Tethered Satellite System

Modern Challenges in Nonlinear Plasma Physics
A Conference Honoring the Career of
Dennis Papadopoulos

presented by

Chia-Lie Chang

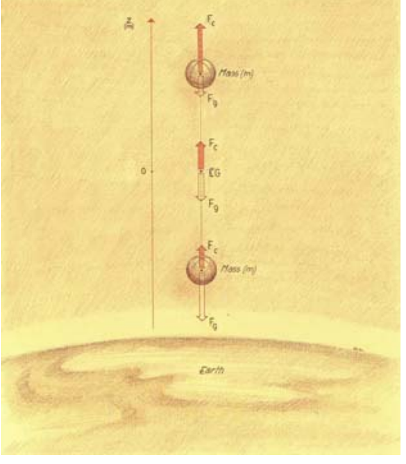
June 18, 2009

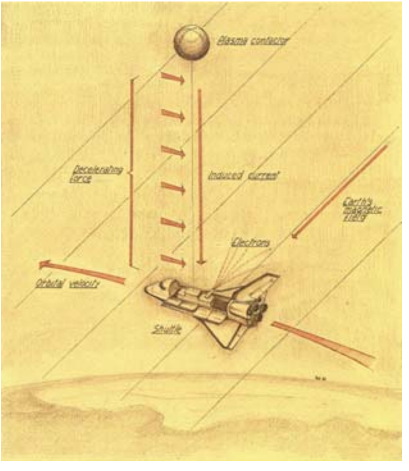
Tethered Satellite System - TSS

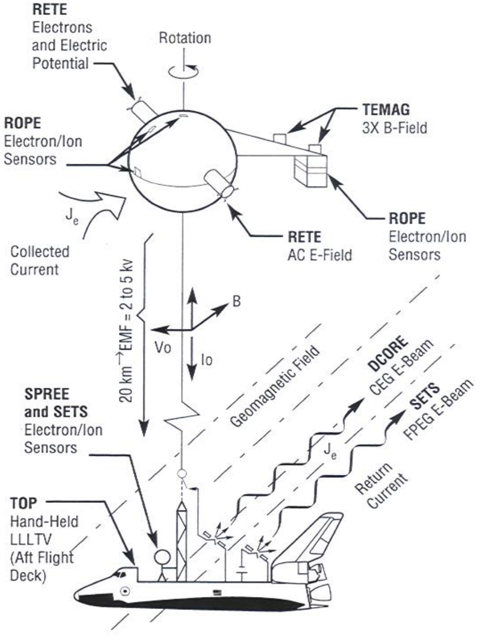
- TSS cuts through earth's B field – emf force creates +V on satellite

$$V_{emf} = v \times B \bullet L$$

- Satellite collects electrons, TSS loses momentum
- Gravitational acceleration at satellite
  - Centrifugal force > G force, tension on tether

