Advanced Propulsion: Electric Sail

Anthony M. DeStefano, Ph.D.
Space Physicist
NASA MSFC Natural Environments Branch

John Inness
GNC Engineer
NASA MSFC Controls Systems Design and Analysis Branch

July 27, 2023
Marshall Partnerships Forum
Yulista Conference Center

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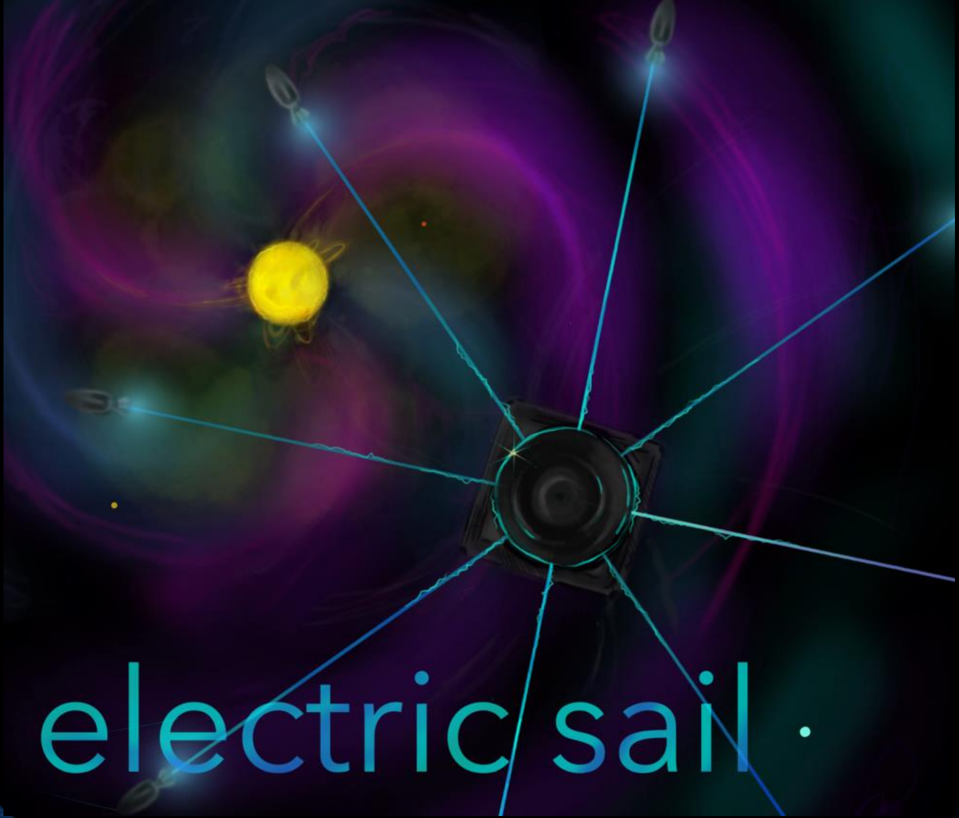
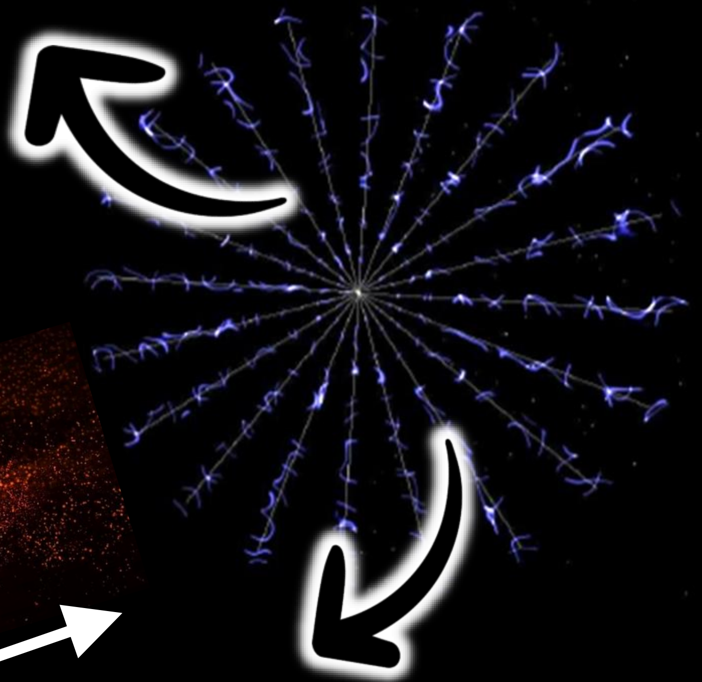


What drives the electric sail?

