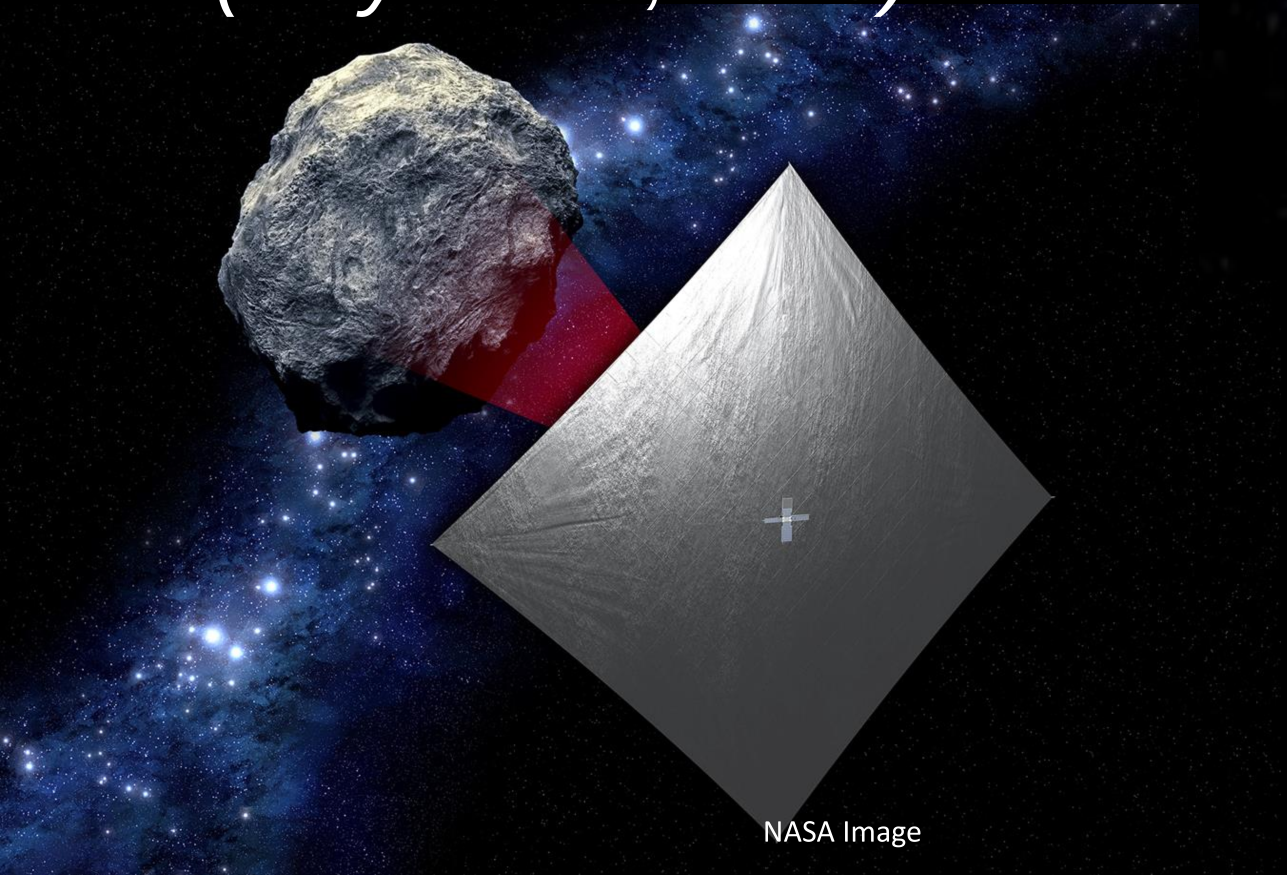
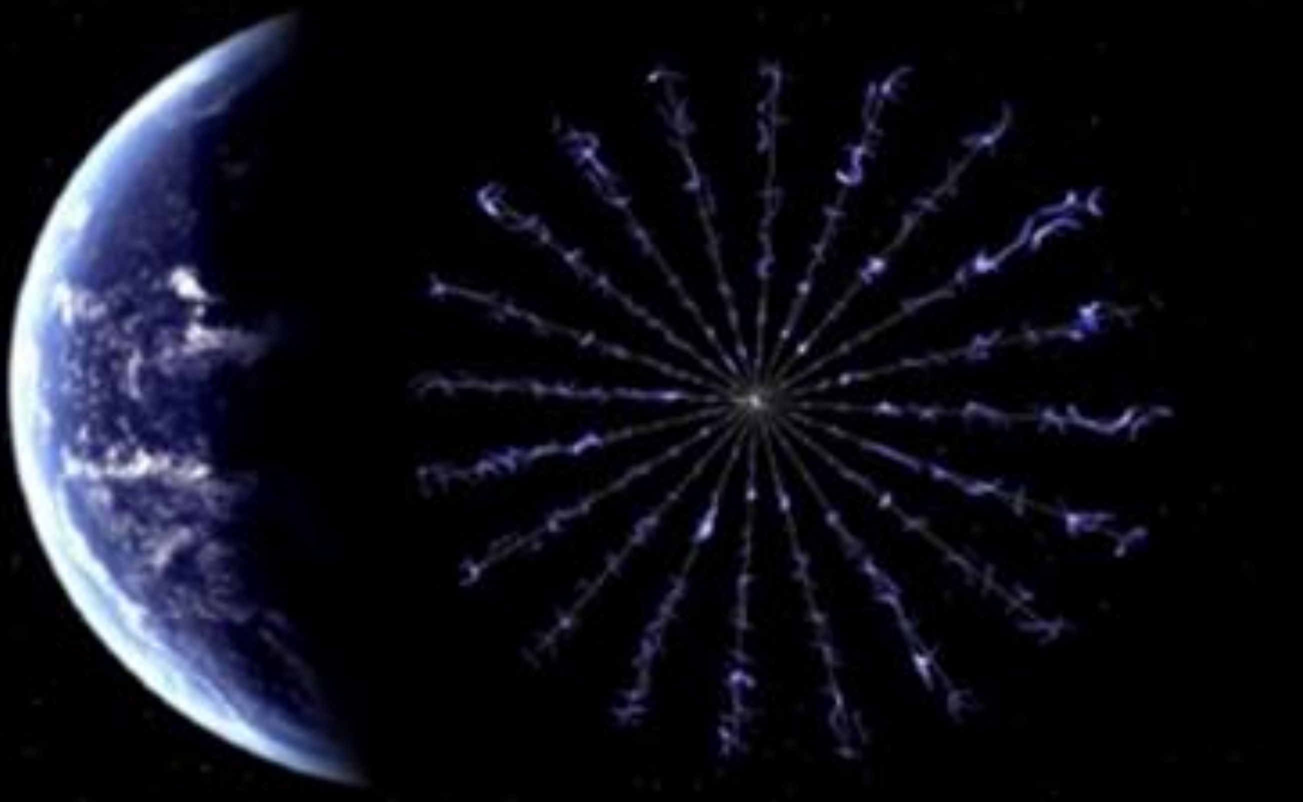
Solar & Electric Sailing Overview

KISS Technology Development Workshop (May 15-18, 2018)