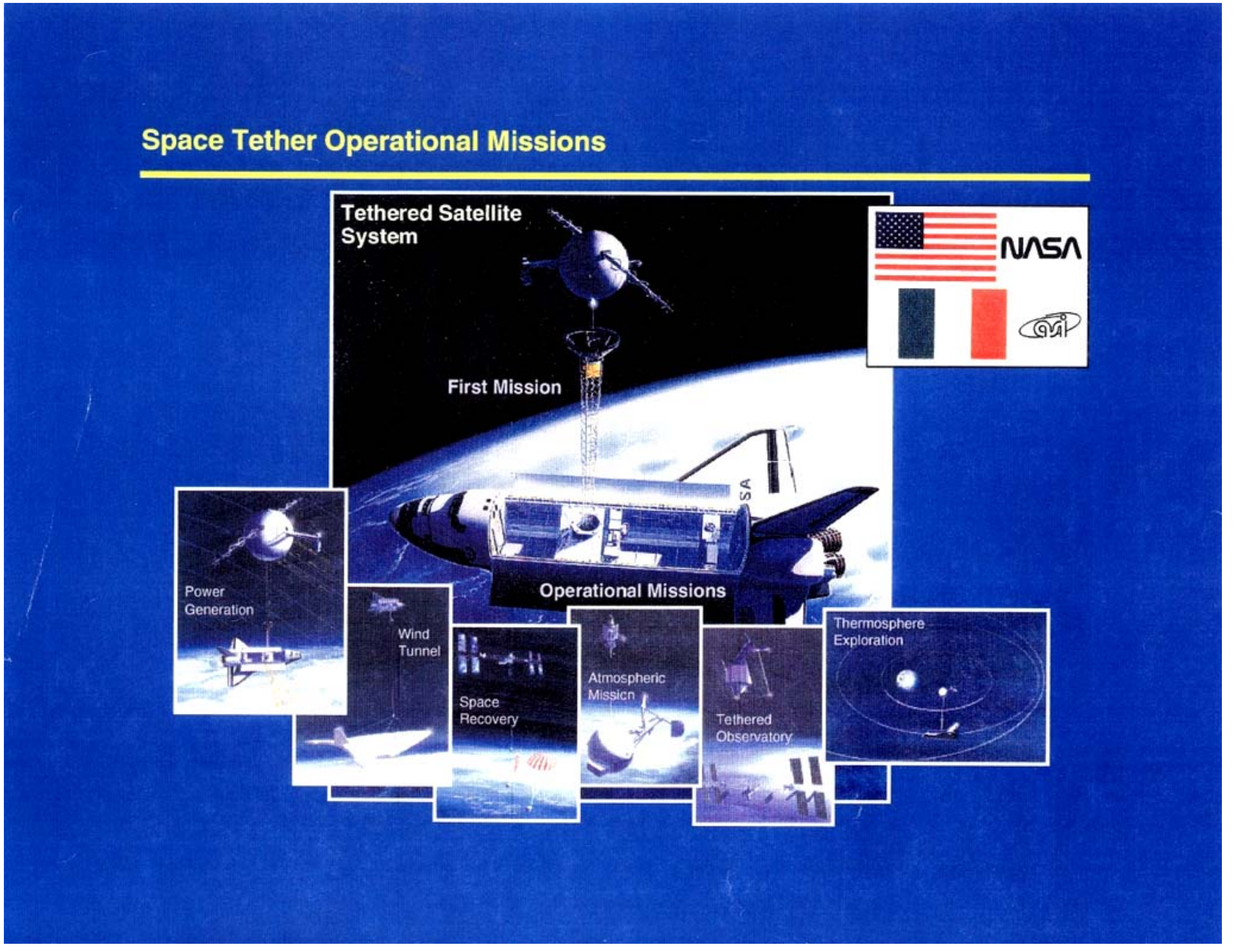






TSS - Applications

- Generating electrical power
- Spacecraft propulsion
- Broadcasting from space
- Studying the atmosphere
- Tether-controlled microgravity lab.
- Using the atmosphere as a wind tunnel

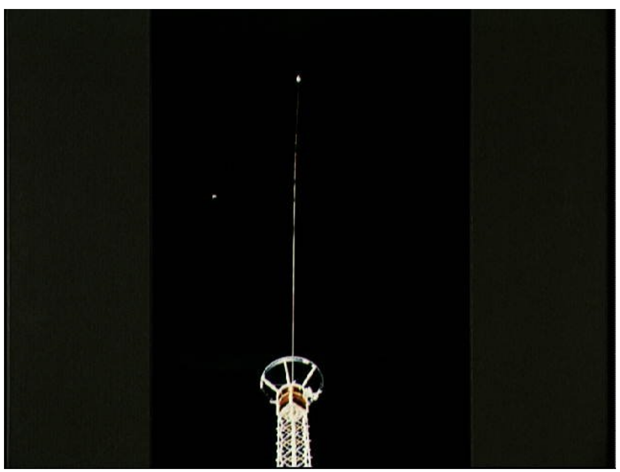


TSS Missions

- Started in 1984 as a joint venture between NASA & ASI (Agenzia Spaziale Italiana)
- Two missions: TSS-1 (1992) & TSS-1R (1996)

TSS-1 Mission

- Launched in Aug. 1992 on Shuttle STS-46 Atlantis
- Tether was snagged after unreeled to ~ 300m
- Dynamics check & low I-V

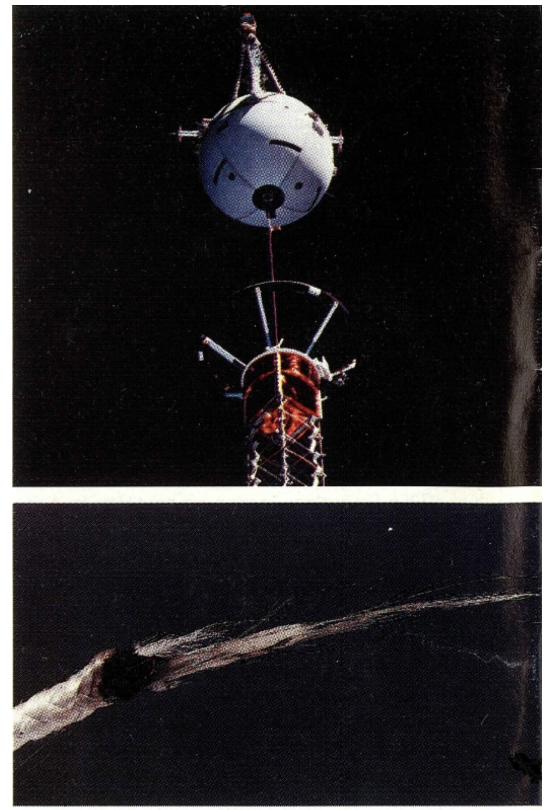


TSS-1R Mission

- Launched in Feb. 1996 on Shuttle STS-75 Columbia
  - Tether broke due to arc on day 4
  - Max. length ~ 19.7 km, 1 km short of full deployment
  - High quality I-V data, a partially successful mission

TSS - Tether Break Event

- TSS-1R tether broke at L ~ 19.7 km (Feb. 26, 1996) due to electric arc
  - Insulation brokedown; possible reasons
    - Metal flake embedded in the insulation
    - Gap in insulation with trapped air
  - Sparks between tether & shuttle body



Above, the Tethered Satellite System at its Feb. 25 deployment. Below, the broken end of the 2.5-millimeter-thick tether shows charring from the electric arc that caused the break.

