Tethered Satellite System

Modern Challenges in Nonlinear Plasma Physics

A Conference Honoring the Career of

Dennis Papadopoulos

presented by

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Tethered Satellite System - TSS

- TSS cuts through earth’s B field – emf force creates +V on satellite
  \[ V_{\text{emf}} = \mathbf{v} \times \mathbf{B} \cdot \mathbf{L} \]
- 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)
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

<table>
<thead>
<tr>
<th>PI/Institution</th>
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<tbody>
<tr>
<td><strong>Orbiter-Mounted</strong></td>
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<tr>
<td>C. Bonifazi/ASI</td>
<td>DCP (e-guns, tether current control; I and V measurements)</td>
</tr>
<tr>
<td>B.E. Glehrich/University of Michigan</td>
<td>SETS (e-guns, tether current control; I, V, and plasma meas.)</td>
</tr>
<tr>
<td>D.A. Hardy/USAF Phillips Lab</td>
<td>SPREE (ion and electron distributions and orbiter potential)</td>
</tr>
<tr>
<td>S. Mendis/Lockheed (Now at U.C. Berkeley)</td>
<td>TOP (low-light-level TV)</td>
</tr>
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</table>

| **Satellite-Mounted** |
| M. Dobrovolsky/CNR/IFIS (Now at ASI) | RETE (ac and dc electric fields, ambient electrons, sat. pos.) |
| P. Mariani/Second University of Rome | TENAG (ac and dc magnetic fields) |
| N.H. Stone/NASA/MSFC | ROPE (ion and electron distributions, satellite potential) |

| **Ground-Based/Theoretical** |
| S. Bergamaschi/Padua University | TELD (theoretical: tether dynamics) |
| A. Drobos/SAIC | TMST (theoretical: plasma-electrodynamical model(s)) |
| R.E. Eisler/SAO | EMET (ground-based measurements; em waves) |
| G. Guallar/AI | IMDN (theoretical: tether dynamics) |
| G. Taccori/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: $V_{emf}$
  - 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

$V_{emf} = (v \times B) \cdot L$

$V_{emf} = V_s + IR + V_g + V_o$
Classical Current Collection Models

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

\[
\frac{I_{BJ}}{I_0} = \left( \frac{N_e V_e}{2.5 \times 10^{12}} \right)^{\frac{4}{7}} a^{\frac{8}{7}} \left( \frac{V_s}{40} \right)^{\frac{6}{7}}
\]

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

\[
V_e = \left( \frac{8 T_e}{\pi m_e} \right)^{\frac{1}{2}}
\]
Classical Current Collection Models

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

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

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

\[
I_0 = eN_e V_e \left( \pi a^2 / 2 \right)
\]
Major TSS Results

• Surprisingly high current collection efficiency, exceeding PM & BJ models by wide margins

• Maximum available power $P = Ix(esm - \Phi_s - \Phi_o)$ is higher than model predictions, and does not saturate at high $I$
  – $I$: current in tether
  – emf: motional emf
  – $\Phi_s$: satellite potential
  – $\Phi_o$: 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 ($\sim$ 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

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Tether Break - Surprise

- $V_{\text{emf}} \approx 3.5$ 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 $\approx 1.1$ 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
Backup Plots

Table 1. TSS-1R Science Investigators Working Group

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<tr>
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<td>Carlo Bonifazi</td>
<td>ASI</td>
<td>CORE (e-guns, tether I and V)</td>
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<tr>
<td>Brian Gilchrist</td>
<td>The University of Michigan</td>
<td>SETS (e-guns, tether I and V)</td>
</tr>
<tr>
<td>Dave Hardy</td>
<td>USAF/Phillips Lab</td>
<td>SPREE (electrons, ions)</td>
</tr>
<tr>
<td>Stephen Mende</td>
<td>Lockheed</td>
<td>TOP (low light level optical)</td>
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<tr>
<td><em>Satellite-Based</em></td>
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<tr>
<td>Marino Debrocienzi</td>
<td>ASI</td>
<td>RETE (electric fields, sat. pot.)</td>
</tr>
<tr>
<td>Franco Mariani</td>
<td>2nd University of Rome</td>
<td>TEMAG (magnetic field)</td>
</tr>
<tr>
<td>Noise Source</td>
<td>NASA/MSFC</td>
<td>ROPE (electrons, ions, sat. pot.)</td>
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<tr>
<td>Silvio Bergamaschi</td>
<td>Inst. of Applied Mechanics</td>
<td>TED (tether dynamics)</td>
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<tr>
<td>Adam Drobot</td>
<td>SAIC</td>
<td>TMST (electrodynamic theory)</td>
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<tr>
<td>Bob Estes</td>
<td>SAO</td>
<td>EMET (RF waves)</td>
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<tr>
<td>Gordon Gulliforsa</td>
<td>SAO</td>
<td>IMEN (tether dynamics)</td>
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<tr>
<td>Georgio Tacconi</td>
<td>University of Genoa</td>
<td>OBSER (RF waves)</td>
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Fig. 2. Construction of the TSS tether.