NASA Image



NASA Image

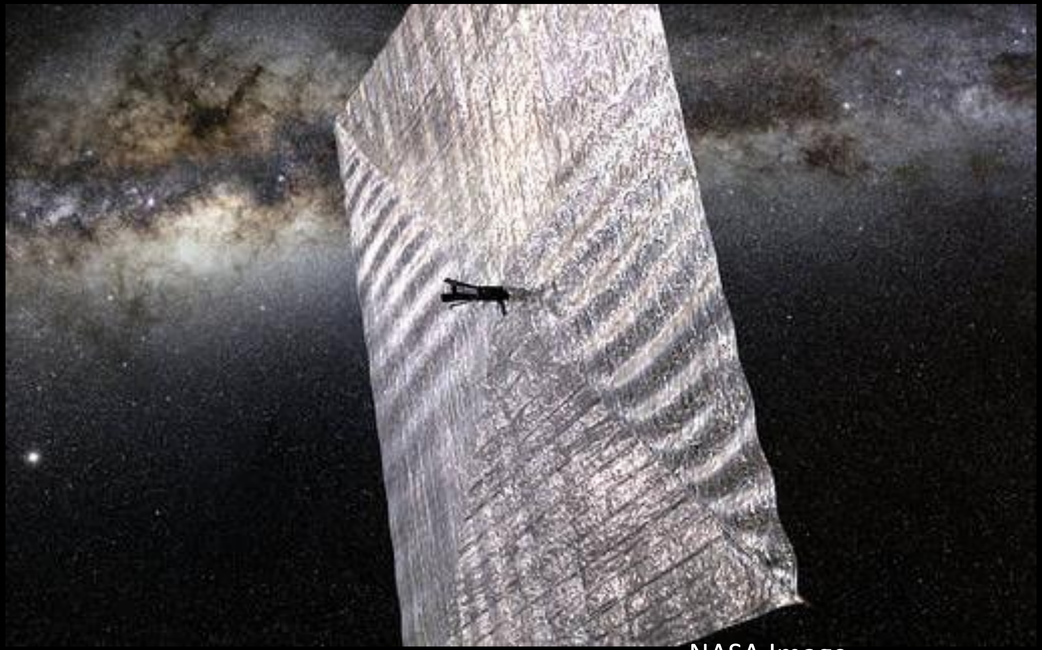
Jared Dervan
NASA/MSFC

Acknowledgments

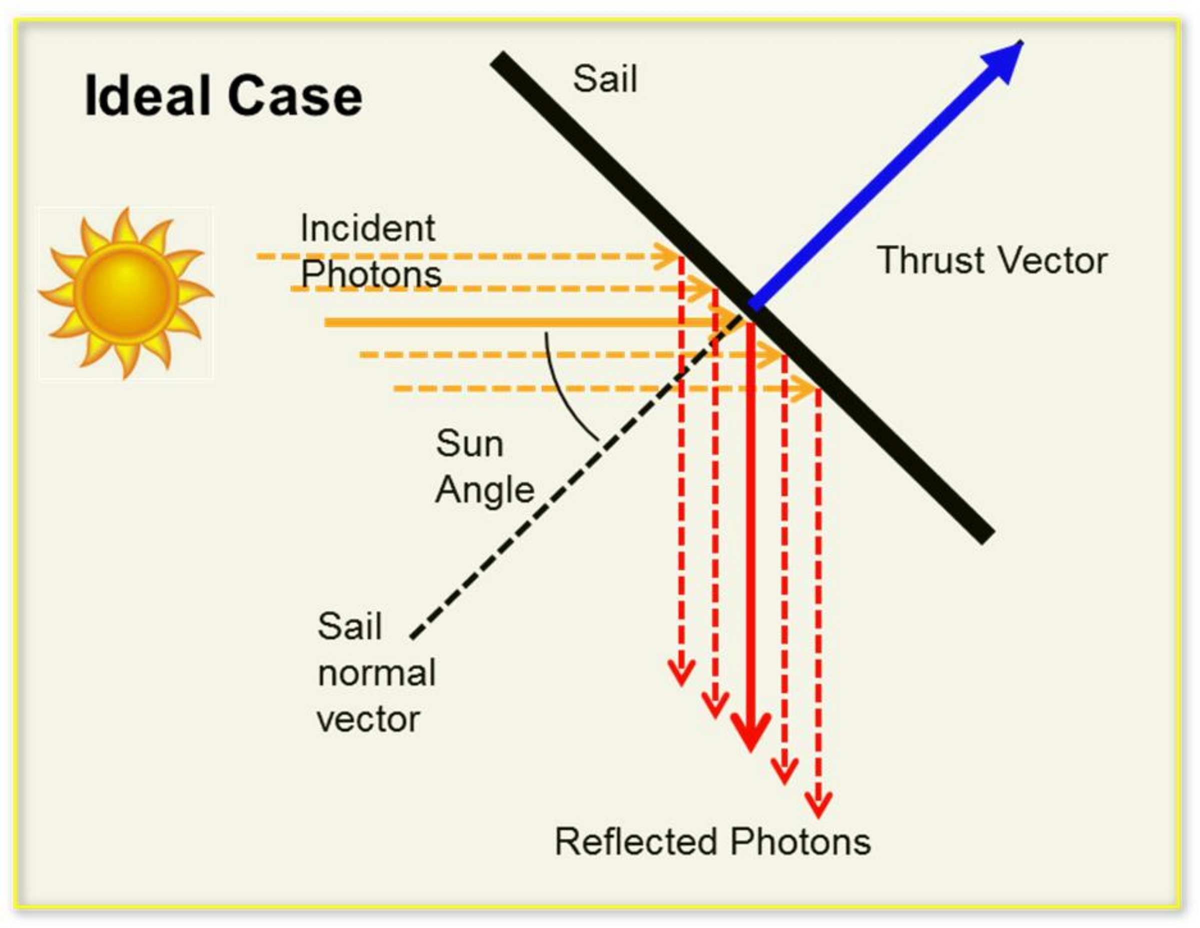
- Les Johnson (MSFC Project Formulation Office)
- Bruce Wiegmann (MSFC Advanced Concepts)
- Tiffany Lockett (MSFC Project Engineering)

Solar Sails Derive Propulsion By Reflecting Photons

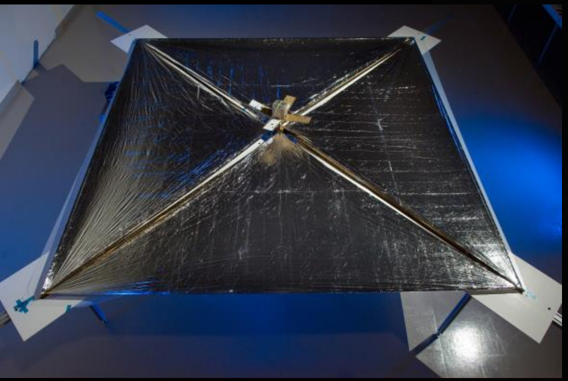
Solar sails use photon "pressure" or force on thin, lightweight, reflective sheets to produce thrust.



NASA Image



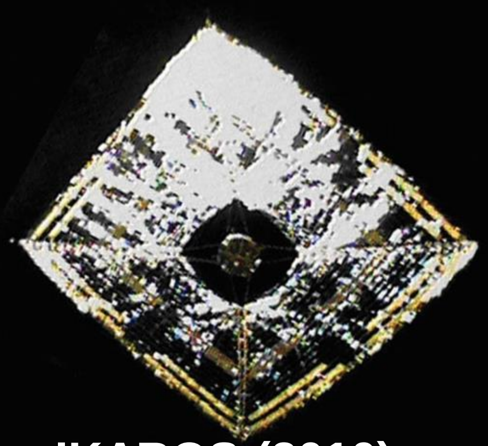
Solar Sail Missions Flown (as of April 11, 2018)