TSS Science Investigations

- Current collection by electrodynamic TSS system
  - Voltage-current characteristics of TSS circuit
  - Collection physics on satellite sheath
  - Plasma waves and current closure
- Dynamics of tethered satellite
  - skip-rope & pendulous motions

PI/Institution	Investigation/Primary Function	
Orbiter-Mounted		
C. Bonifazi/ASI	DCORE	(e-guns, tether current control, I and V measurements)
B.E. Gilchrist/University of Michigan	SETS	(e-guns, tether current control; I, V, and plasma meas.)
D.A. Hardy/USAF Phillips Lab	SPREE	(ion and electron distributions and orbiter potential)
S. Mende/Lockheed (Now at U.C. Berkeley)	TOP	(low light-level TV)
Satellite-Mounted		
M. Dobrowolny/CNR/IFIS (Now at ASI)	RETE	(ac and dc electric fields, ambient electrons, sat. pot.)
F. Mariani/Second University of Rome	TEMAG	(ac and dc magnetic fields)
N.H. Stone/NASA/MSFC	ROPE	(ion and electron distributions, satellite potential)
Ground-Based/Theoretical		
S. Bergamaschi/Padua University	TEID	(theoretical: tether dynamics)
A. Drobot/SAIC	TMST	(theoretical: plasma-electrodynamic models)
R.E. Estes/SAO	EMET	(ground-based measurements: em waves)
G. Gullahorn/SAO	IMDN	(theoretical: tether dynamics)
G. Tacconi/University of Genoa	OESEE	(ground-based measurements: em waves)

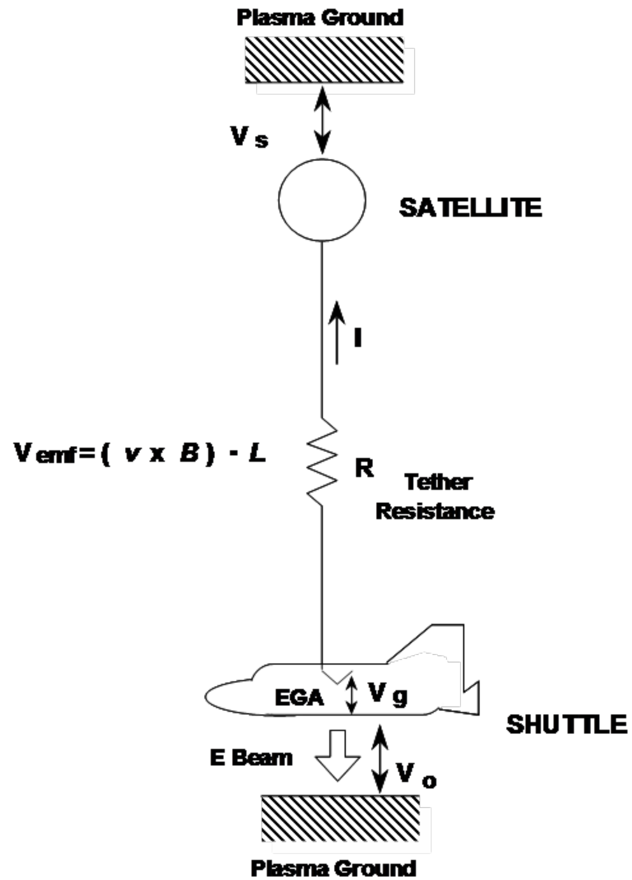
TMST (SAIC): Theory & Modeling in support of TSS

TSS – TMST Team

- Theoretical & modeling in support of Tether (TMST)
  - Under NASA-SAIC contract
- Ionospheric current collection
  - Satellite plasma sheath
  - Orbiter plasma sheath
  - IV characteristics of TSS
- Ionospheric current closure
  - by whistler & Alfven waves
- Real time ionospheric cond.
  - Den. & Temp. along TSS orbit
  - SUNDIAL

TSS Circuit

- Motional emf: Vemf
  - Known L and speed V
- EGA gun in shuttle
  - Release electrons
  - Control I-V steps
- Tether resistance R
  - Orbit/temp. dependent
- Satellite potential
  - Deduced from circuit with error bar



$$V_{emf} = V_s + I\,R + V_g + V_o$$

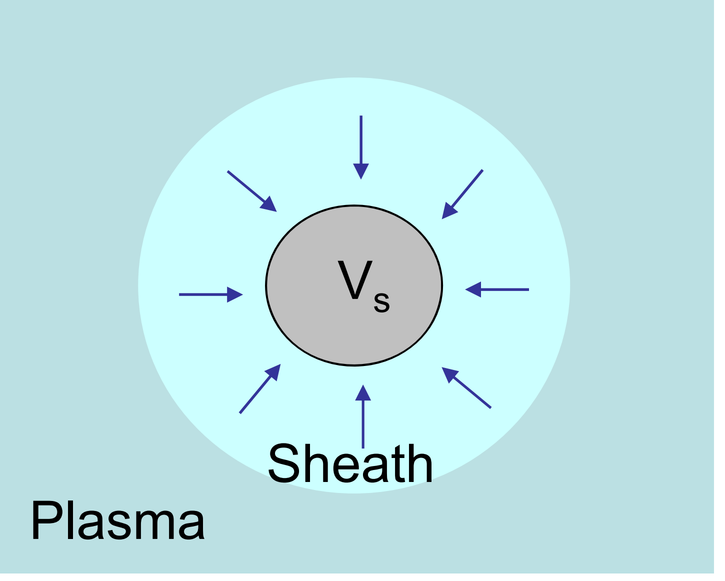
Classical Current Collection Models

- Beard-Johnson model (1961)
- Isotropic sheath - no B field, no motion
- Upper limit of current collection

