The Conceptual Design of an Electric Sail Technology Demonstration Mission Spacecraft

NASA Innovative Advanced Concepts

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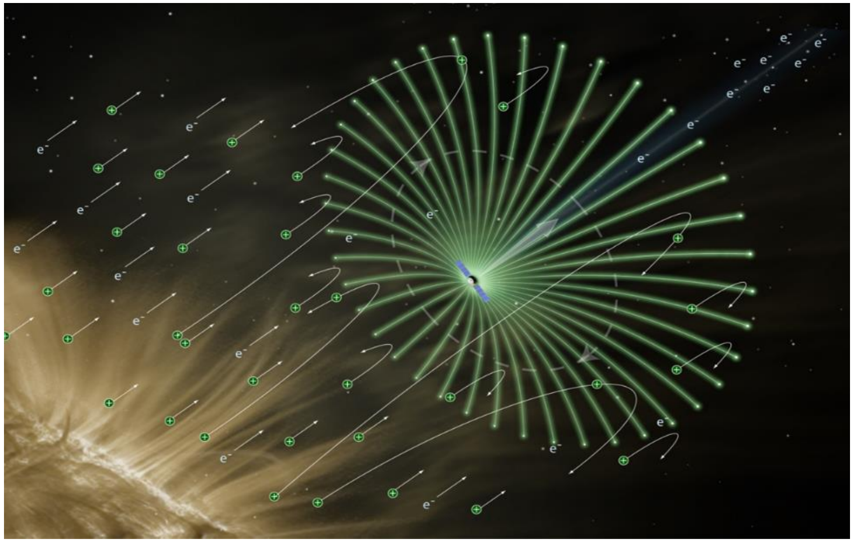
Presentation Agenda

- HERTS/Electric Sail background information
- Findings from the Phase I NIAC
  - This propulsion technology enables trip times to the Heliopause in 10 – 12 years
  - Fastest transportation method to reach Heliopause of near term propulsion technologies
- Current Phase II NIAC tasks
  - Plasma chamber testing
  - Particle-in-cell (PIC) space plasma to spacecraft modeling
  - Tether material investigation
  - Conceptual design of a TDM spacecraft
  - Mission capture



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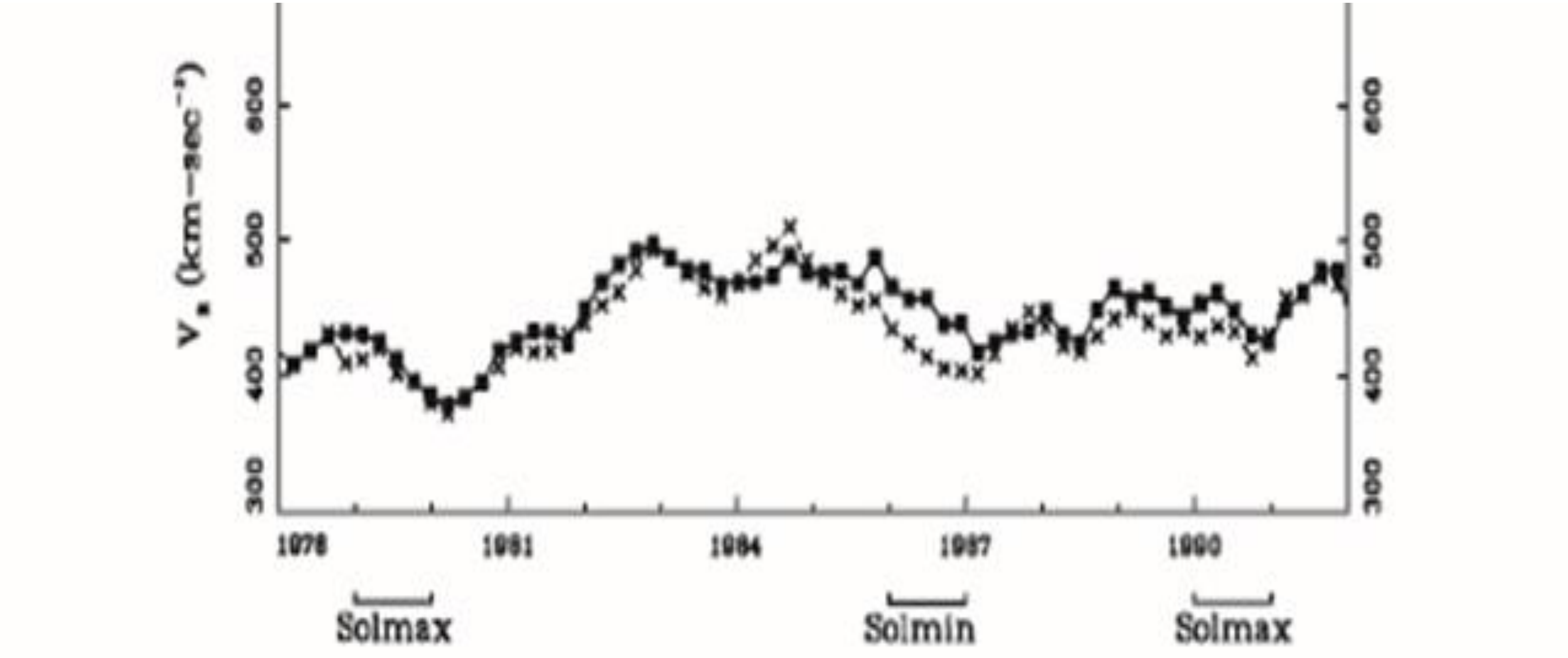
Solar Wind Basics-> Solar Sail



- **The relative velocity of the Solar Wind through the decades**

The solar wind ions traveling at 400-500 km/sec are the naturally occurring (free) energy source that propels an E-Sail

Electric Sail Origins

The electric solar wind sail, or electric sail for short, is a propulsion invention made in 2006 at the Kumpula Space Centre by Dr. Pekka Janhunen.

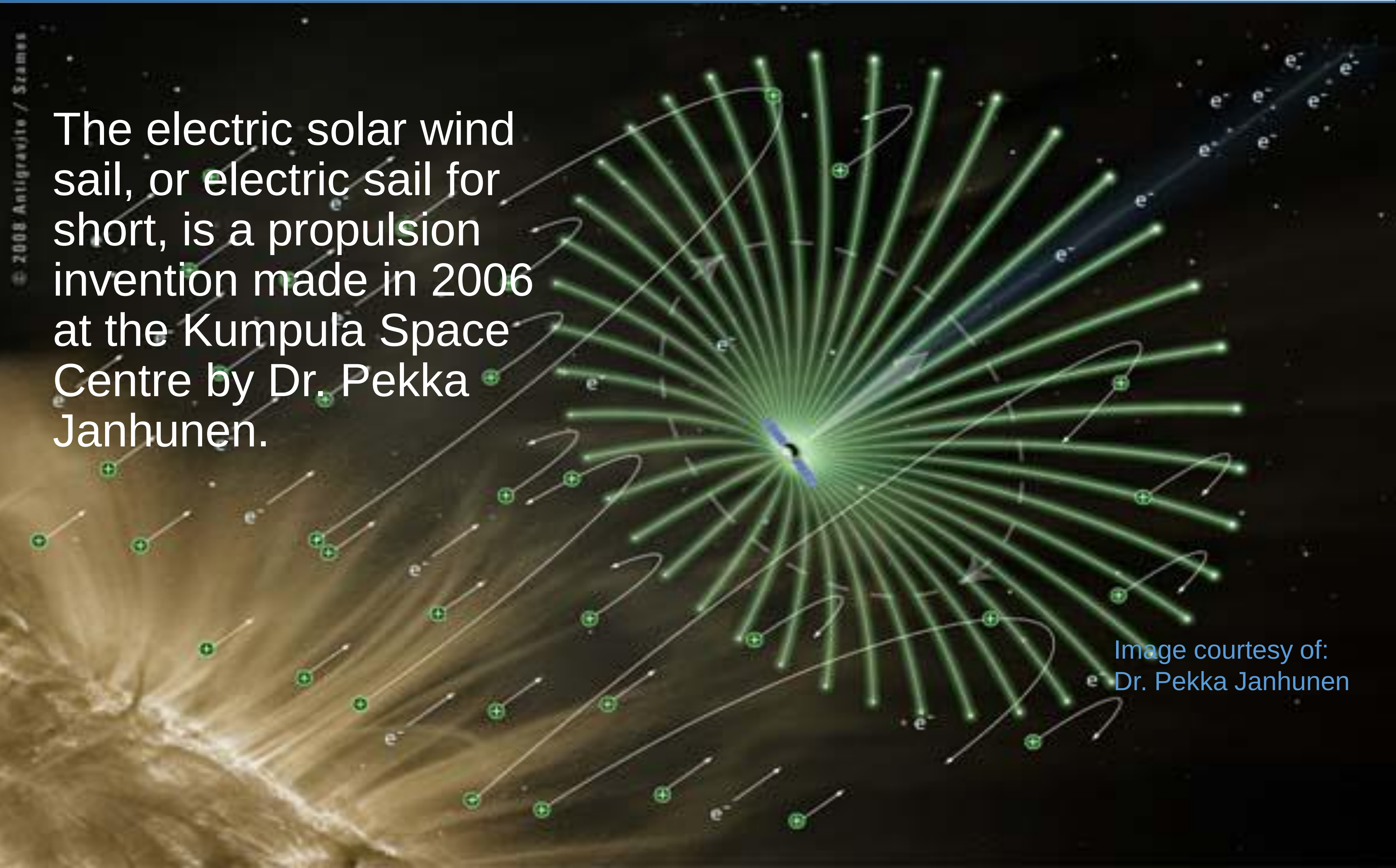


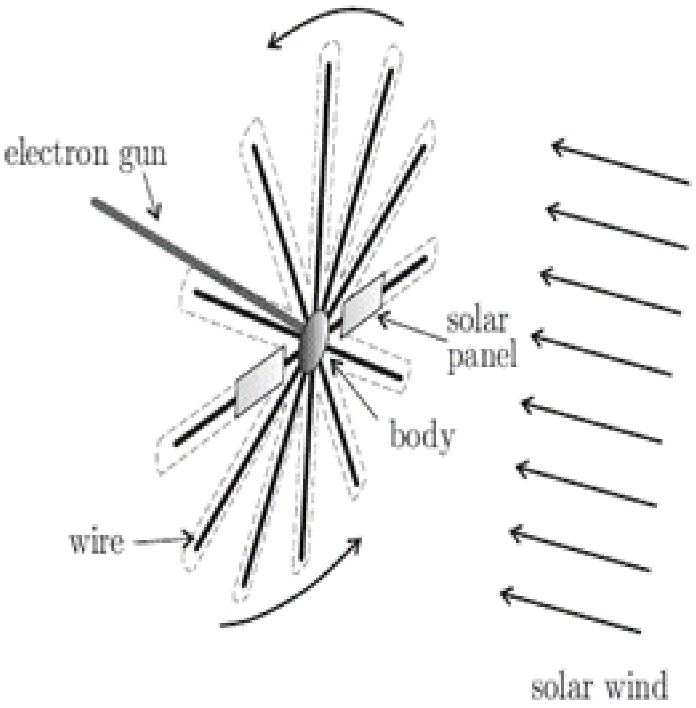
Image courtesy of:
Dr. Pekka Janhunen

Phase I Findings

- Electric-Sail propulsion systems are the fastest method to get spacecraft to deep space destinations as compared to:
  - Solar sails,
  - All chemical propulsions,
  - Electric (ion) propulsion systems
- Technology appears to be viable .
- Technology Assessment – Most subsystems at high state of readiness except:
  - Wire-plasma interaction modeling,
  - Wire deployment, and
  - Dynamic control of E–Sail spacecraft…
  - These are the three areas of focus for the current Phase II NIAC

