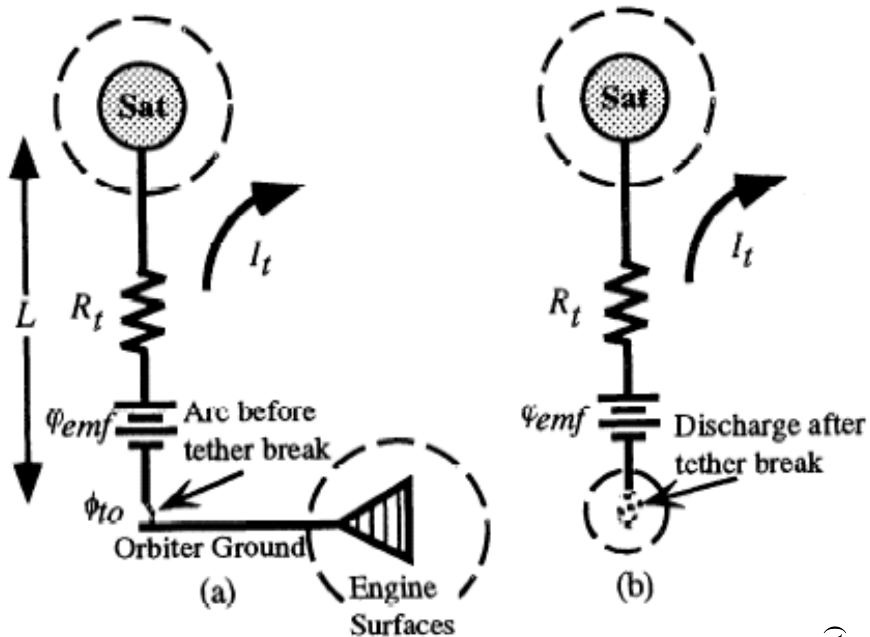


N. Stone (1998)

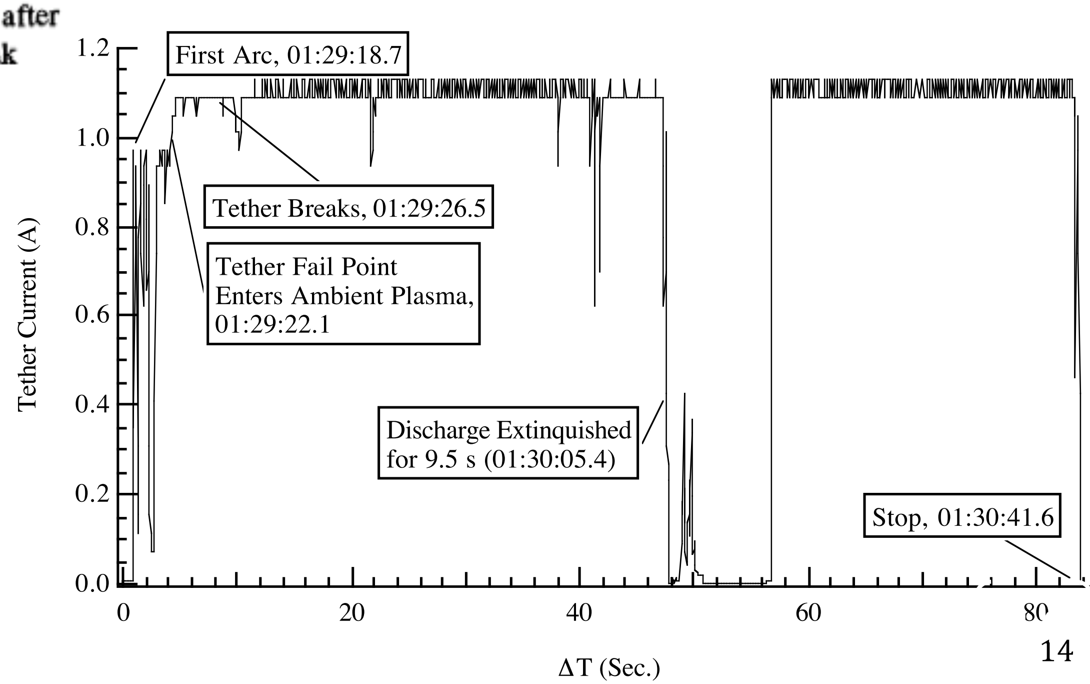
Valuable practical information about ED Tethers learned from TSS-1R mission

