Electric Sail Propulsion to Enable Quick Heliopause and Beyond Missions of Scientific Discovery

NASA

NIAC
NASA Innovative Advanced Concepts

Presentation to:
NASA NIAC Symposium
August 23, 2016

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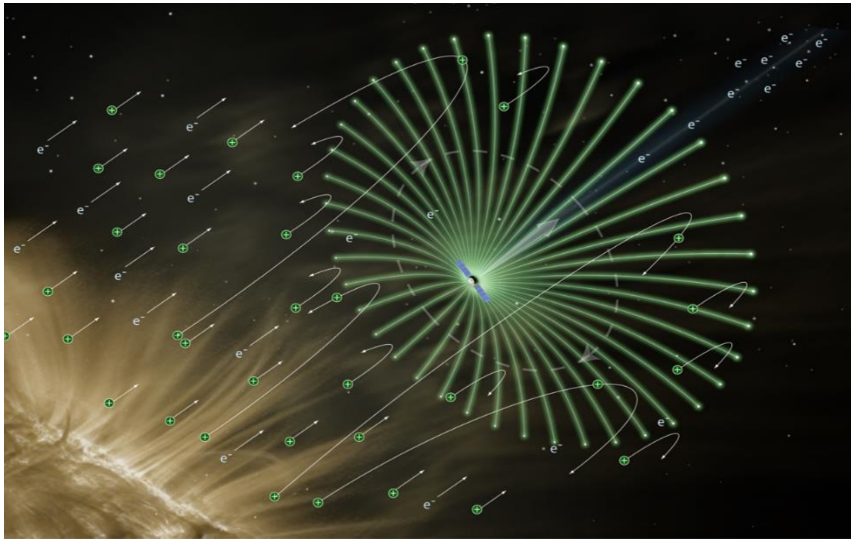
Presentation Agenda

- HERTS/Electric Sail background information
- Phase II NIAC tasks
  - Particle-in-cell (PIC) space plasma to spacecraft Modeling
  - Plasma chamber testing
  - Low thrust trajectory model enhancements
  - Tether material investigation
  - Conceptual spacecraft design
- Future activity
  - STMD sub-orbital rideshare
  - 2017 MSFC TIP
  - AU ME senior design project
  - ARM deep space cubesat BAA



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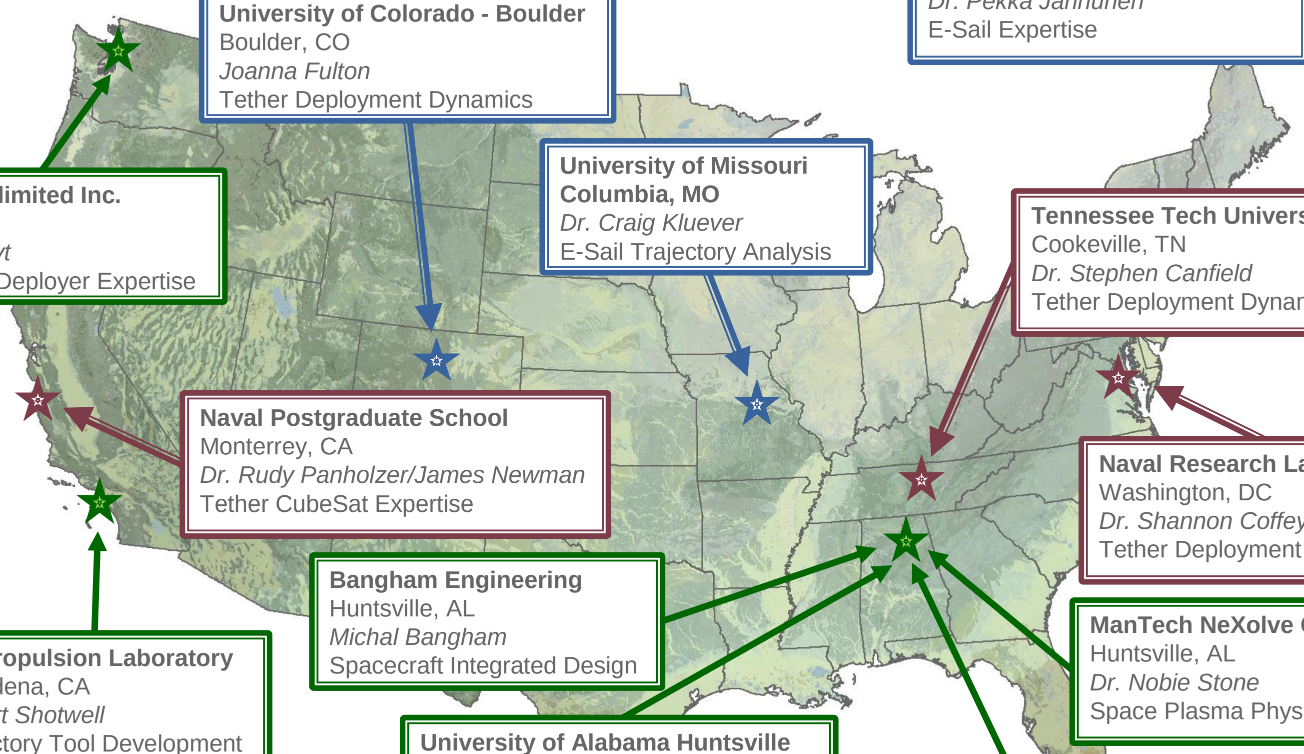
The Phase II HERTS Team



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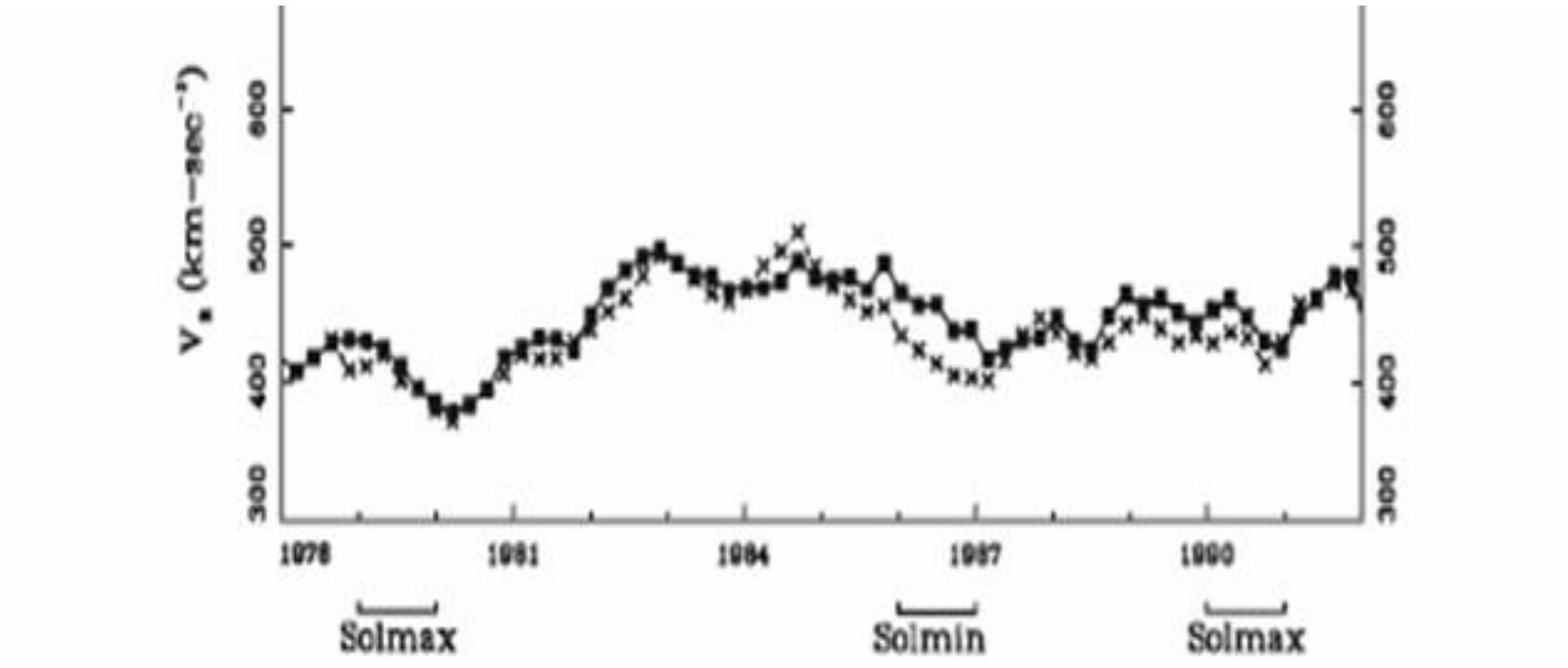
Plasma Chamber Testing