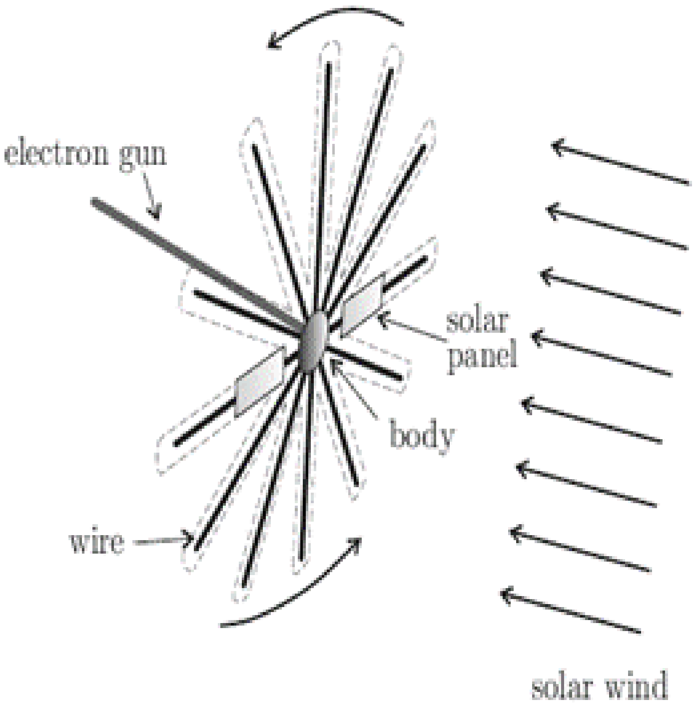
Electric Sail – Concept of Operations

- The E-sail consists of 10 to 20 conducting, positively charged, bare wires, each 1–20 km in length.
- Wires are deployed from the main spacecraft bus and the spacecraft rotates to keep wires taut.
- An electron gun is used to keep the spacecraft and wires in a high positive potential (~6 t0 20 kV).
- Positive ions in the solar wind are repulsed by the field and thrust is generated.



Electric Sail – By The Numbers
An Example

- 10 – 20 wires
- 5 - 20 km long
- 25 microns thick
- Wires kept at ~6 kV potential
- The electric field surrounding each wire extends ~ 10 meters into the surrounding plasma and gradually expands as the distance from the sun increases.
- Produces ~1 mm/s^2 acceleration at 1 AU



Why An Electric Sail?

- Has the potential to fly payloads out of the ecliptic and into non-Keplerian orbits, place payloads in a retrograde solar orbit, missions to terrestrial planets and asteroids, and position instruments for off-Lagrange point space weather observation.
- Low mass/ low cost propulsion system
- Electric sail acceleration extends deep into the solar system (6 times further than a solar sail)
- Propulsion system is scalable to small spacecraft
- Readily meets the requirements for relatively near-term interstellar precursor missions out to 500 AU

Velocity vs. Radial Distance Comparison for Equal Mass Spacecraft

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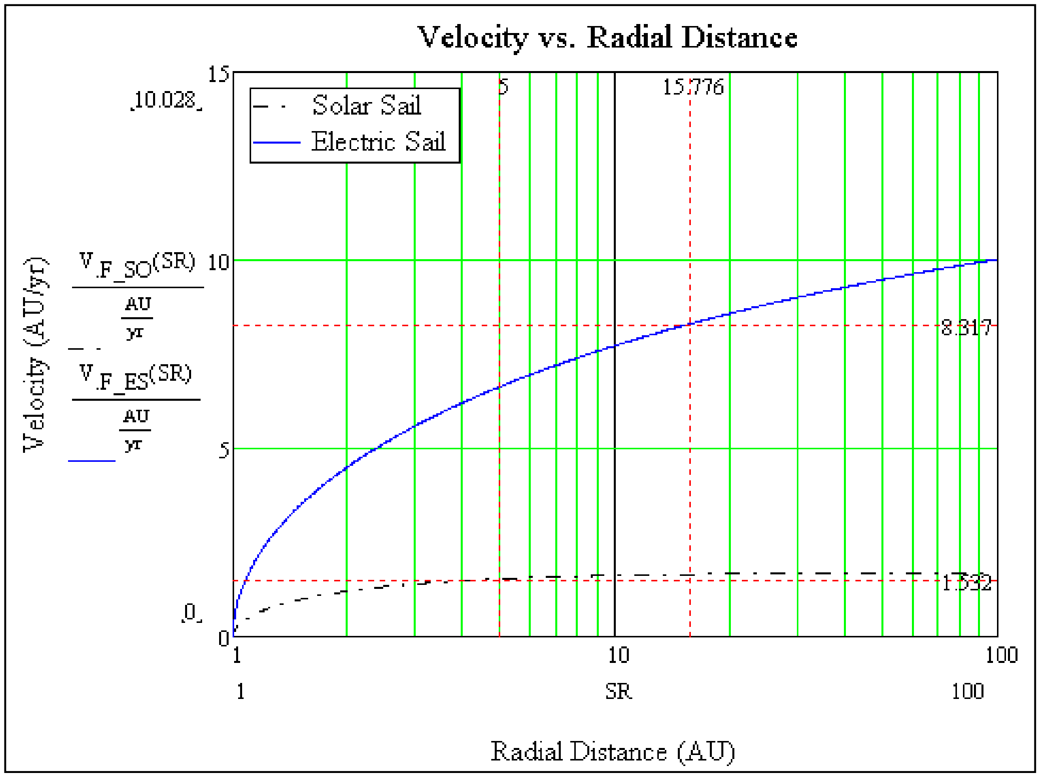
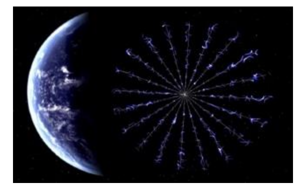
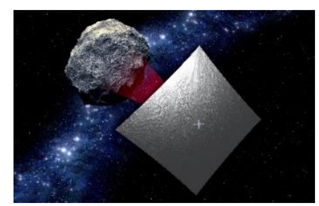
- Thrust drops as $1/r^2$ for the solar sail and $1/r^{7/6}$ for the electric sail

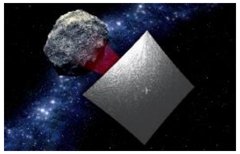


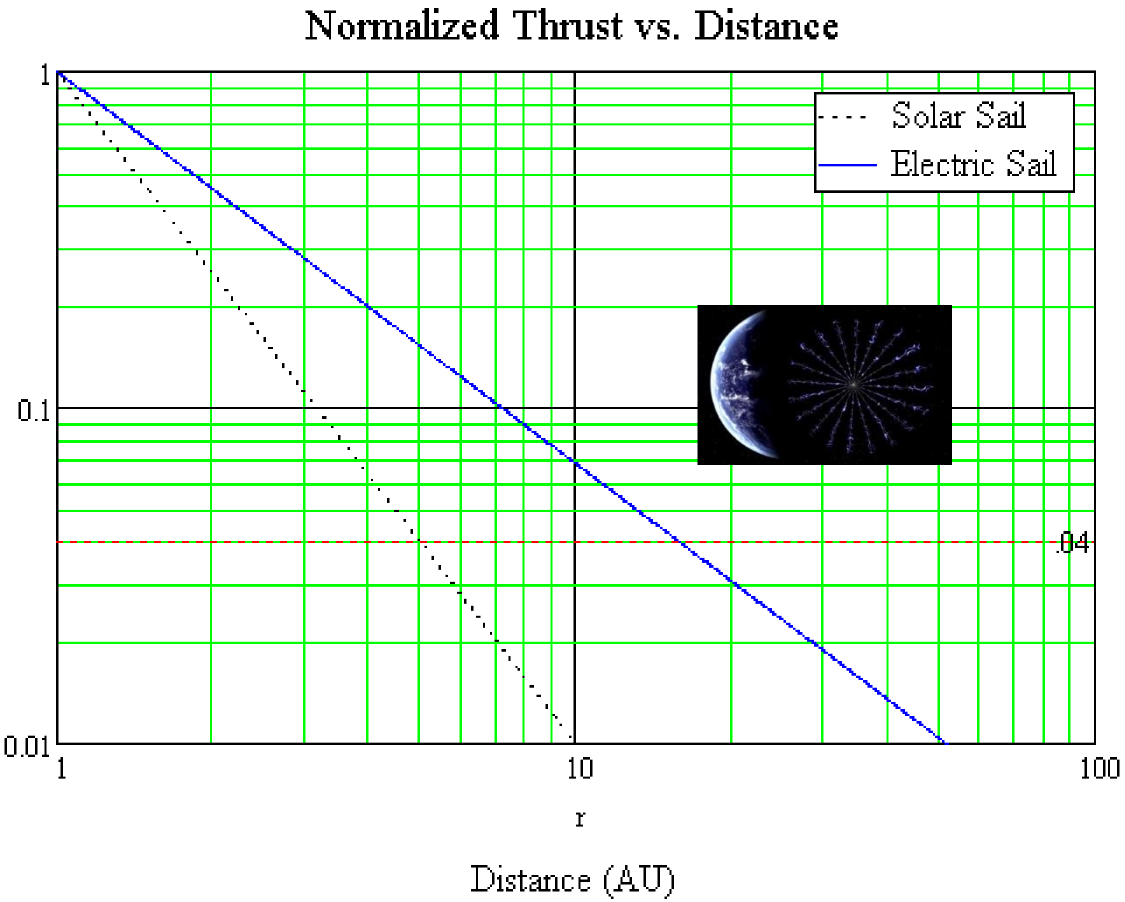




- The solar sail system velocity is limited to 1.5 AU/year since the system stops accelerating at distance of 5 AU: whereas,
- The E-Sail accelerates to 15.8 AU, thereby creating a velocity of 8.3 AU/year

