MSFC-023-ABSTRACT

Why Not Space Tethers?

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ABSTRACT

The Tethered Satellite System Space Shuttle missions, TSS-1 in 1993 and TSS-1R in 1996, were the height of space tether technology development. Since NASA's investment of some $200M and two Shuttle missions in those two pioneering missions, there have been several smaller tether flight experiments, but interest in this promising technology has waned within NASA as well as the DOD agencies. This is curious in view of the unique capabilities of space tether systems and the fact that they have been flight validated and shown to perform as, or better than, expected in earth orbit. While it is true that the TSS-1, TSS-1R and SEDS-2 missions experienced technical difficulties, the causes of these early developmental problems are now known to be design or materials flaws that are (1) unrelated to the basic viability of space tether technology, and (2) they are readily corrected. The purpose of this paper is to review the dynamic and electrodynamic fundamentals of space tethers and the unique capabilities they afford (that are enabling to certain types of space missions); to elucidate the nature, cause, and solution of the early developmental problems; and to provide an update on progress made in development of the technology. Finally, it is shown that (1) all problems experienced during early development of the technology now have solutions; and (2) the technology has been matured by advances made in strength and robustness of tether materials, high voltage engineering in the space environment, tether health and status monitoring, and the elimination of the broken tether hazard. In view of this, it is inexplicable why this flight-validated technology has not been utilized in the past decade, considering the powerful and unique capabilities that space tethers can afford that are, not only required to carryout, otherwise, unobtainable missions, but can also greatly reduce the cost of certain on-going space operations.

MSFC-023-PRESENTATION

SRS TECHNOLOGIES

Why Not Space Tethers?

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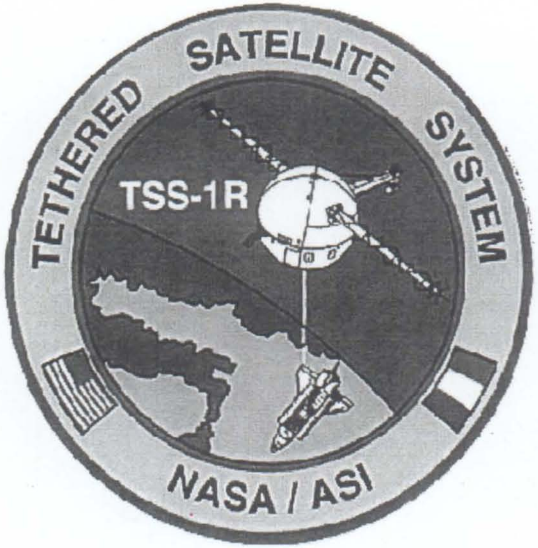
54th JANNAF Propulsion Meeting

Denver, Colorado
May 14-18, 2007

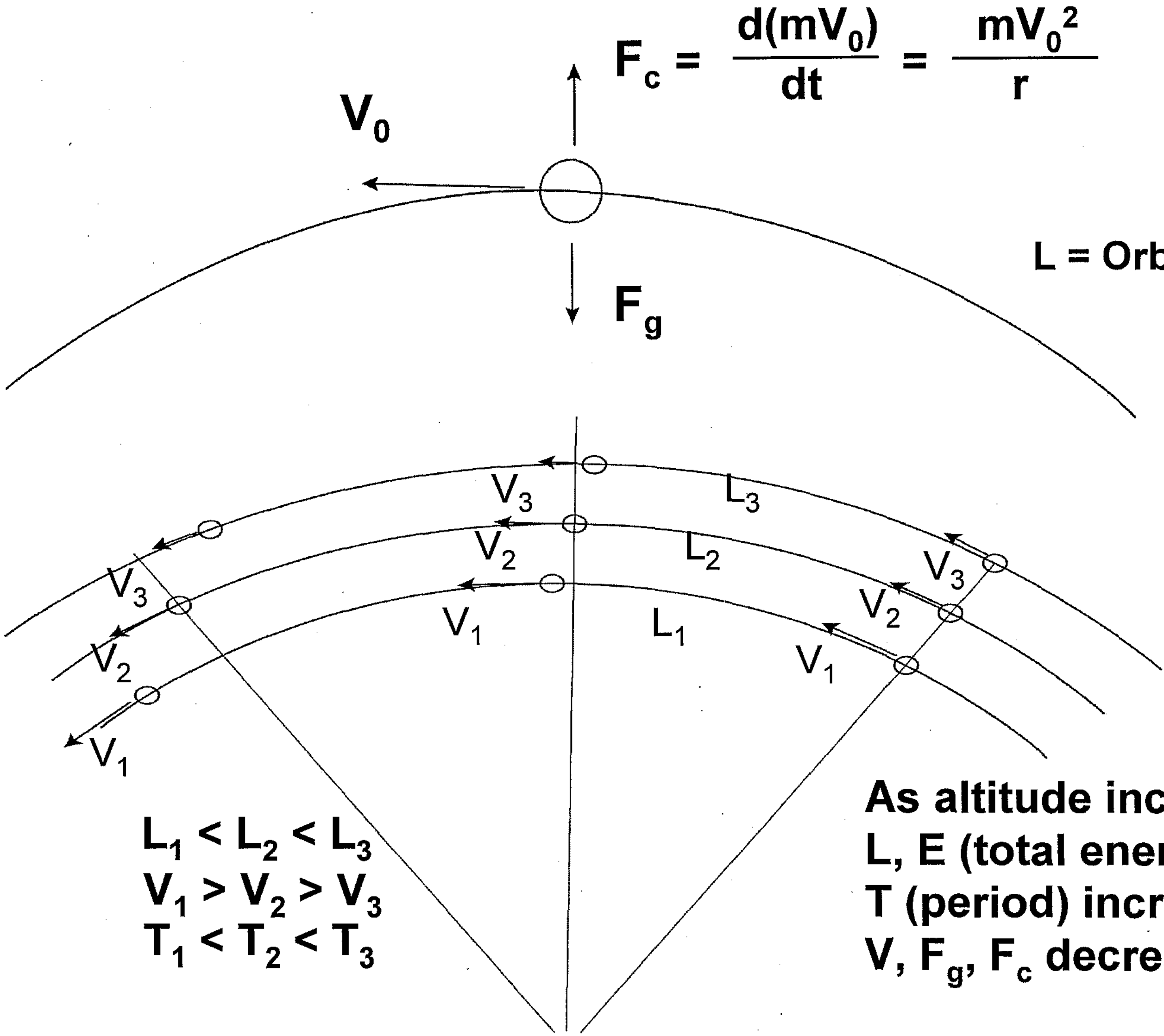


Developmental History of
Space Tethers

1970's	Dynamics of long gravity-gradient stabilized tethers shown feasible/ NASA presented TSS concept	Giuseppe Colombo & Mario Grossi, SAO
1979-80	NASA/OSSA Facilities Requirements Definition Team (FRDT)	Peter Banks, chair (U of Mich.)

1980's	NASA OSF Ivan Becky	Technological interests formulated - electrical power generation - orbital transfer - de-orbit, etc.
August 1992	TSS-1	Electrodynamic: 20-km conducting tether w/Reel-type deployer (NASA/ASI)
1993, 1994	SEDS-1 and 2	Dynamic: 20-km Non-Conducting Tether w/ Spindle Type Deployer (NASA)
June 1993	PMG	Bi-polar operation; i.e., generator and motor modes (NASA)
February 1996	TSS-1R	Electrodynamic: 20-km conducting tether w/Reel-type deployer (NASA/ASI)
June 1996	TiPS	Dynamic: 4 km long x 2 mm diameter tether (NRL)

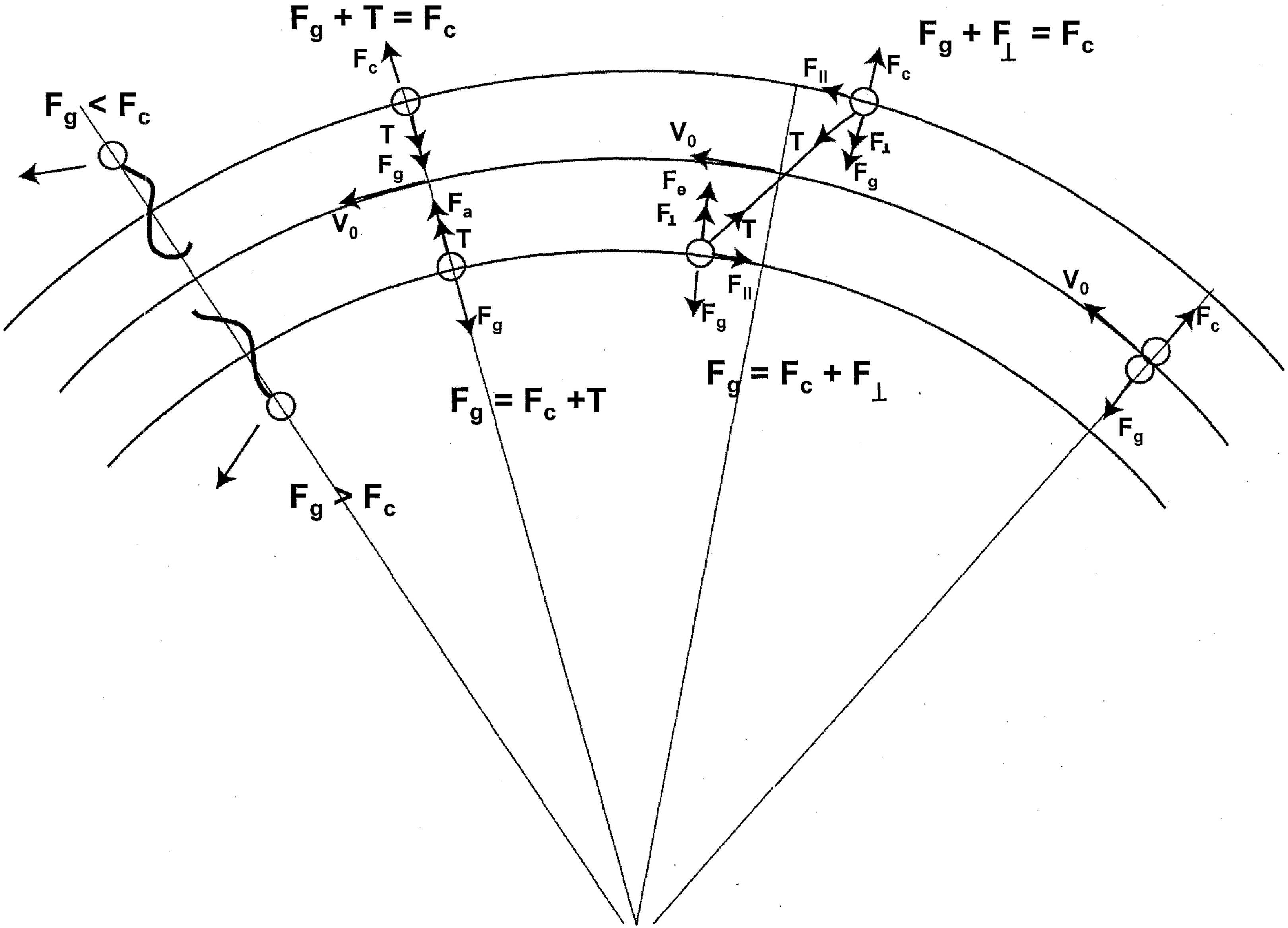
Tethered Satellite Orbital Dynamics



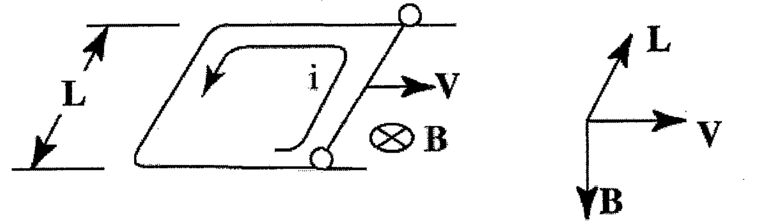
$L_1 < L_2 < L_3$
$V_1 > V_2 > V_3$
$T_1 < T_2 < T_3$

As altitude increases
L, E (total energy,
T (period) increase
V, F_g, F_c decrease

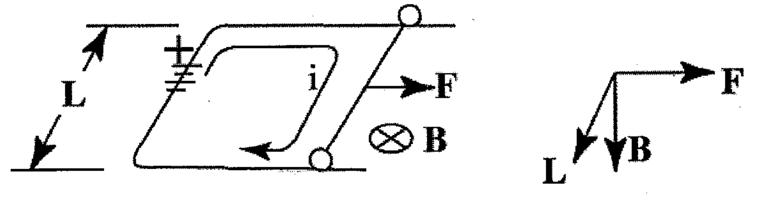
Tethered Satellite Orbital Dynamics



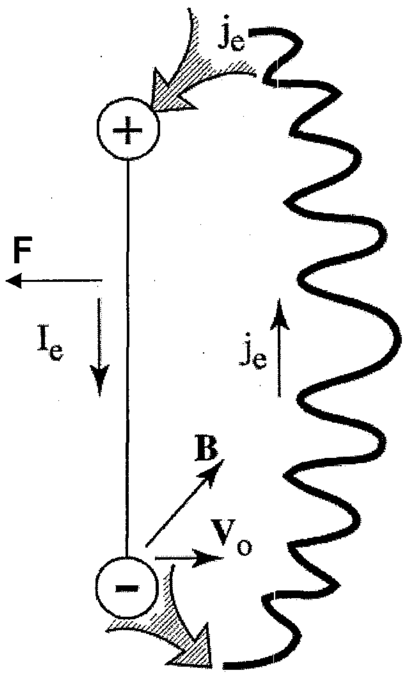
Generation Mode

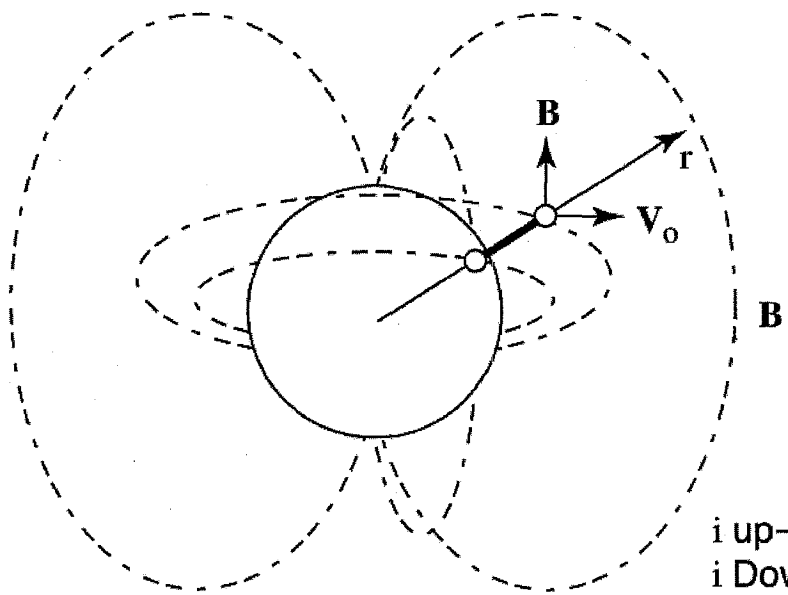


Motor Mode



$\mathbf{F} = i\,(\mathbf{L} \times \mathbf{B})$





i up→ Negative Acceleration
i Down→ Positive Acceleration

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End-body Stabilization Requirement