$$\frac{I_{BJ}}{I_0} = \left(\frac{N_e V_e}{2.5\times10^{12}}\right)^{-\frac{4}{7}} a^{-\frac{8}{7}} \left(\frac{V_s}{40}\right)^{\frac{6}{7}}$$

$$I_0 = eN_e V_e \left(\pi\, a^2\ /2\right)$$

$$V_e = \left(\frac{8\,T_e}{\pi\, m_e}\right)^{\frac{1}{2}}$$



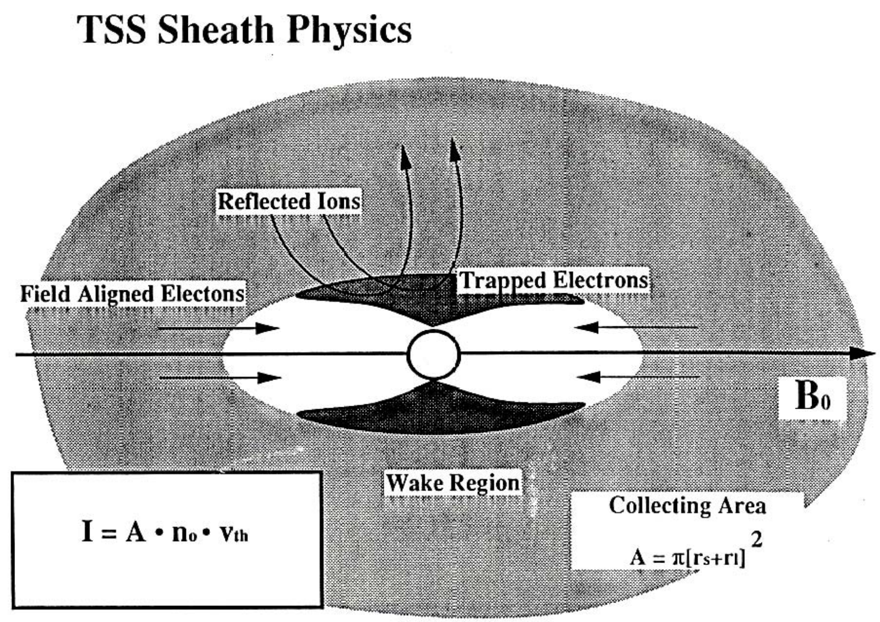
Classical Current Collection Models

- Parker-Murphy model (1965)
- Sheath along B, no motion (1965)
- $I_{PM} < I_{BJ}$

$$\frac{I_{PM}}{I_0} = 1 + 2\left(\frac{V_s}{V_0}\right)^{\frac{1}{2}}$$

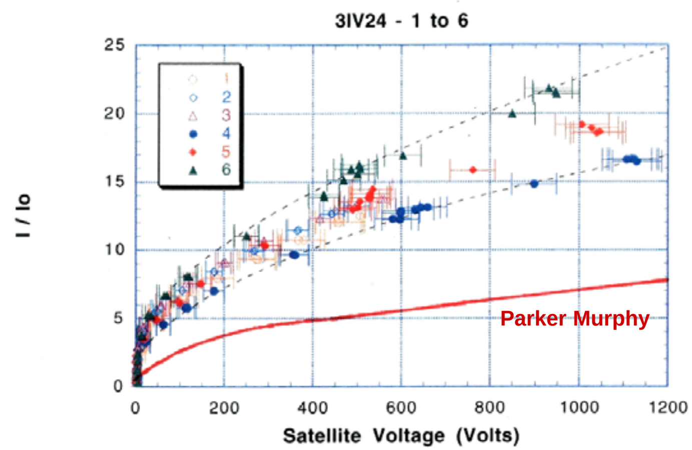
$$V_0 = \frac{m_e \Omega_e^2 a^2}{2e}$$

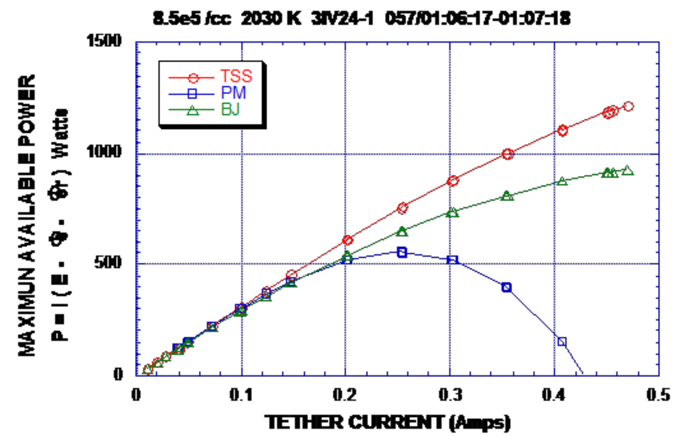
$$I_0 = eN_e V_e \left(\pi a^2 / 2\right)$$