NanoSail-D (2010)
NASA

Earth Orbit
Deployment Only

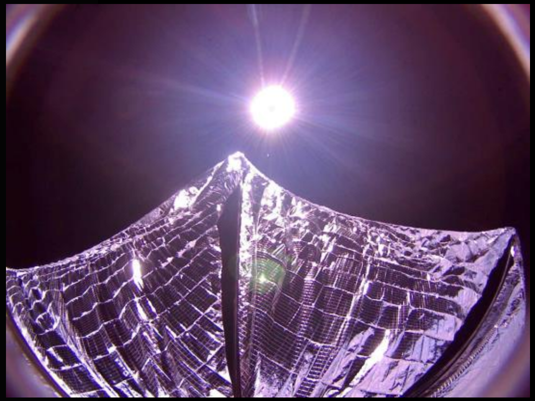
3U CubeSat
10 m^2



IKAROS (2010)
JAXA

Interplanetary
Full Flight

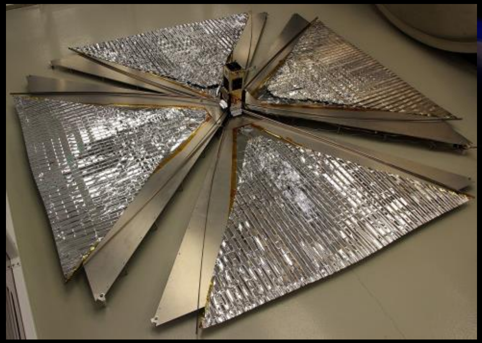
315 kg Smallsat
196 m^2



LightSail-1 (2015)
The Planetary Society

Earth Orbit
Deployment Only

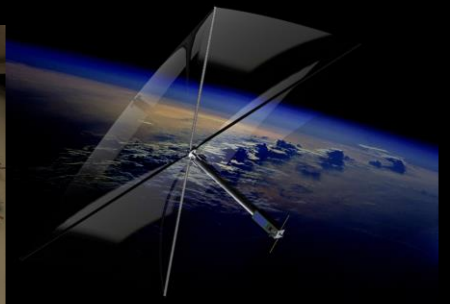
3U CubeSat
32 m^2



CanX-7 (2016)
Canada

Earth Orbit
Deployment Only

3U CubeSat
<10 m^2

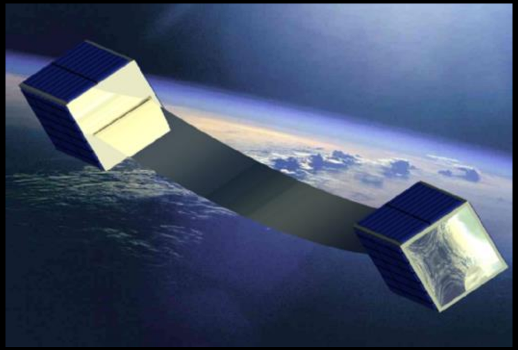


InflateSail (2017)
EU/Univ. of Surrey

Earth Orbit
Deployment Only

3U CubeSat
10 m^2

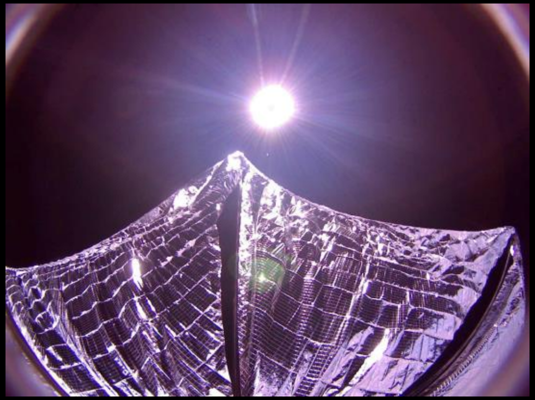
Planned Solar Sail Missions (as of April 11, 2018)



CU Aerospace (2018)
Univ. Illinois / NASA

Earth Orbit
Full Flight

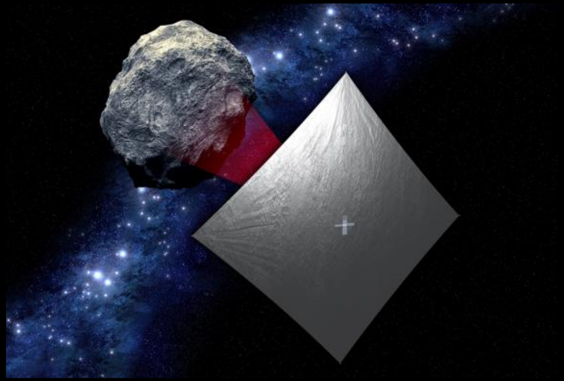
3U CubeSat
20 m^2



LightSail-2 (2018)
The Planetary Society

Earth Orbit
Full Flight

3U CubeSat
32 m^2



Near Earth Asteroid Scout (2019) NASA

Interplanetary
Full Flight

6U CubeSat
86 m^2

NASA’s Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will:

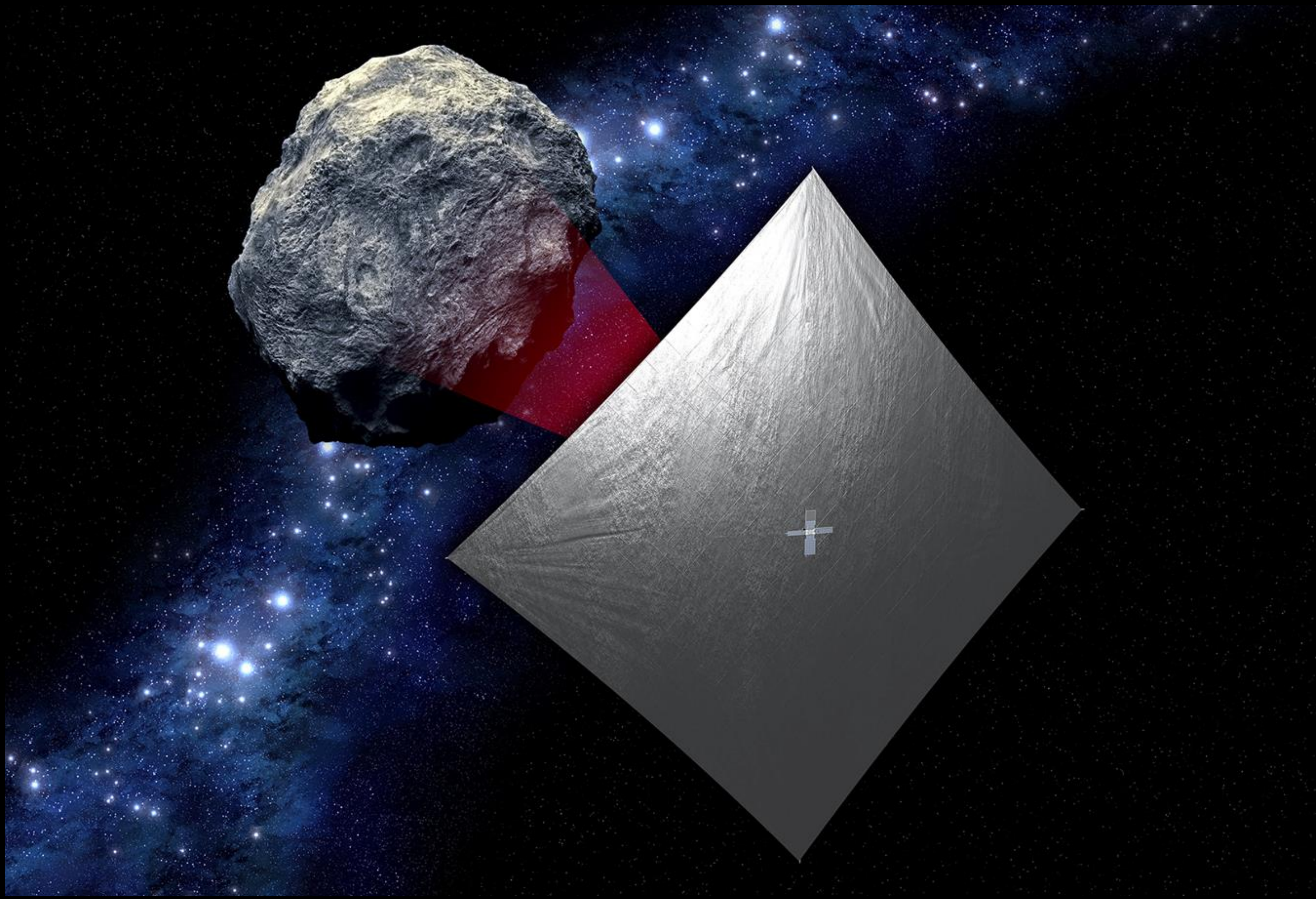
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2019)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