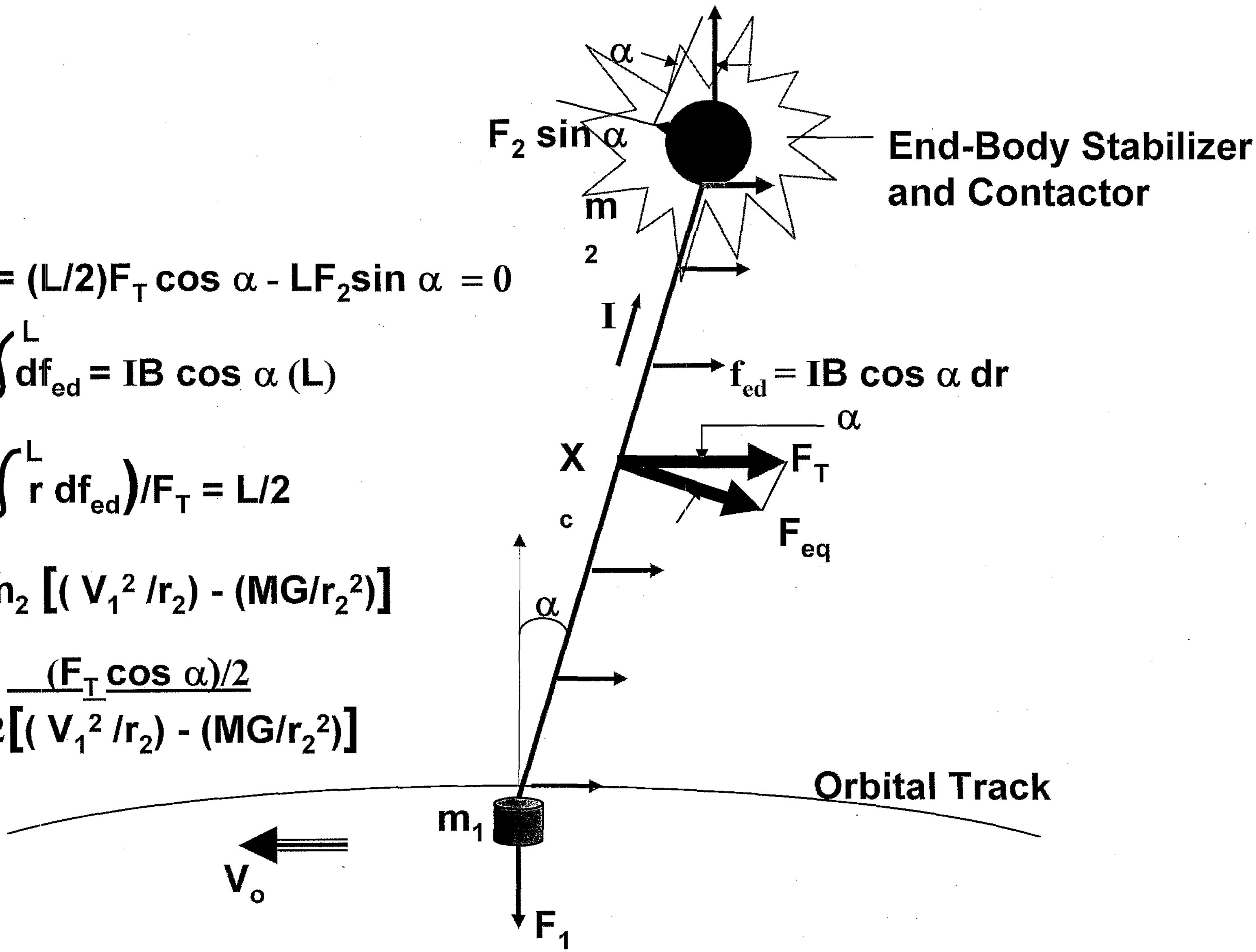
$$\Sigma M_1 = (L/2)F_T \cos\alpha - LF_2 \sin\alpha = 0$$

$$F_T = \int_0^L df_{ed} = IB\cos\alpha\,(L)$$

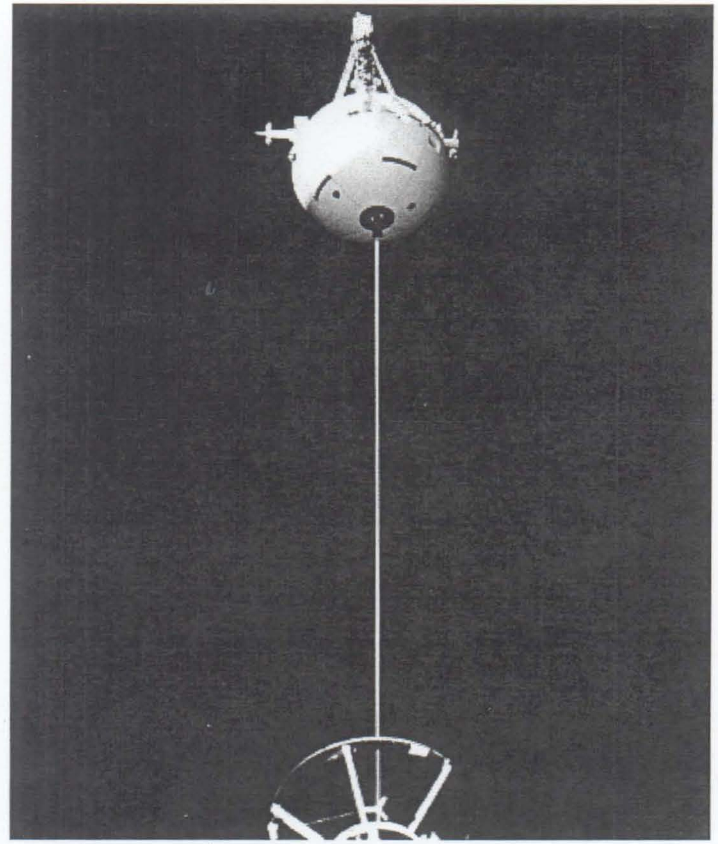
$$X_c = \left(\int_0^L r\,df_{ed}\right)/F_T = L/2$$

$$F_2 = m_2\left[\left(V_1^2/r_2\right) - \left(MG/r_2^2\right)\right]$$

$$M2 = \frac{(F_T \cos\alpha)/2}{2\left[\left(V_1^2/r_2\right) - \left(MG/r_2^2\right)\right]}$$



Positive Results from Tether Missions



<u>**Dynamics**</u>

- **Dynamic Stability (TSS-1)**
  Gravity-gradient stabilization achieved at < 300 m.
- **Ease of Deployment and Control (SEDS-1/2 & TSS-1)**
  Deployment to 20 km, station keeping for more than 20 hrs, and satellite retrieval have been demonstrated.
- **Recovery from Dynamic Upsets & Slack Tether**
  TSS recovered from severer dynamic perturbations, slack tether and satellite pendulous motions.
- **Retrieval (TSS-1)** Near retrieval (most critical aspect) from 276 m was nominal (shown at right).

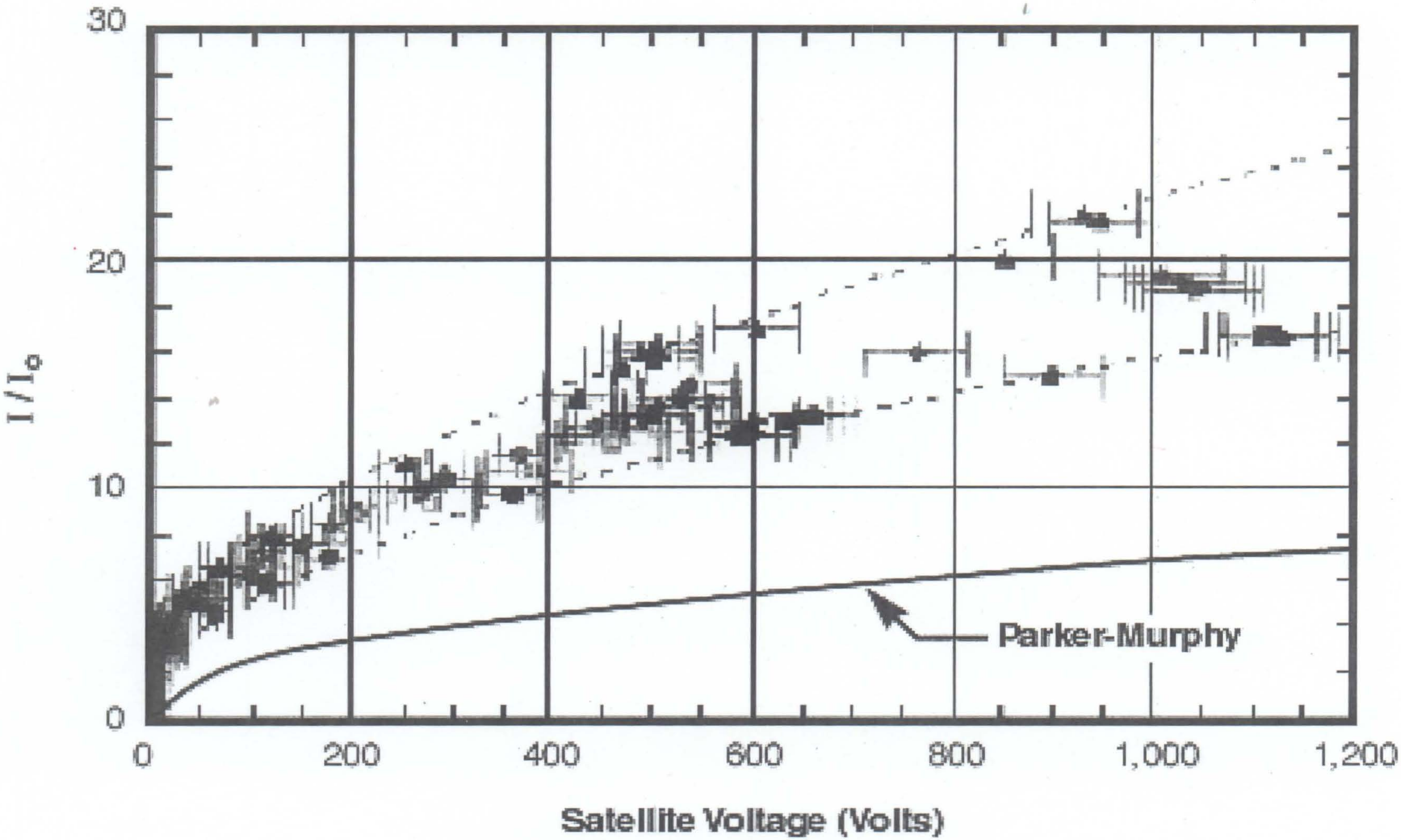
<u>**Electrodynamics**</u>

- **Current collection in space <u>*ten times more*</u> efficient than predicted (TSS-1R)**
  Even greater efficiency obtained w/gas emissions. Pre-TSS theoretical models much too conservative.
- **Energy conversion from spacecraft orbit into electrical power demonstrated (TSS-1R)**
  A peak power of > 3.5 kW was generated.
- **Bi-polar operations (PMG)** Polarity and current flow reversal performed, demonstrating power and propulsive thrust generation.

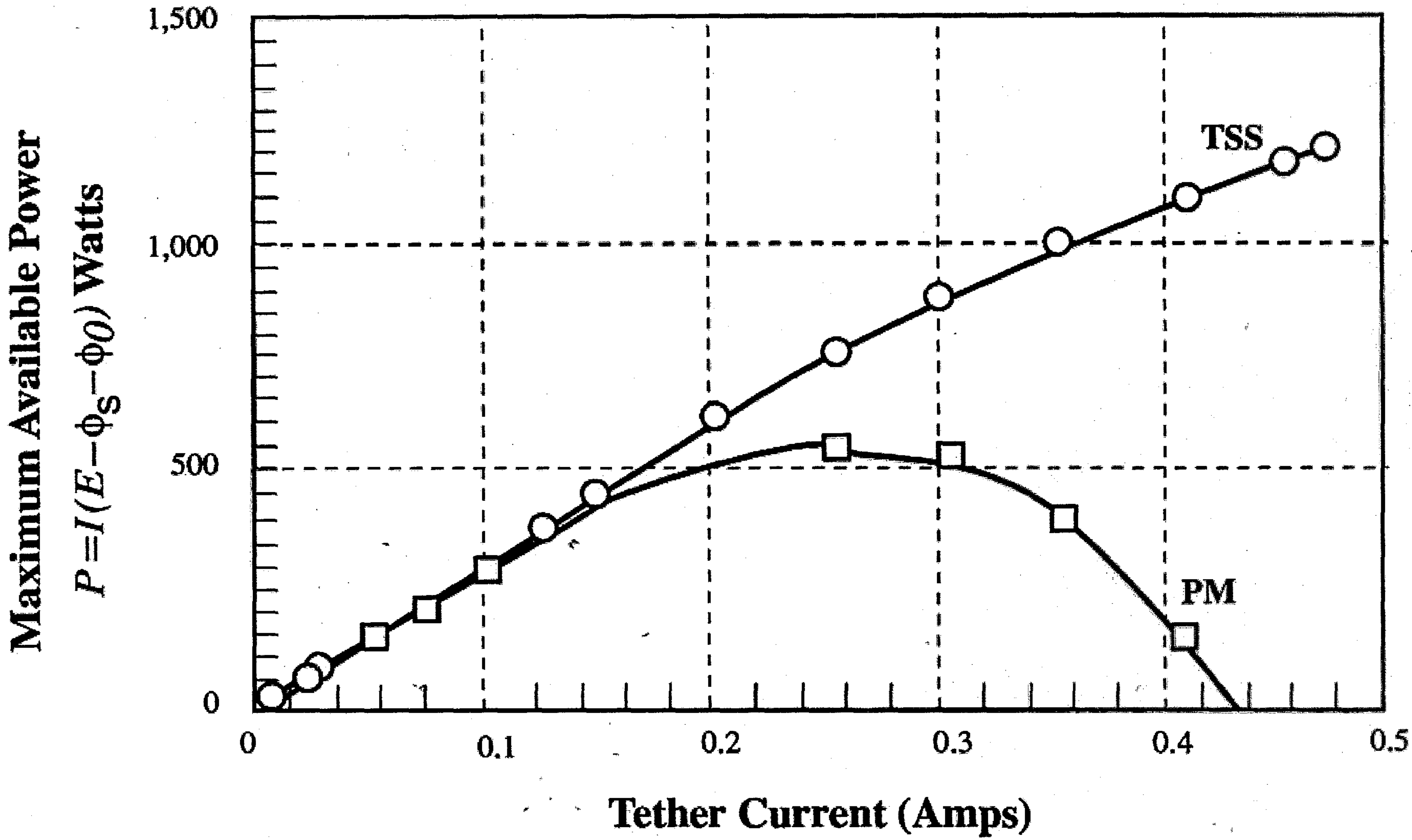
<u>**Hardware Flight Heritage**</u>

- **Tether Survivability Demonstrated In-Space (TiPS)**
  The TiPS tether (2 mm x 4 km) remains intact on orbit for 10 years.
- **Deployer In-Space Validation (6 missions)**
  Successful deployment with simple spool deployer (SEDS-1 & 2, PMG and TiPS), and with real type (TSS).