~1 A Currents During TSS-1R

$$V_{emf} = V_{sat} + I_t \cdot R_t \cdot L + V_{to} - V_{cathode}$$

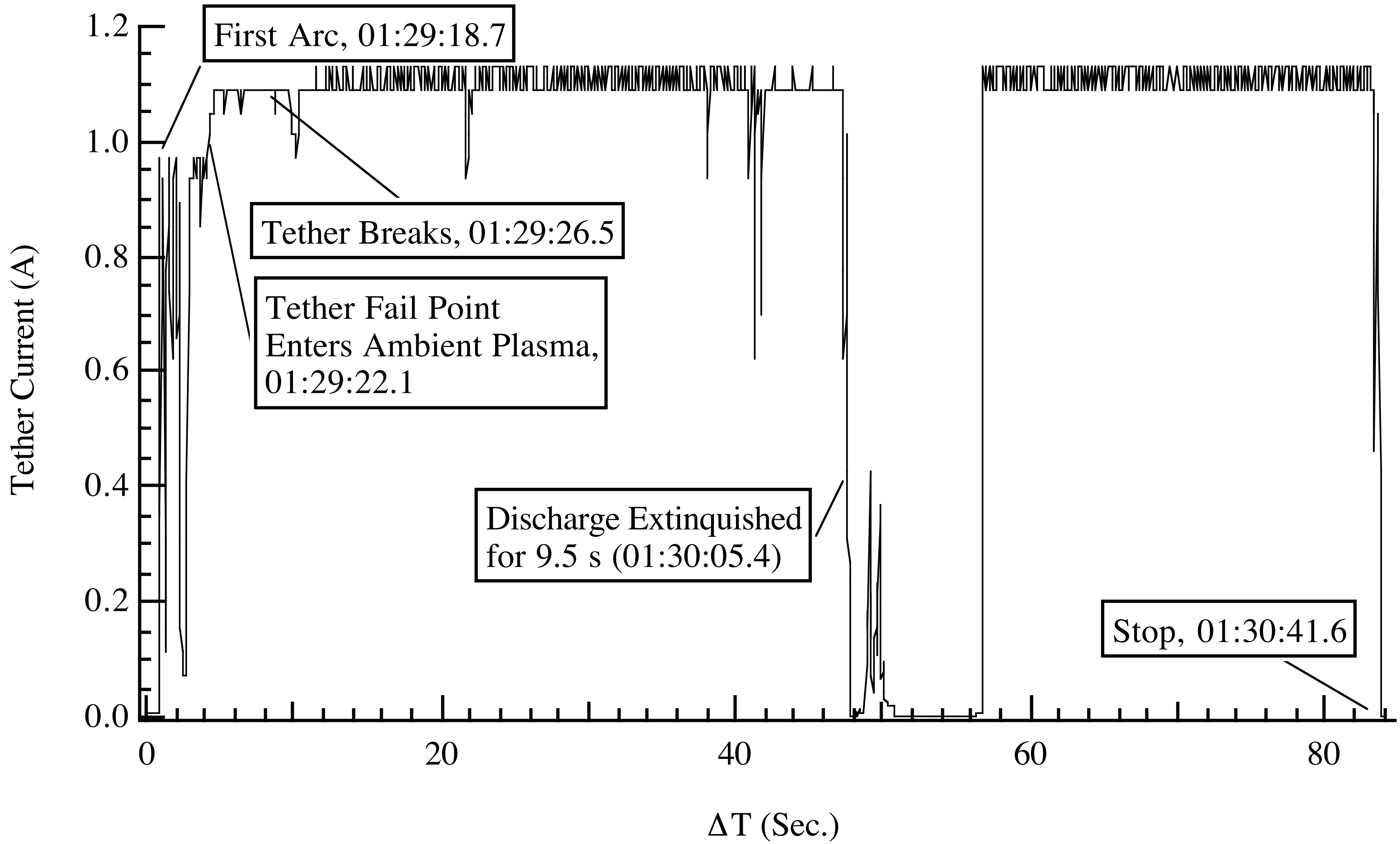


- Dramatic current increase with tether shorted to Orbiter
- Even larger current when in "contact" with Ionosphere
- Tether current limited by tether resistance
- What is ultimate limit for electron emission?



- Laboratory demonstration verified ability to support discharge via
  - Trapped gas
  - Teflon ablation