Funded Team Members

Unfunded Collaborators

Future Partners

Solar Wind Basics-> Solar Sail

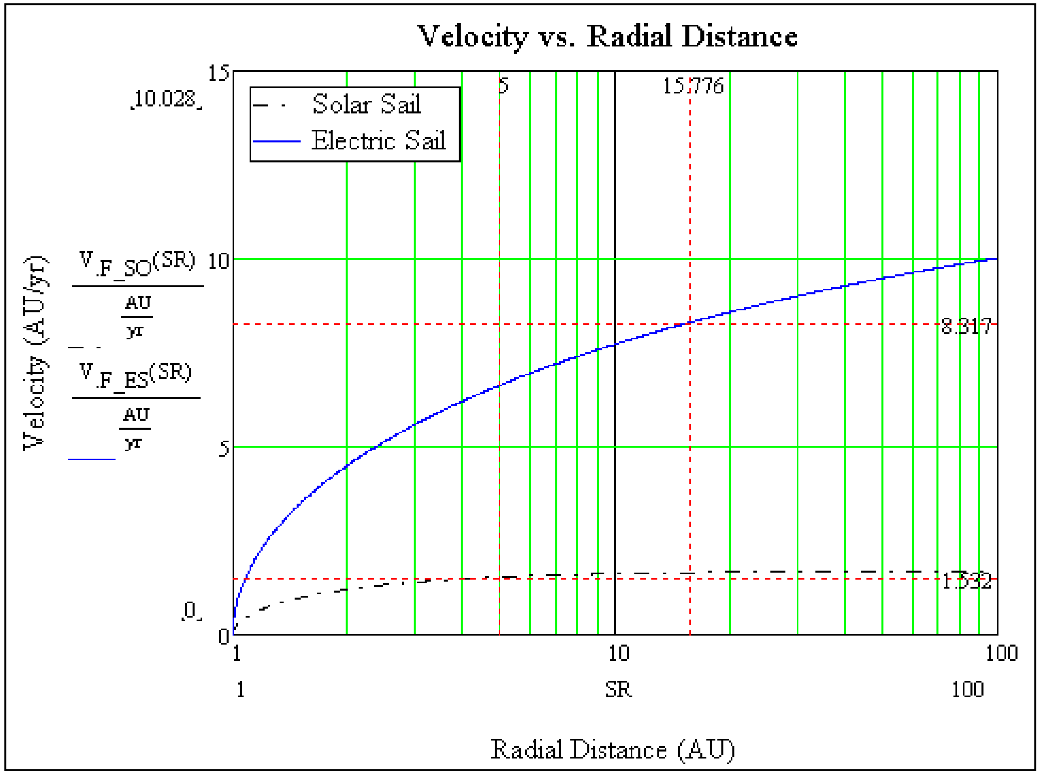


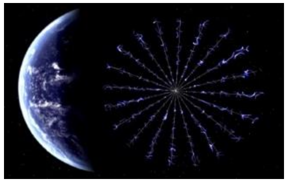
- **The relative velocity of the Solar Wind through the decades**

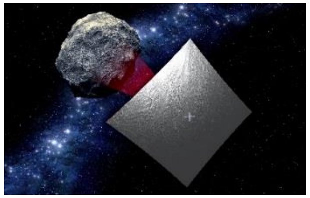
The solar wind ions traveling at 400-500 km/sec are the naturally occurring (free) energy source that propels an E-Sail

Velocity vs. Radial Distance Comparison for Equal Mass Spacecraft

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

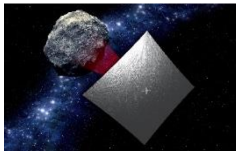


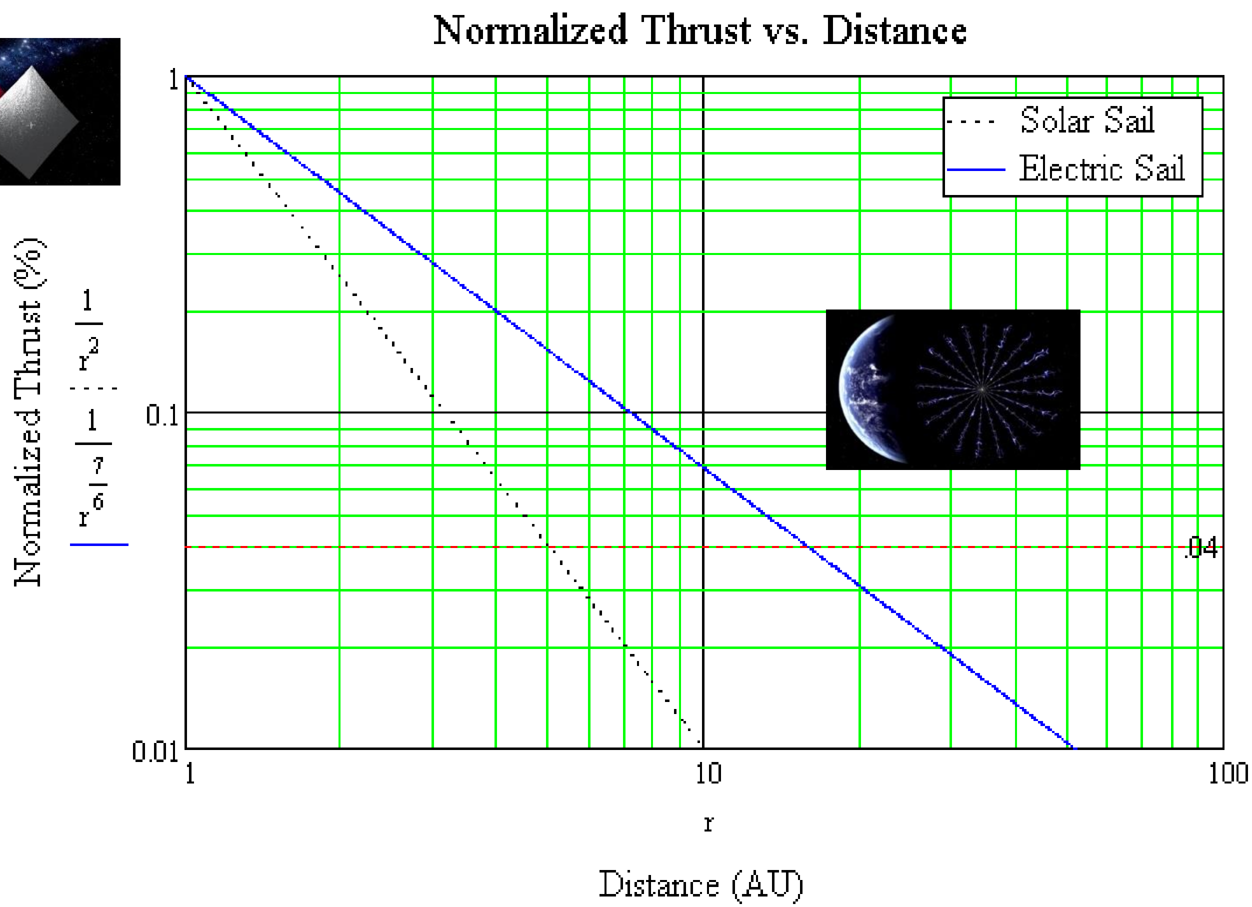




The solar sail system velocity is limited to 1.5 AU/year since the system stops accelerating at distance of 5 AU: whereas,
The E-Sail accelerates to 15.8 AU, thereby creating a velocity of 8.3 AU/year