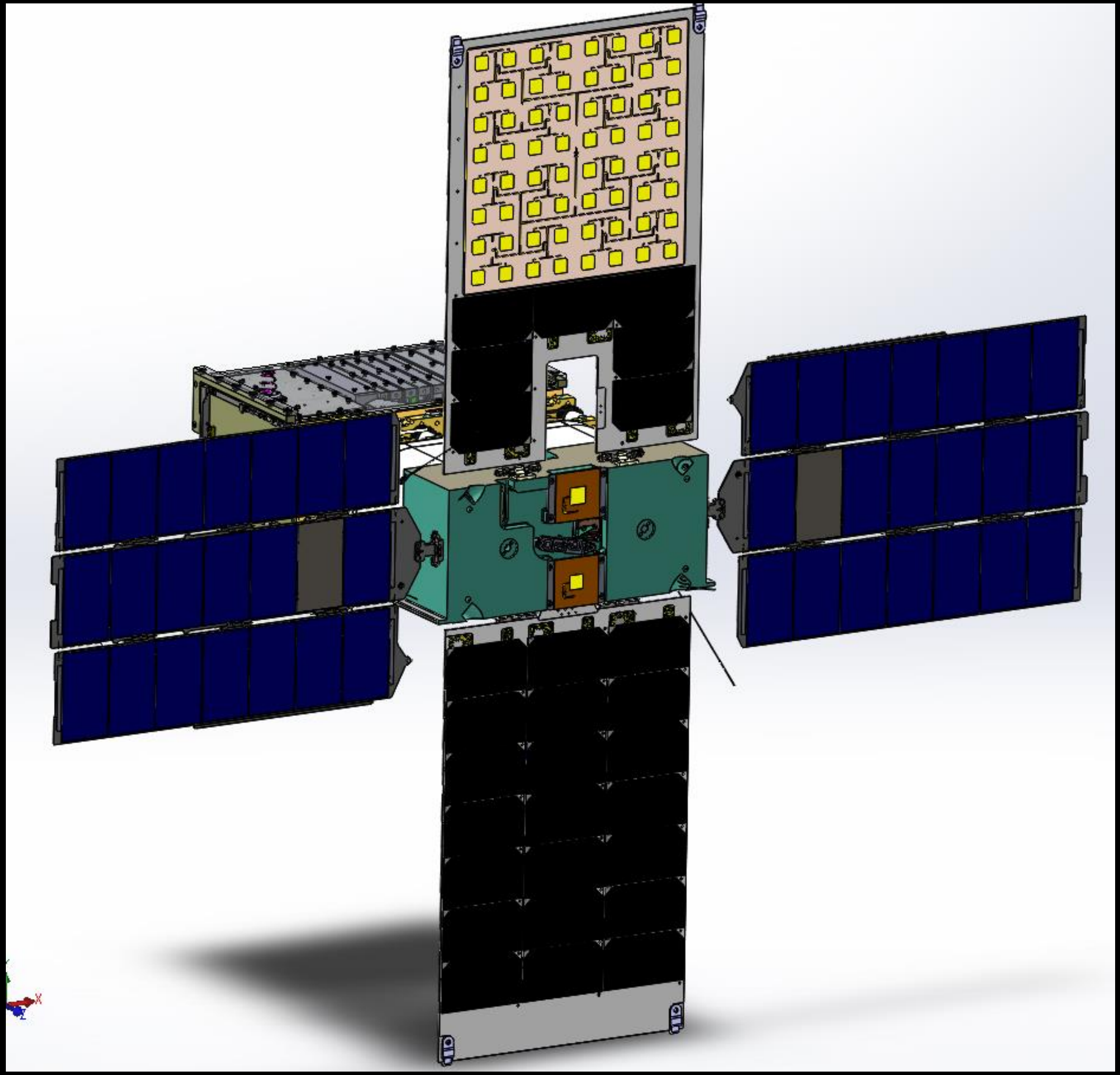
Solar Sail Propulsion System Characteristics

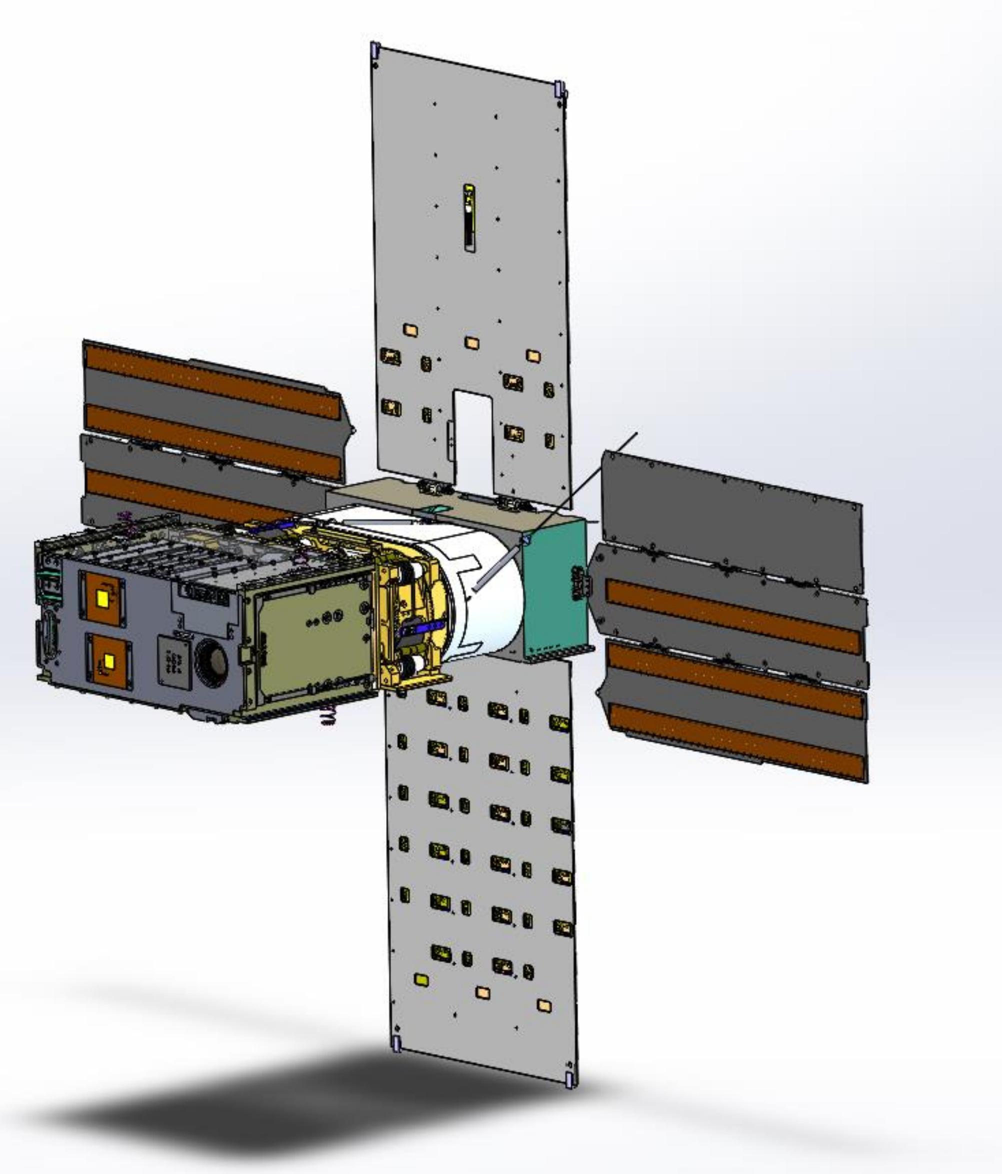
- ~ 7.3 m Trac booms
- 2.5μ aluminized CP-1 substrate
- > 90% reflectivity