Protons from the **solar wind** are **repelled** by the **charged tethers** providing ***thrust*** !



What drives the electric sail?

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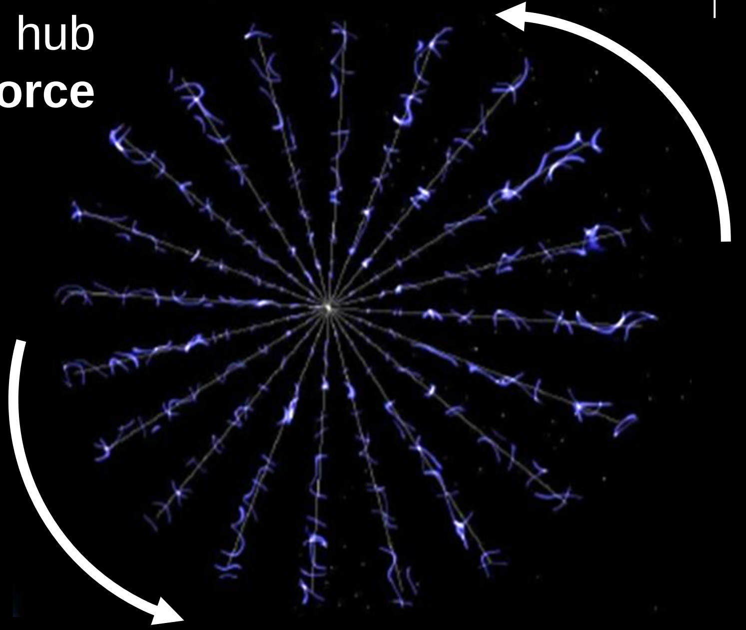
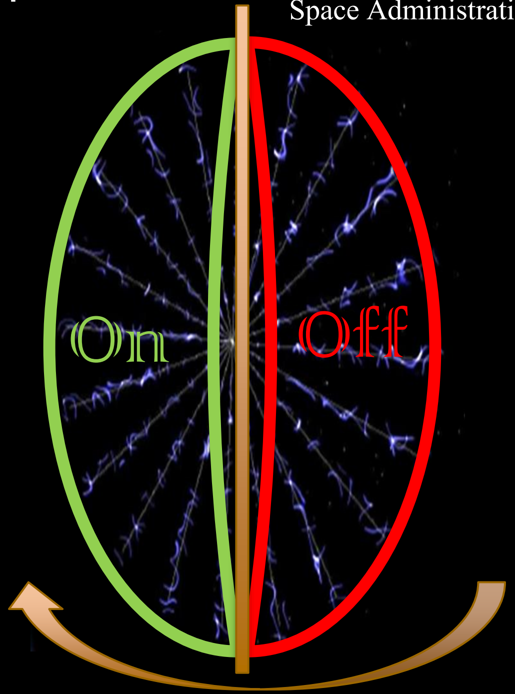
To keep the charged tethers **taut** the tether system **spins** about the central hub creating a **centripetal force**



Keeping the ‘sails’ open

By reducing the voltage of tethers in half of the spin plane, steering is possible