Normalized Thrust Decay Comparison





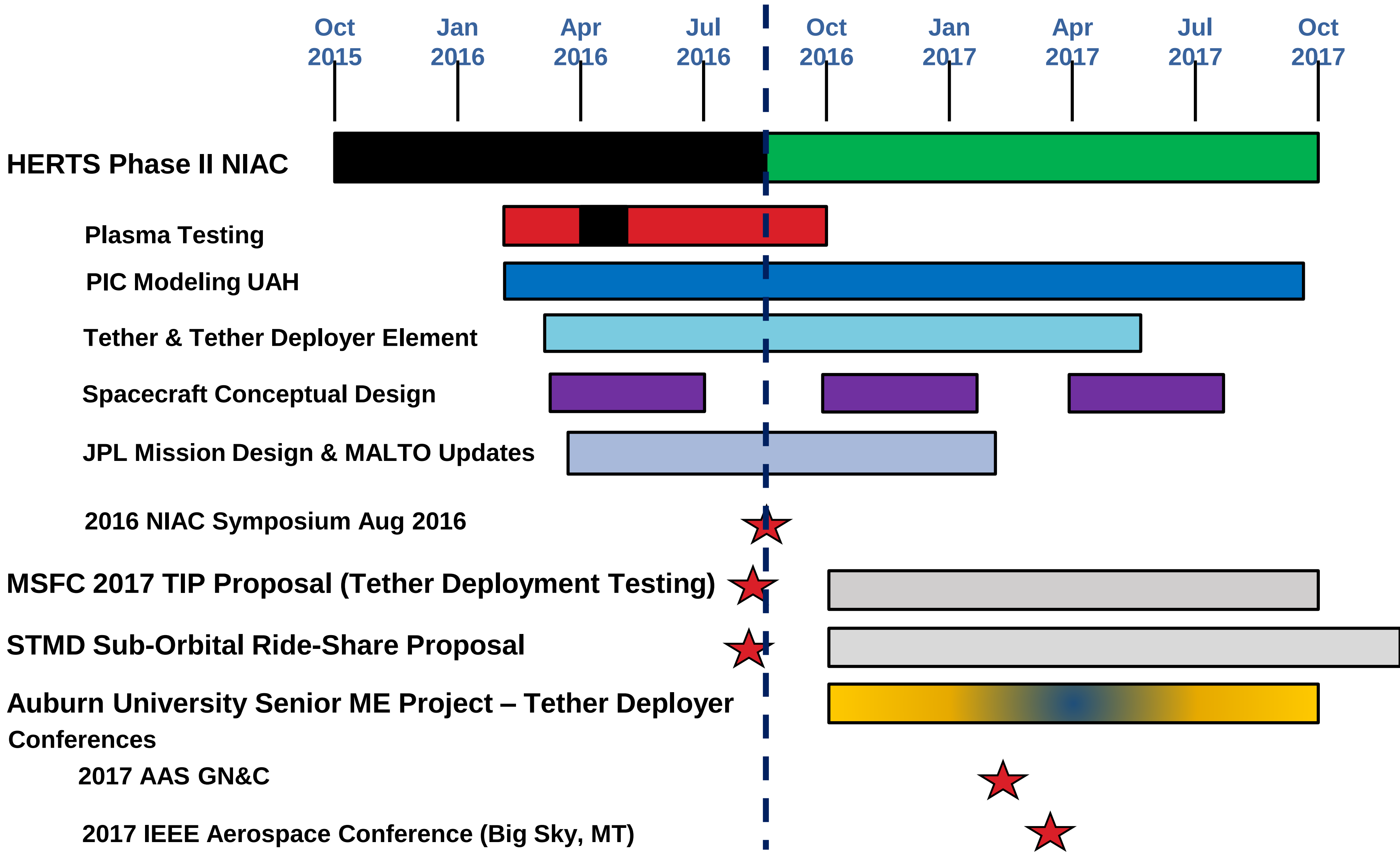
The AU distance where the thrust generated by each system = 0.04 * Thrust $_{(1AU)}$ is 5AU for the solar sail system and 15.8 AU for the E-Sail system

Major Thrusts of HERTS Phase II NIAC

NASA Innovative Advanced Concepts

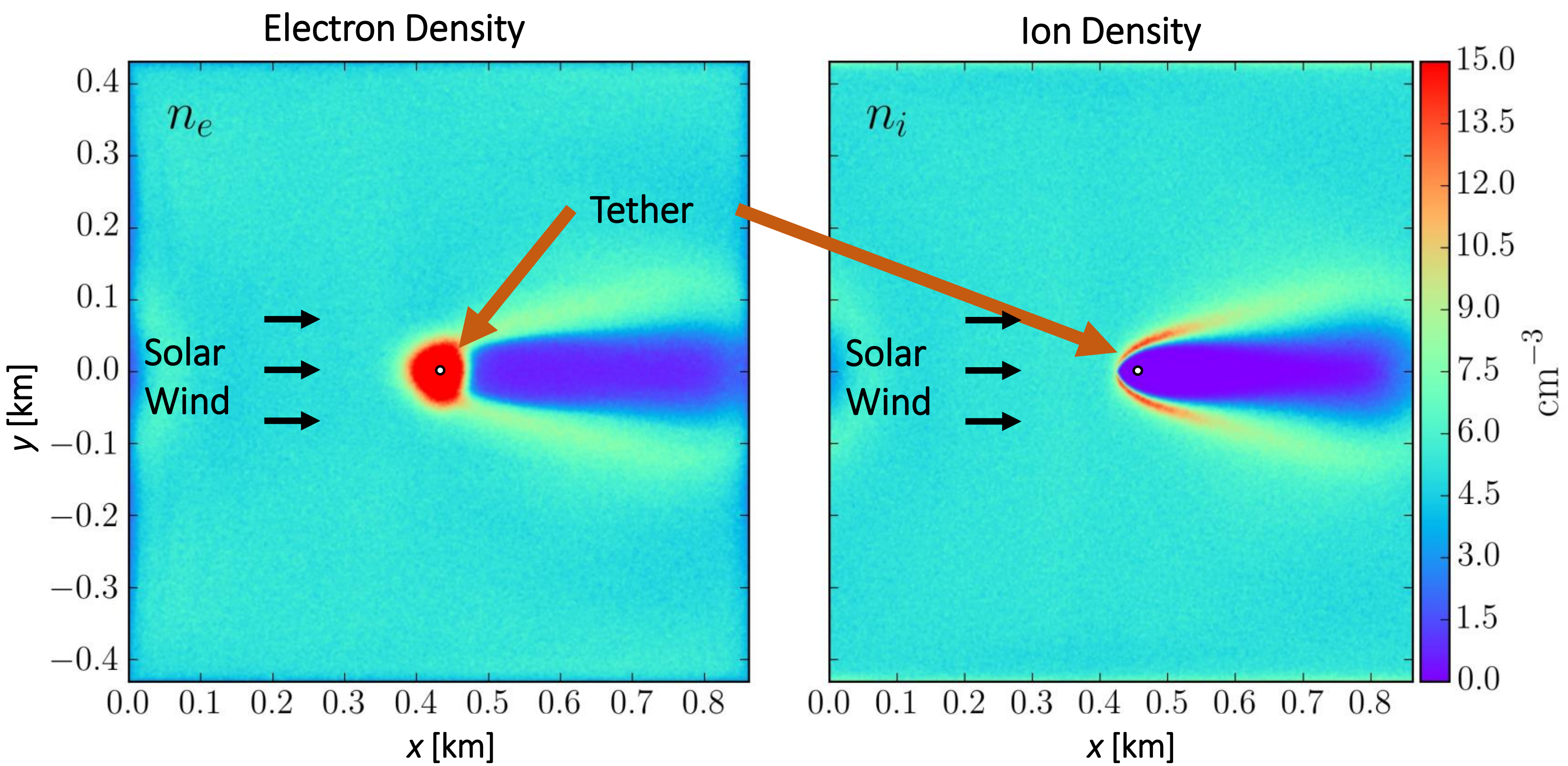
- Develop a particle-in-cell (PIC) model of the space plasma dynamics and interaction with a spacecraft propelled by an electric sail
  - The development of the model requires experimental data from ground tests (MSFC plasma chamber)
- Investigate tether material and deployment
- Perform a conceptual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