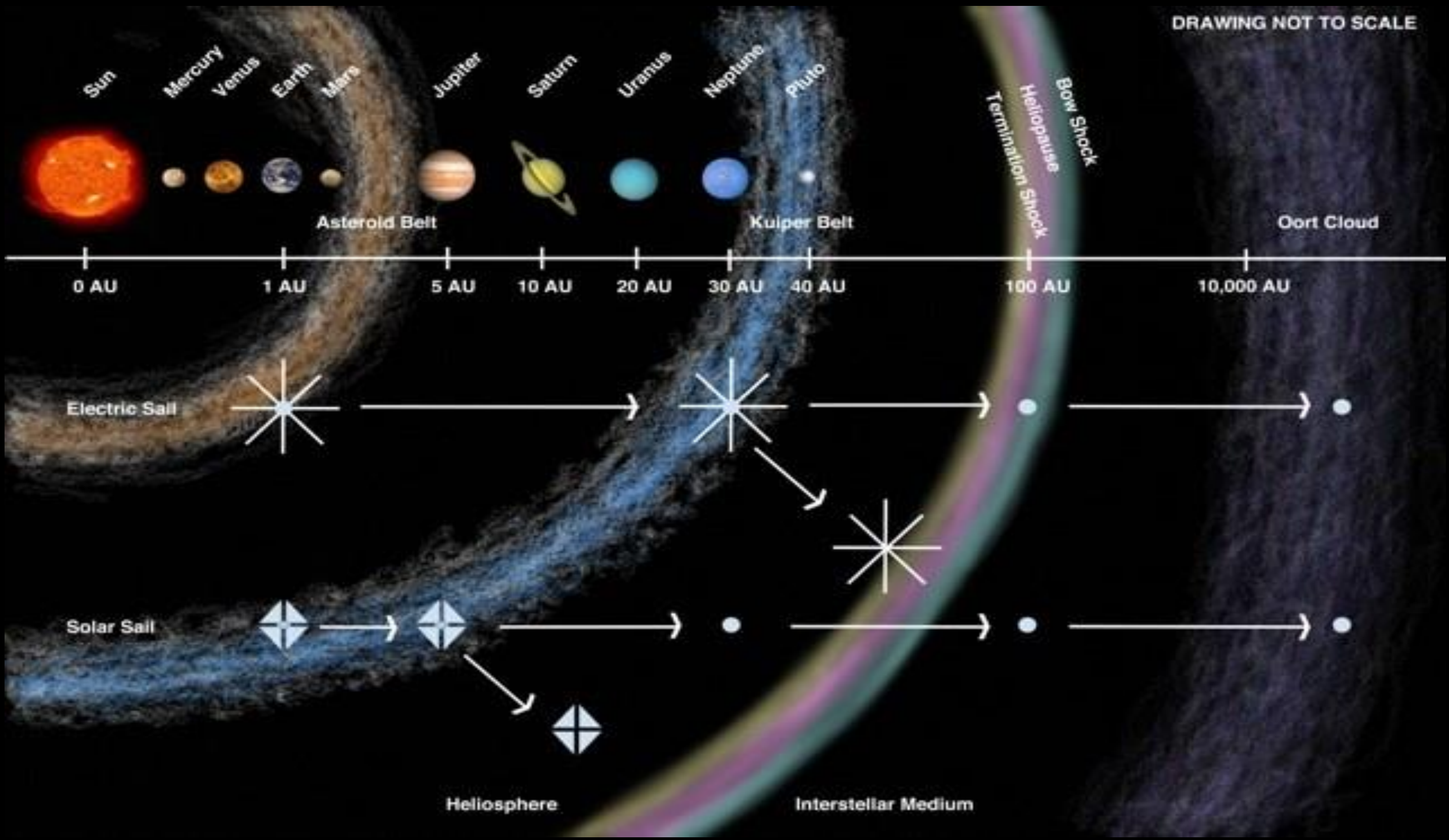
Normalized Thrust Decay Comparison





The AU distance where the thrust generated by each system = 0.04 * Thrust $_{(1AU)}$ is 5AU for the solar sail system and 15.8 AU for the E-Sail system

E-Sail vs Solar Sail Mission Ops

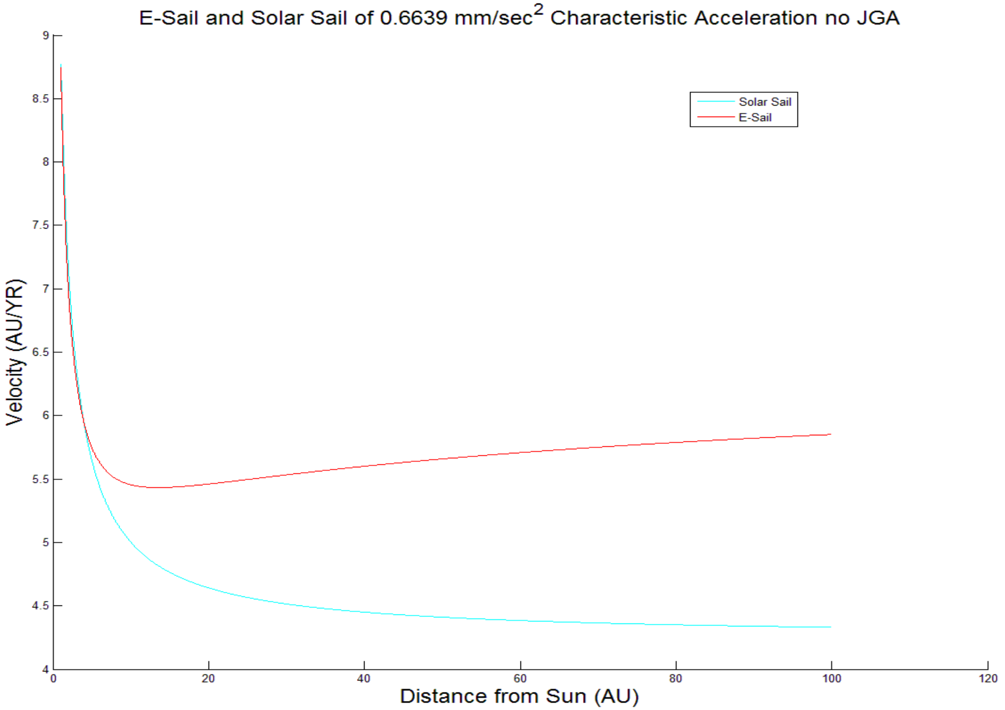


The Solar Sail spacecraft stops accelerating at ~ 5AU whereas the E-Sail spacecraft continues to accelerate over distances of ~20 – 30 AU

Velocity Comparison Between E-Sail and Solar Sail Propulsion Systems

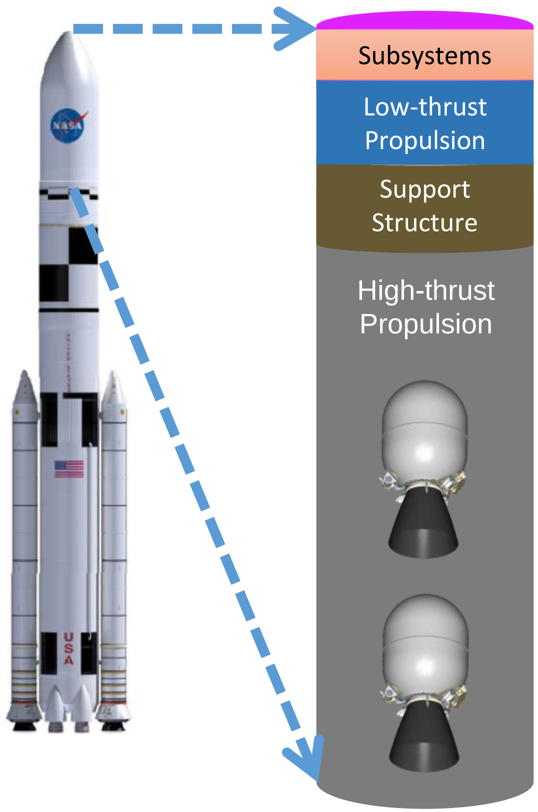
- E-sail velocities are 25% greater than solar sail option because of the rate of acceleration decline ($1/r^{7/6}$) vs solar sail acceleration decline ($1/r^2$)

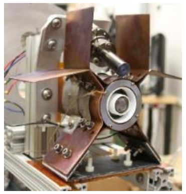
- E-Sail and Solar Sail propulsion options exceed the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU/yr

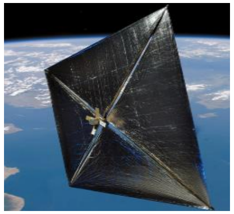


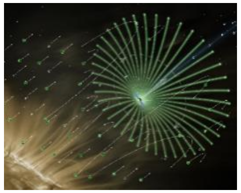
In-Space Propulsion Options Compared for a Heliopause Mission

- High-thrust propulsion option (All chem)
  - 1 to 2 solid rocket motors (SRM) in SLS stack
- Low-thrust propulsion options:
  - MaSMi Hall thruster
    - 50,000 hr. life
  - Solar sail
    - @ 10 g/m2; Characteristic Acceleration = 0.43 mm/sec2 (Near-Term technology)
    - @ 3 g/m2; Characteristic Acceleration = 0.66 mm/sec2 (Enhanced technology)
  - Electric sail
    - Characteristic Acceleration = 2mm/sec2
    - Characteristic Acceleration = 1mm/sec2