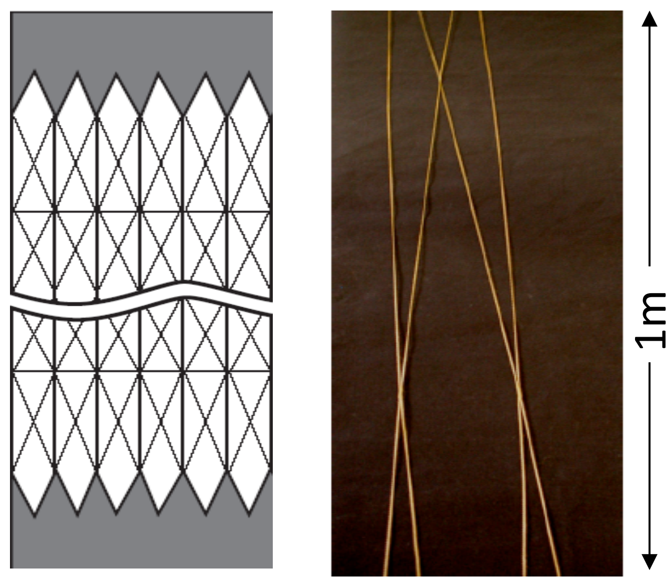
~1 A Currents During TSS-1R



TSS-1R – Lesson Learned

- Insulated Tether Can Be (Will Be) Breached
- Design for that Reality
  - High Voltage
  - Micrometeors