Phase II HERTS NIAC Schedule



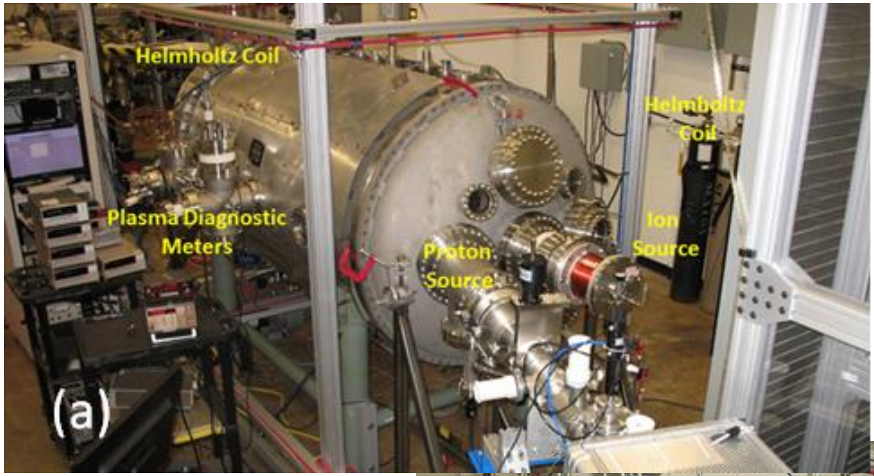
Particle-in-Cell Modeling

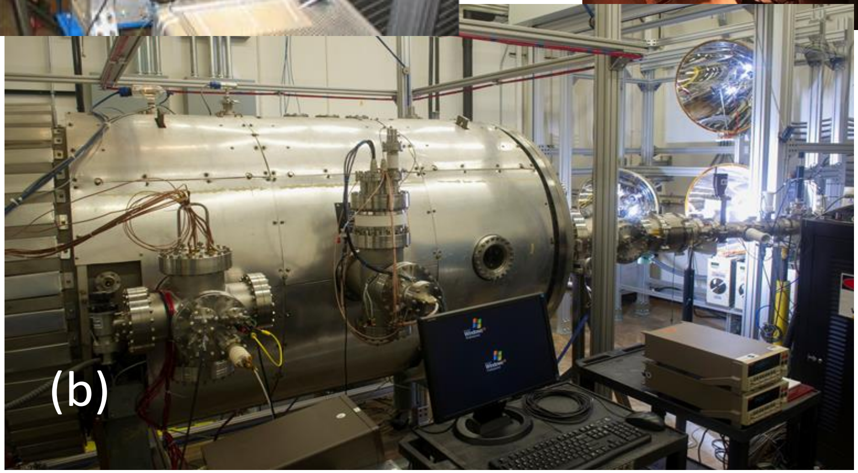
- Simulation of solar wind particles near a charged wire using the LANL VPIC code



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

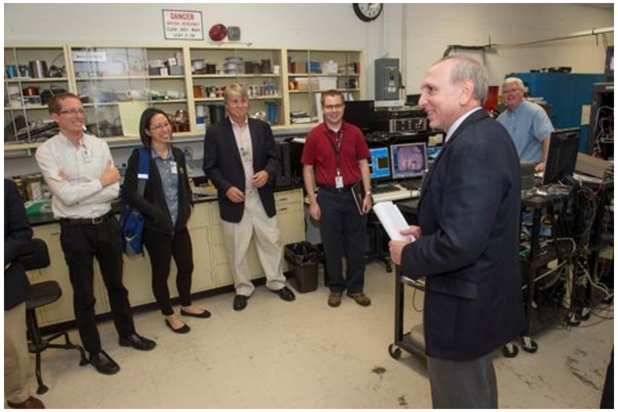
E-Sail Plasma Physics Testing

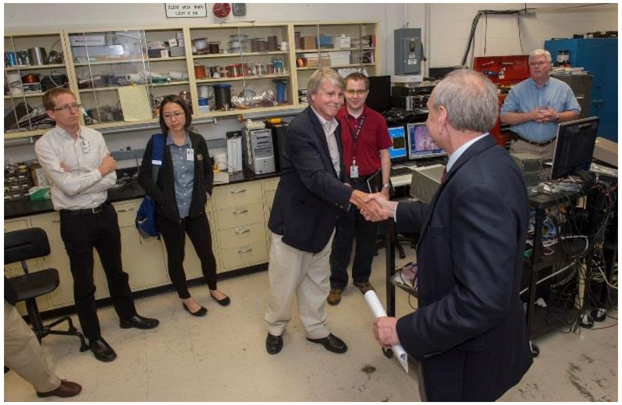




Marshall has a unique history and knowledge base related to plasma experimentation and applications to space tethers.