Steering the electric sail

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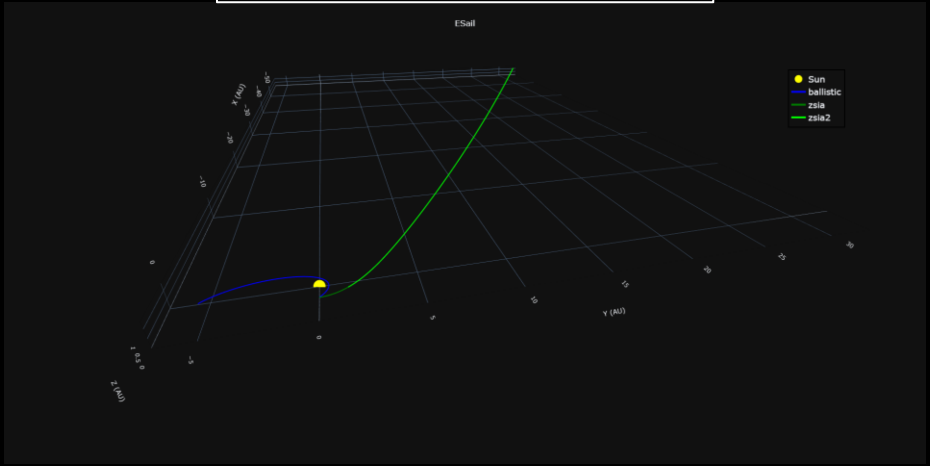
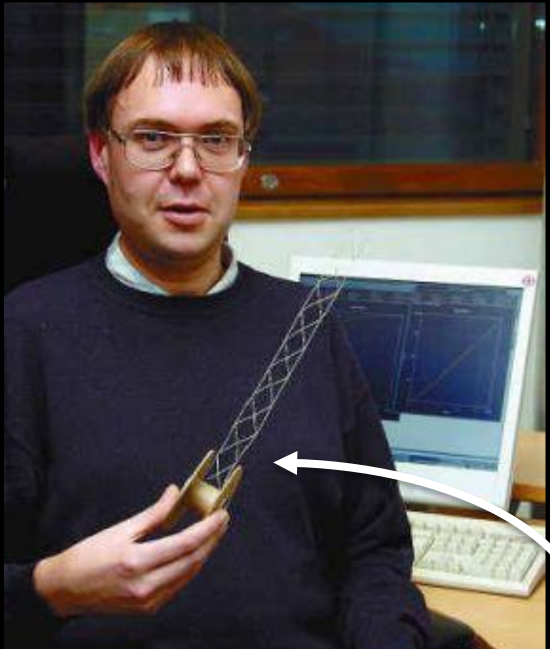
With Electric Sails, a characteristic acceleration of 2 mm/s^2 or greater is possible which enables rapid transit to distant and hard to reach orbits

- Rapid transit to heliopause, approximately 100 AU (~10 years w/o a gravity assist)
- Transit and orbit capture to outer planets
- Solar Gravitational Lens, ~550 AU
- And more!

Heliopause trajectory



Mission Potentials with E-Sail



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Electric Sail for Spacecraft Propulsion

Pekka Janhunen*
Finnish Meteorological Institute/Geophysical Research,
FIN-00101, Helsinki, Finland

Volume 20, Number 4 • July 2004

I. Introduction

IT has been previously proposed that a magnetic sail, that is, an artificial magnetosphere, could be used for extracting solar wind momentum for spacecraft propulsion purposes.[1,2] Here we consider an alternative approach, which does not require a magnetic field.

Hoytether – to protect against meteoroid impacts

Inventor of E-sail: Pekka Janhunen

Mission Name	Agency	Date	Tether Length	Outcome
Gemini 11	NASA	1966	30 m	Successful
OEDIPUS A	???	1989	958 m	Successful
TSS-1 (Shuttle)	NASA, ISA	1992	256 m	Tether jammed
PMG	NASA	1993	500 m	Successful
SEDS-1	NASA	1993	20 km	Successful
SEDS-2	NASA	1994	20 km	Successful
OEDIPUS B	???	1995	1174 m	Successful
TSS-1R (Shuttle)	NASA, ISA	1996	19.7 km	Successful*, tether broke after 5 hrs
TiPS	NRL	1996	4 km	Successful (lasted 10 years)
TSS-2	NASA, ISA	x	0 m	Not Flown
YES	ESA	1997	0 m	Not deployed
ATEx	NCST	1999	22 m	Deployment failure
YES2	ESA	2007	32 km	Lost com, but indication of full deploy
MAST	NASA STTR (TUI)	2007	1 m	Lost com, but indication of partial deploy
STARS	Kagawa University	2009	7 cm	Deployment failure
T-REX	JAXA	2010	300 m	Successful
ESTCube-1	Estonia	2013	0 m	Deployment failure
STARS-II	Kagawa University	2014	0 m	Deployment not confirmed
KITE	JAXA	2016	0 m	Not deployed
STARS-C	Shizuoka University	2016	30 m	No data on deployment, indicated by drag
TEPCE	NRL	2019	1 km	No data on deployment, indicated by drag

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Close-up view of the Tethered Satellite System (TSS-1) in orbit above the Space Shuttle Atlantis