TSS-1R Tether



Schematic of Hoytether™

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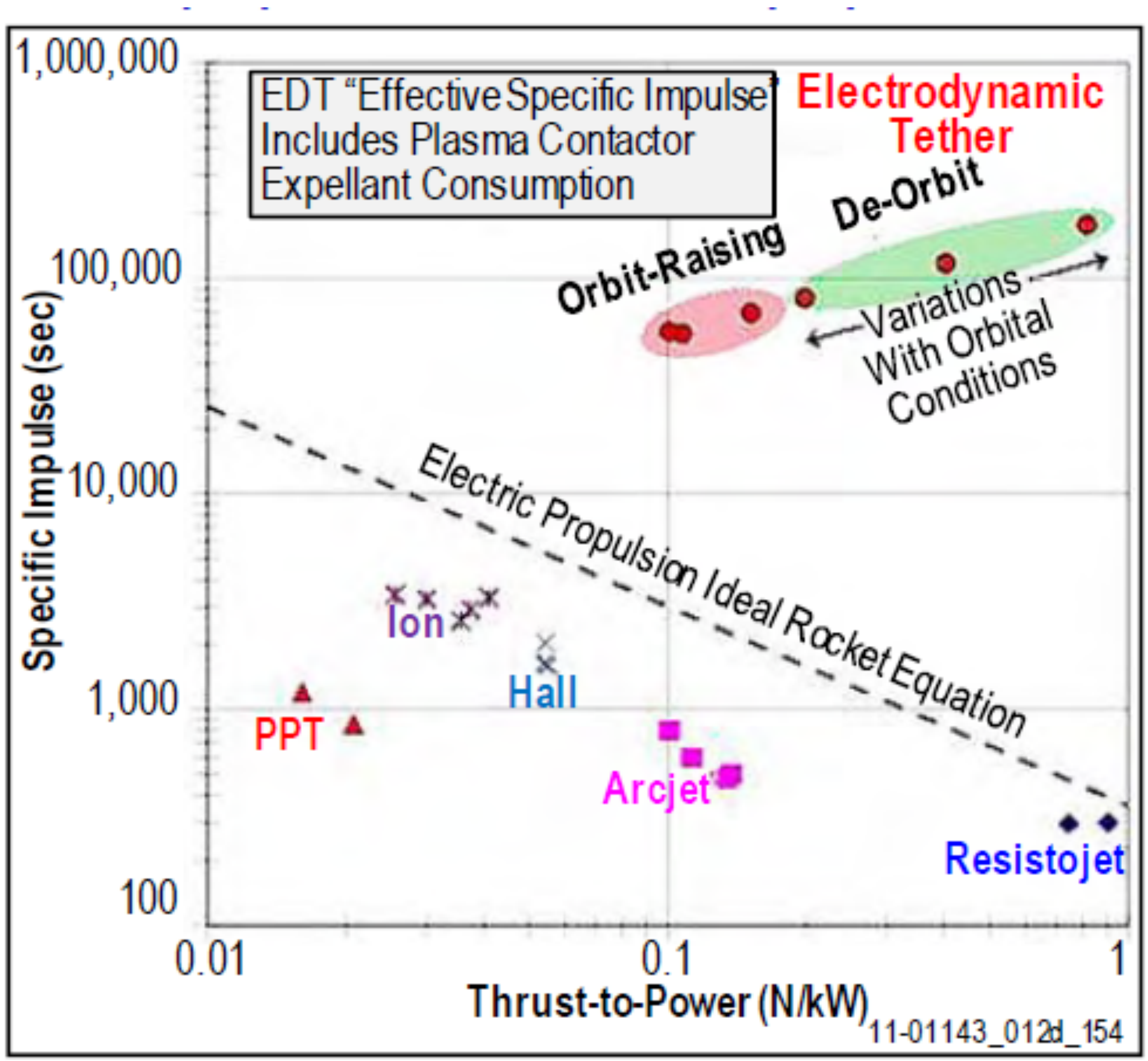
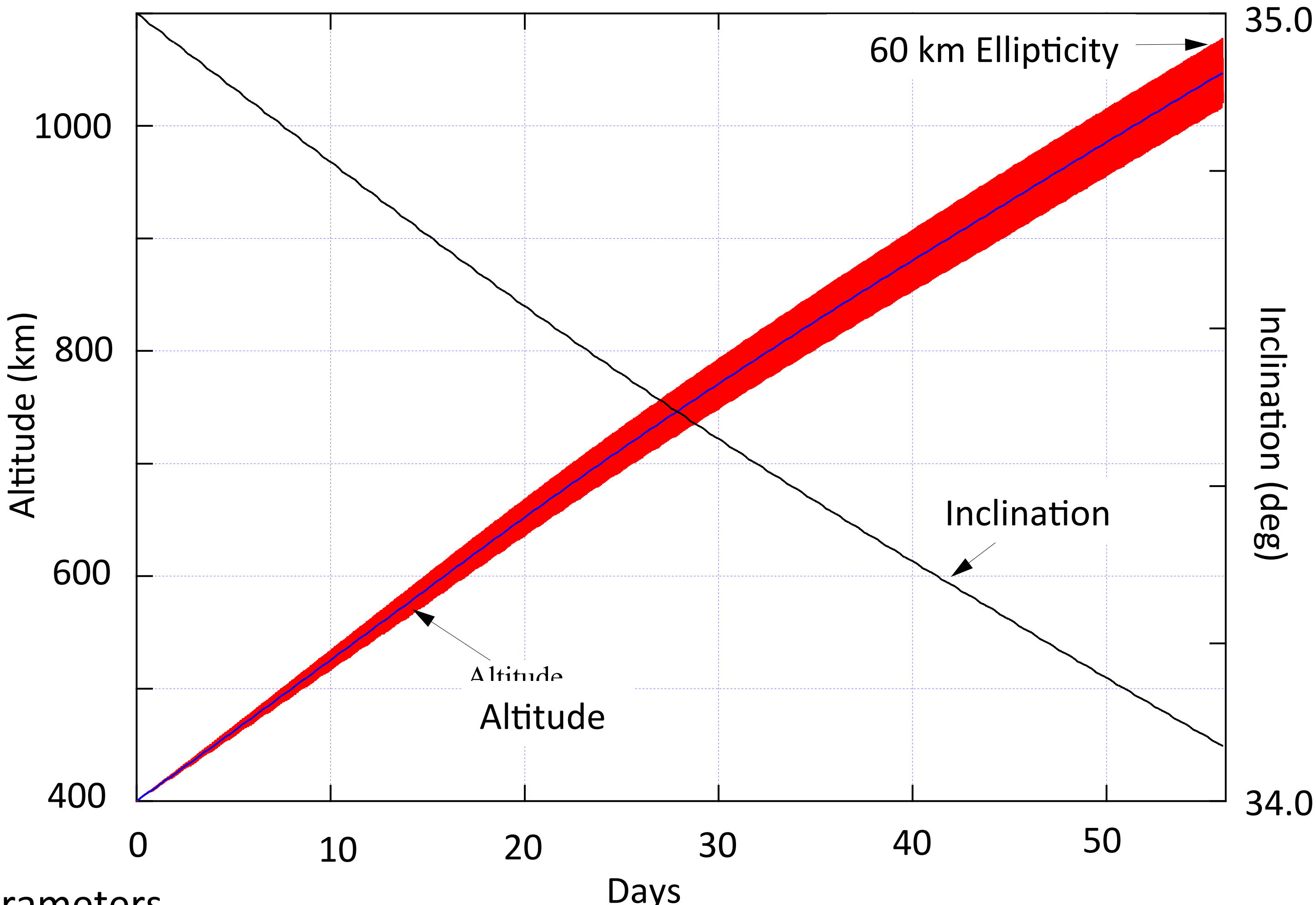
ED Tethers vs. Electric Propulsion