Major TSS Results

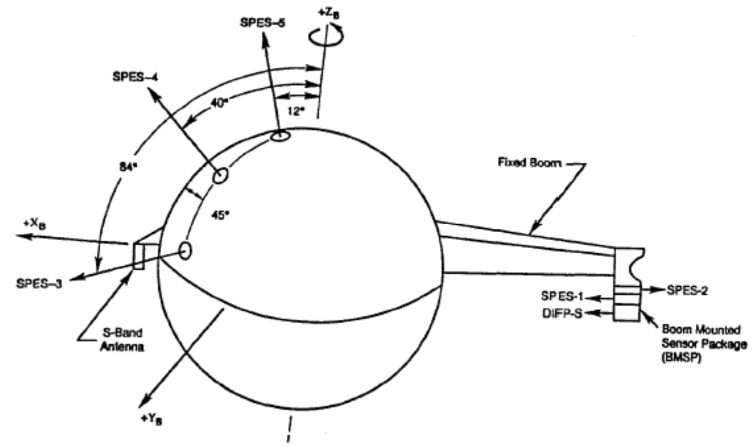
- Surprisingly high current collection efficiency, exceeding PM & BJ models by wide margins
- Maximum available power $P= I x(emf-\Phi_s- \Phi_o)$ is higher than model predictions, and does not saturate at high I
  - I: current in tether
  - emf: motional emf
  - Φ_s: satellite potential
  - Φ_o: Orbiter potential

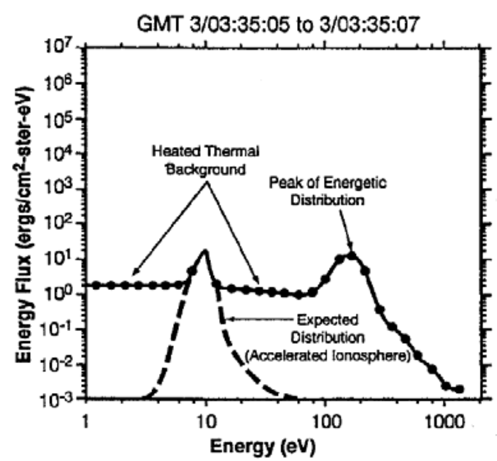




Major TSS Results

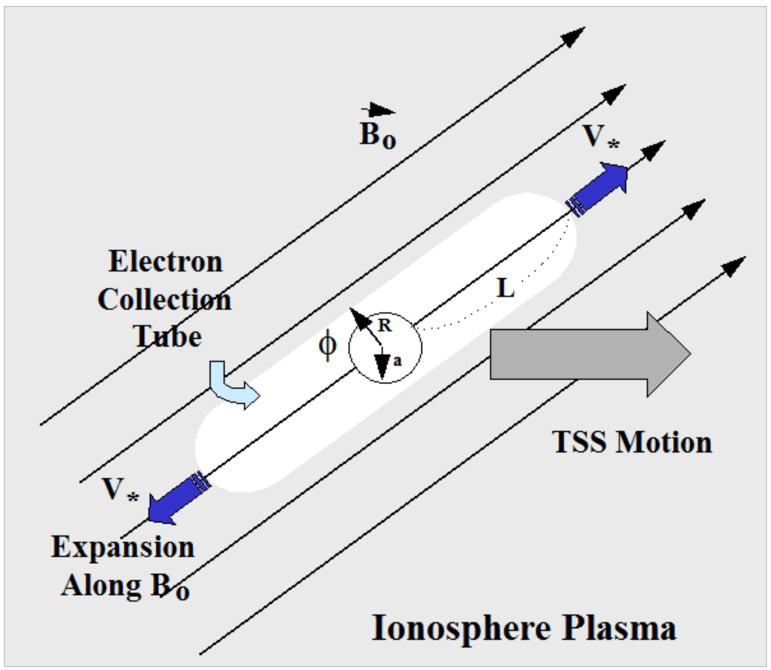
- Energetic electrons reaching the satellite
  - Up to KeV electrons > 10 times sheath potential
  - Occurred when sat. potential > 5 V
- Ion reflection when satellite potential exceeds ram energy of O^+ ion (~ 5 eV)