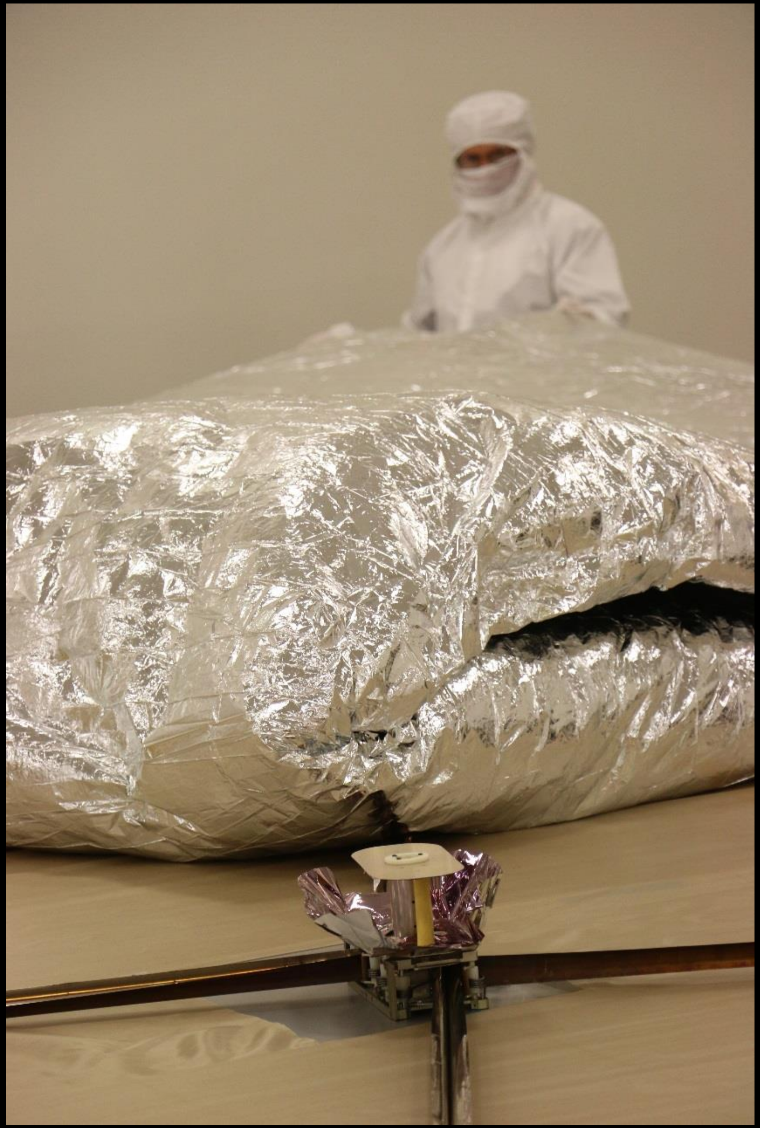
NASA Image

NEA Scout Flight System





NEA Scout Hardware Overview



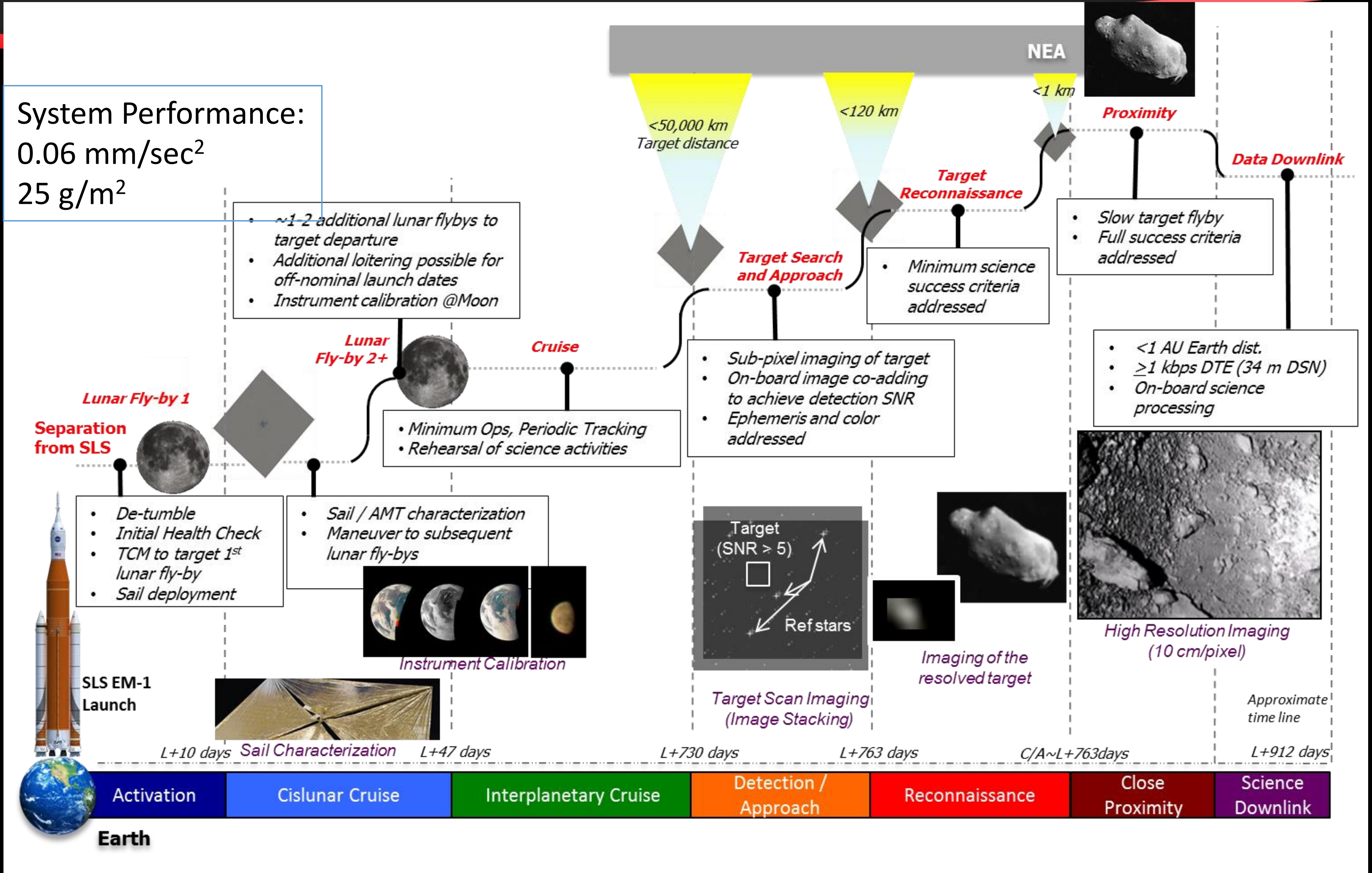
NEA Scout Full Scale Successful Deployment

NASA Image

NEA Scout EDU Full Scale Deployment

NEA Scout – Mission Overview

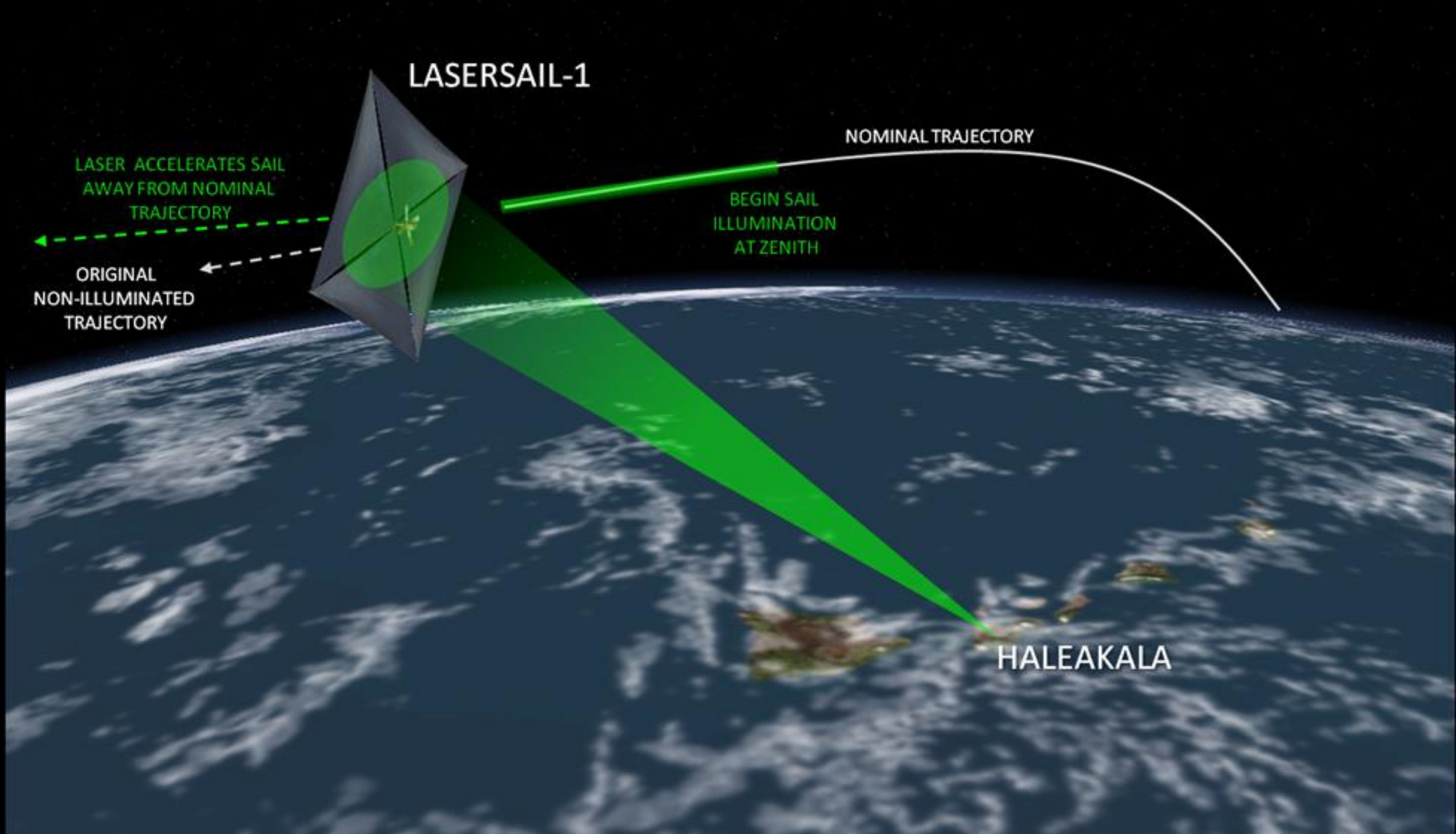
System Performance:
0.06 mm/sec^2
25 g/m^2