TSS Data –vs- Standard Theory

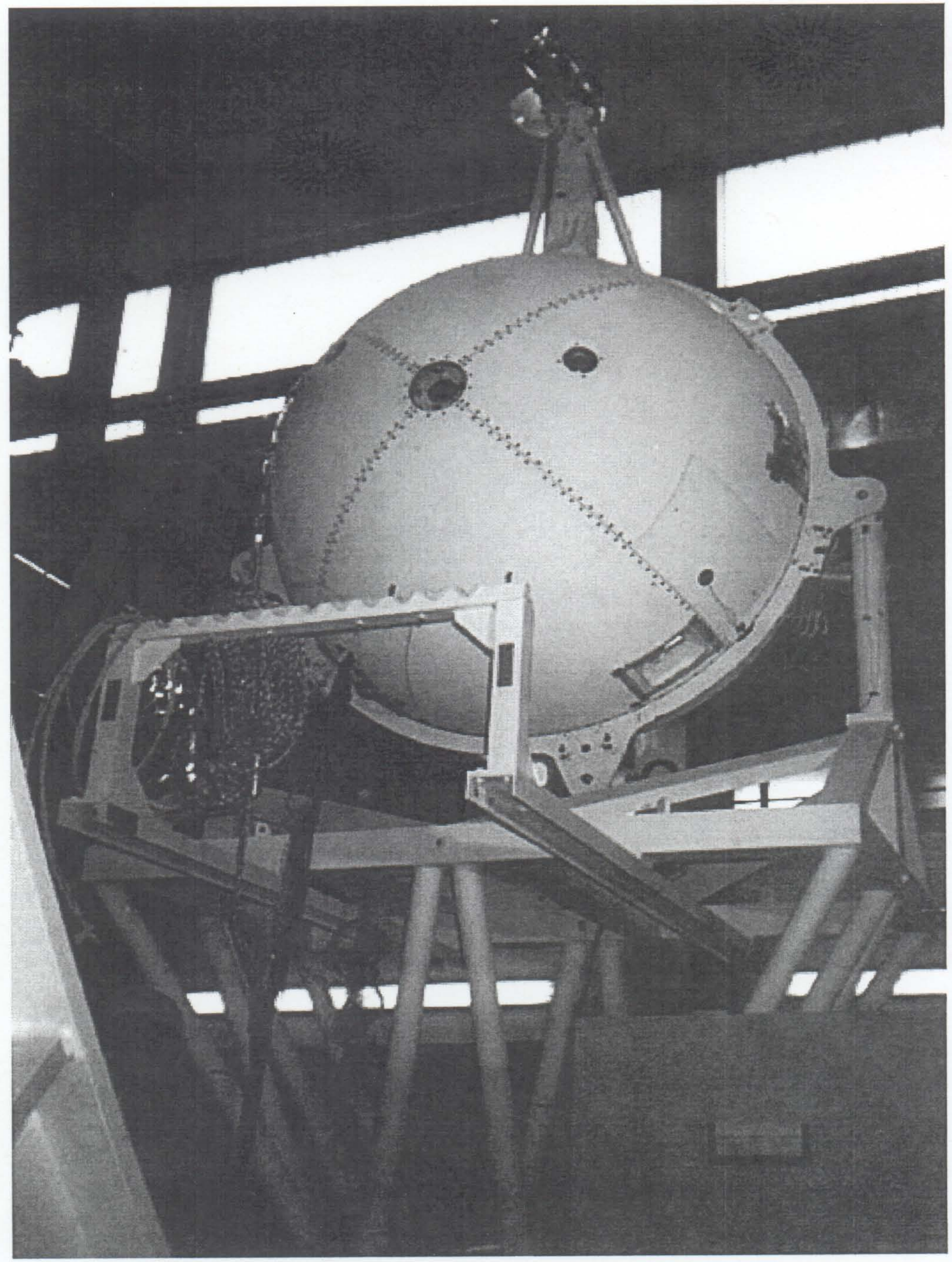


Usable Power: TSS-1R Data vs Theory

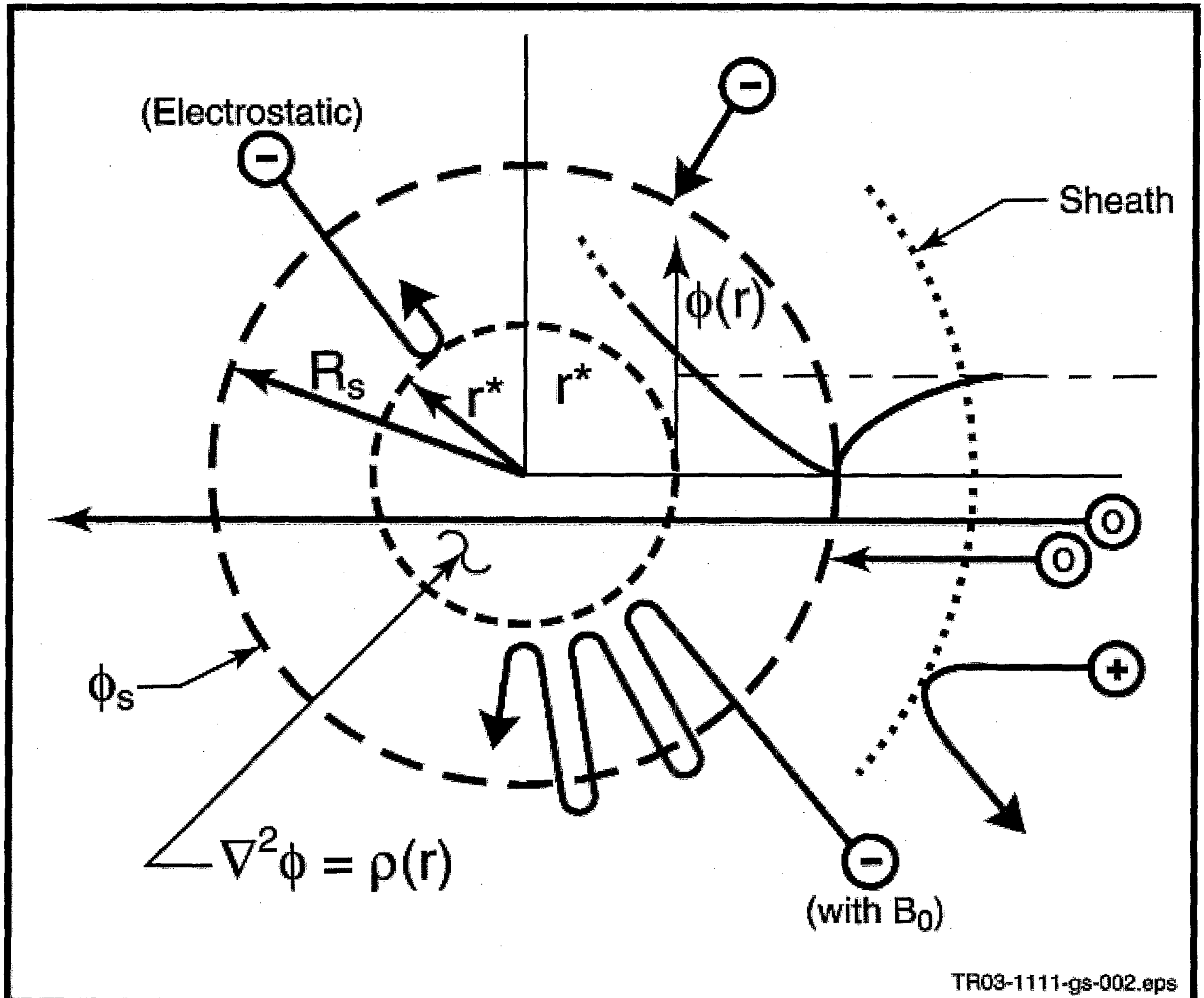


Open Issues

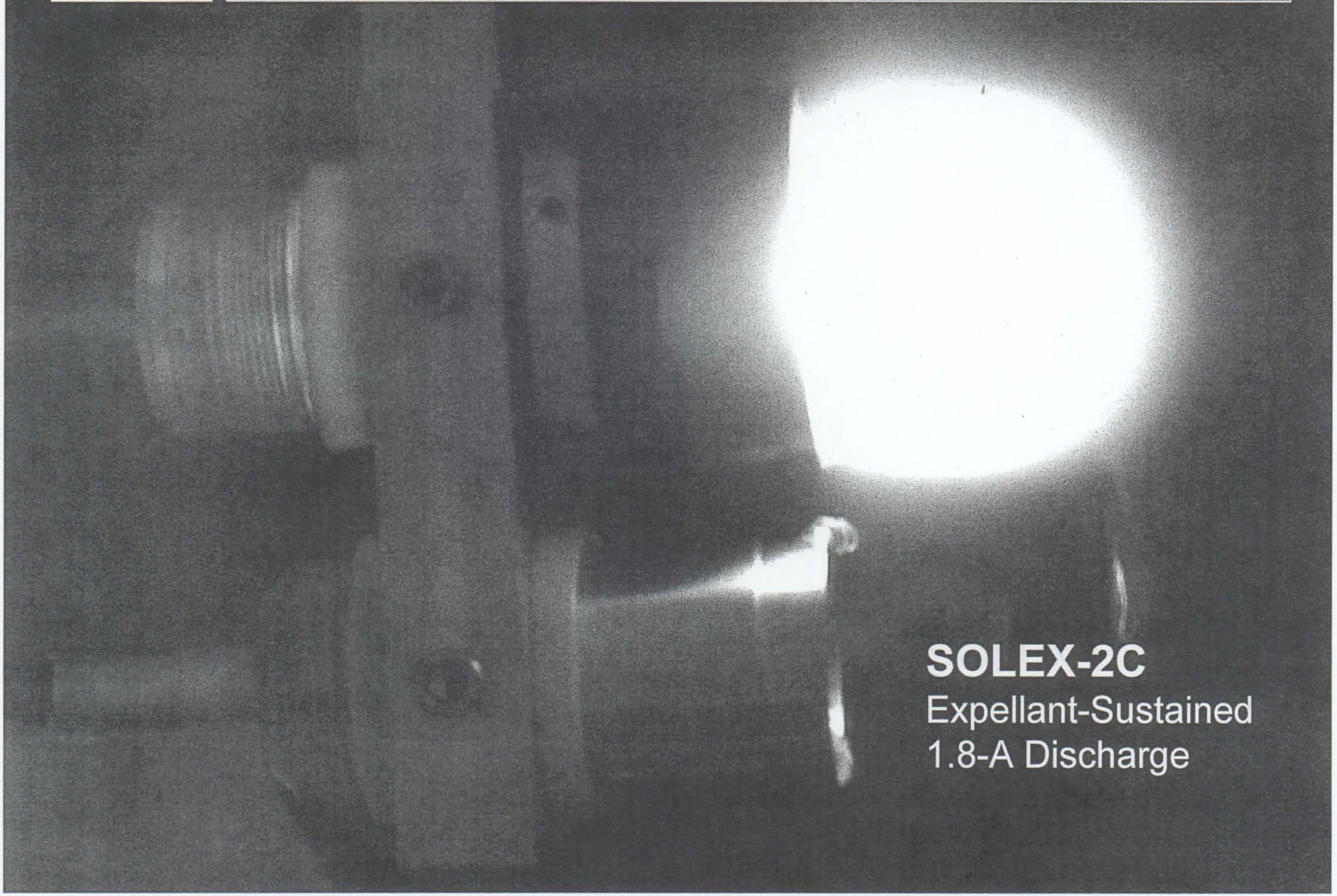
- **Tether long-term survivability**
  in meteorite, debris, and atomic oxygen environments
- **Broken Tether Hazard**
  entanglement of mother s/c by slack tether following rebound
- **Stability**
  long-term electrodynamic-dynamic coupling (with tether current)
- **Deployer development**
  simple, robust, low mass, multi-purpose
- **Plasma contactor development**
  simple, low consumables, mass and power—or passive