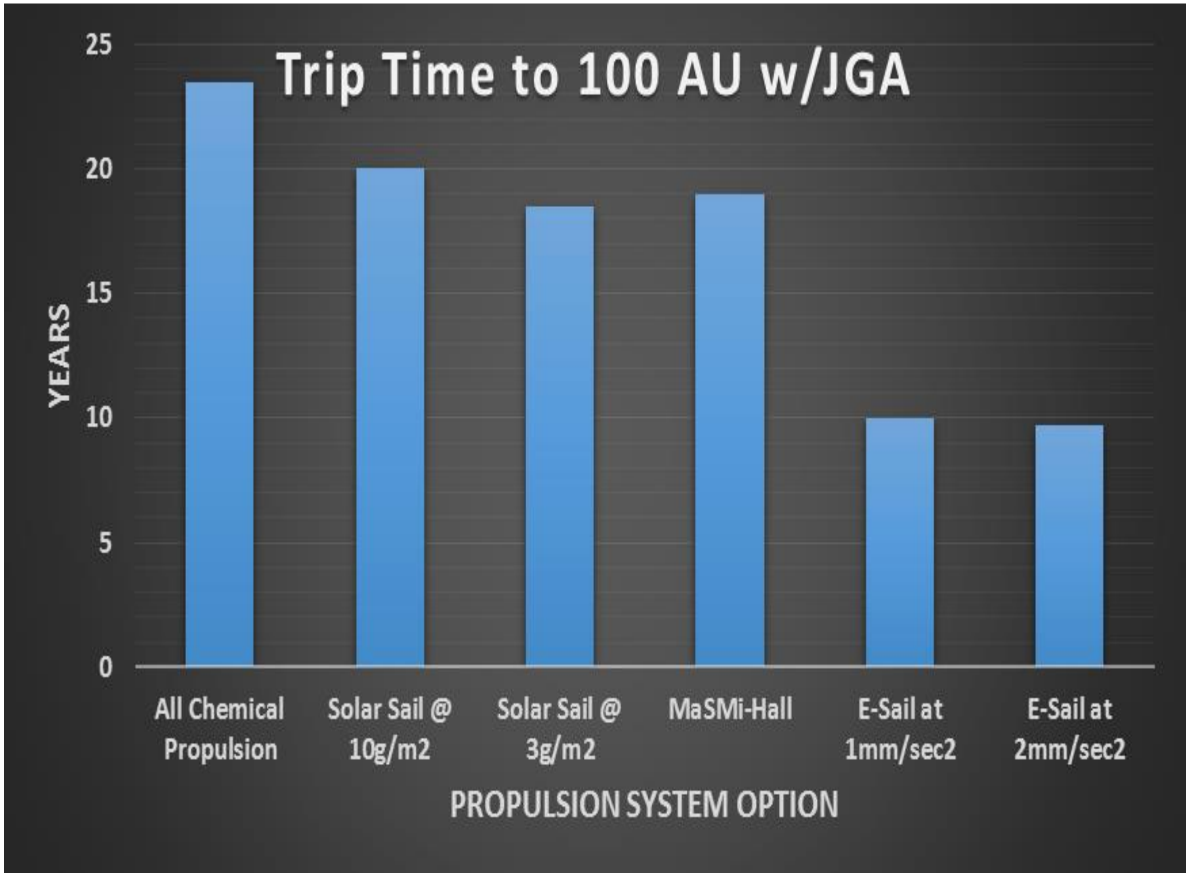


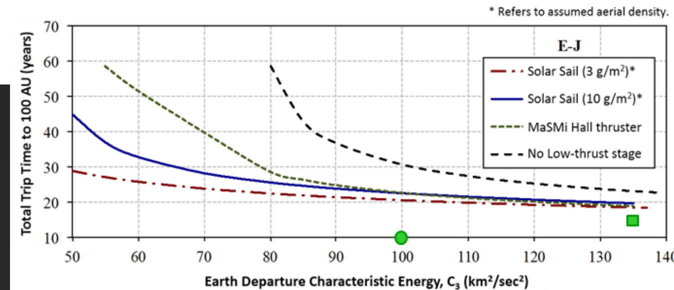


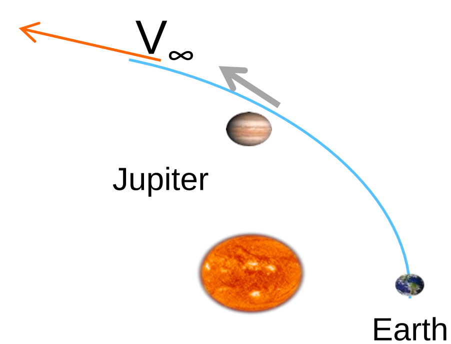




Trip Time Comparison Between E-Sail and Solar Sail Propulsion Systems





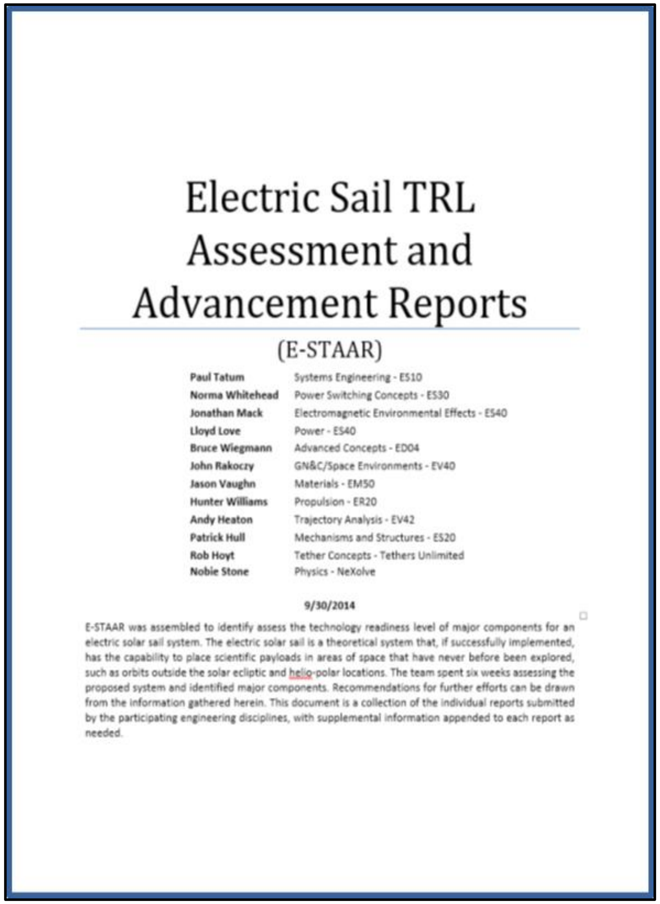


Direct escape using SLS, Jupiter Gravity Assist (JGA) and onboard in-space propulsion system.

The HERTS/E-Sail option dramatically reduces trip times by ~50% to 100 AU

HERTS Technology Readiness Level (TRL) Assessment and Advancement

- MSFC conducted a TRL assessment of E-Sail systems and components
- Most E-Sail components are at relatively high TRL, but three elements significantly reduce the system-level TRL
  - Uncertainty of plasma physics model (used to determine current collection, hence, thrust)
  - Wire deployment
  - E-Sail spacecraft trajectory guidance & control via offsetting the applied S/C Cp through the voltage biasing of individual wires



Electric Sail TRL Assessment and Advancement Reports

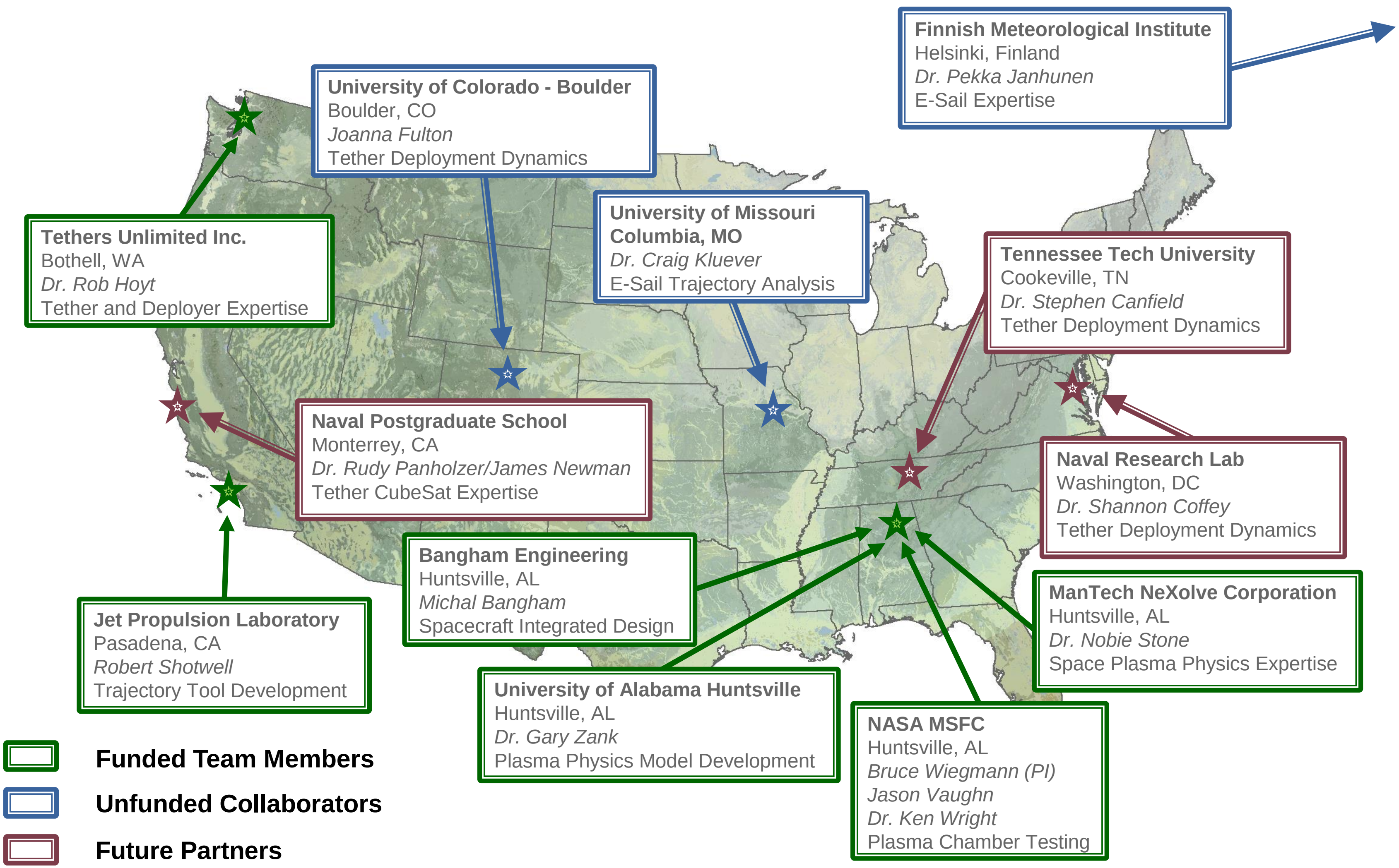
(E-STAAR)

Paul Tatum	Systems Engineering - ES10
Norma Whitehead	Power Switching Concepts - ES30
Jonathan Mack	Electromagnetic Environmental Effects - ES40
Lloyd Love	Power - ES40
Bruce Wiegmann	Advanced Concepts - ED04
John Rakoczy	GN&C/Space Environments - EV40
Jason Vaughn	Materials - EM50
Hunter Williams	Propulsion - ER20
Andy Heaton	Trajectory Analysis - EV42
Patrick Hull	Mechanisms and Structures - ES20
Rob Hoyt	Tether Concepts - Tethers Unlimited
Nobie Stone	Physics - NeXolve

9/30/2014

E-STAAR was assembled to identify assess the technology readiness level of major components for an electric solar sail system. The electric solar sail is a theoretical system that, if successfully implemented, has the capability to place scientific payloads in areas of space that have never before been explored, such as orbits outside the solar ecliptic and helio-polar locations. The team spent six weeks assessing the proposed system and identified major components. Recommendations for further efforts can be drawn from the information gathered herein. This document is a collection of the individual reports submitted by the participating engineering disciplines, with supplemental information appended to each report as needed.