Past tether missions

Reference: https://en.wikipedia.org/wiki/Space_tether_missions

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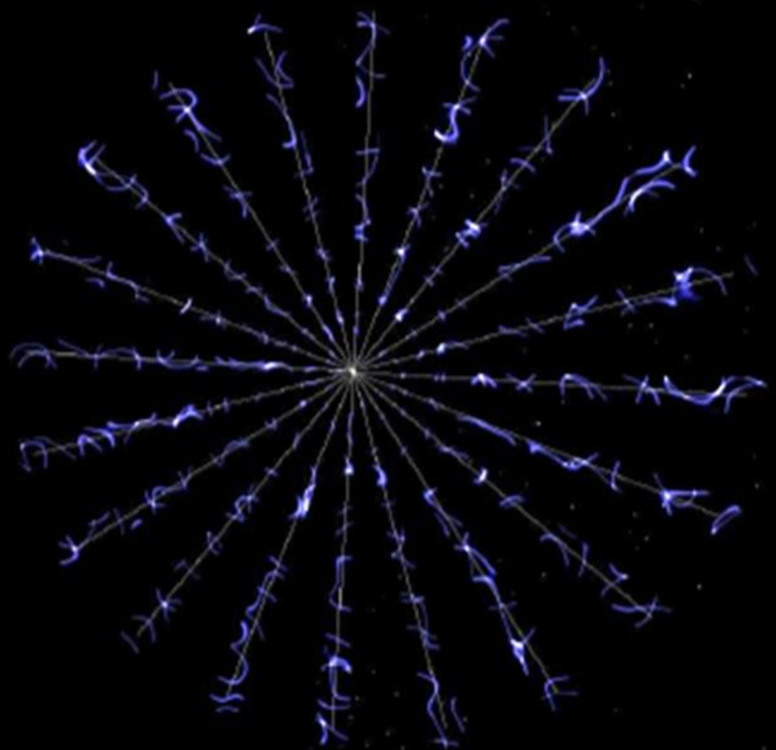


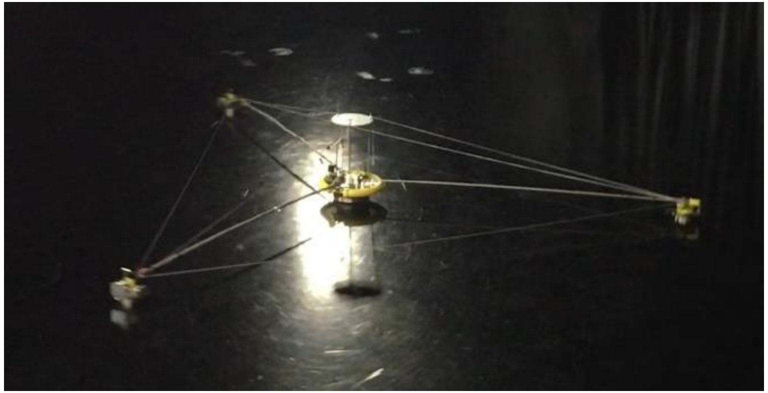
Areas of need, interest, and potential collaboration

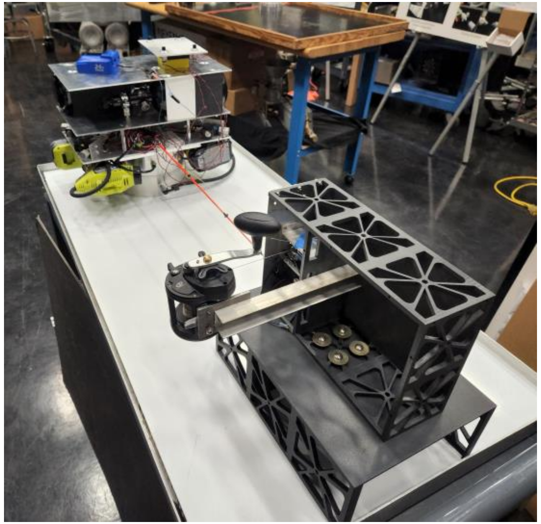
Tether Deployment

Before an Electric Sail spacecraft is operational, it first must **deploy the multi-km** long tethers which requires the following:

- Space-grade tether spools to hold the tether
- Demonstration of an end-to-end deployment
- Tether braking device

Three-tether test bed on epoxy floor

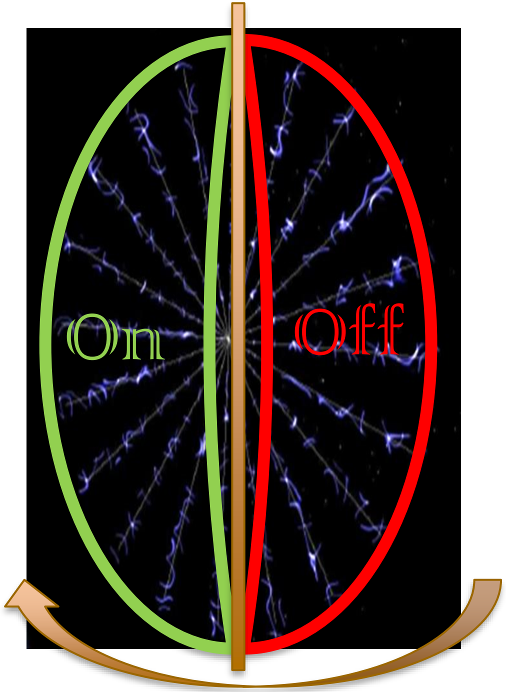




Tethered space tug simulator

Controlling the Electric Sail throughout flight is a multifaceted controls problem with several needs:

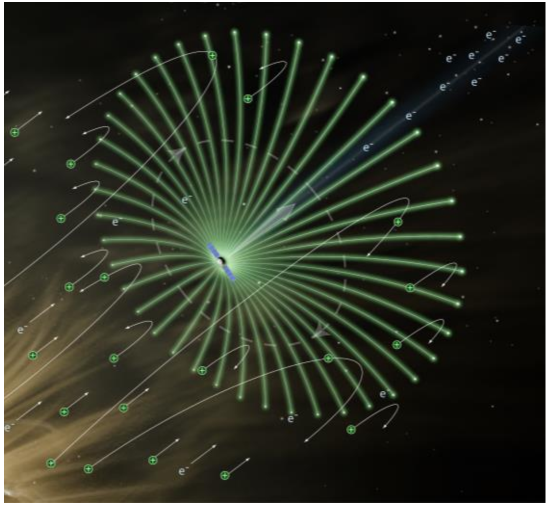
- **Multi-tether dynamics**
- **Formation control** of end masses
- **Relative navigation** of end masses
- Determining state of the tether during flight
- Actuation methods for adjusting end mass location other than thrusters
- **Pointing performance** with the central mass for science and other instruments



Guidance, Navigation, and Control

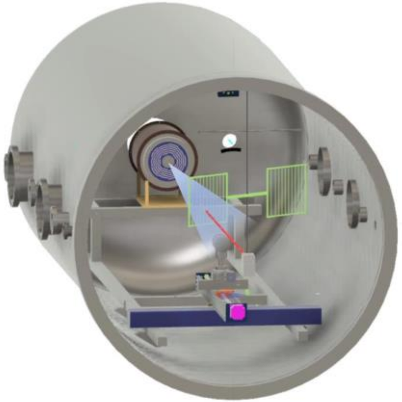
Electric Sail tethers are charged with an **induced voltage** upwards to 20 kilovolts which creates a **flow of electrons** into the system

- **Electrons** from the solar wind are **continuously captured** by the tethers
- An **electron gun** completes the circuit to keep the **high voltage difference** from the background plasma
- Trades on **tether material** with tensile strength and resistance needed to make the system possible
- Capability to change voltage while system is spinning in response to GNC commands



Charge Control

- Simulating the **plasma interaction** between the **solar wind** and **charged tethers** allows for estimation of the Electric Sail **thrust**
  - State-of-the-art simulations techniques include fully kinetic particle-in-cell models
- To **validate** plasma simulation codes, **direct thrust measurements** in the laboratory are needed



Inverted pendulum thrust stand in vacuum chamber

Plasma Modeling: E-Sail Thrust

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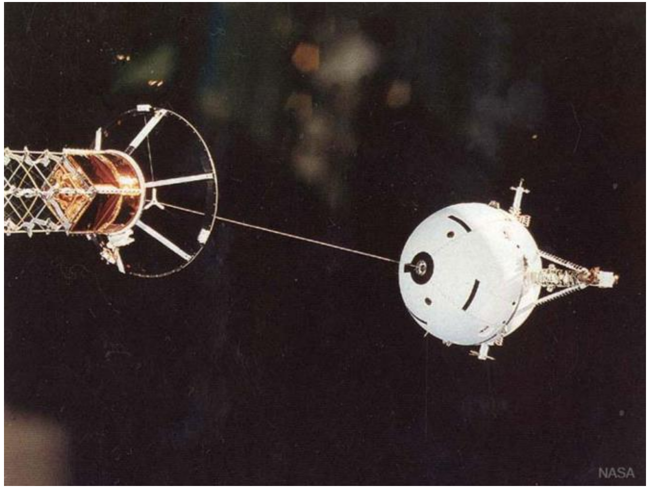
- Deorbit Device using electrodynamic tethers in place of electrostatic tethers (proven concept in Earth orbit)
- Tethered small satellite for On-Orbit Servicing, Assembly and Manufacturing (OSAM)
- On orbit propulsive device using electrodynamic tethers
- Lengthy linear science instrumentation
- Deployed sensor array



What ideas do you have?

Alternative Technology Spinoffs

Thank you!

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