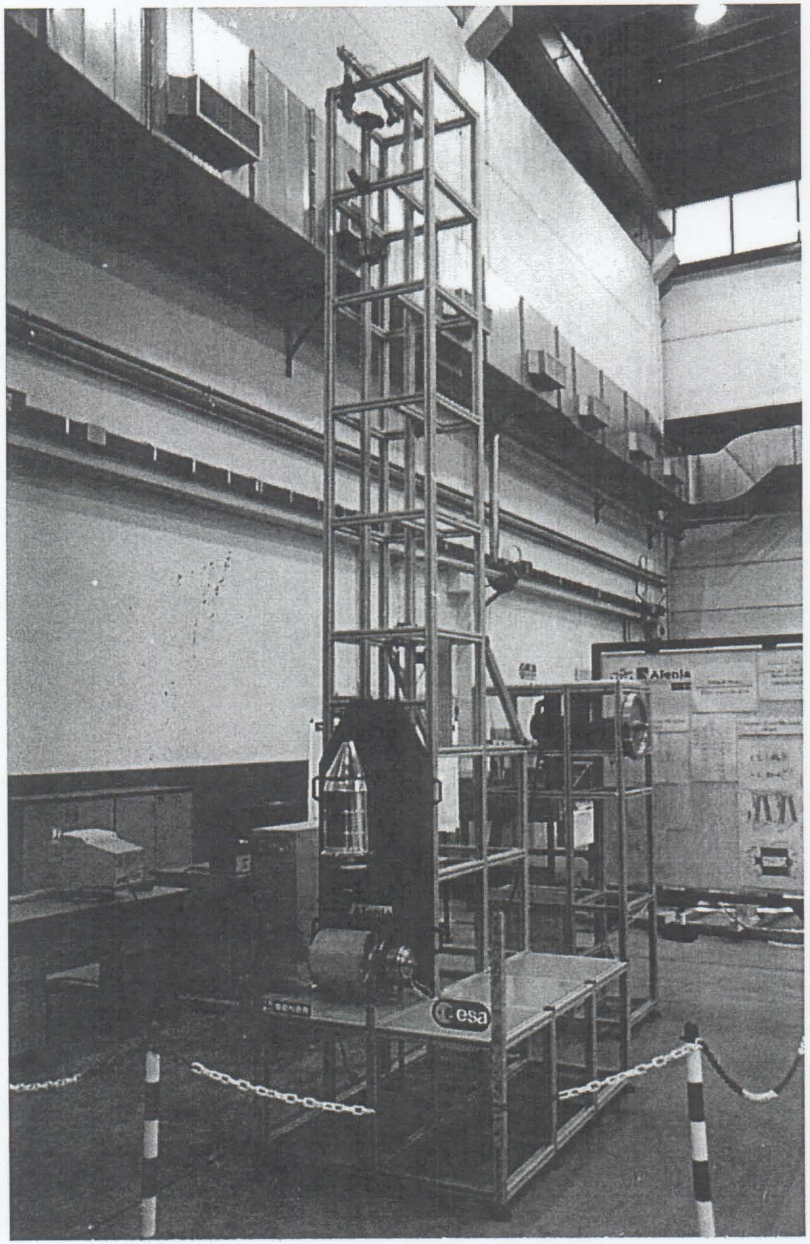
Grid-Sphere Low-Drag Electrode

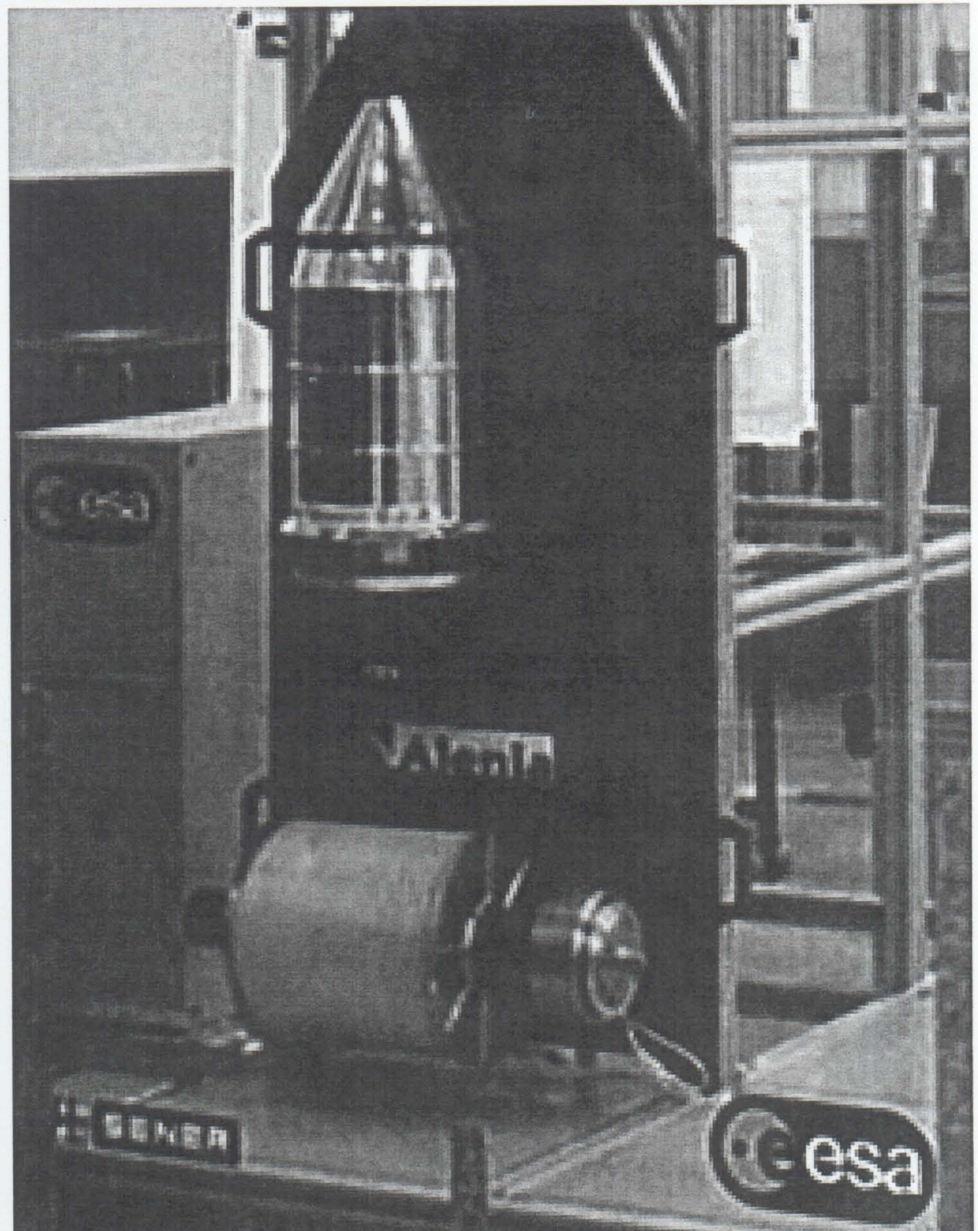


SOLEX Plasma Mode Discharge

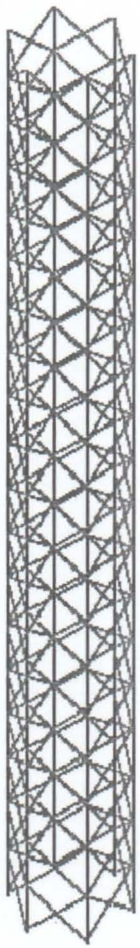


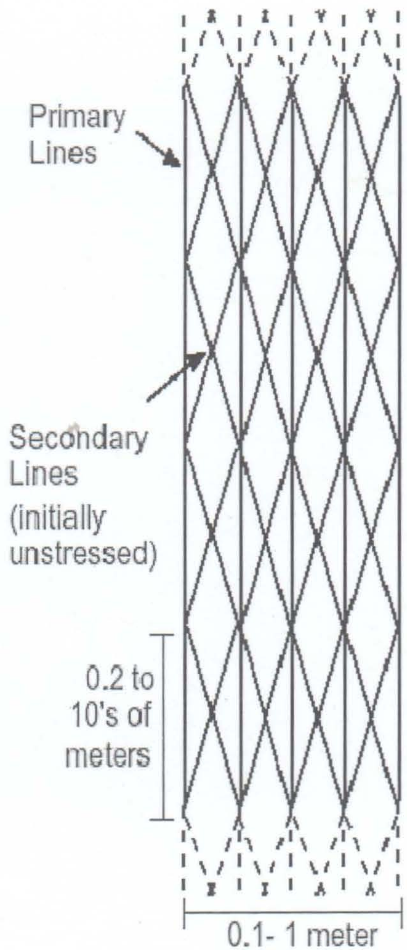
Alenia Tether Deployer Hardware

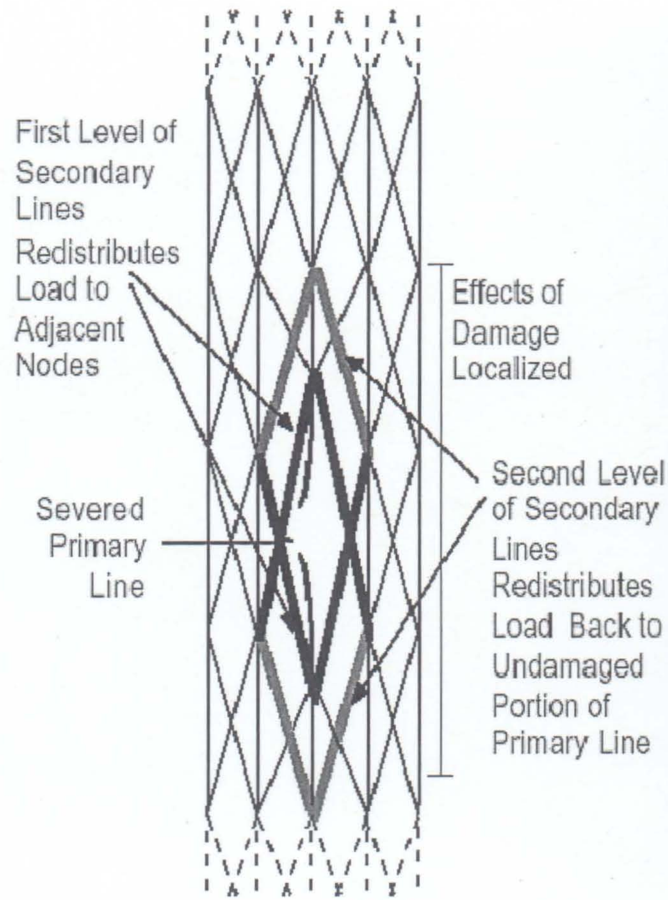


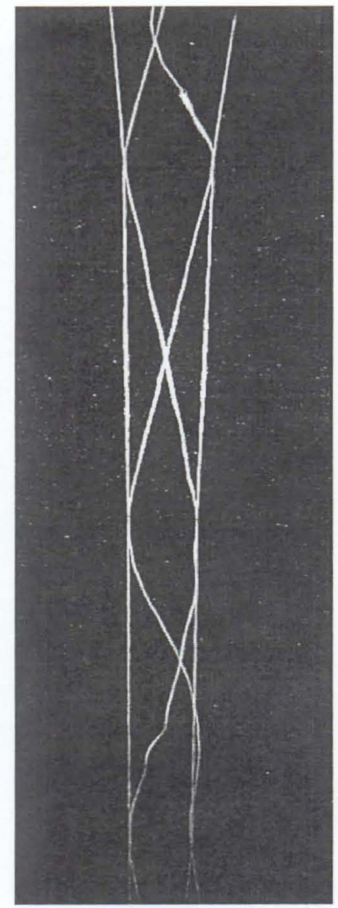


Long-Life Tether Designs









Prototype Hoytether Tether

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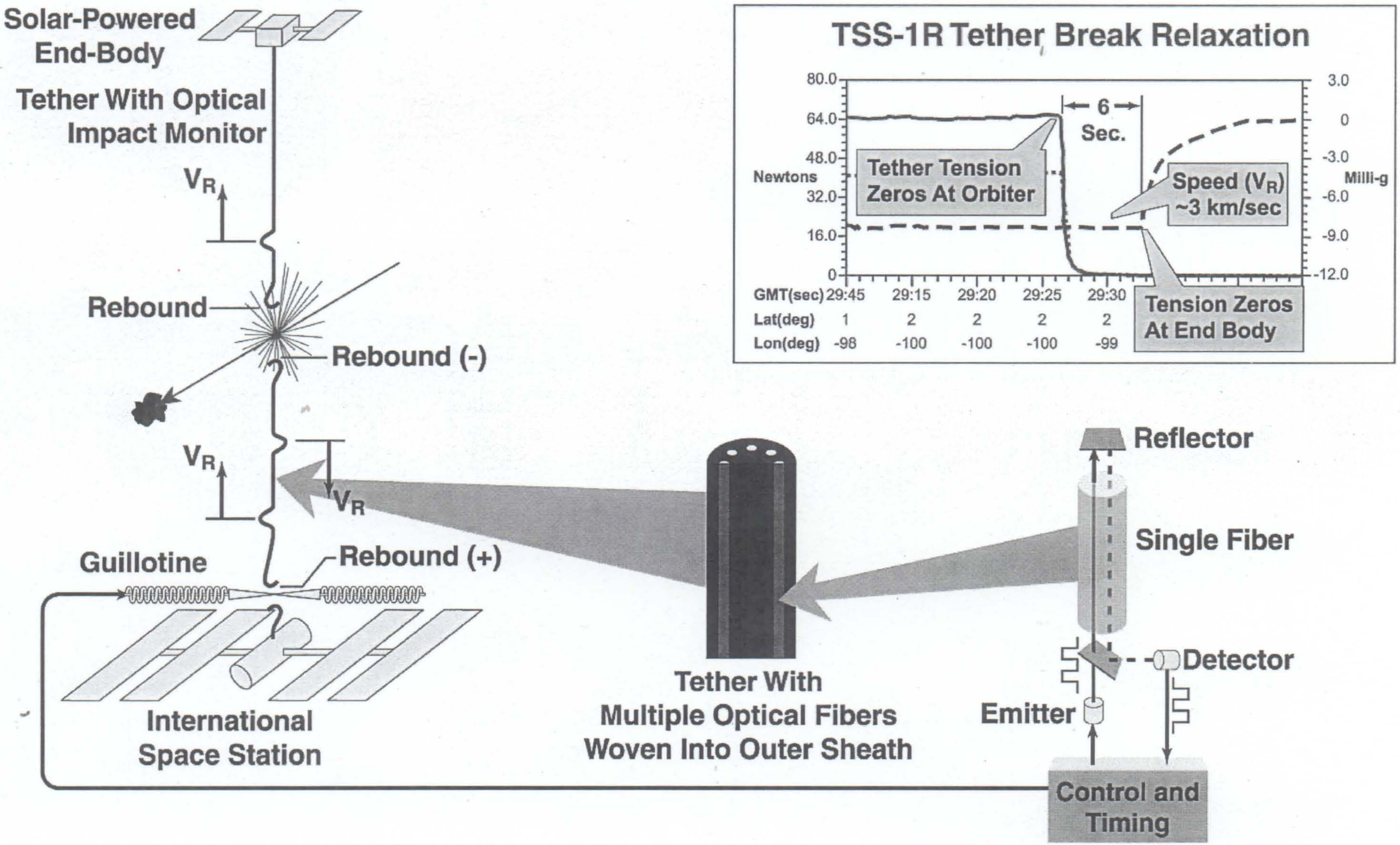
Tether Optical Fiber Impact Monitor