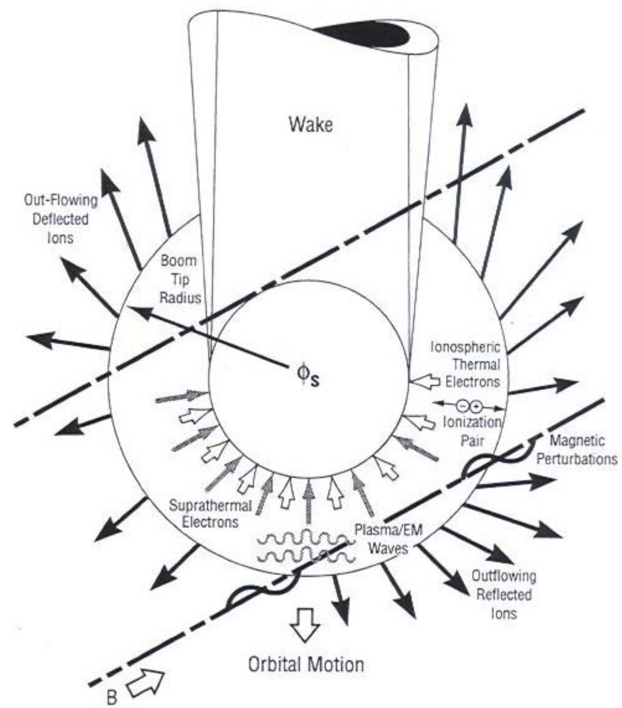


TSS New Physics

- Dynamic current collection
- Turbulent transport
- Ionization of neutrals

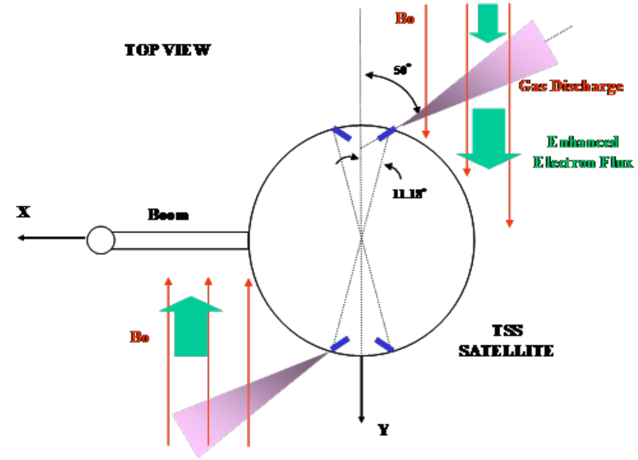


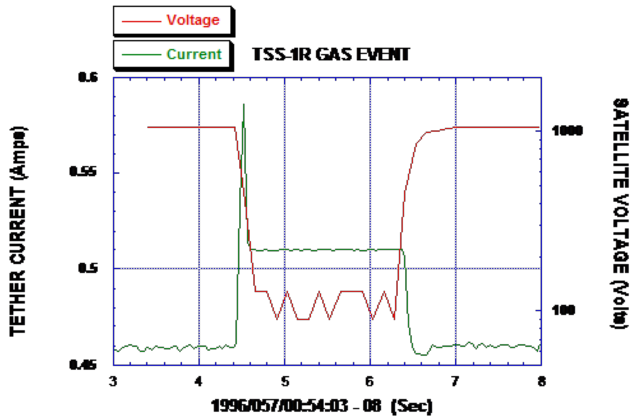
- Electron energization by wave-particle interactions



TSS - Gas Event

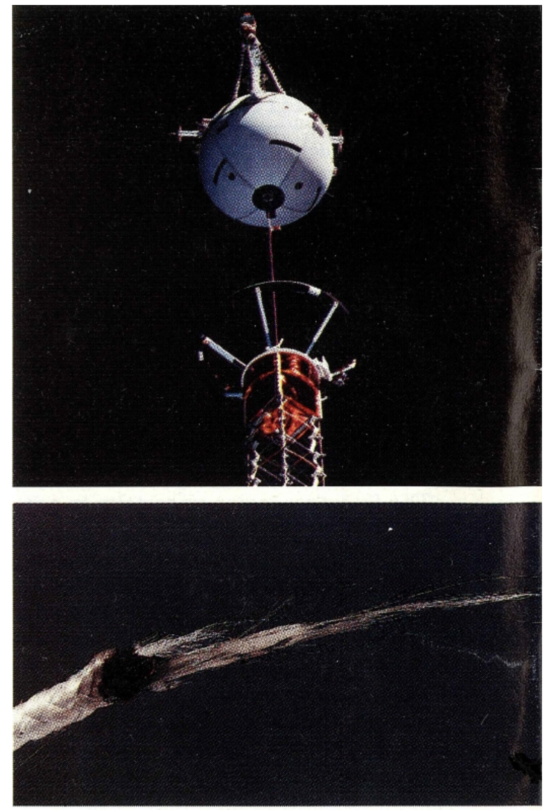
- Yaw thruster fired 1 s during a DC24 cycle
- Sat. voltage collapsed & current jumped up
- From: 1 kV, 0.46 A
- To: 100 V, 0.59 A → 0.51 A
- Discharge of neutrals increases electron density inside the sheath, enhance current collection





TSS - Tether Break Event

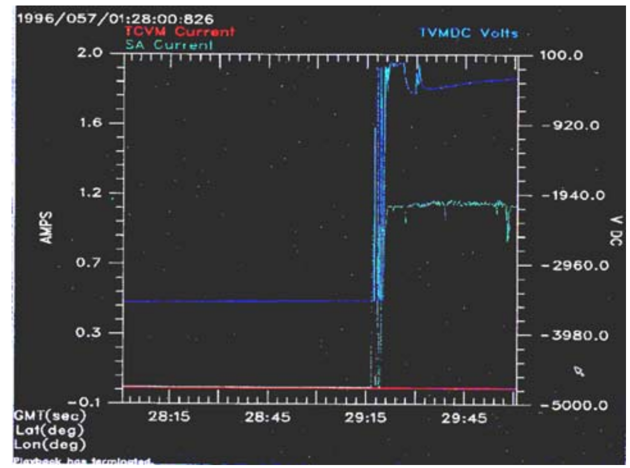
- TSS-1R tether broke at L ~ 19.7 km (Feb. 26, 1996) due to electric arc
  - Insulation brokedown; possible reasons
    - Metal flake embedded in the insulation
    - Gap in insulation with trapped air
  - Sparks between tether & shuttle body