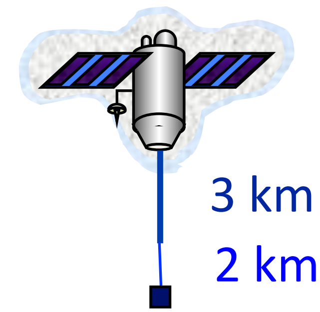
<u>EDTs provide</u>

- high-thrust-to-power
- extremely high specific impulse performance



Example: Orbit Raising Performance





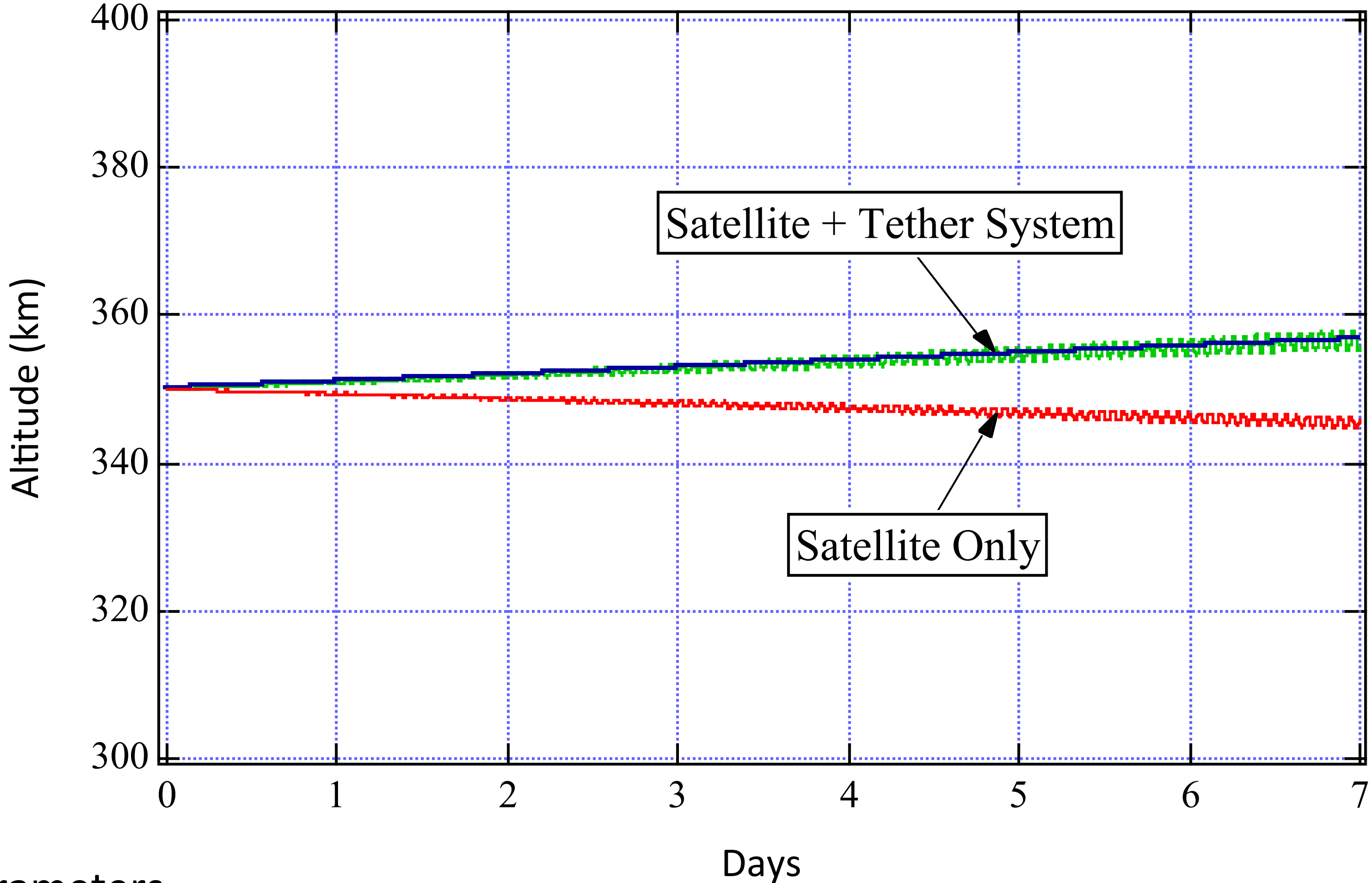
Parameters

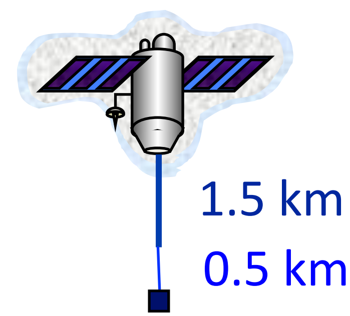
- Orbit: 400 km circular, 35° inclination
- Mass: 1,000 kg
- 5-km tether (3 km insulated, 2 km bare, 125 Ω series resistance)
- Power supply: **1 kW, Continuous**
- Thrust limited to within +/-45° of orbit plane (not severe restriction)

Simplifying assumptions

- Tether in local vertical orientation
- Thermal effects ignored
  - Solar heating
  - I^2R power loss