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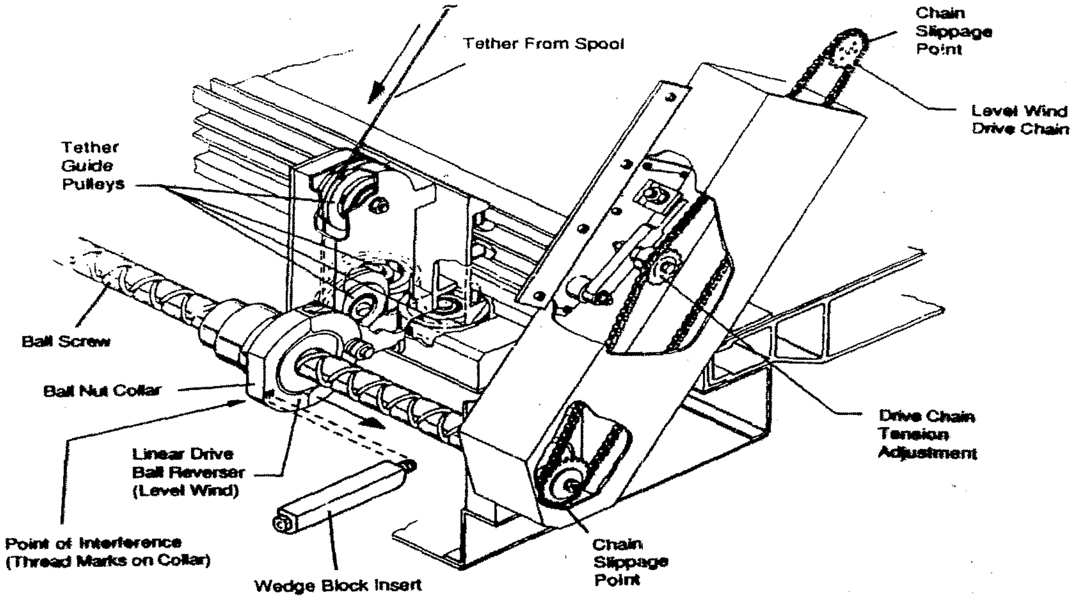
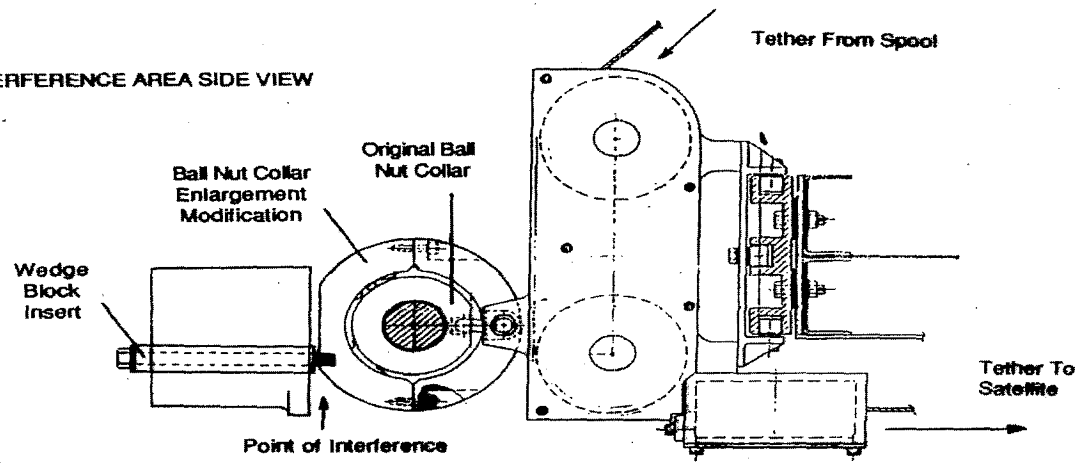
TSS-1 Tether Jam Anomaly

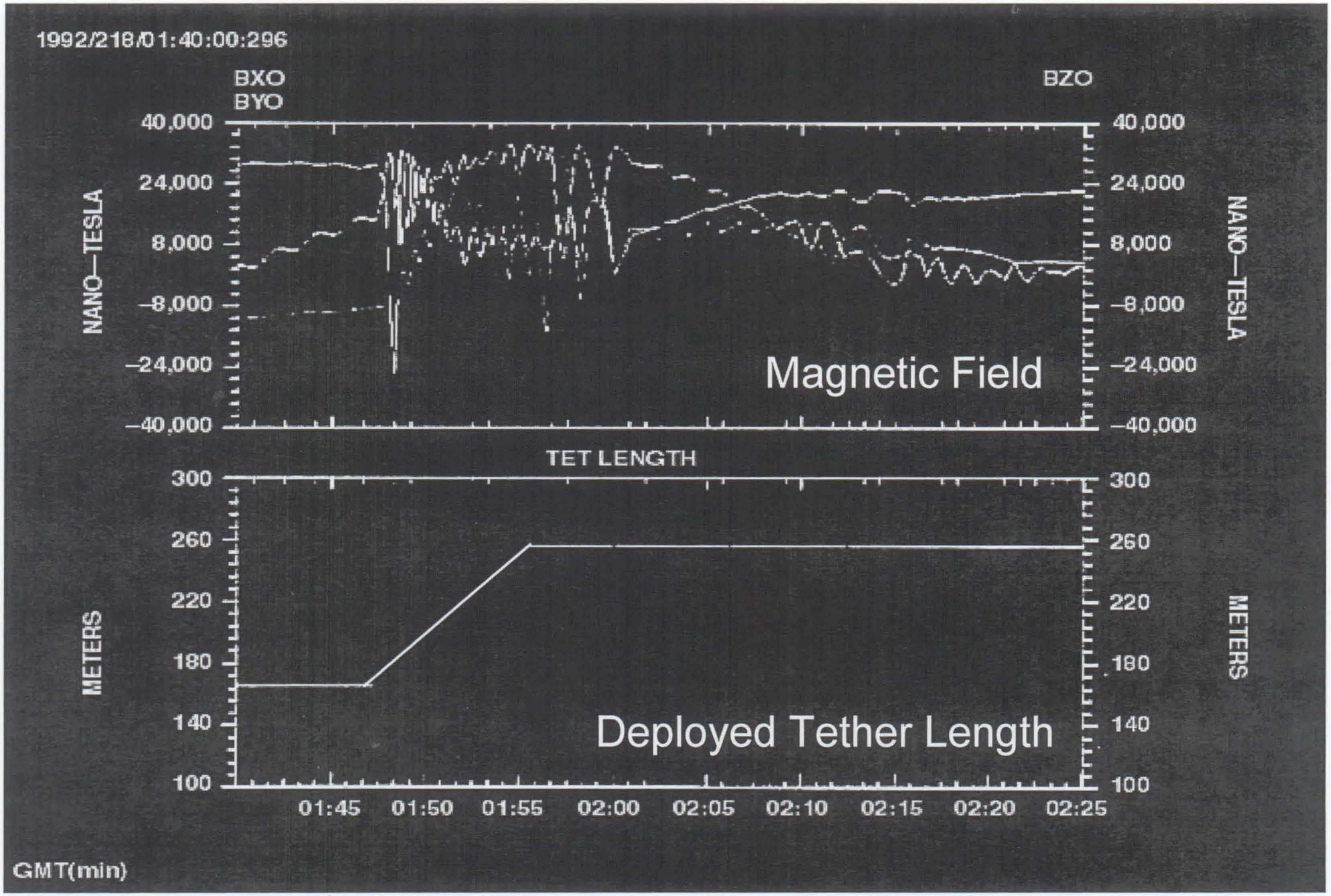
S-875-92-46-01



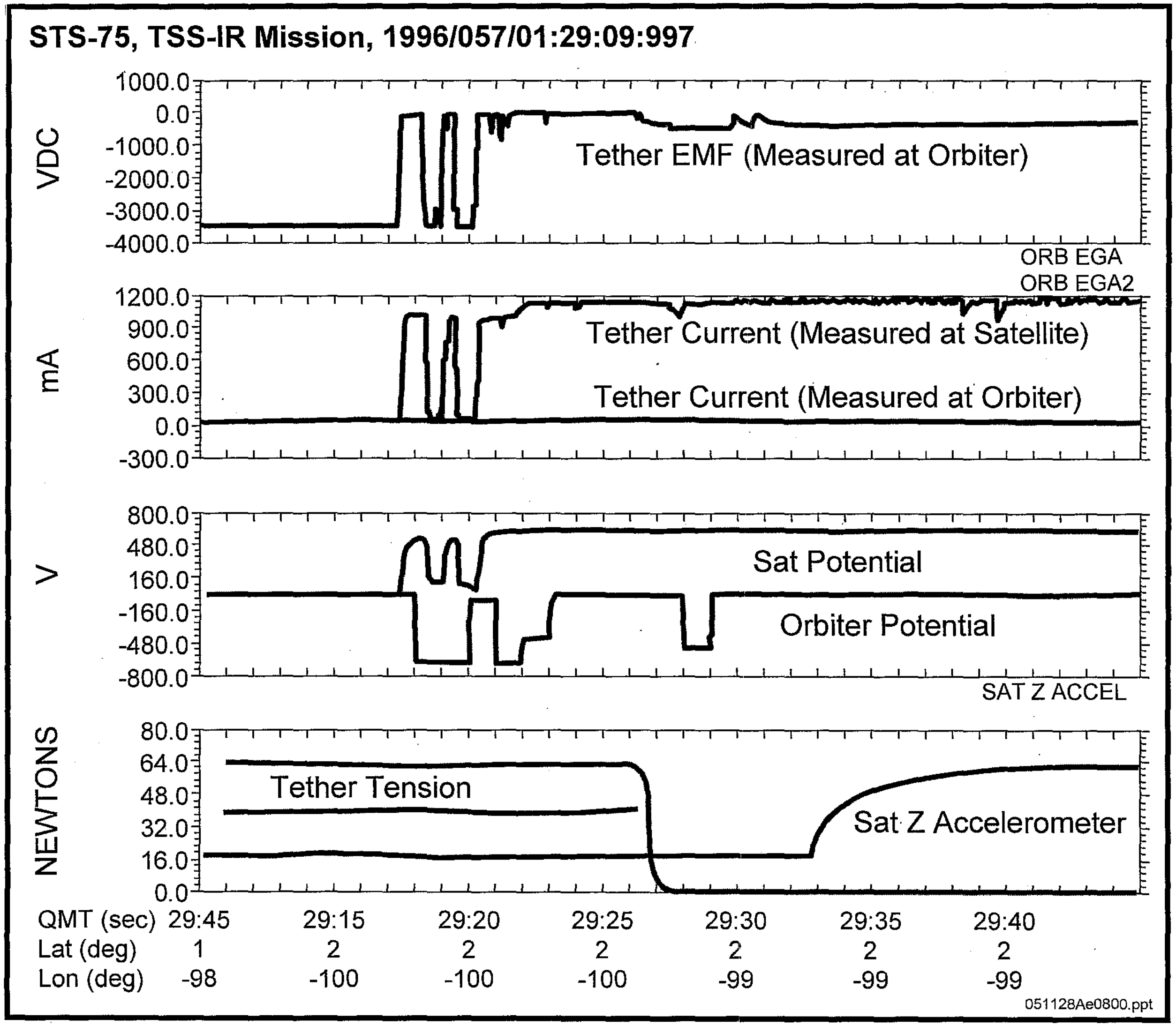
INTERFERENCE AREA SIDE VIEW



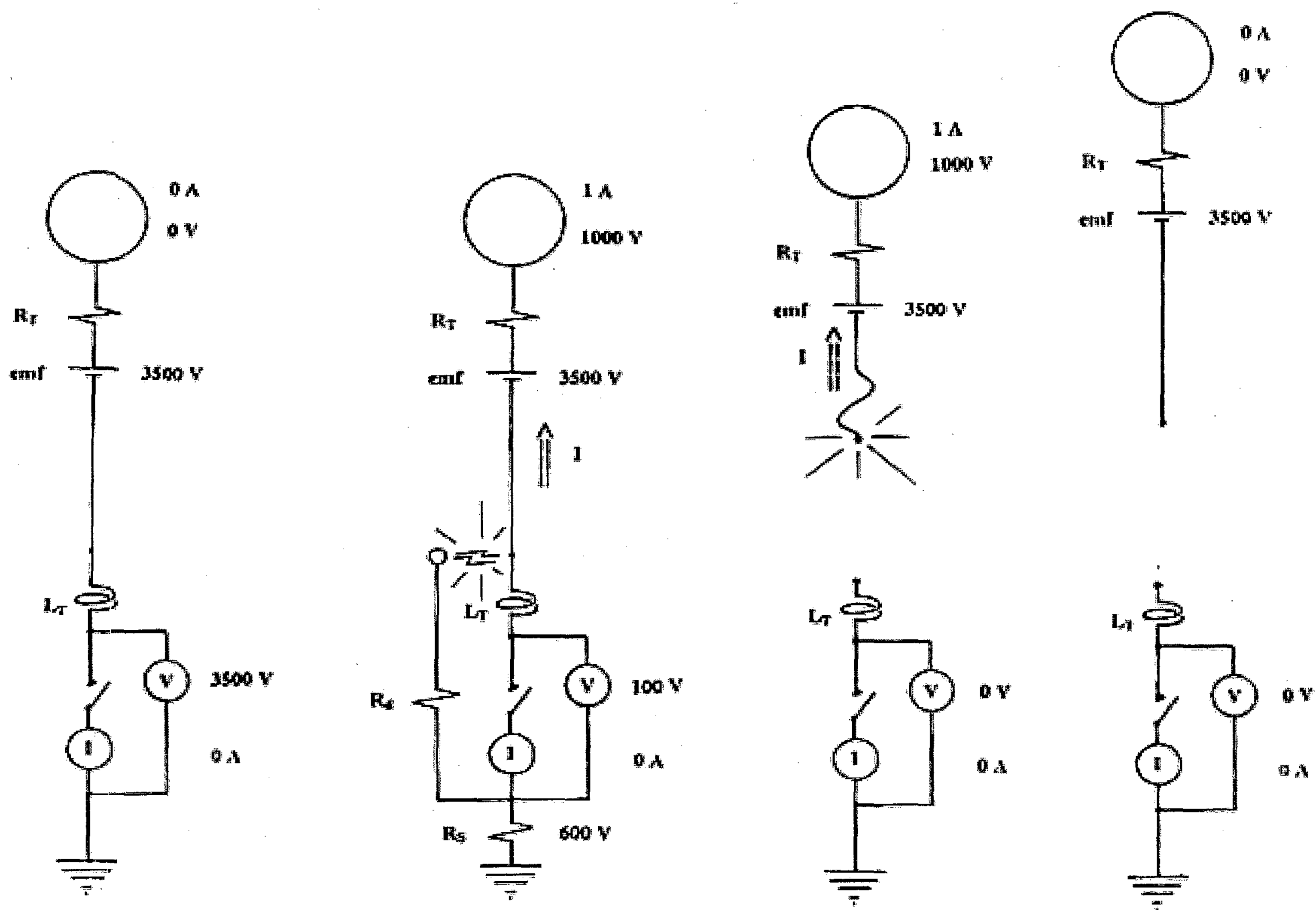
Dynamic Up-Set and Relaxation



TSS-1R Tether-Break Data



TSS-1R Tether-Break



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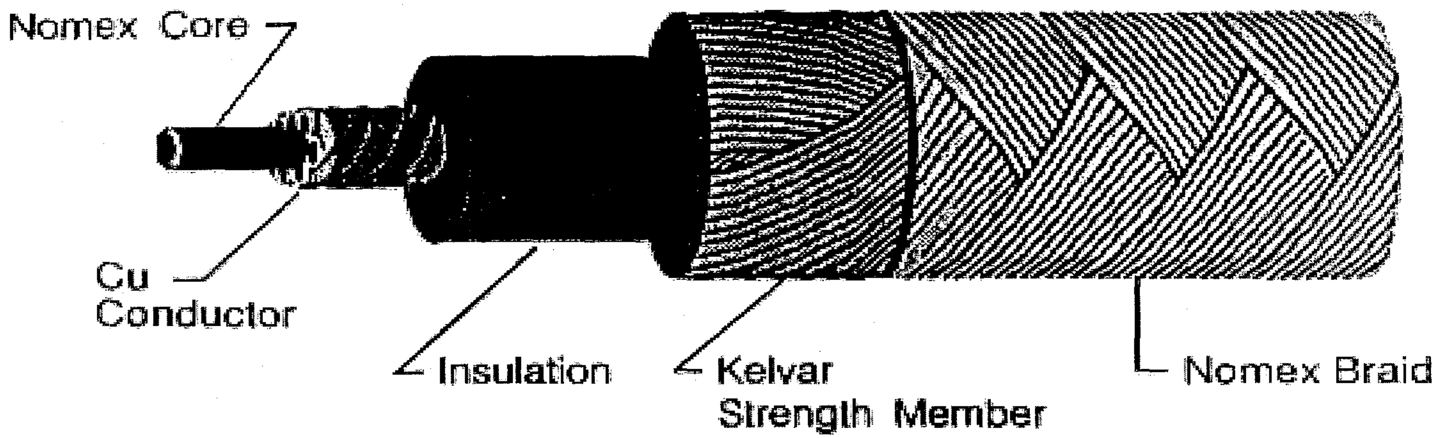
TSS-1R Tether Design