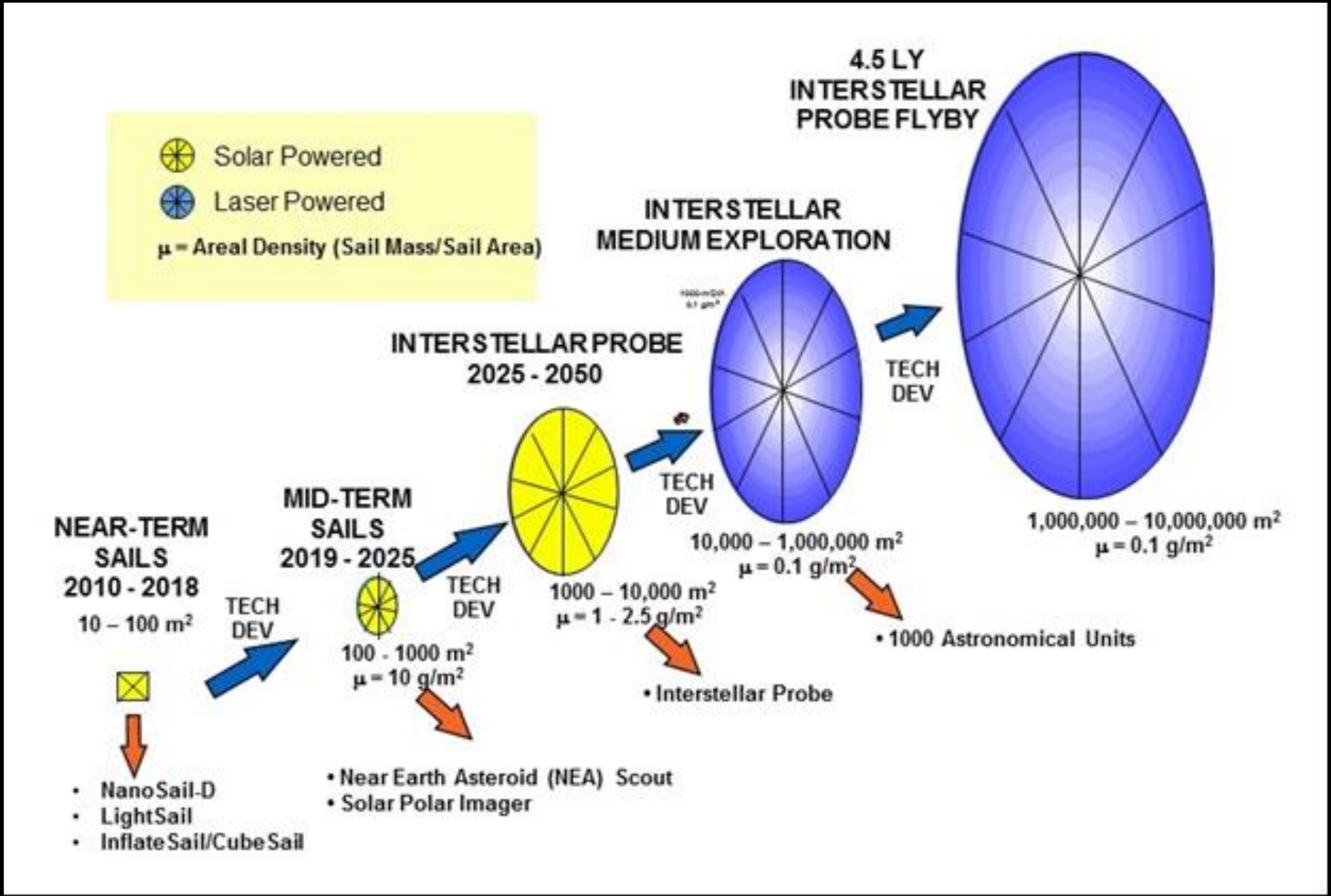
Laser Sailing: The Next **Big** Step

Ground to space laser illumination of a solar sail to impart measurable ΔV

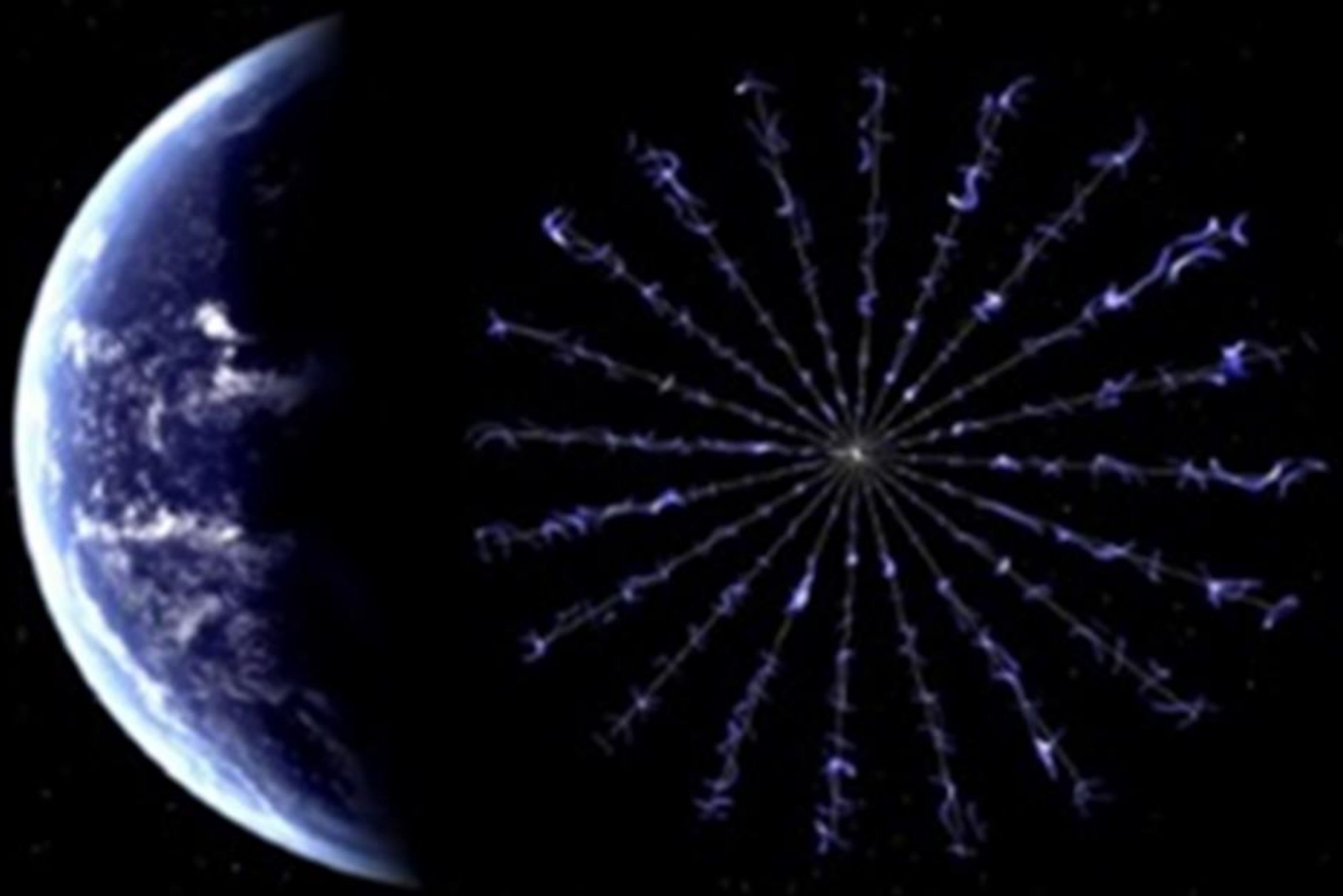
Provide a sail in a mid-inclination orbit and <u>we can make it happen!</u>