The Phase II HERTS Team



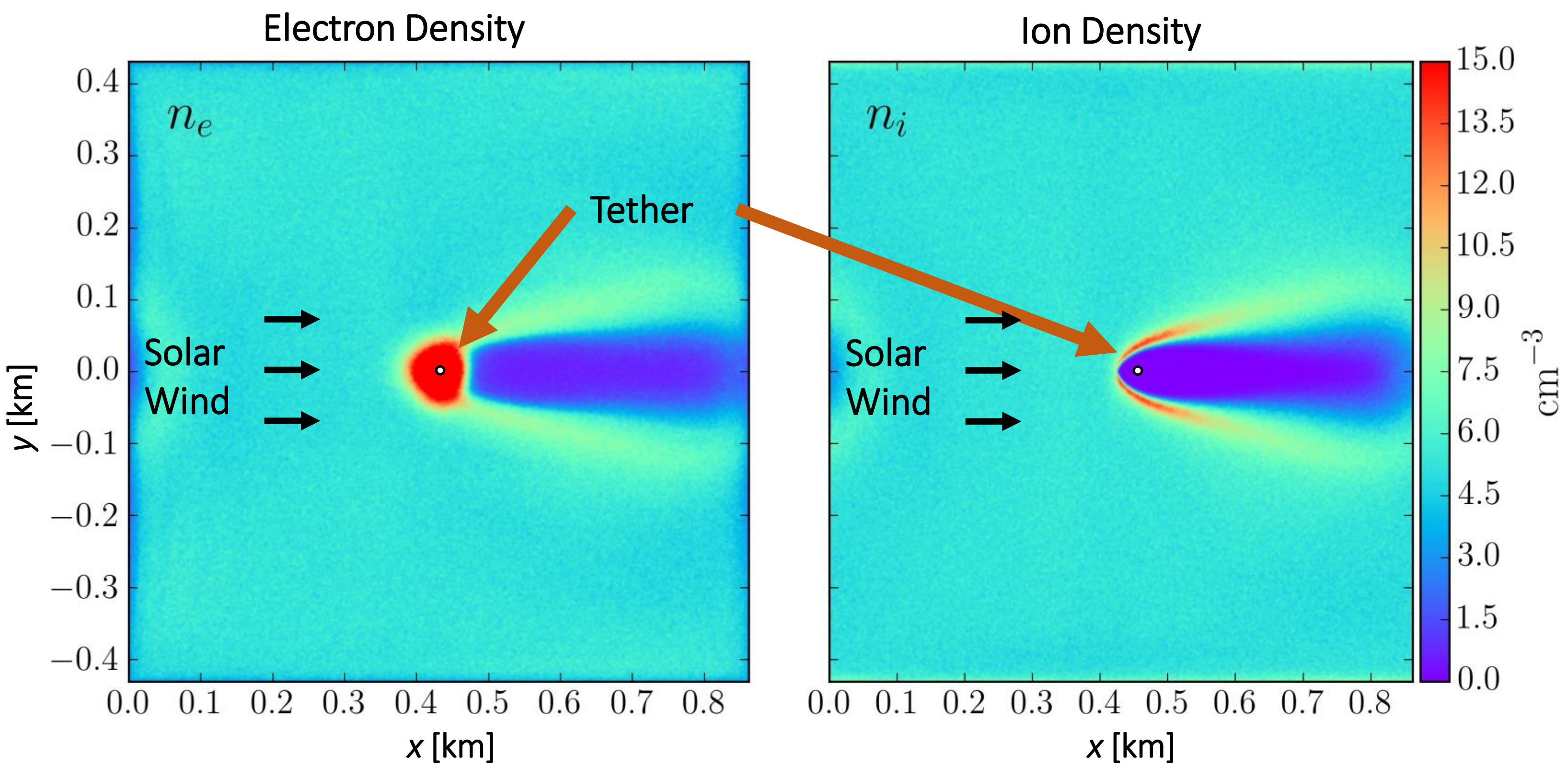
Animation of E-Sail vs Other Options

Major Thrusts of Phase II NIAC

- Develop a particle-in-cell (PIC) model of the space plasma dynamics and interaction with a spacecraft propelled by an electric sail
  - The development of the model requires experimental data from ground tests (MSFC plasma chamber)
- Investigate tether material and deployment
- Perform a conceptual spacecraft study on a HERTS TDM spacecraft
- Investigate HERTS spacecraft navigation & control
- Enhance low thrust trajectory models (JPL)

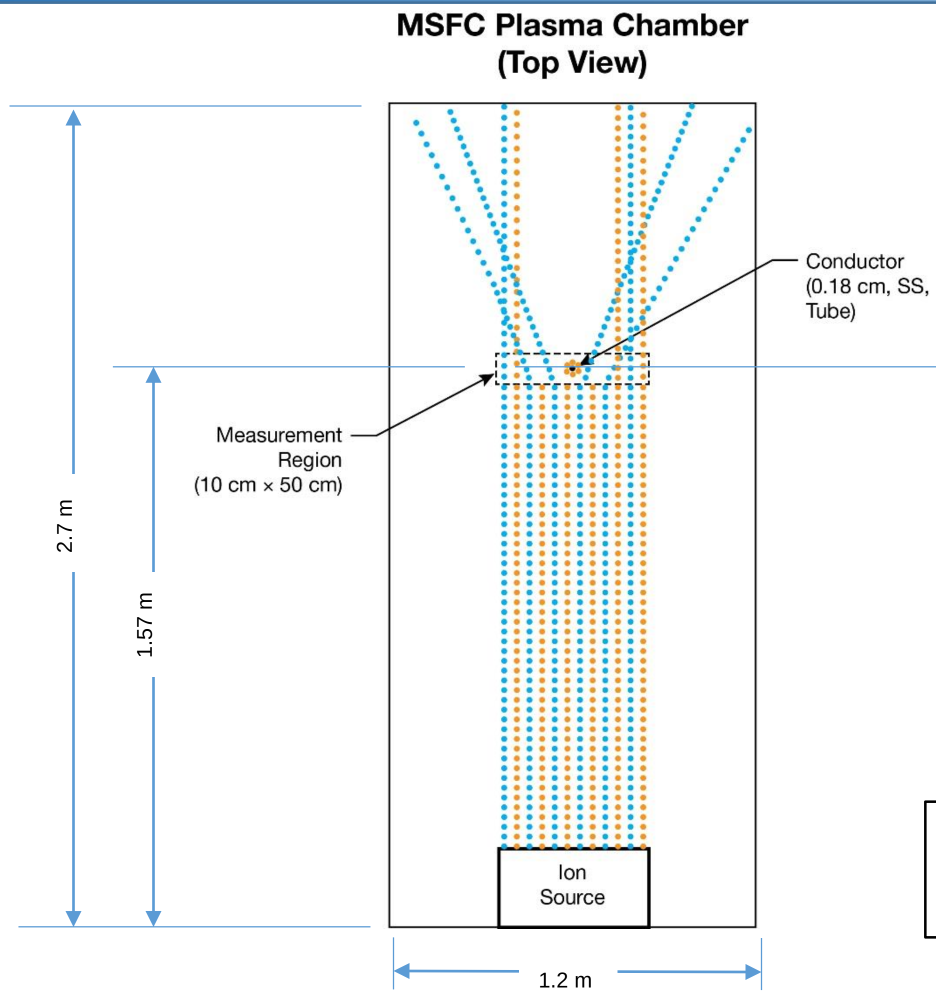
Particle-in-Cell Modeling

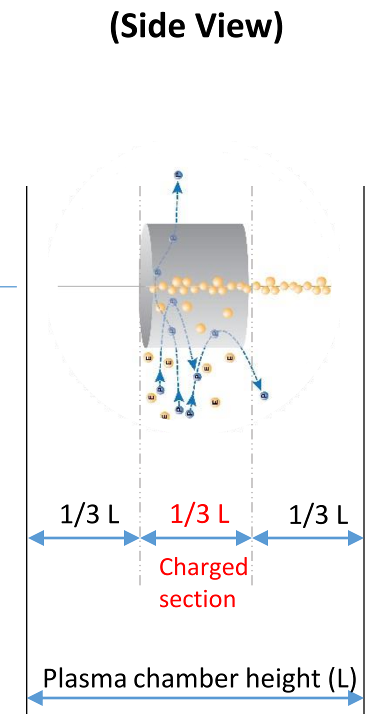
- Simulation of solar wind particles near a charged wire using the LANL VPIC code



Results to date comparable with published values from Dr. Pekka Janhunen.

Plasma Chamber Testing





The middle third of the SS tube is positively charged and a sheath is created that deflects protons. Then measurements are made to determine degree of deflection of these protons

Charged ions (protons and electrons) flow from the ion source towards the end of the chamber.
Electrons are collected onto the positively charged wire & the current is measured.
Protons are deflected by the charged Debye sheath

E-Sail Plasma Physics Testing

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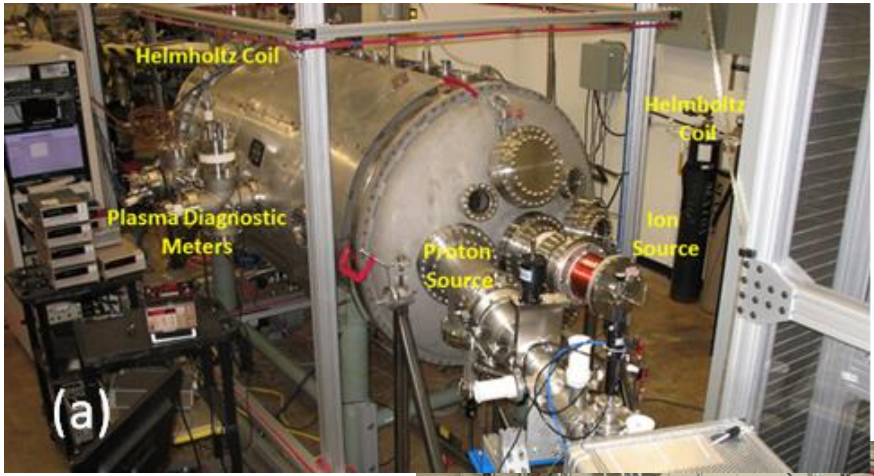
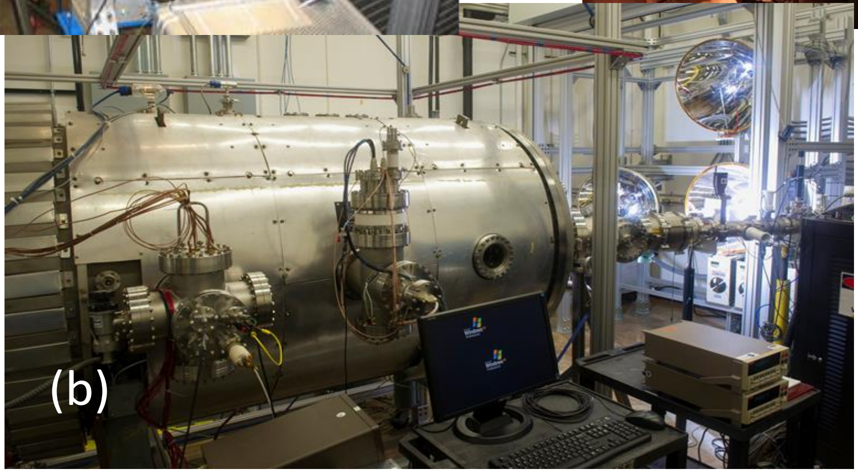
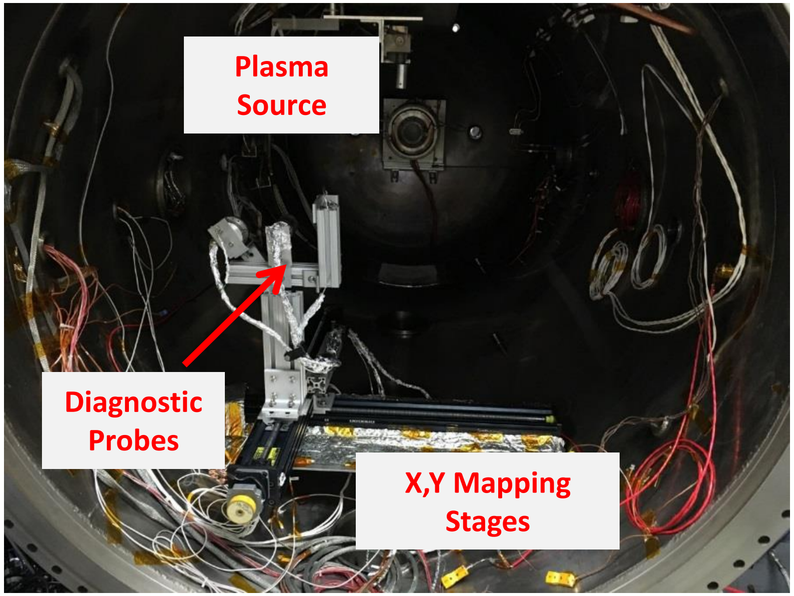




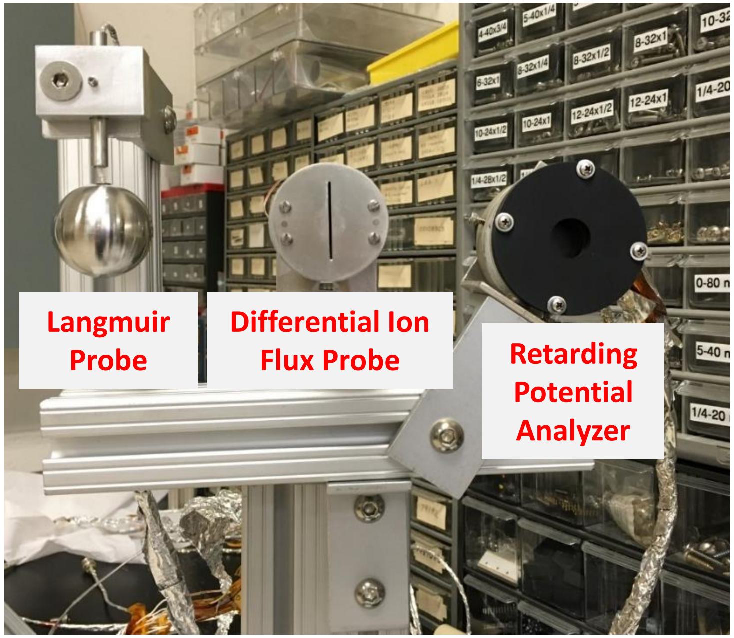
NASA MSFC has a unique history and knowledge base related to plasma experimentation and applications to space tethers.