TSS Tether Construction



Diameter	2.54 mm (0.1 in)
Max Mass	8.2 kg/km (5.5 lb/kft)
Breakstrength	1780 N (400 lb)
Temp Range	-100° to +125° C (-148° to +257° F)
Elect Characteristics	Carry 1-A Current at 10 kV
	0.2 Ω/m
	5 mA (Max) Leakage
Max Elongation	5% at 1780 N

MARTIN MARIETTA

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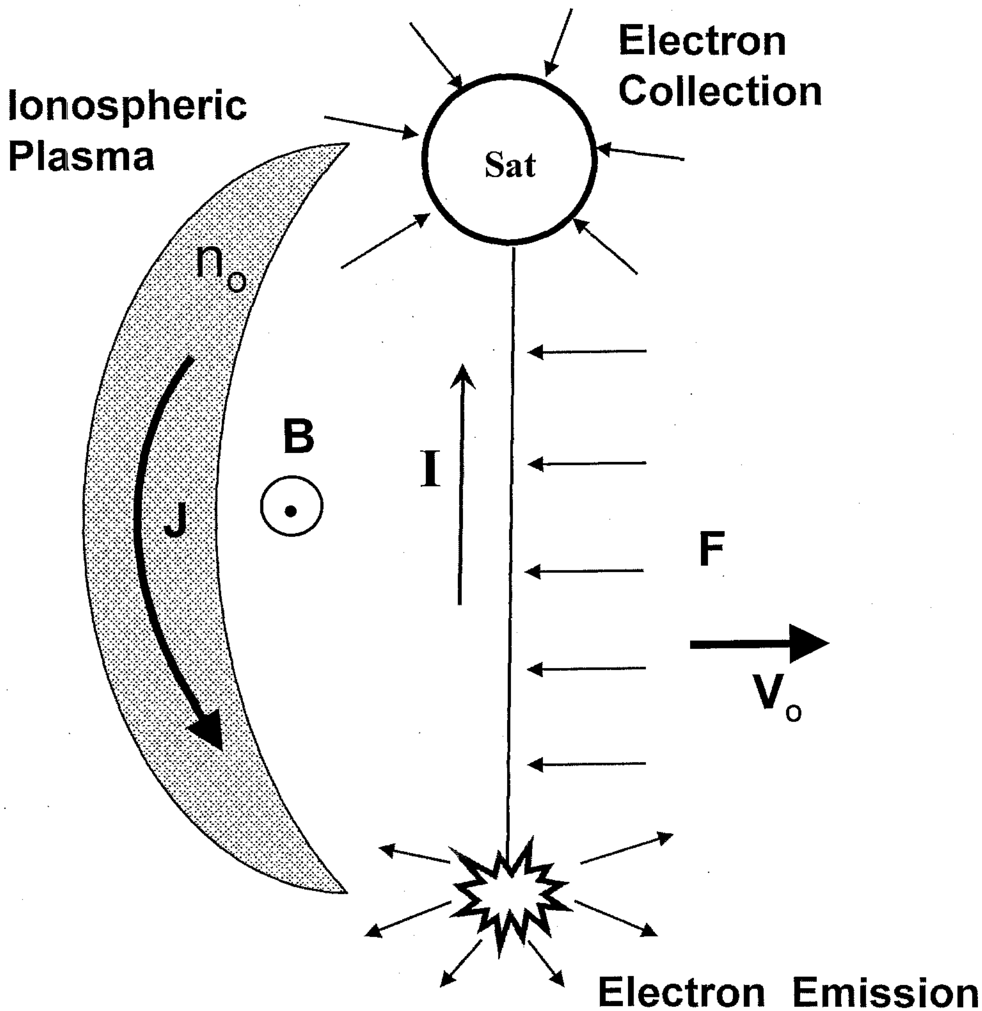
Classical ED Configuration



$$\mathbf{F} = I\,(\mathbf{B} \times \mathbf{L})$$

$$I = JA_{sheath}$$

$$= \frac{e\,n_o A}{4}\,(kT_e/m_e)^{1/2}$$

Orbital ED Force Variations

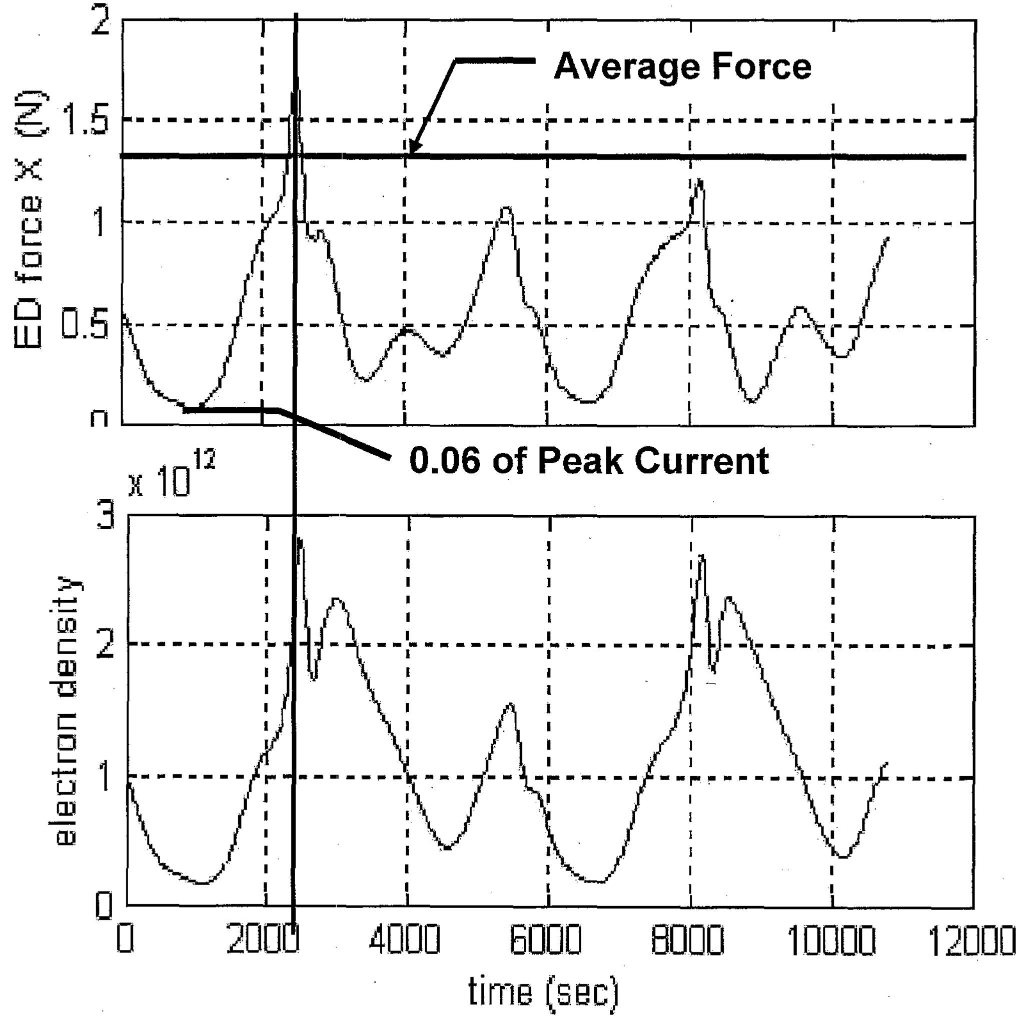
Tether
- Type: Insulated
- Length: 2.5 km

Electrode
- Diameter—15 m dia Grid-Sphere
- Bias— +50 V

Orbit
- Altitude—400 km
- Inclination—51.5°

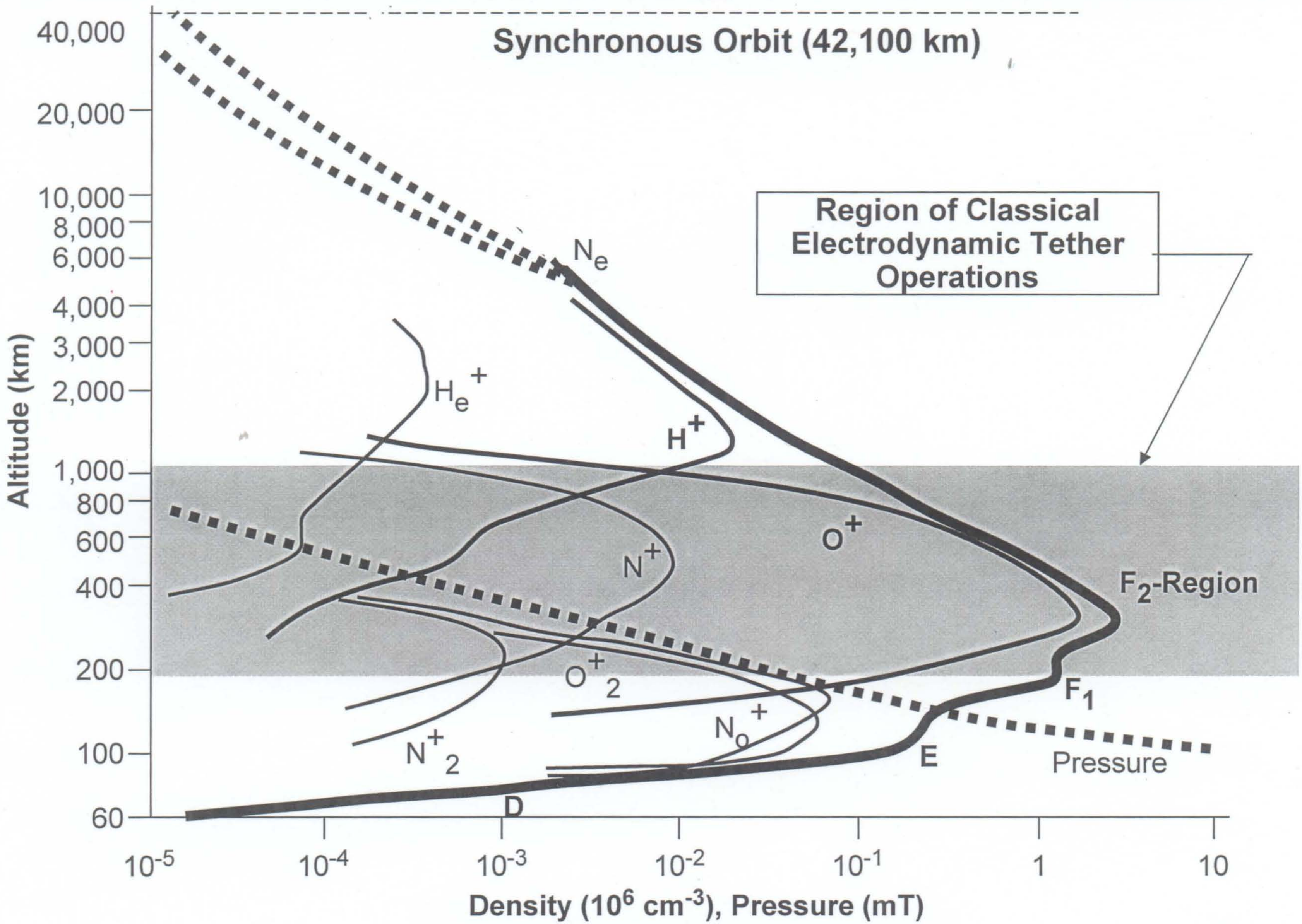
Current Collection
Model—Parker-Murphy EBC