Example 2: Drag Make-Up

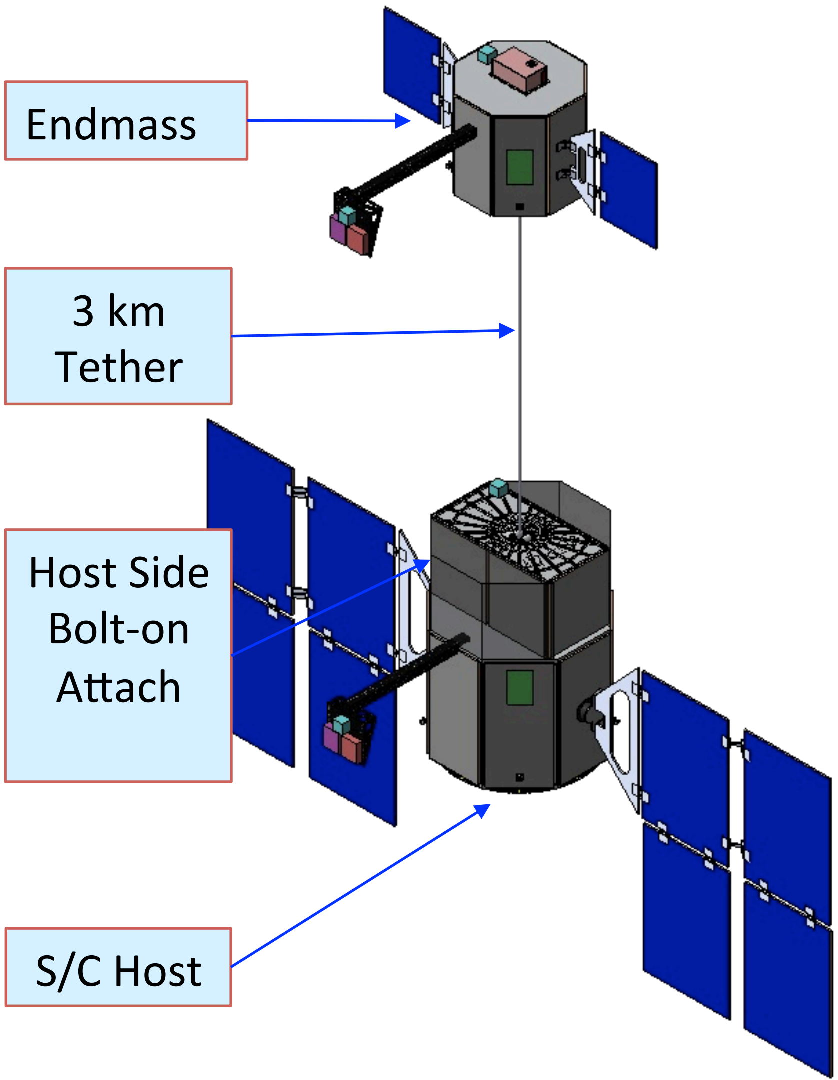




Parameters

- Orbit: 350 km circular, 35^{o} inclination
- Mass: 1,000 kg
- 2-km tether (1.5 km insulated, 0.5 km bare, 50 Ω series resistance)
- Power supply: **150 W, Continuous**
- Thrust limited to +/-25^{o} of orbit plane -> 49% duty cycle