Inside the Plasma Chamber

- Developed diagnostic suite to measure ion flow vector, ion energy, and electron temperature
  - Differential Ion Flux Probe (DIFP) measures ion flow vector in 2D plane
  - Retarding Potential Analyzer (RPA) measures ion energy
  - Langmuir Probe measures electron temperature
- Measurements of plasma free stream underway, E-Sail wire simulator being installed



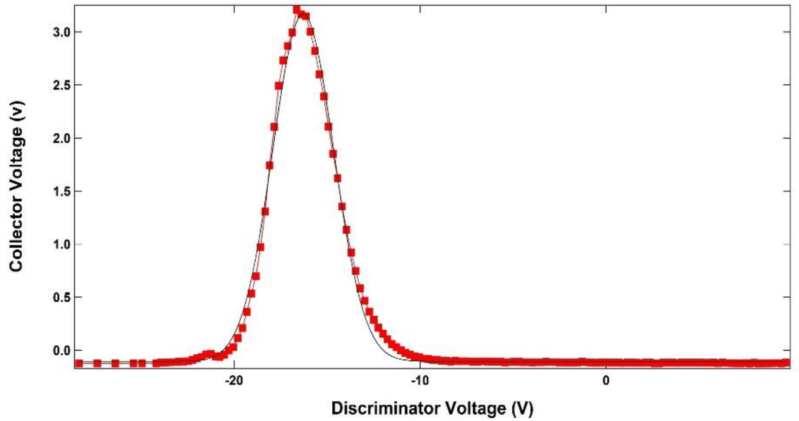
X-Y Stage to Map Measurement Region



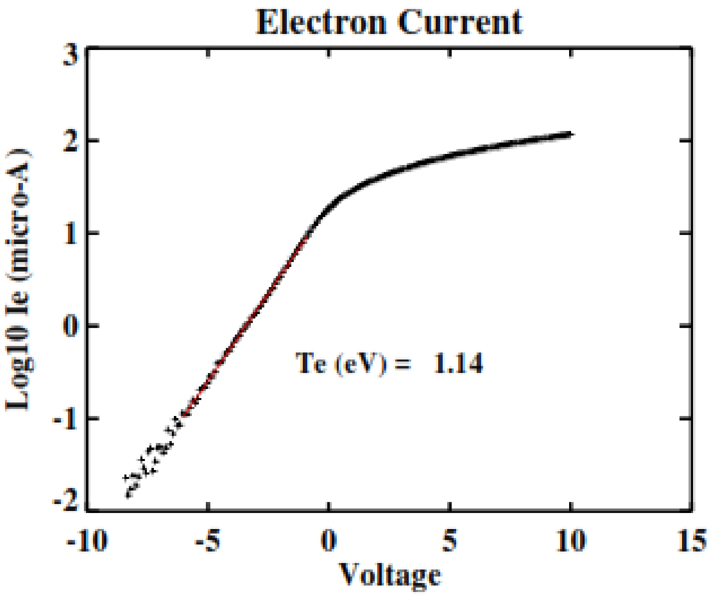
Diagnostic Probe Suite

A Sample of Plasma Chamber Data

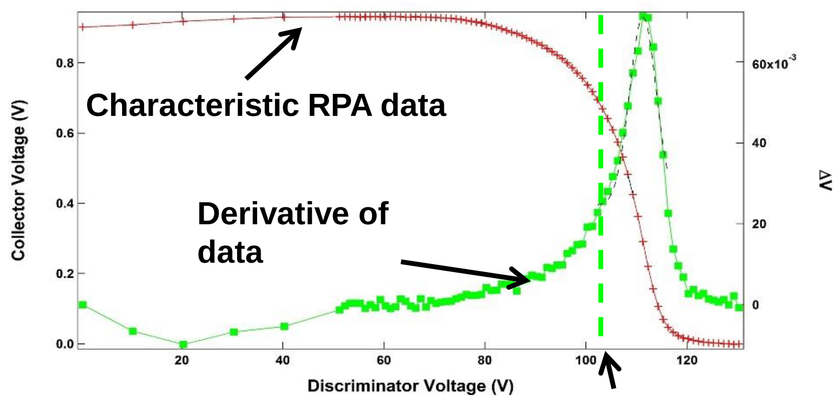
- Chamber calibration underway with new ion source
- E-Sail wire being installed



Differential Ion Flux Probe Data



Langmuir Probe Data



Retarding Potential Analyzer Data

Three discrete types of experimental data are being collected which will be used by the PIC model team to anchor model being developed

JPL MALTO Tool Enhancement

- **MALTO (Mission Analysis Low Thrust Optimization)** is the go-to NASA preliminary mission design tool for electric propulsion ion engines and solar sails. MALTO was critical to the mission design of DAWN (ion engines) and is currently being used to design the NEA Scout mission (solar sail) and the Psyche Step 2 Discovery proposal (Hall thrusters).
    - JPL is adding an Electric Sail model to MALTO that includes two key parameters that can be varied.
    - The first parameter is variation with distance from Sun (roughly 1/r but some models use $1/r^{7/6}$)
    - The second parameter is variation with respect to Sun incidence angle (a function of cosine)
- The addition of an E-Sail model to MALTO will allow rapid mission design studies with a validated low thrust optimization design tool that is a standard for NASA
- Thrust model (in terms of acceleration):

$$\vec{a} = a_0\left(\frac{R_E}{r}\right)^{c1} \cos^{c2}(\alpha)\vec{n}$$

$\vec{a}$ =acceleration
a_0 = characteristic acceleration defined as thrust/mass at normal incidence (α=0) at 1 AU
R_E = constant of 1 AU
r = distance from sun
c1 = constant of radial variation (typically either 7/6 or 1)
c2 = constant of angular variation (typically between 1 and 2)
α = incidence angle to solar wind of body vector to reference plane of E-sail
$\vec{n}$ = thrust/acceleration reference frame of E-sail

Why a Technology Demo Mission?

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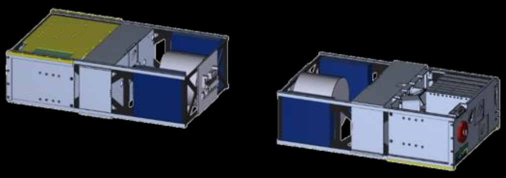
- Before NASA could consider an un-proven propulsion technology to propel future Heliopause missions in the 2025 to 2035 timeframe,

- Our team believes that a Technology Demonstration Mission (TDM) must first be developed & flown in deep-space to prove the actual propulsion capabilities of an E-Sail propelled spacecraft



Therefore, members of our team performed a conceptual design for an E-Sail propelled spacecraft for consideration as a future TDM

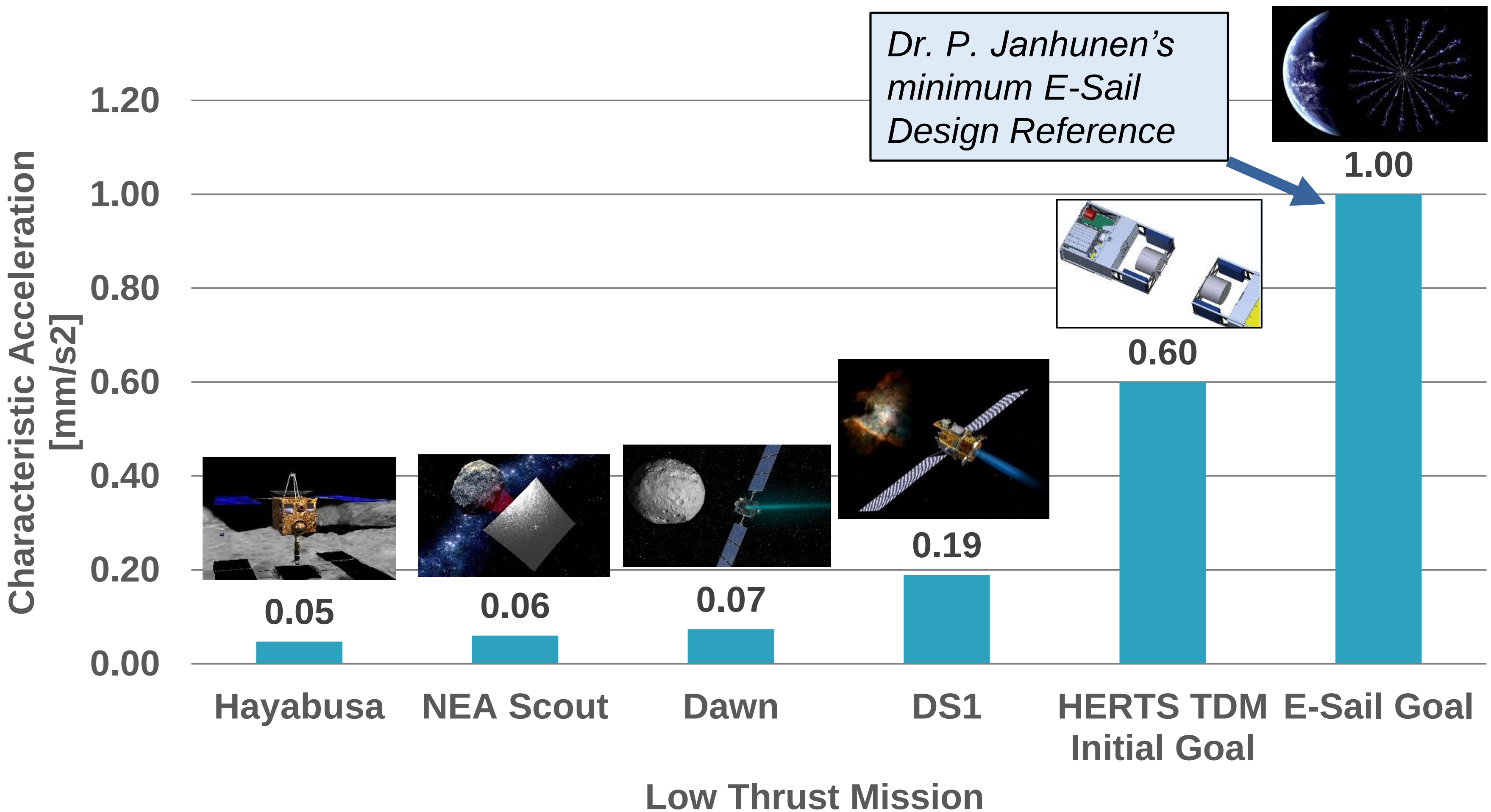
Overall Focus & Goals of the E-Sail Tech Demo Mssn Conceptual Design