Resulting Force Variation

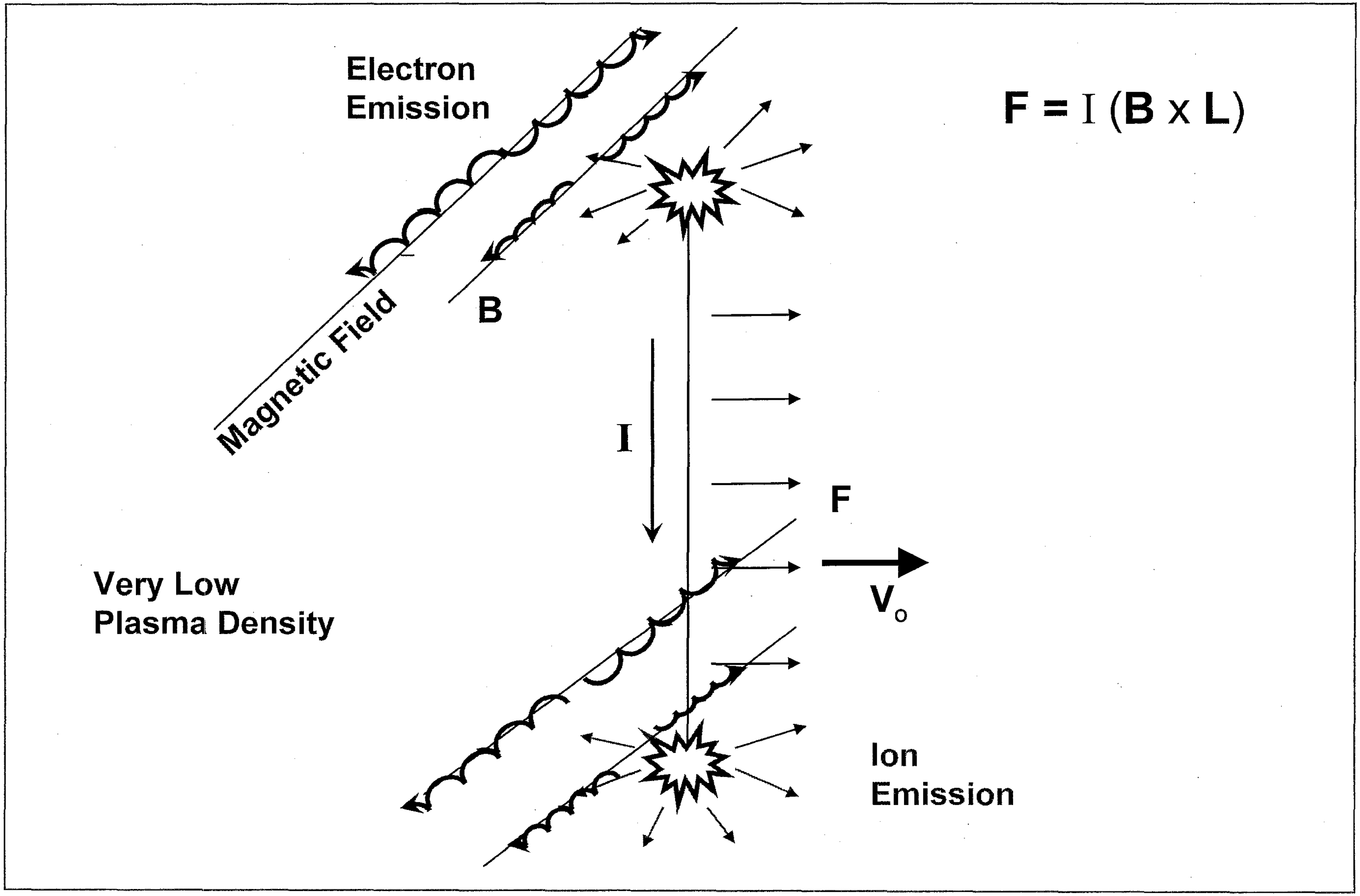


Diurnal Density Variation

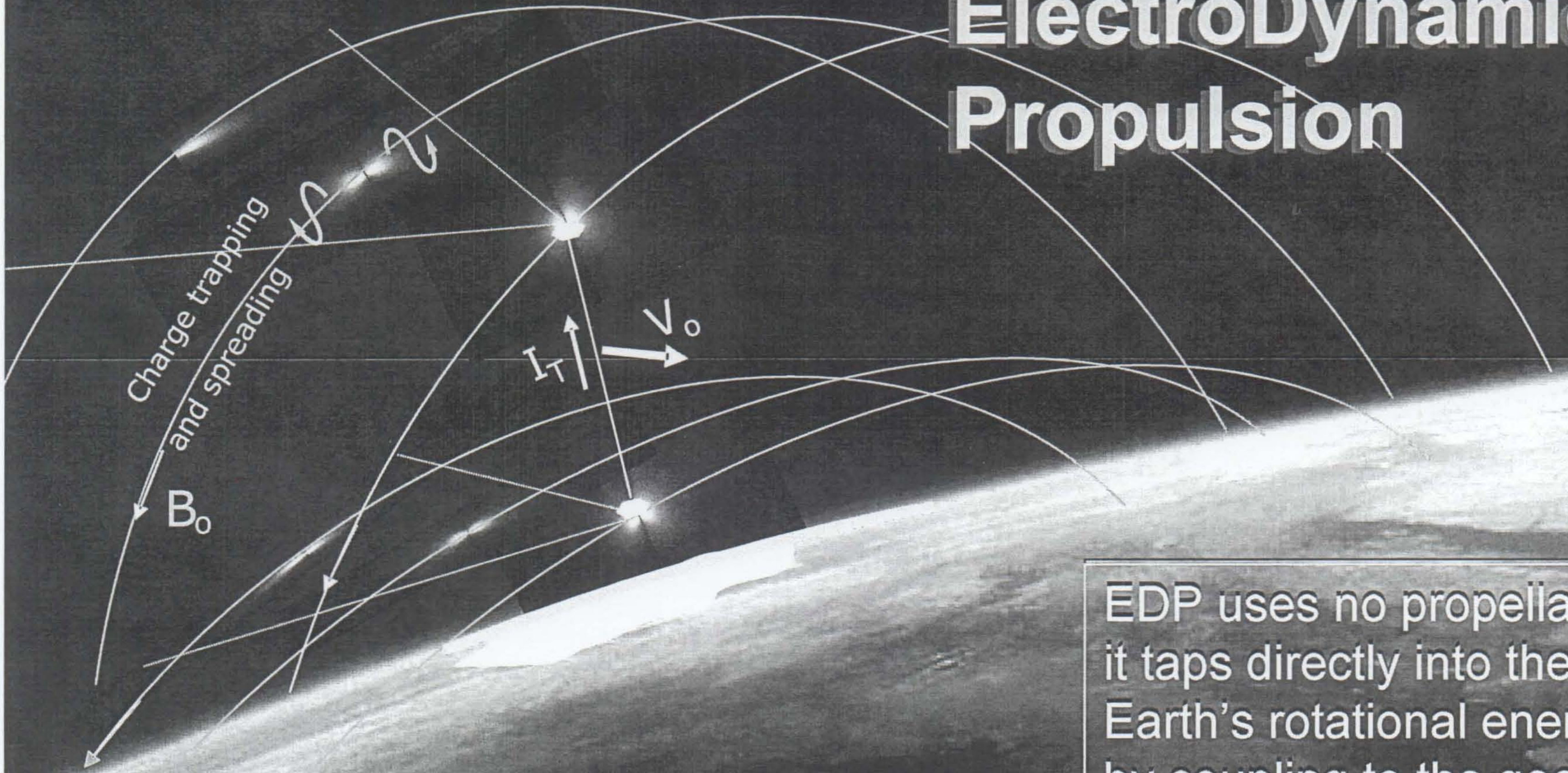
Magnetospheric Plasma Profile



"Vacuum-Field" Configuration



ElectroDynamic Propulsion

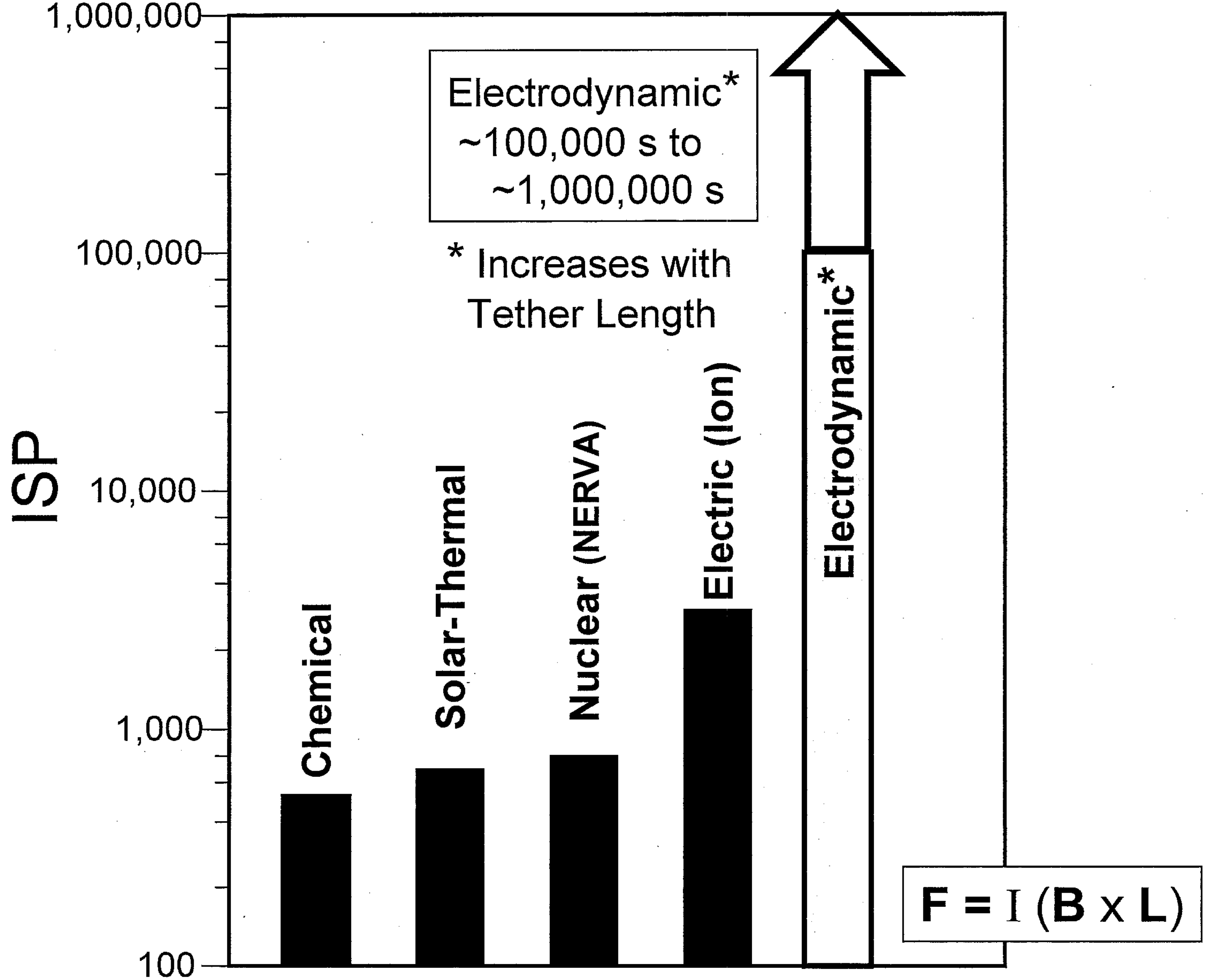


EDP uses no propellant—it taps directly into the Earth's rotational energy by coupling to the geo-magnetic field via a solar powered current system.

Unique Capabilities

- **Orbit Control**
- **Drag ΔV Recovery**
- **Electrical Power Generation**
- **LEO-GEO Operational Range** (170-42,000 km)
- **Long-Life Capability** (10+ yrs)

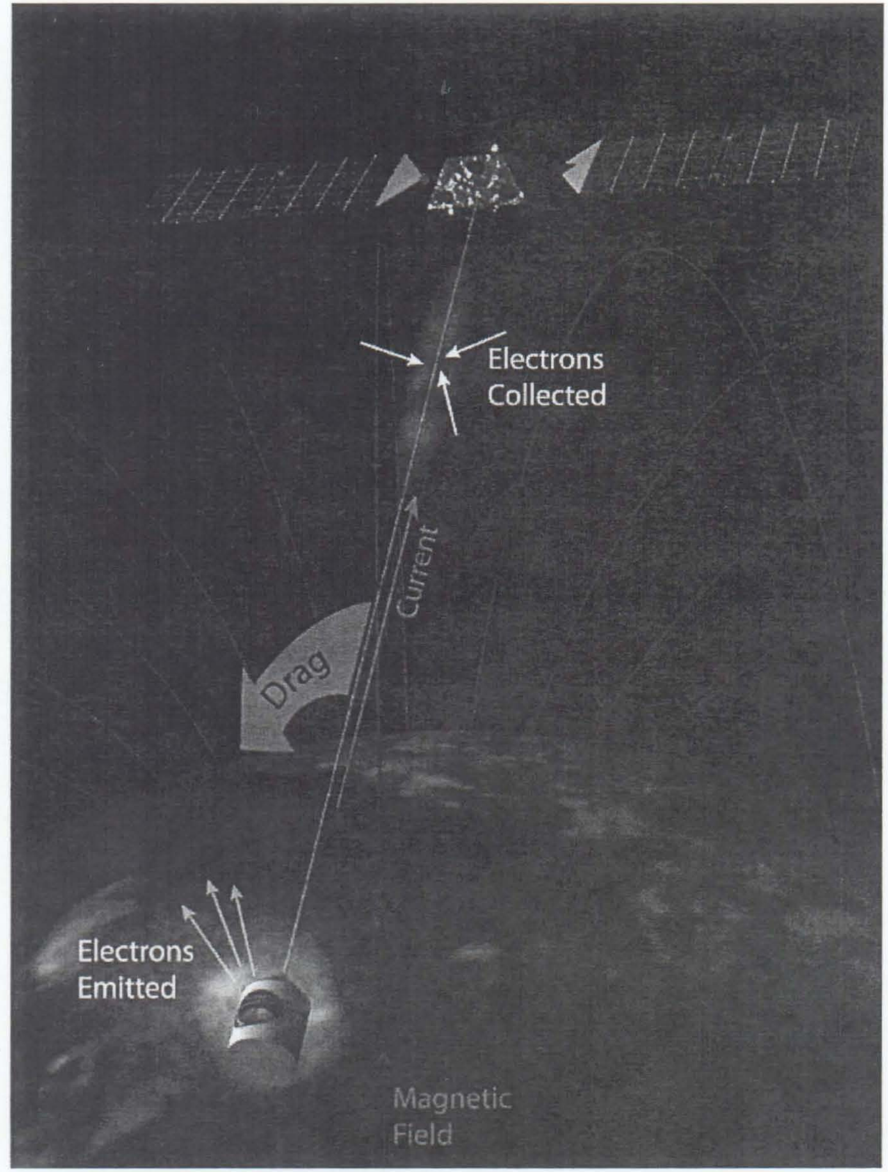
Comparative "Propellant" Efficiencies

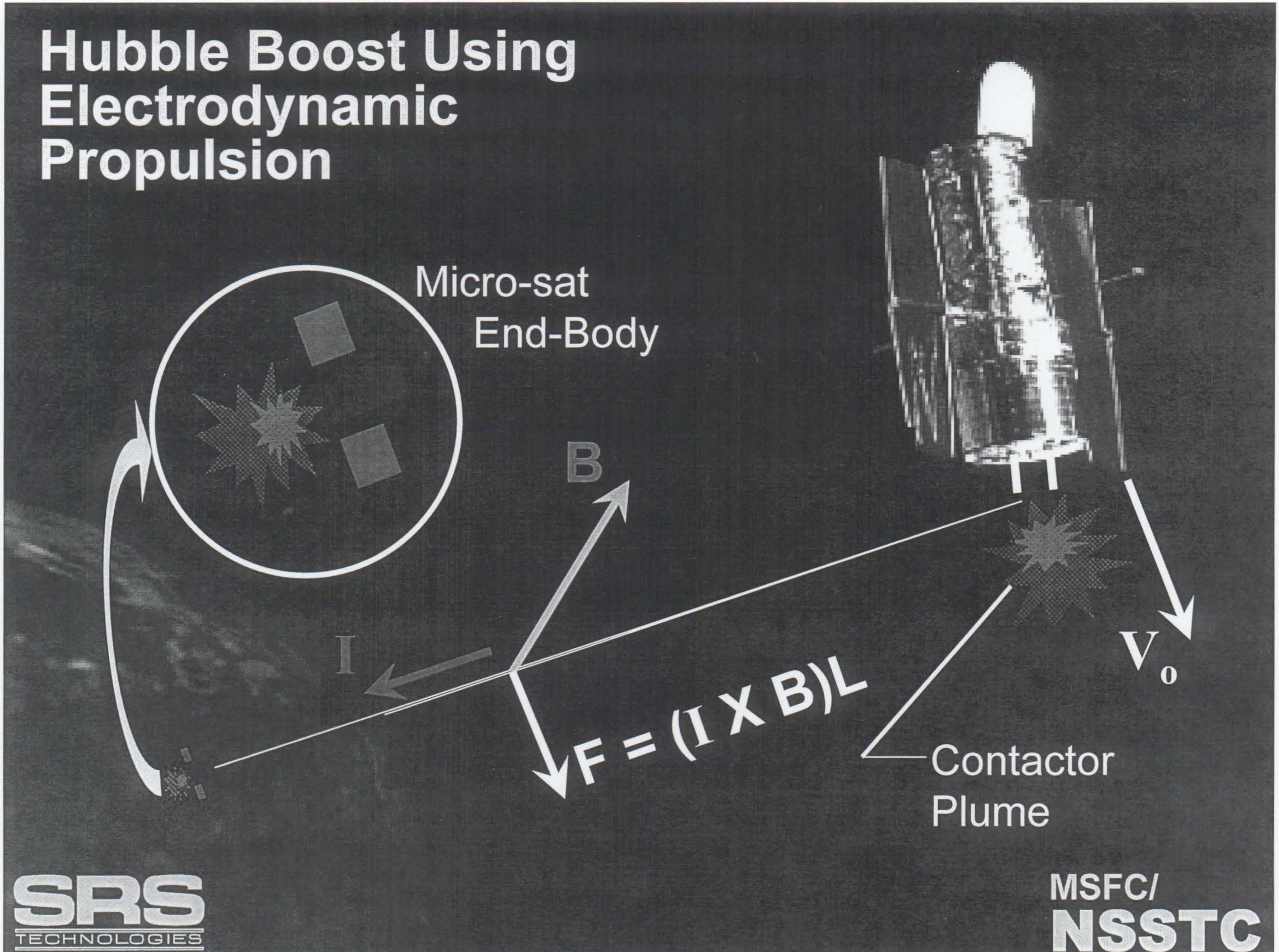


TUI Terminator Tether™

Characteristics & Capabilities

- Device Masses < 2% of host mass
- Dormant during satellite operation
- Deploys tether when satellite dies
- Tether drags against geomagnetic field, de-orbits satellite in weeks
- No propellant required
- Self-powered — needs no input power
- Can deorbit a dead satellite