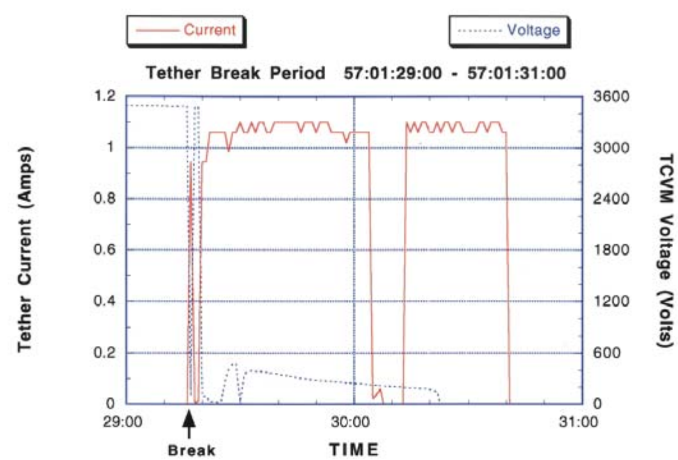


Above, the Tethered Satellite System at its Feb. 25 deployment. Below, the broken end of the 2.5-millimeter-thick tether shows charring from the electric arc that caused the break.

Tether Break - Surprise

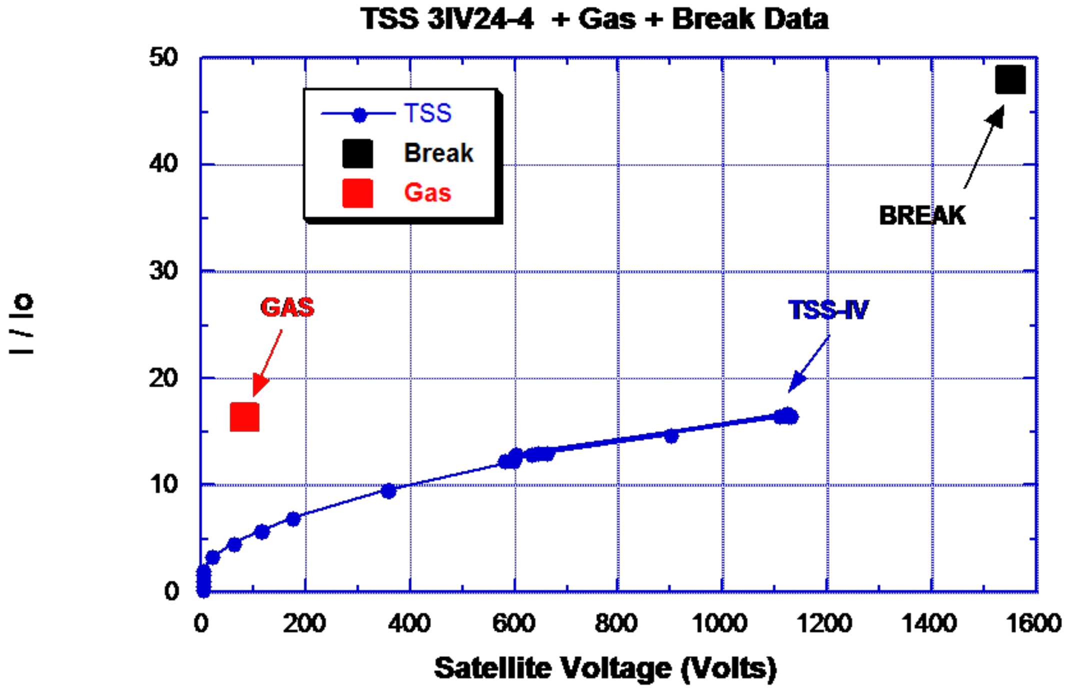
- V_{emf} ~ 3.5 kV between tether & body of Shuttle
- Voltage spikes started GMT 1996 057/01:29:17
- Spikes lasted 9 sec. before tether was broken
- Tether current ~ 1.1 A lasted 70 sec after spikes started (1 min. aft. break)
  - Far surpass model/preflight estimates
  - Vapor from burning tip sustain vacuum discharge?