Briefing to STMD Associate Administrator

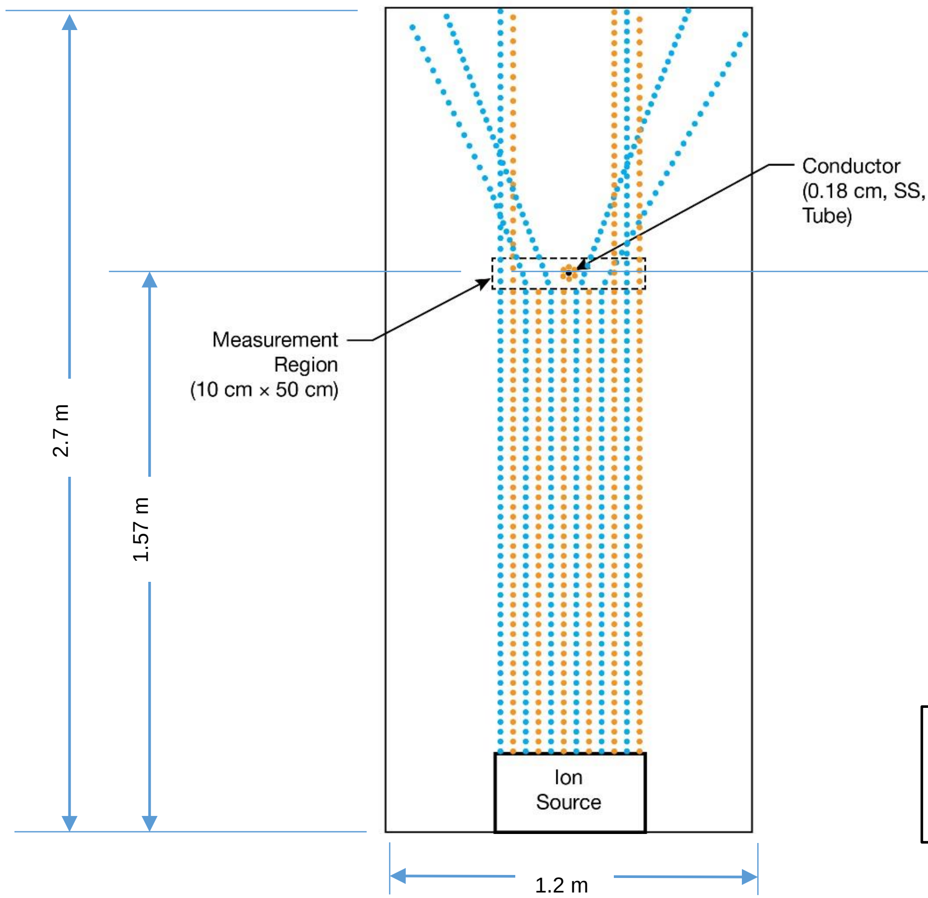




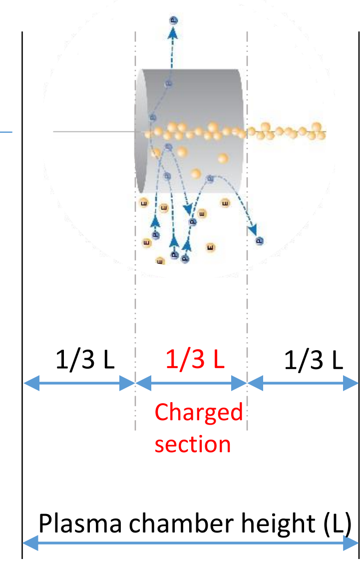
The MSFC HERTS team had an opportunity to brief the NASA STMD Director (Mr. Jurczyk) on July 19, 2016

Plasma Chamber Testing

MSFC Plasma Chamber
(Top View)



(Side View)

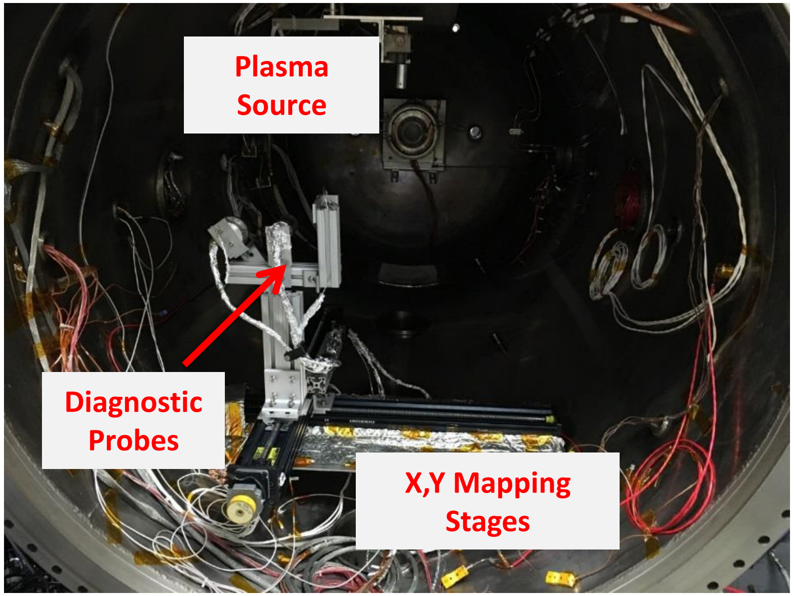


The middle third of the SS tube is positively charged and a sheath is created that deflects protons. Then measurements are made to determine degree of deflection of these protons

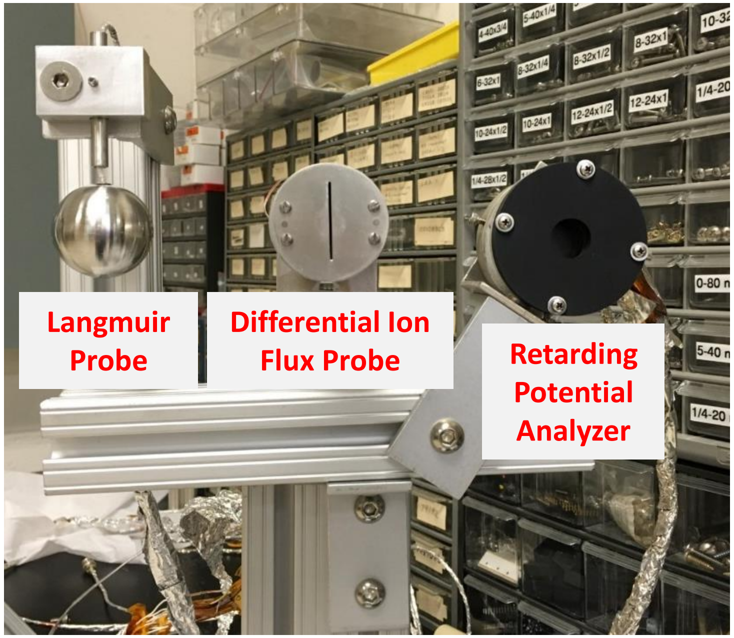
Charged ions (protons and electrons) flow from the ion source towards the end of the chamber.
Electrons are collected onto the positively charged wire & the current is measured.
Protons are deflected by the charged Debye sheath