Hubble Boost Using Electrodynamic Propulsion
Micro-sat End-Body
B
I
F = (I X B)L
V o
Contactor Plume
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MSFC/ NSSTC

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Rational for ED Boost of HST

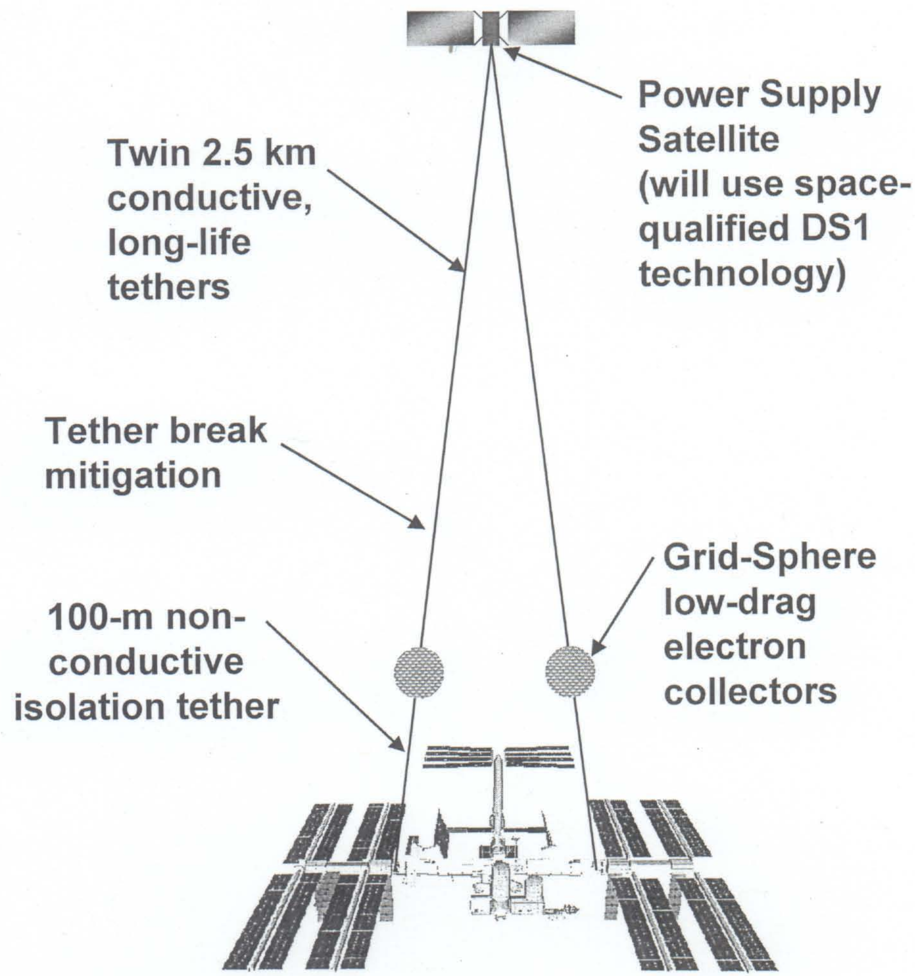
Raising HST to a Permanent Parking Orbit:

- Removes HST from active space w/o its destruction and at potentially a lower cost to NASA.
- Circumvents any possibility of impacting populated regions on earth.
- Provides flexibility—allows extended orbit maintenance and future recovery from parking orbit.

ISS Tether Reboost System (TRS)

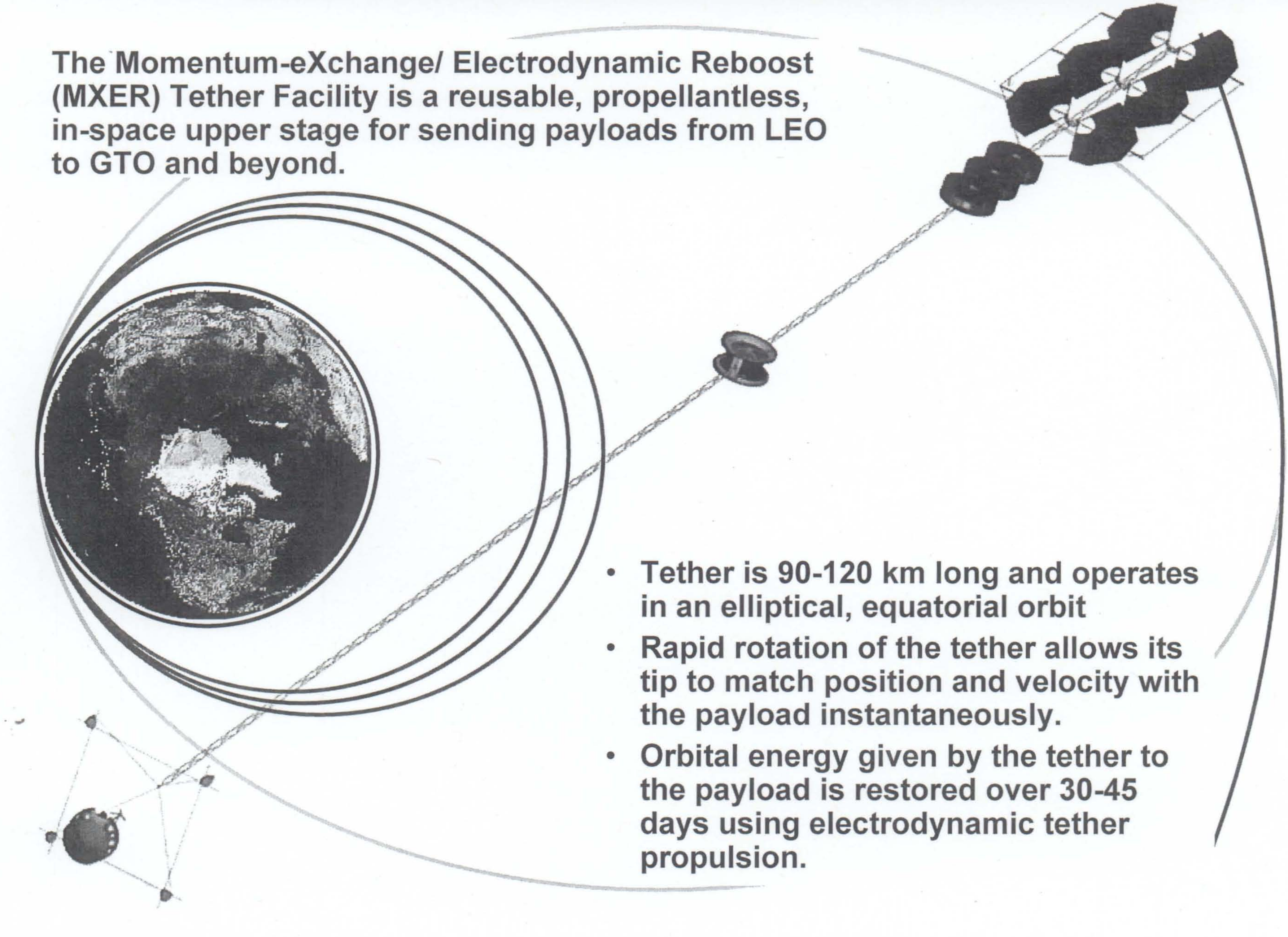
TRS Design Features

- Twin 2.5 km electrodynamic tethers
- Enables orbit maintenance and reboost
- Only mechanical interface with ISS
- Uses no Station power
- Acceptable Station CM shift (<3 m)
- Naturally stabilizes station attitude (roll axis)
- No expellant re-supply over design life (5 yr)
- Total system mass <1000 kg
- Tether monitoring & break protection
- Instantaneously jettisonable



Momentum Exchange ED Reboost (MXER)

The Momentum-eXchange/ Electrodynamic Reboost (MXER) Tether Facility is a reusable, propellantless, in-space upper stage for sending payloads from LEO to GTO and beyond.



- Tether is 90-120 km long and operates in an elliptical, equatorial orbit
- Rapid rotation of the tether allows its tip to match position and velocity with the payload instantaneously.
- Orbital energy given by the tether to the payload is restored over 30-45 days using electrodynamic tether propulsion.

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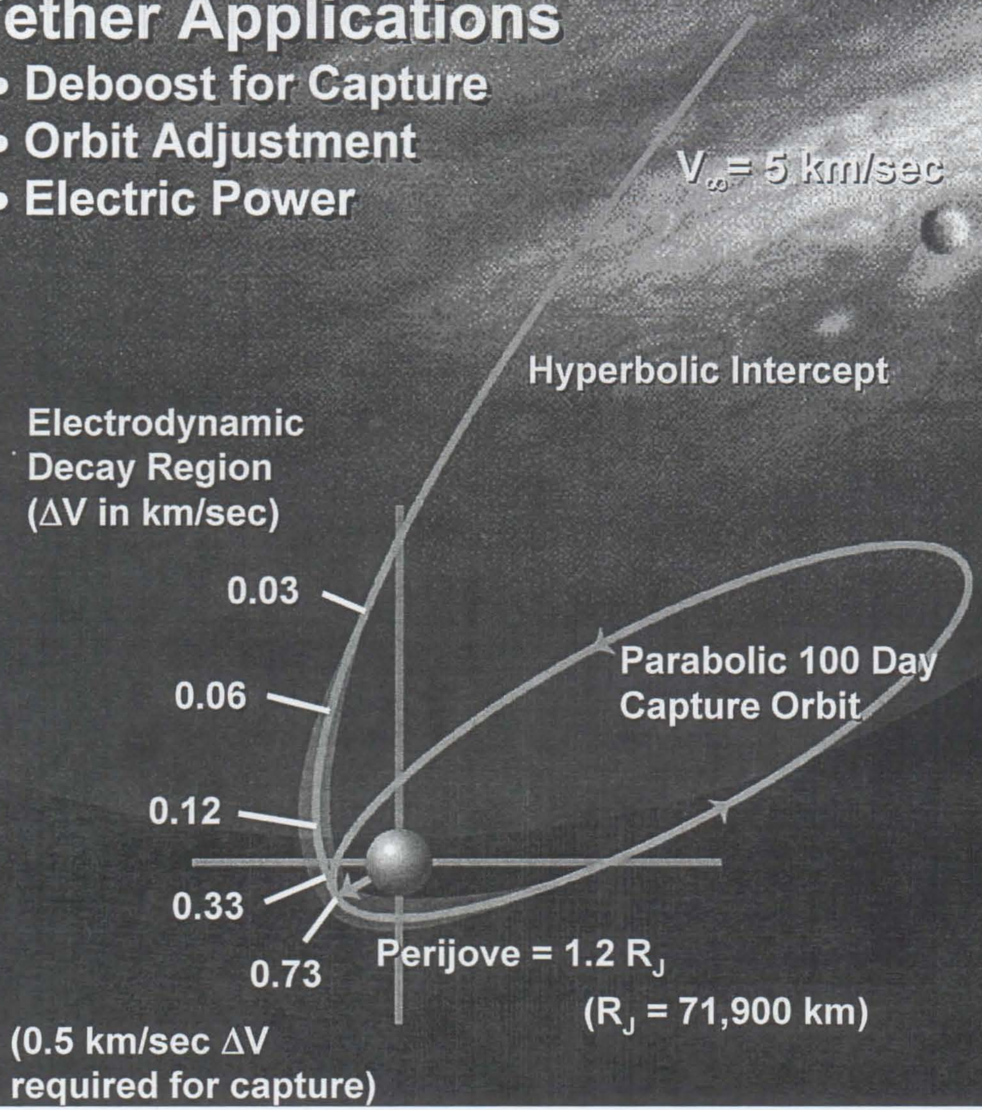
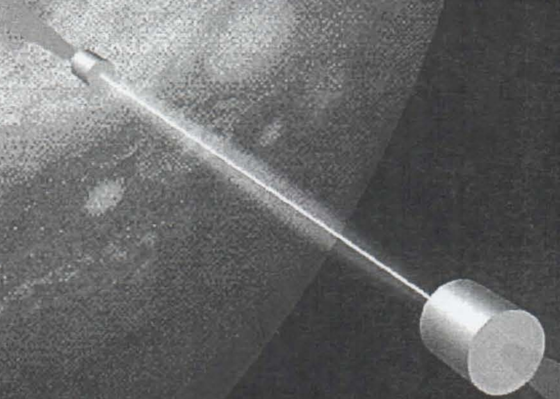
Jovian Electrodynamic Capture

Tether Applications

- Deboost for Capture
- Orbit Adjustment
- Electric Power





Tether System

- Spacecraft Payload Mass 500kg
- 10km Conducting Tether
- Tether Resistance: 96Ω
- Plasma emitter at each end
- Propulsion Mass Budget

– Tether	98kg
– Emitter Expellant	22kg
– Deployer and Controls	≤128kg
– Total	≤240kg