- Focus of study
  - To determine if all components necessary for an E-Sail TDM can be packaged within a singular 12U spacecraft or 2-6U spacecraft (12U)

- Primary goals of mission:
  - To develop a CubeSat that can do the following (**DAS**):
    - **D**eploy a 16,000 m conductive tether
    - **A**ccelerate the spacecraft, &
    - **S**teer

- Secondary goals of mission:
  - Collect meaningful science data

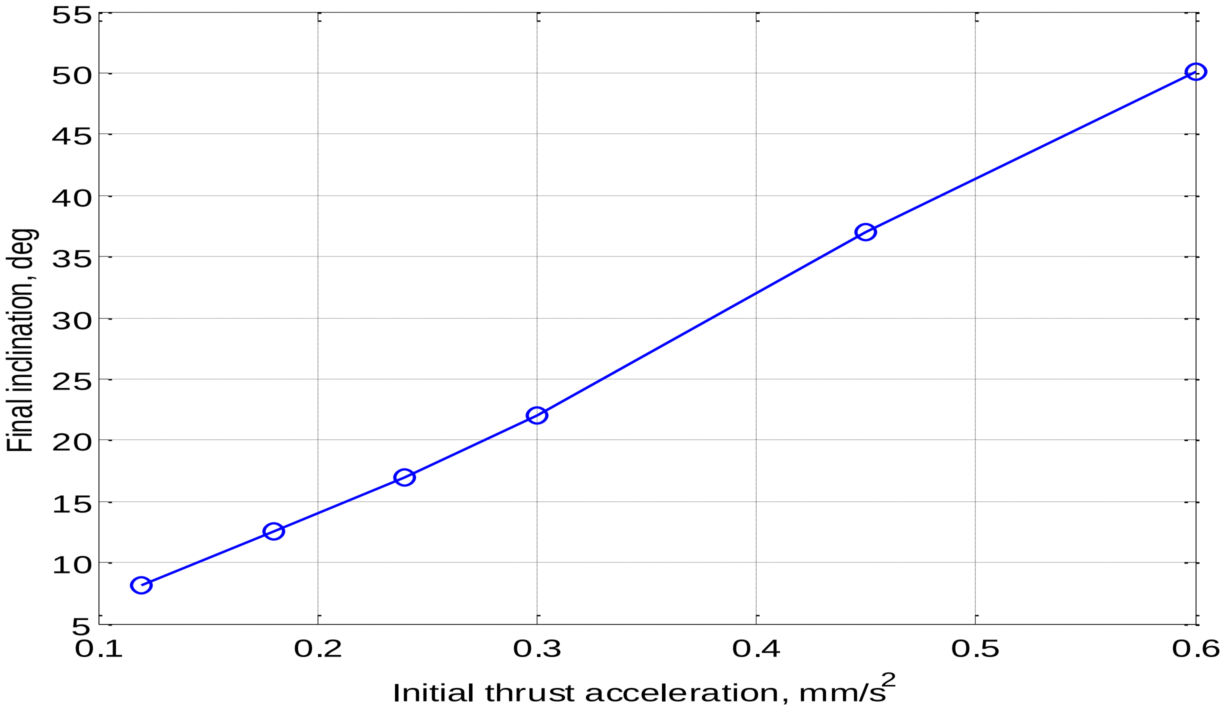
Comparison of E-Sail Proposed Characteristic Acceleration Rates to Other Spacecraft



The conceptual design of an E-Sail propulsion system for a proposed TDM was designed with a characteristic acceleration that is 10 times greater then the NEA Scout Solar Sail

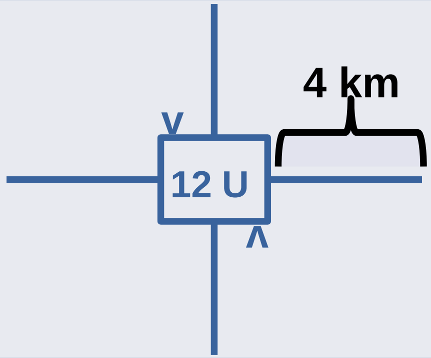
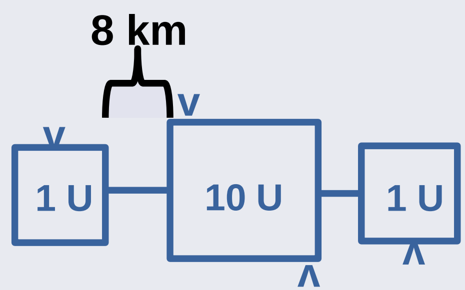
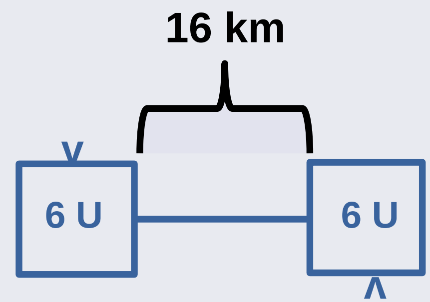
Out of Plane Capabilities within a Three Year Operational Life

- Results provided by Dr. Craig Kluever of the University of Missouri, College of Engineering



A characteristic acceleration that is 10 times that of a Solar Sail will enable the E-Sail TDM spacecraft to get 50 degrees out of the ecliptic plane within 3 years

TDM Configurations Investigated

	"Hub and Spoke"	"Hybrid"	"Barbell"
			
Tether Length	4 Tethers, each 4 km length	Two tethers, each 8 km length	Single 16 km tether
Feasible on Full Scale	No	Yes	No
Spin Up ΔV	Many km/s (impossible at long lengths)	3 m/s deployment, 21 m/s spin up	3 m/s deployment, 5 m/s spin up
Propellant Mass	Infeasible	0.24 kg	0.5 kg
Steering Capability	Different tether voltages	Different tether voltages	Insulator/switch at center

Down-Selected Tether Material Options for Further Study

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- 32 gauge wire; 16,500 m; AmberStrand for baseline design

	Miralon (CNT)	Copper	Aluminum	AmberStrand
Mass [kg]	0.60	6.69	2.02	0.99
Tensile Load at Yield [N]	40.72	3.17	12.49	40.48
Voltage Drop [V]	2,431.5	51.1	80.6	902.4

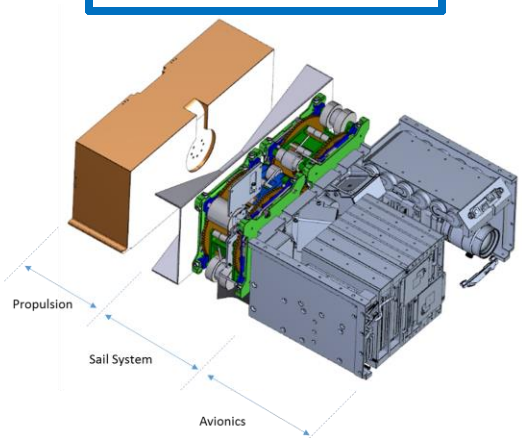
Unquantified figures of merit:

- **UV degradation**
- **Thermal properties**
- **Workability/reliability of material**
- **Deployment friction**

AmberStrand is currently the leading contender for use in a TDM spacecraft
But recent technical discussions with UK's Manchester University have occurred that are investigating the use of Manchester U's developed Graphene materials

HERTS TDM Spacecraft will Leverage Prior Investments

NEA Scout (6U)



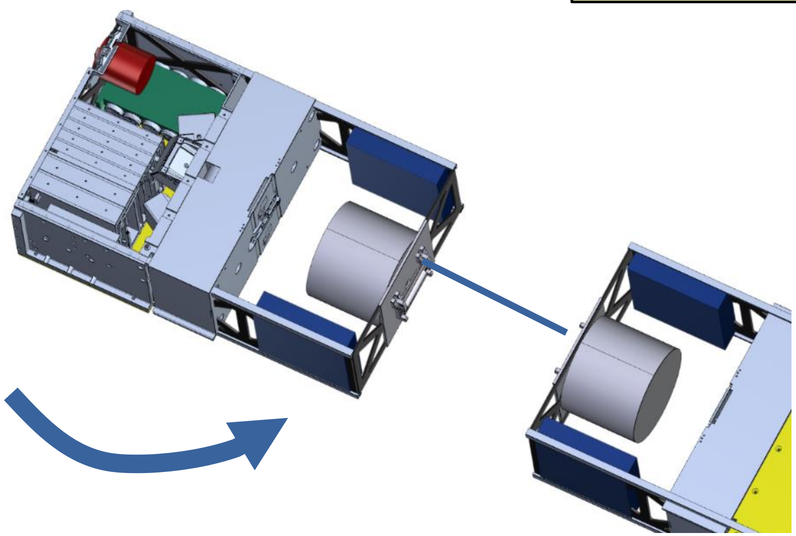
NEAS Components Used

- **Avionics**
- **Communication**
- **Reaction Control**
- **Power**
- **Attitude Control**

HERTS TDM (12U)