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



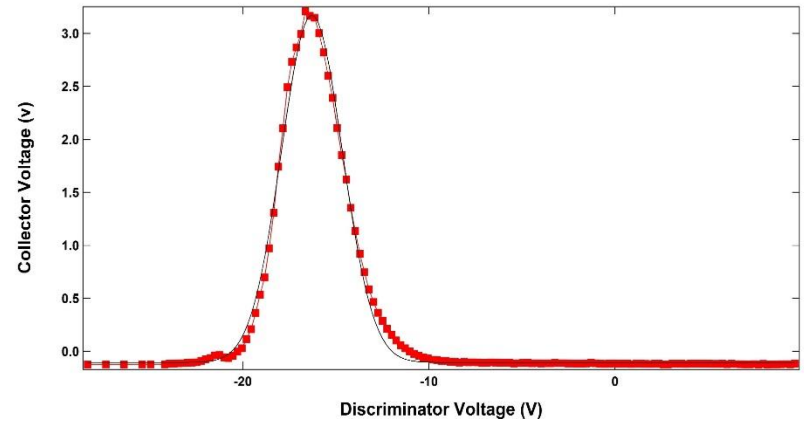
X-Y Stage to Map Measurement Region



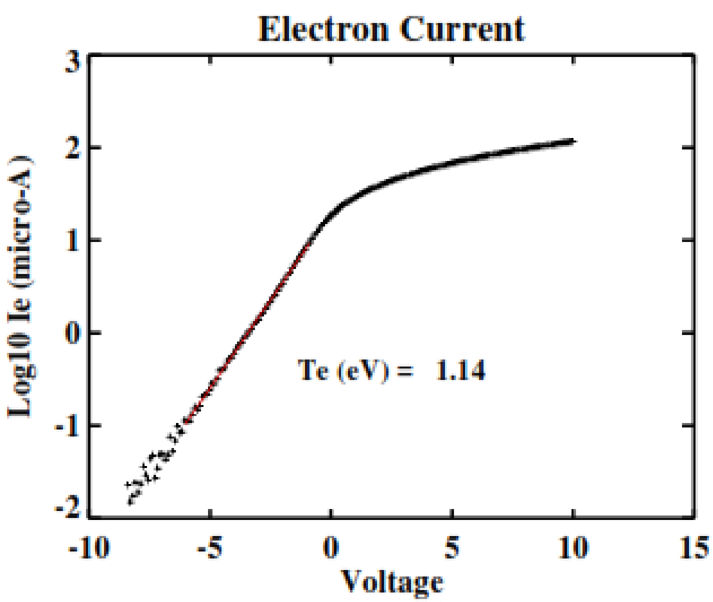
Diagnostic Probe Suite

A Sample of Plasma Chamber Data

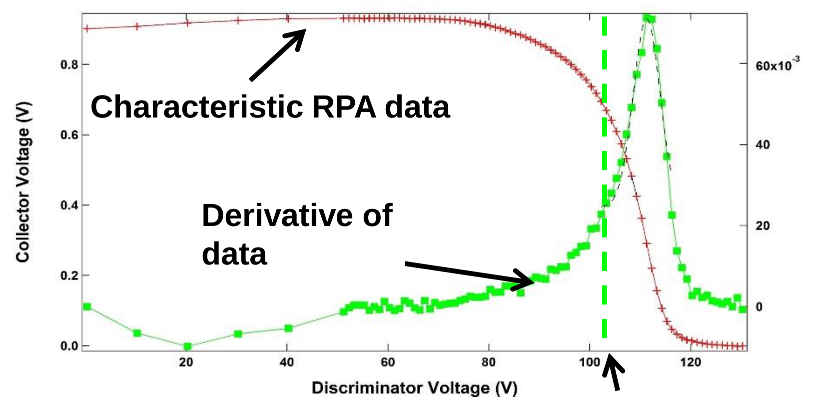
- Chamber calibration underway with new ion source
- E-Sail wire being installed



Differential Ion Flux Probe Data



Langmuir Probe Data



Retarding Potential Analyzer Data

Ion Beam Energy

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

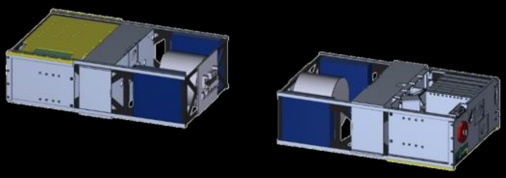
- **MALTO (Mission Analysis Low Thrust Optimization)** is the go-to NASA preliminary mission design tool for electric propulsion ion engines and solar sails. MALTO was critical to the mission design of DAWN (ion engines) and is currently being used to design the NEA Scout mission (solar sail) and the 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?

- 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 TDM 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)

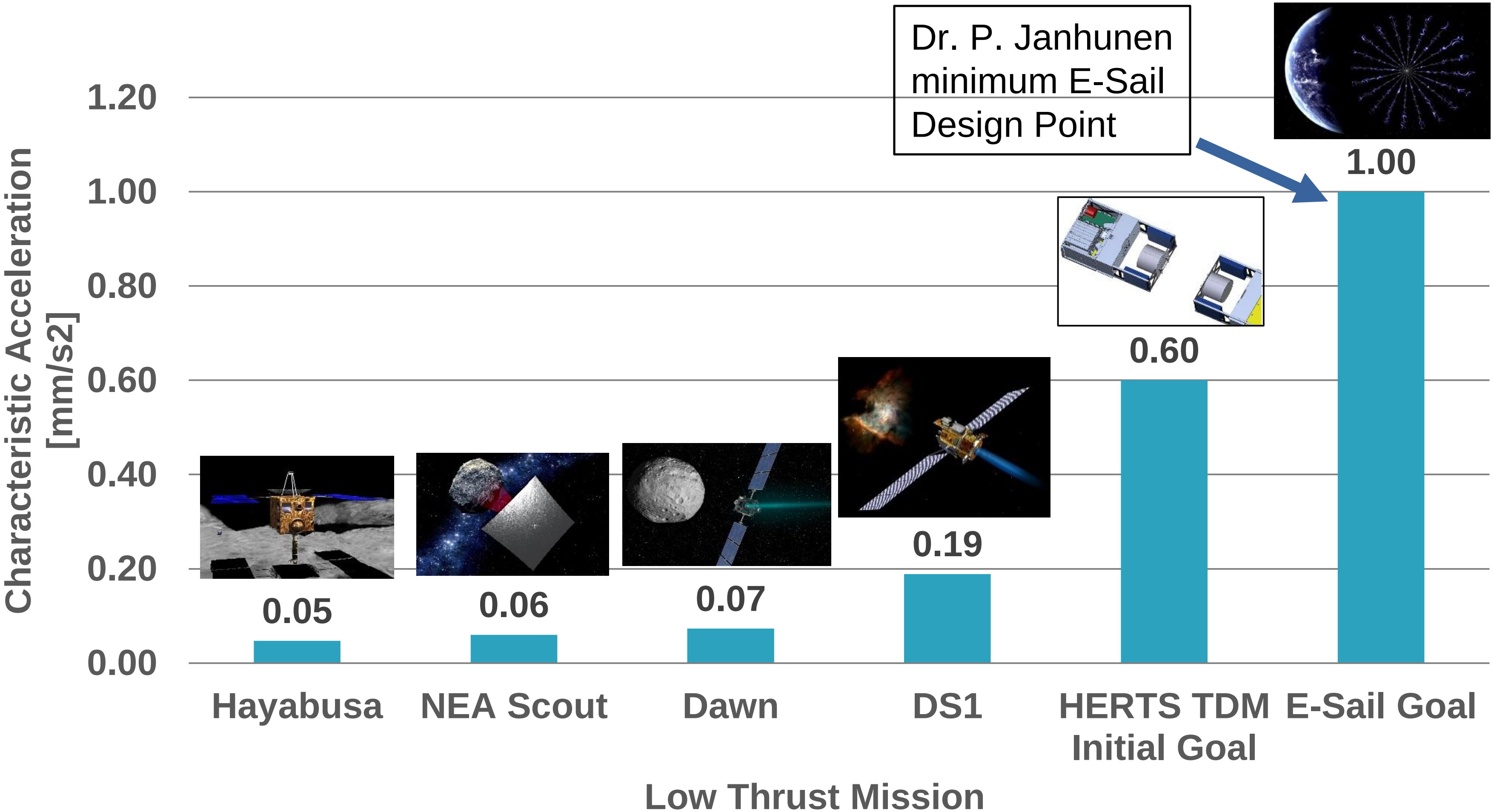
- Primary goals of mission:
  - To develop a CubeSat that can do the following (**DAS**):
    - **D**eploy a 16,000 m conductive tether
    - **A**ccelerate the spacecraft, &
    - **S**teer

- Secondary goals of mission:
  - Collect meaningful science data

The Objectives of the HERTS TDM Spacecraft 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)

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 that of a 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

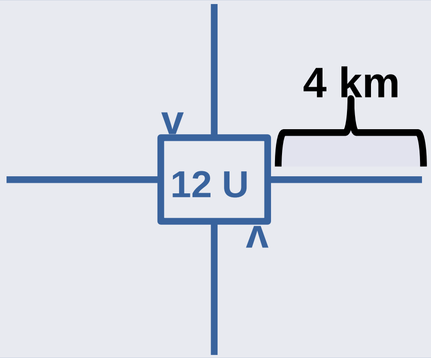
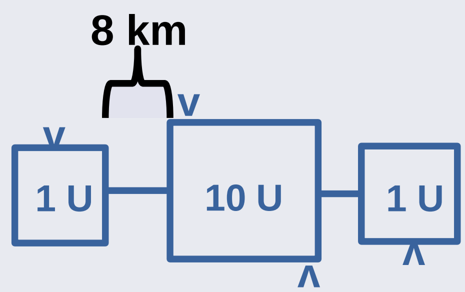
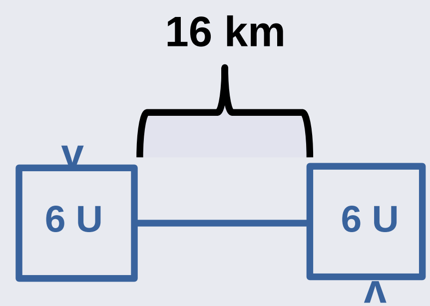
Initial Thrust Acceleration (mm/s^2)	Final Inclination (deg)
0.12	8.1
0.18	12.5
0.24	17.0
0.30	22.0
0.45	37.0
0.60	50.1