PropEL Mission

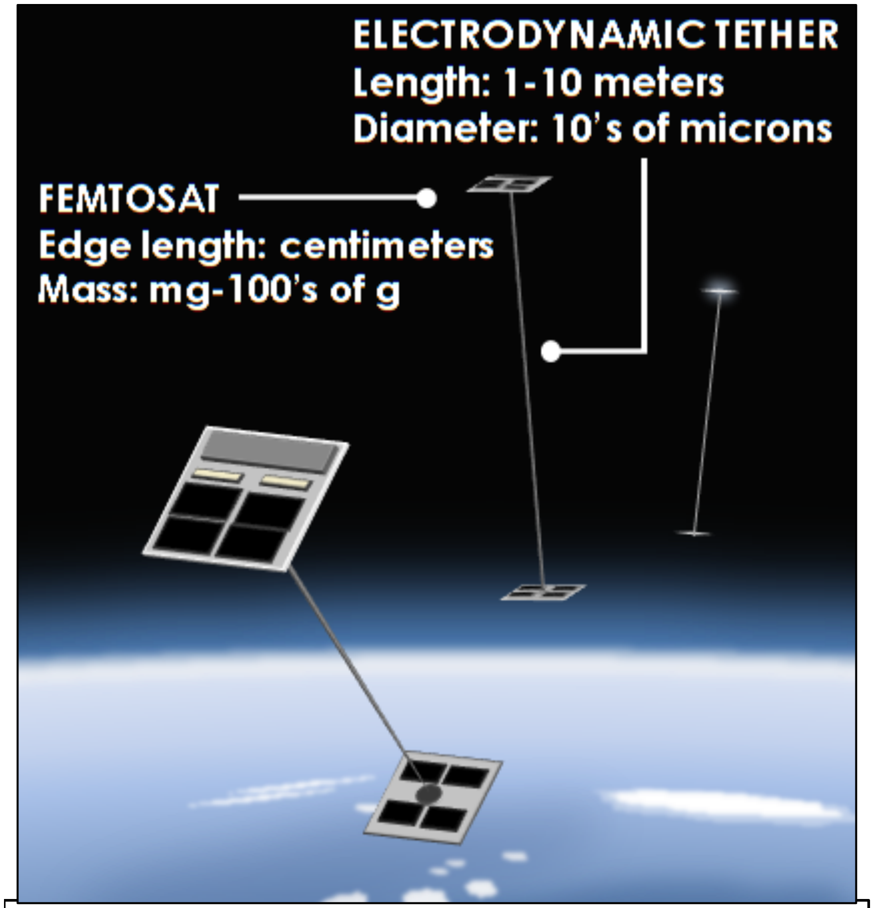


PropEl will demonstrate robust and safe electrodynamic tether propulsion in Low Earth Orbit to enable multiple Space Science, Exploration and Space Utilization Missions for a variety of users

- LEO propulsion and station-keeping without use of fuel
- Multipoint *in situ* LEO plasma measurements
- Enabling technology for more ambitious reusable tether upper stages
- Critical evaluation for future MW power generation and propulsion at Gas Giants

PropEl Delivers Space Flight Demonstration of ED Tether Propulsion for Rapid Infusion into Future Missions

Motivation for using Miniature Electrodynamic Tethers (EDTs)



- EDT can provide <u>propulsion</u>
  - ✓ Drag make-up
  - ✓ Change inclination, altitude, etc.
  - ✓ No consumable propellant
- <u>Additional benefits</u> of tether:
  - ✓ Provided gravity gradient stability
  - ✓ Tether as antenna
  - ✓ Ionospheric plasma probe
- PhD research: Iverson Bell

Bell III, Iverson C., Brian Gilchrist, Jesse K. McTernan, and Sven G. Bilén, Investigating miniaturized electrodynamic tethers for picosatellites and femtosatellites, J. Spacraft and Rockets (2016), accessed Oct 27, 2016.

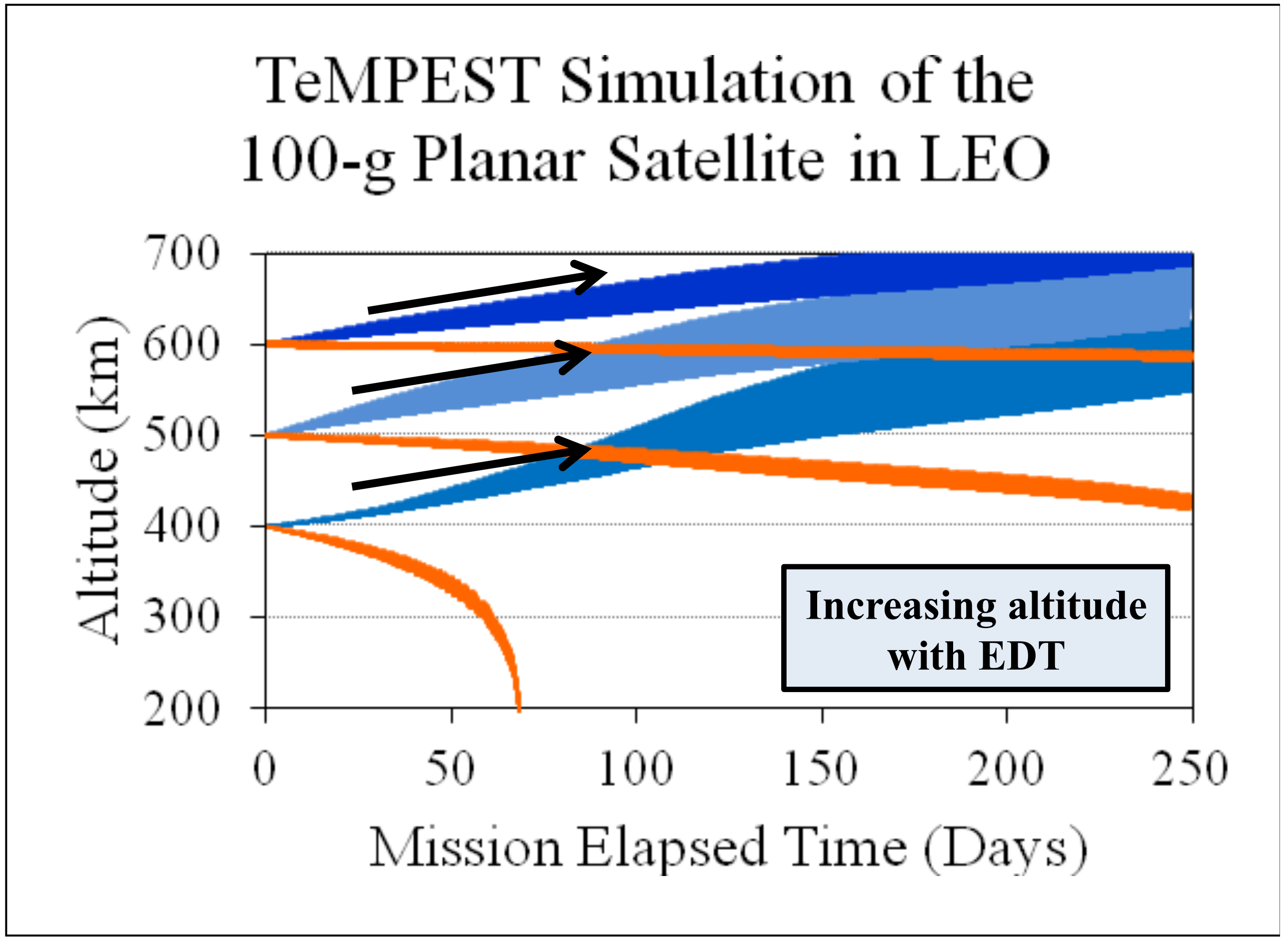
Research questions:

Can electrodynamic tethers provide ultra-small satellites with lifetime enhancement and maneuverability? Can it provide other capabilities?

Performance Simulation -100-g Sat

TeMPEST software was used to simulate orbital dynamics of:

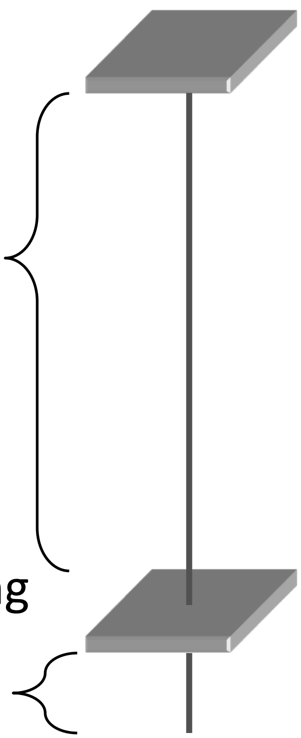
- Single 100-g satellite at 400 km, 500 km, and 600 km (**orange**)
- Dual satellites with ED tether (**blue**)



100-g satellite can boost at 400 km, 500 km, and 600 km

Using Short Conducting Tether as Antenna

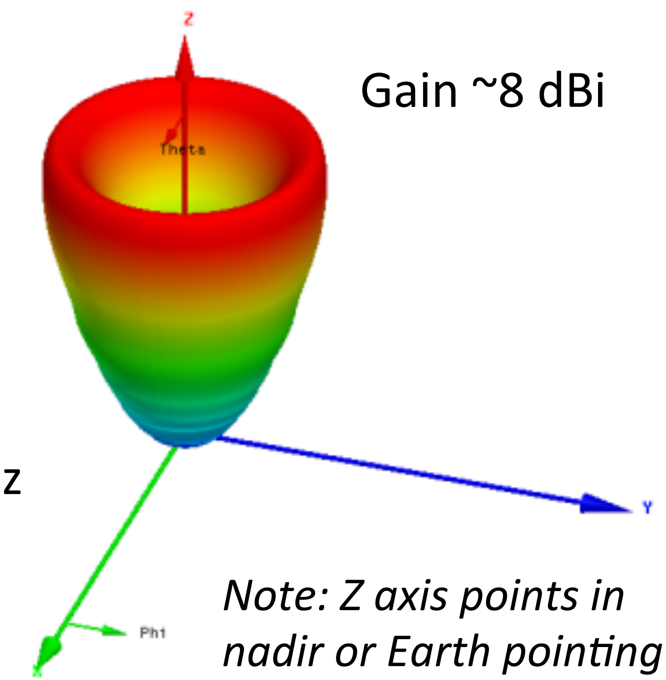
ED Tether Antenna



~10 m tether

~10 of cm long tether *or* cubesat frame

Simulated ED Tether Radiation Pattern



Gain ~8 dBi

F = 430 MHz

Note: Z axis points in nadir or Earth pointing direction

HFSS antenna model

Tether provides directional, traveling wave type radiation pattern

Conclusions

- Space Tethers can provide unique capabilities
  - Multipoint measurements
  - Double (Multi-) probes
  - Propellantless Propulsion
  - Antennas
  - Etc.
- Most tether missions have been successful
- Thank you!

- QUESTIONS