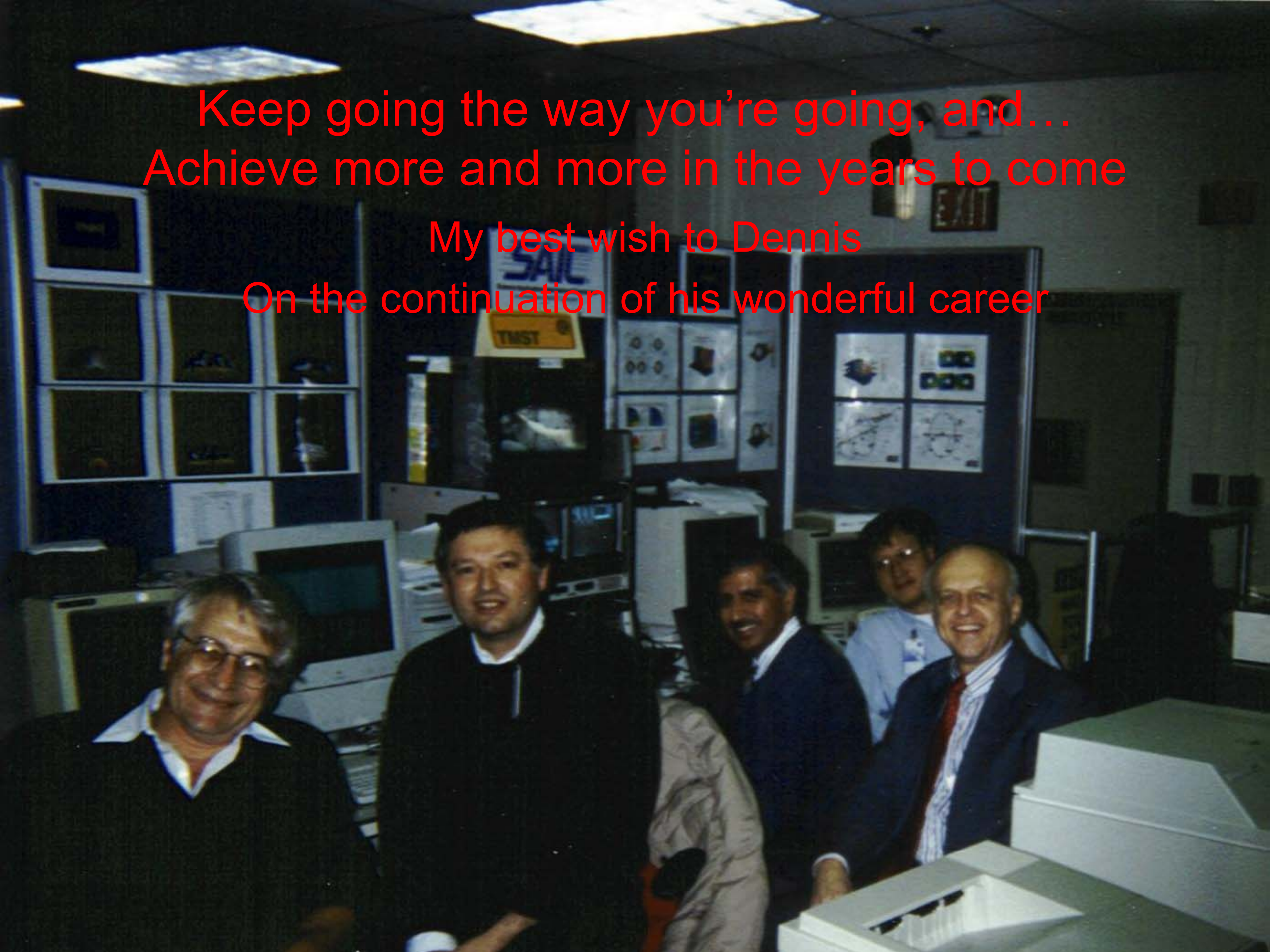




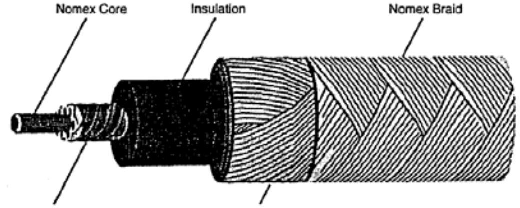
TSS - Gas & Break Events

- Efficiency of current collection is much higher than nominal operations




Keep going the way you're going, and…
Achieve more and more in the years to come
My best wish to Dennis
On the continuation of his wonderful career
SAIC
TMST
EXIT

Backup Plots



Diameter	2.54 mm (0.1in)
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

Fig. 3. Construction of the TSS tether.

Table 1. TSS-1R Science Investigators Working Group

PI	Institution	Investigation (Primary Function)
Orbiter-Based		
Carlo Bonifazi	ASI	CORE (e-guns, tether I and V)
Brian Gilchrist	The University of Michigan	SETS (e-gun, tether I and V)
Dave Hardy	USAF/Phillips Lab	SPREE (electrons, ions)
Stephen Mende	Lockheed	TOP (low light level optical)
Satellite-Based		
Marino Dobrowolny	ASI	RETE (electric fields, sat. pot.)
Franco Mariani	2nd University of Rome	TEMAG (magnetic field)
Nobie Stone	NASA/MSFC	ROPE (electrons, ions, sat. pot.)
Ground-Based & Theoretical		
Silvio Bergamaschi	Inst. of Applied Mechanics	TEID (tether dynamics)
Adam Drobot	SAIC	TMST (electrodynamic theory)
Bob Estes	SAO	EMET (RF waves)
Gordon Gullahorn	SAO	IMDN (tether dynamics)
Georgio Tacconi	University of Genoa	OESEE (RF waves)