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

The Key Driving Requirements of a HERTS TDM

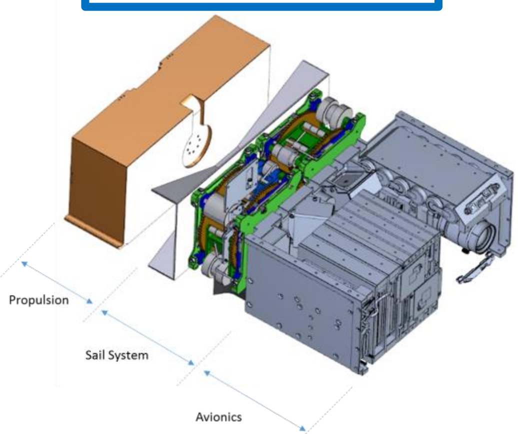
Key Driving Requirements (KDRs) of the HERTS TDM spacecraft	
1	The HERTS TDM spacecraft shall have a characteristic acceleration greater than or equal to 0.6 mm/sec^2 at 1 AU
2	The HERTS TDM spacecraft conductors shall be deployed ouside of Earth's Magnetosphere region
3	The HERTS TDM spacecraft shall 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.)

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

HERTS TDM Spacecraft Leverages Prior Investments

NEA Scout (6U)



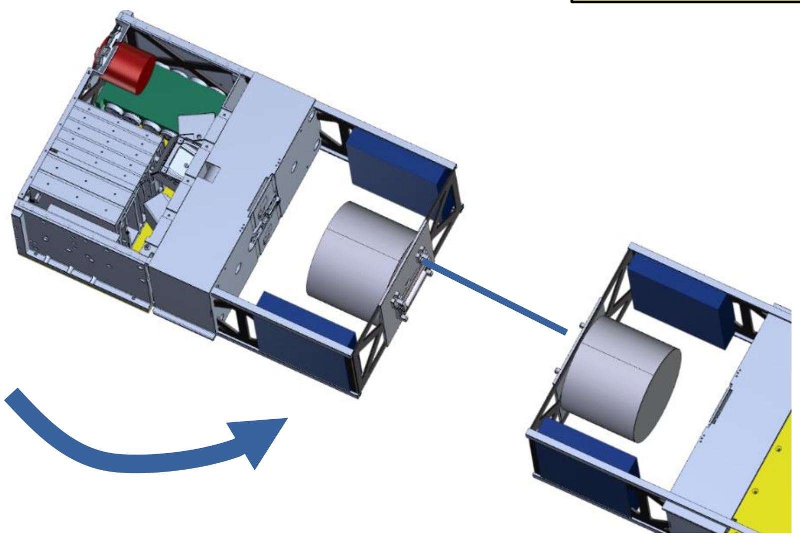
NEAS Components Used

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

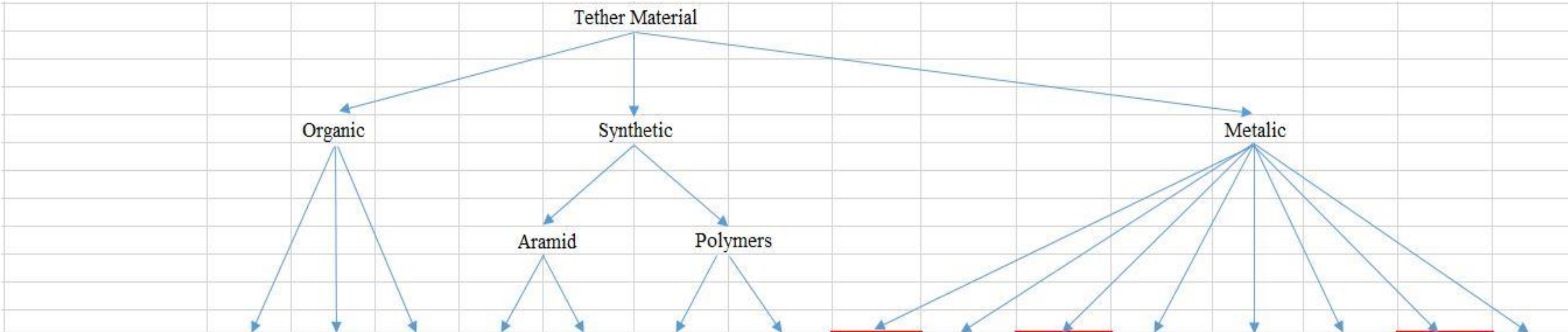
HERTS TDM (12U)

New Components Needed (TRL)

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



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

Down-Selected Tether Material Options for Further Study

NIAC NASA Innovative Advanced Concepts

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

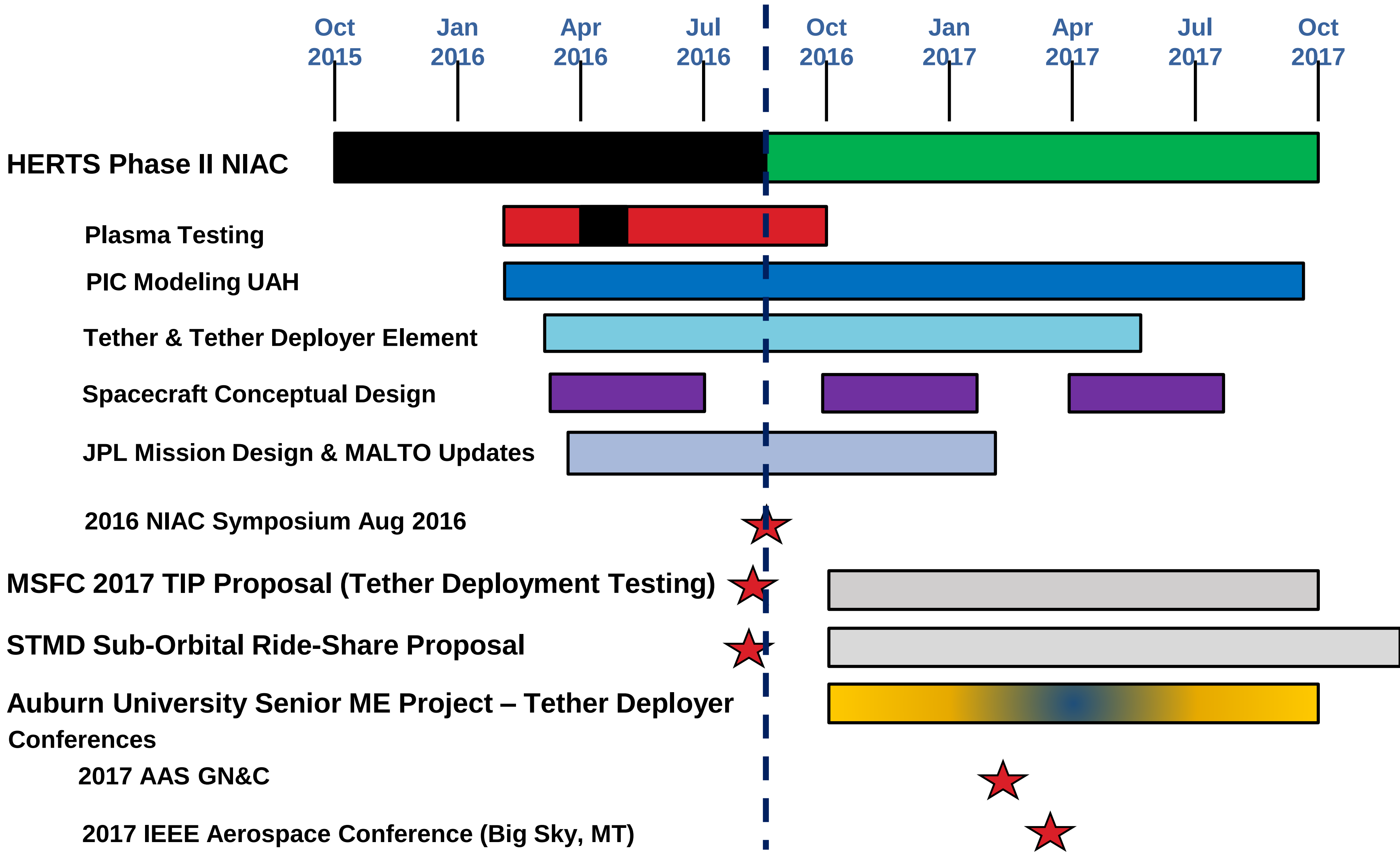
	Miralon (CNT)	Copper	Aluminum	AmberStrand
Mass [kg]	0.60	6.69	2.02	0.99
Tensile Load at Yield [N]	40.72	3.17	12.49	40.48
Voltage Drop [V]	2,431.5	51.1	80.6	902.4