Notional Roadmap To The Future of Solar Sails



Electric Solar Wind Sails



Electrostatic Sail Origins & Benefits

Benefits of Electrostatic Sail Propulsion

- Revolutionary propellant-less propulsion
- Ability to survey entire Solar System
- Very rapid speeds are attainable (>10 AU/yr)

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

EU Investments (2010-2013) thru FMI direction: ~$2 M (1.7 mil Euros)

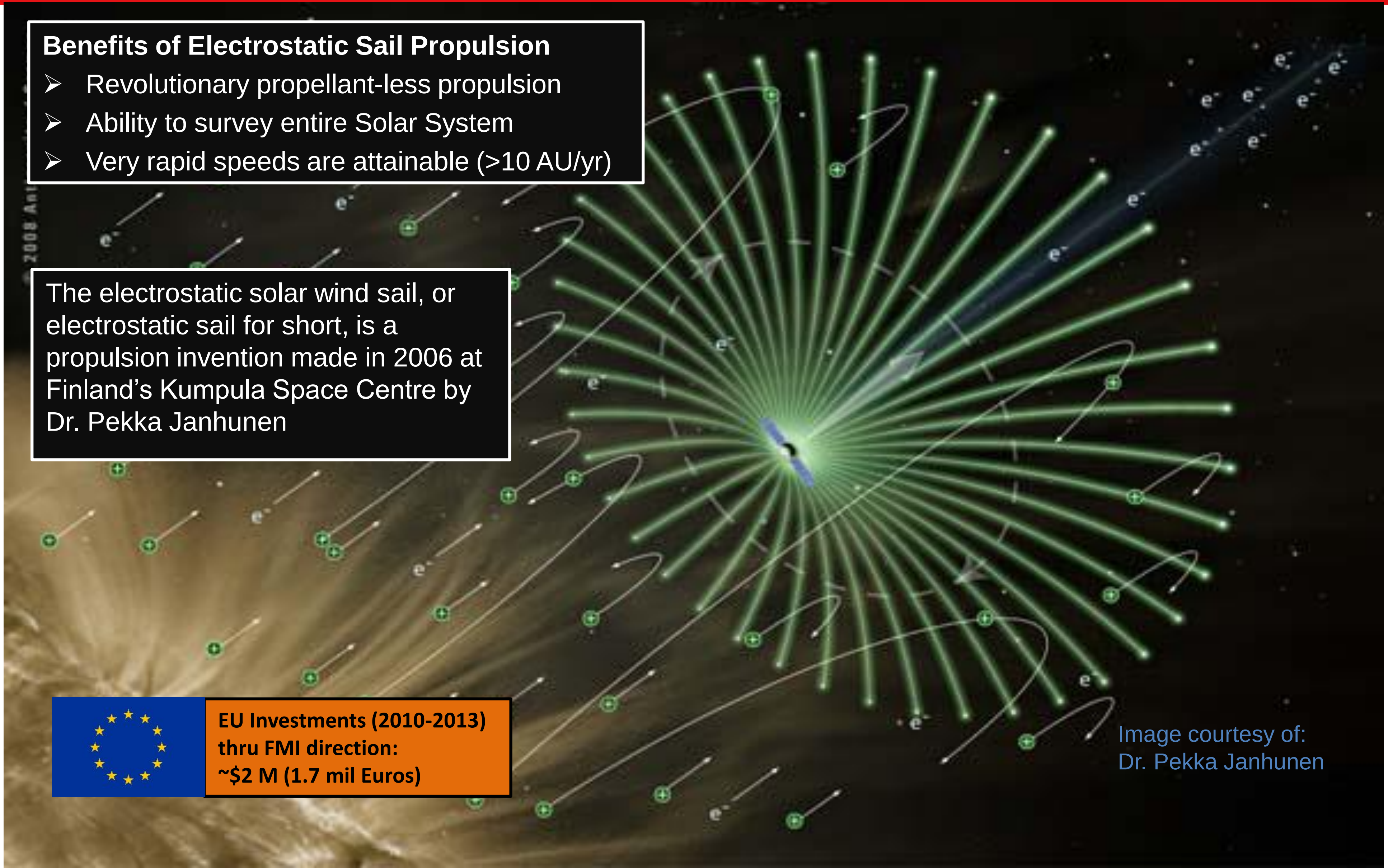
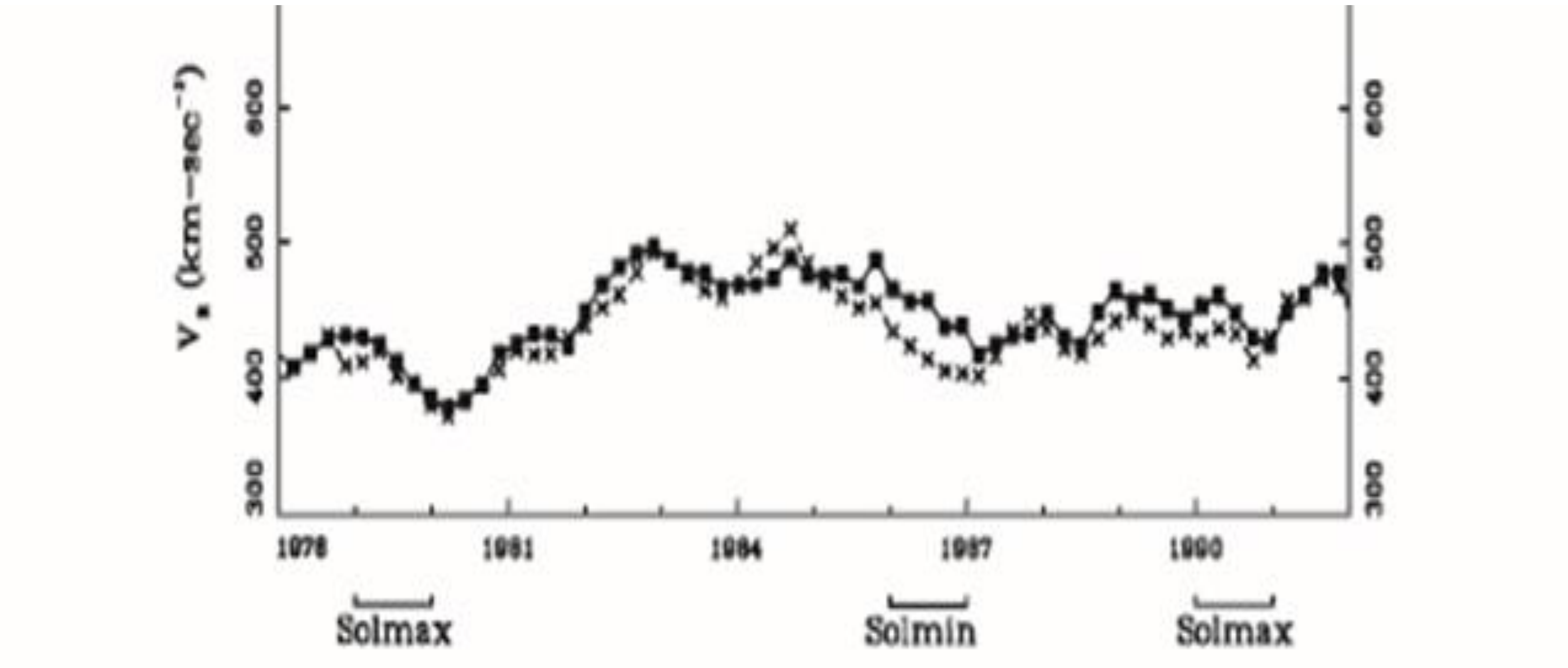