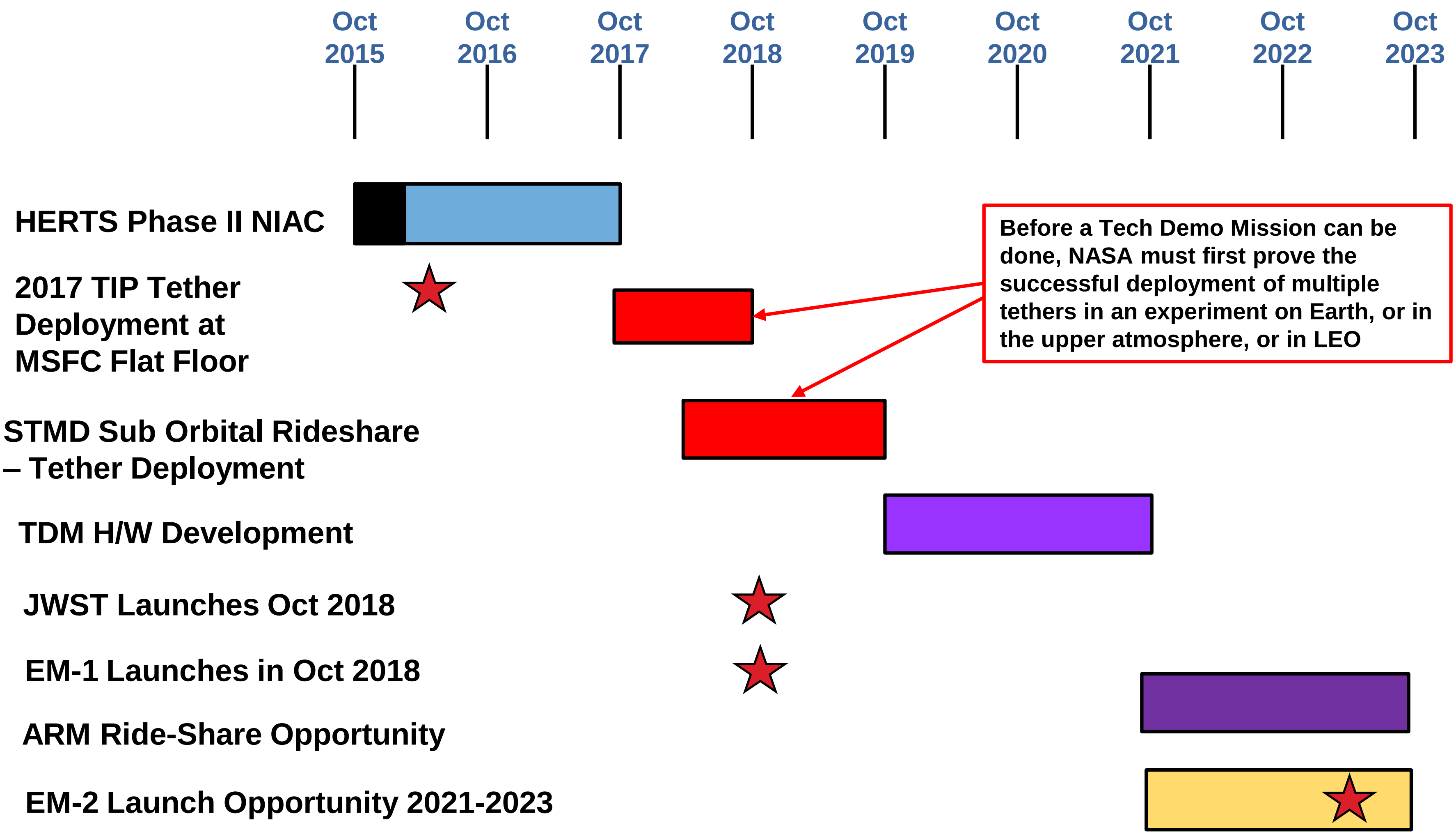
New Components Needed (TRL)

- **Tether Deployer (9)**
- **Conductive Tether (3-9)**
- **Electron Gun (7-9)**
- **6 kV Power Supply (5/6)**



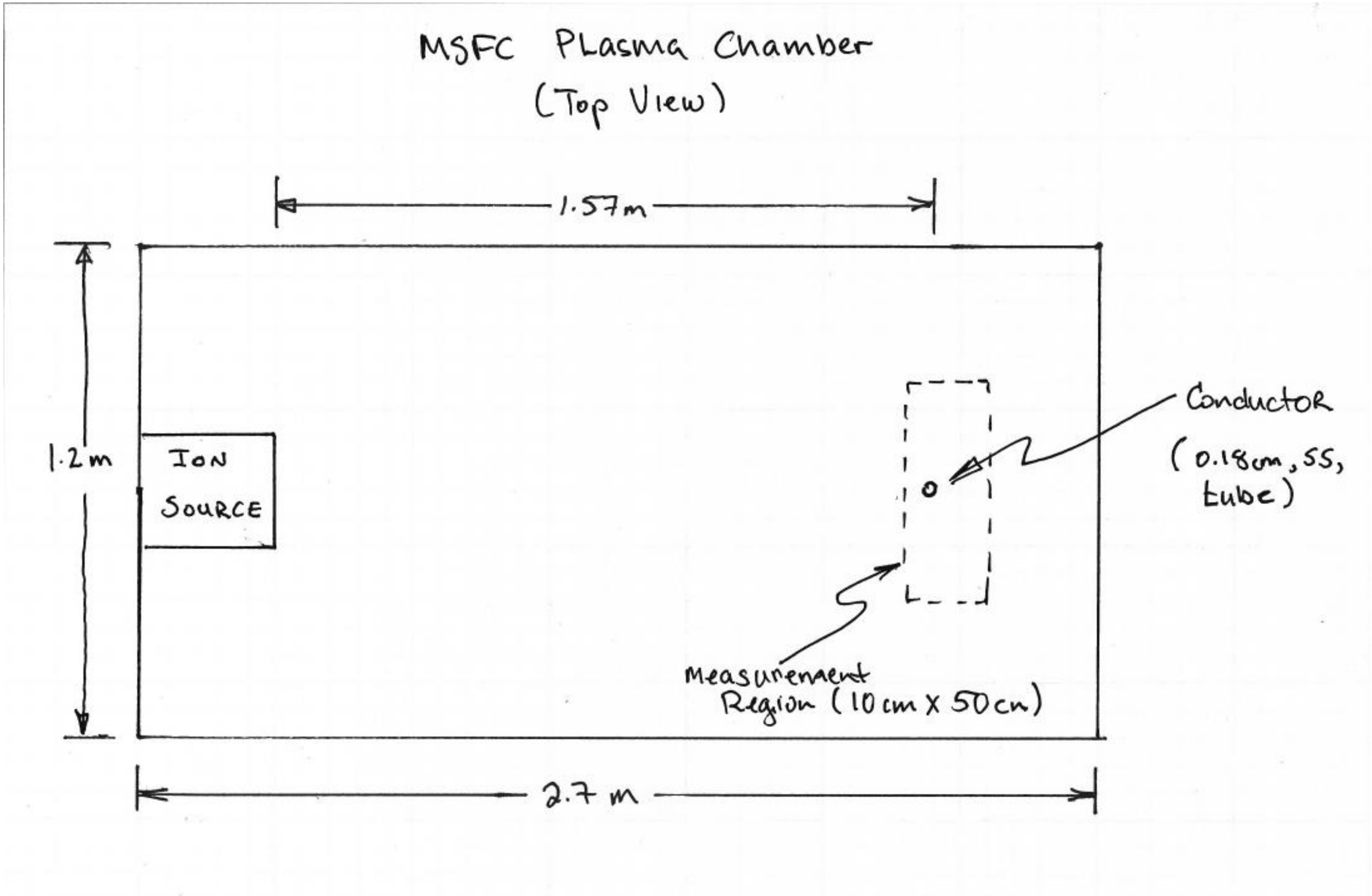
Animation of Proposed E-Sail TDM (2023)

Schedule to HERTS TDM Demo



Backup Slides Follow

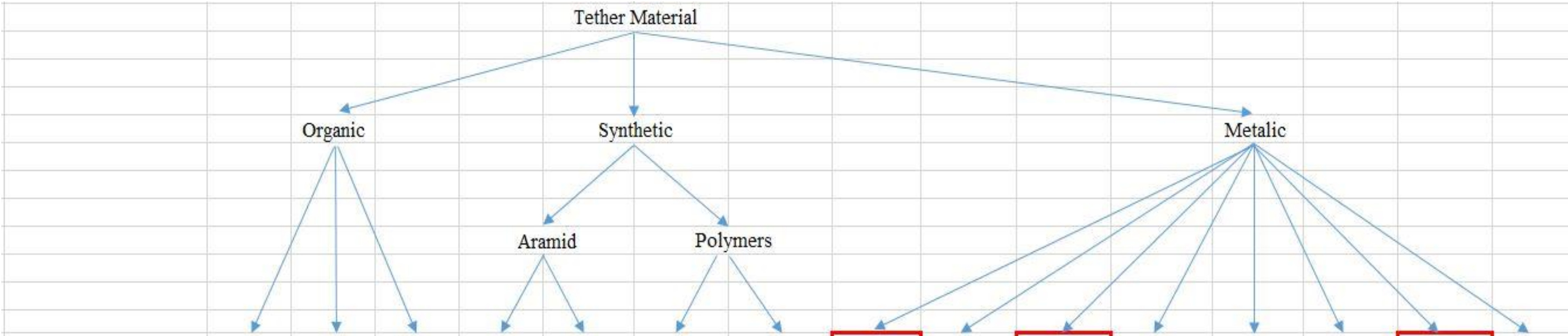
Plasma Chamber Testing



Key Driving Requirements of a HERTS TDM

Key Driving Requirements (KDRs) of the HERTS TDM spacecraft	
1	The HERTS TDM spacecraft shall have a characteristic acceleration greater than or equal to 0.6 mm/sec^2 at 1 AU
2	The HERTS TDM spacecraft conductors shall be deployed ouside of Earth's Magnetosphere region
3	The HERTS TDM spacecraft shall have a mission operational life of 3 years, minimum
4	The HERTS TDM spacecraft shall have the capability to steer
5	The HERTS TDM spacecraft shall be packaged within a 12U volume
6	The HERTS TDM spacecraft shall have a mass less than 24 kg
7	The HERTS TDM spacecraft conducter maximum voltage shall be 6 kV
8	The HERTS TDM spacecraft shall use the Deep Space Network to communicate
9	The HERTS TDM spacecraft shall use the natural environments as spec'ed for the NEAScout Mission
10	The HERTS TDM spacecraft shall be able to perform a propulsion system diagnostics
12	The HERTS TDM spacecraft shall have the capability to take high speed video of tether deployment
13	The HERTS TDM spacecraft shall use NEA Scout Mission heritage components (avionics, GN&C, etc.)

HERTS Tether Material Trade Space



	Spider Silk	Silk Worm	Zylon (Fiber Line)	Kevlar	Nomex	Nylon (Not Carbon Composite)	Amberstrand	Carbon Nanotube Miralon	Silver	Aluminum Wire (2 mm)	Aluminum Helsinki	Copper	YES 2 Dyneema	Graphene (composite or coating)	Stainless Steel
Tensile Strength (MPa)	1052	500	5900	3000	≈100	900	4067	530	170	276	≈14.55	70	3600	130000	1500
Density (g/cm^3)	1.31	1.3	1.54	1.44	1	1.15	Varies	0.54	10.49	2.7	2.7	8.96	0.99	N/A	8.05
Weight of 16 km (g)	658.477	653.451	774.088	723.822	502.654	578.0526	960	22.4	5272.845	1357.167	176*	4503.78	497.6279	N/A	4046.37
UV Degradation	YES	YES	YES	YES	NO*	YES	NO	NO	YES	NO	NO	NO	NO	NO	NO
Conductivity (1/Ω*m)	N/A	N/A	N/A	N/A	N/A	1.00E-11	yes**	1.00E+04	6.29E+07	3.50E+07	3.50E+07	6.00E+07	1.00E-12	1.00E+08	1.45E+06
Voltage Drop (V)	N/A	N/A	N/A	N/A	N/A	4.24E+20	N/A	2.43E+03	6.74E+01	1.16E+02	1.21E+02	7.35E+01	4.24E+21	4.24E+01	2.93E+03
Operating Temp. (K)	293-330	293-330	TBD	253-573	700	253-423	Space Rated	3000	700	80-673	80-673	900	500	2000	873
Emissivity		0.72				0.85			0.02	0.03	0.03	0.04			0.075
Absoptivity									-	0.09	0.09	0.65			-

The tether design required is key to mission success. Therefore the team developed an overall tether trade tree to justify our down-selections of materials