Unquantified figures of merit:

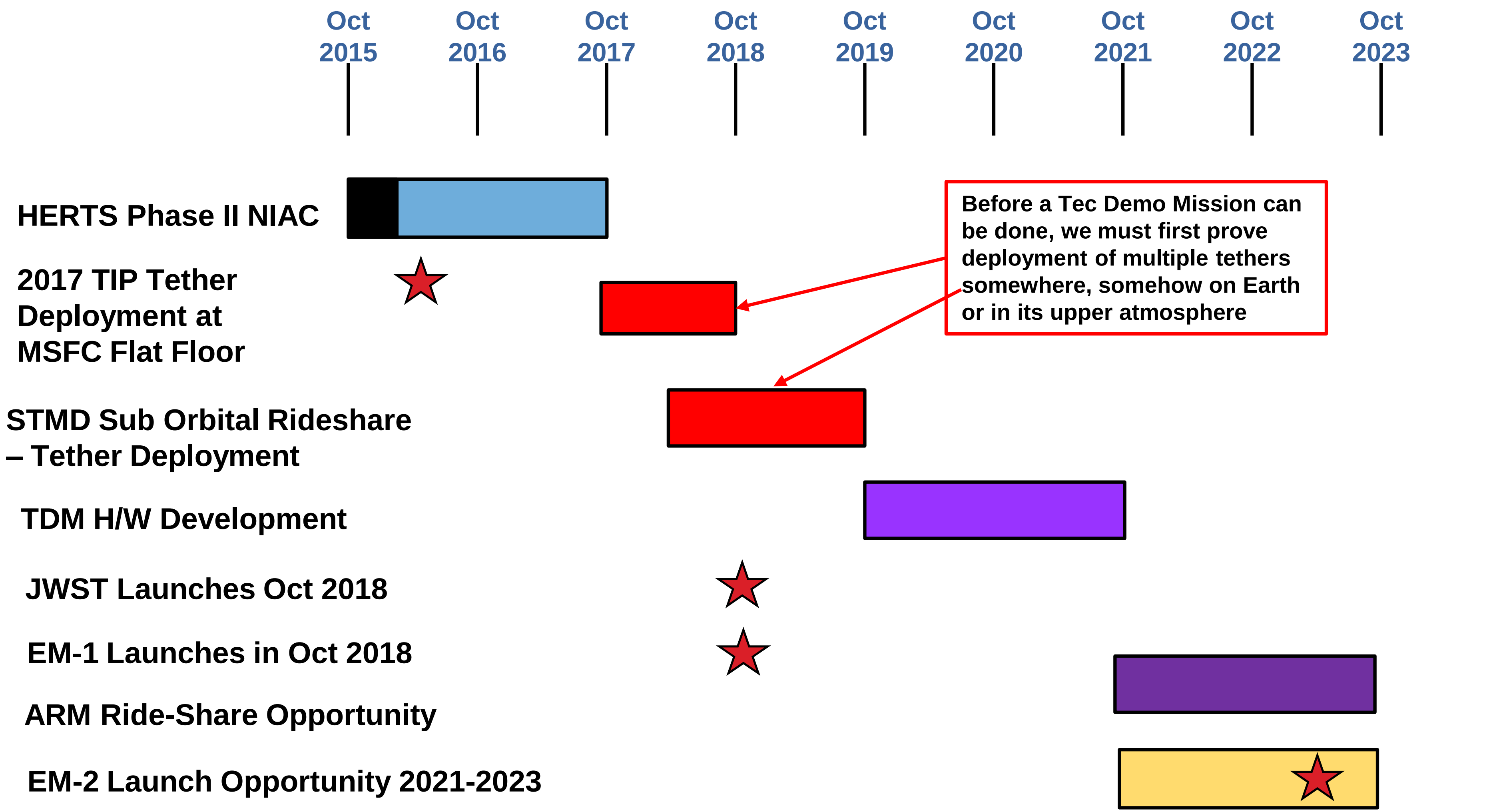
- **UV degradation**
- **Thermal properties**
- **Workability/reliability of material**
- **Deployment friction**

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

Phase II HERTS NIAC Schedule



HERTS Out-Year Schedule



HERTS Team Response to Recent STMD Sub-Orbital Call
Space Tether Deployment Test

Technology Need

There has been no successful multi-km length space tether deployed from a US agency or firm since 1996. For Electric Sails to be implemented, successful deployment of a multi-km length tether must be proven. This sub-orbital test is a cost effective way to prove the deployer.

Technology Concept

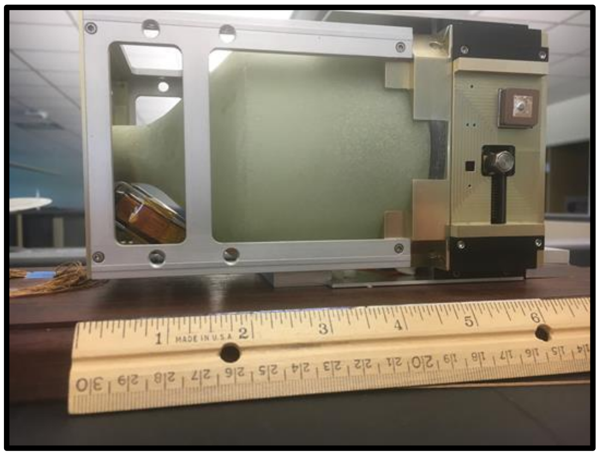
This flight opportunity will provide access to space so a space tether and deployer system can be tested in 0-g

Technology Development Team

The NIAC PHASE II NIAC Heliopause Electrostatic Rapid Transit System (HERTS) team at MSFC including Tethers Unlimited (Dr. Rob Hoyt) and ARC personnel (avionics)

Test Apparatus

The hardware will consist of a tether deployer (Improved version from 2007 NASA STTR experiment (MAST done by Tethers Unlimited), the tether (up to 100 meters and an end mass. Total mass of system 3 kg. Size of system is estimated at 10" long by 4" deep and 4" wide



Flight Requirements/Objectives

One (1) flight of a 80+km with payload ejection at apogee sub orbital flight
Earliest payload would be ready is April 2018

Technology Advancement

Flight will prove tether deployment from enhanced tether deployer. Current TRL is 4/5; Expected TRL at end of flight is 7/8

Technology End Users

NASA HERTS team, World-wide Electric Sail investigators, DOD such as NRL and USAF, and Heliophysics scientists

2.3.2 Electric Sail Propulsion