Image courtesy of:
Dr. Pekka Janhunen

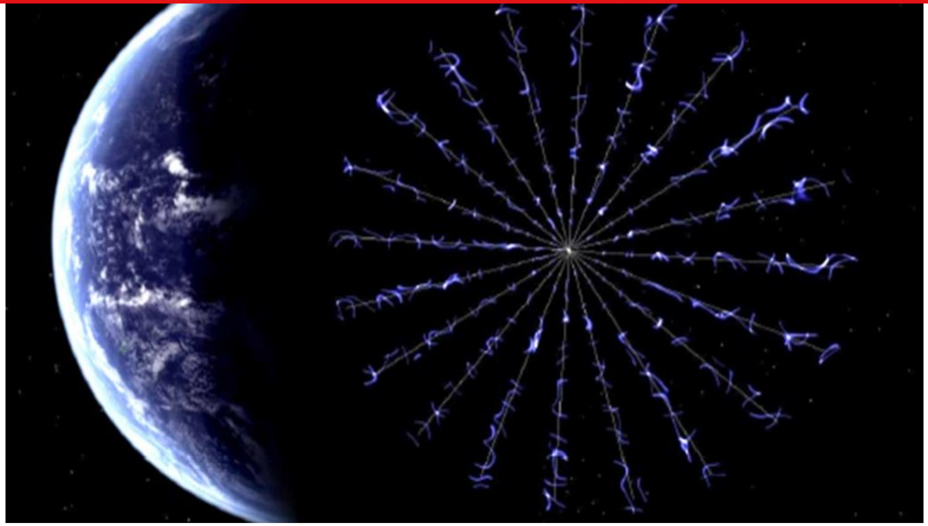
Solar Wind --> Electric Sail



- **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

What is an Electrostatic Sail?



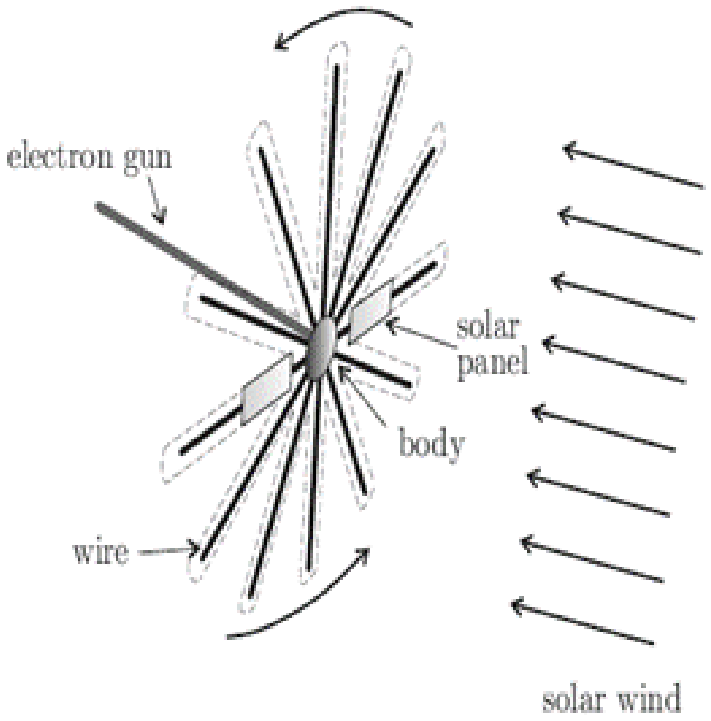
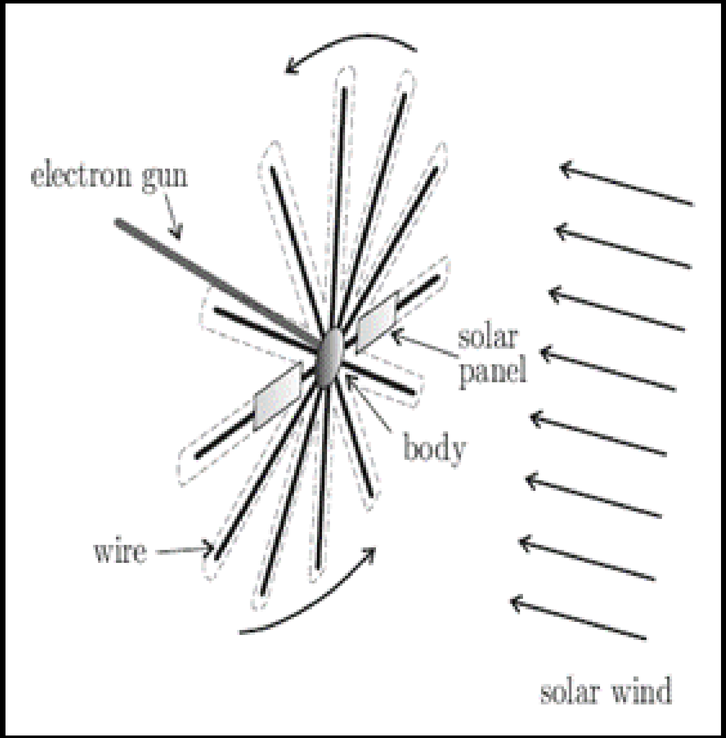


Figure credit: Mengali, et al., J. Spacecr. Rockets, 45, 122-129, 2008.

- An Electrostatic Sail propulsion system is designed to harness the solar wind proton energy by electrostatic repulsion of the protons
- A high voltage (kV) bias is applied to conductive tether/s extending radially outward from the spacecraft body
- A plasma sheath will form around each conductive tether to create an enhanced interaction region to maximize the proton momentum exchange
- To maintain the high voltage bias on each tether requires emitting collected electrons back into the deep space media via an electron gun on the spacecraft

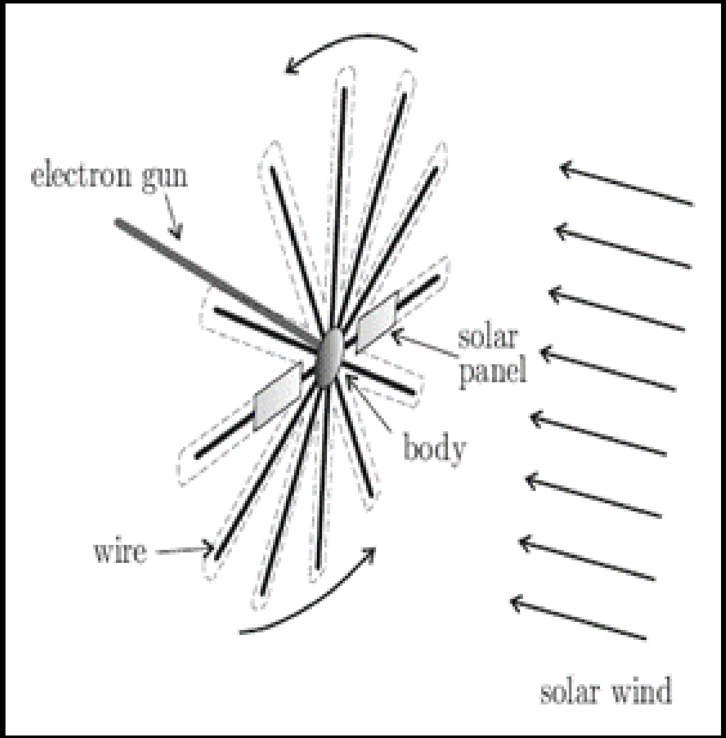
Electrostatic Sail (E-Sail): Operational Principles

- The E-sail consists of 1 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.
- The wires are positively biased to a 6 kV-20 kV potential
- The electric field surrounding each wire extends ~ 66 m into the surrounding plasma at 1 AU
- Positive ions in the solar wind are repulsed by the field created surrounding each wire and thrust is generated.

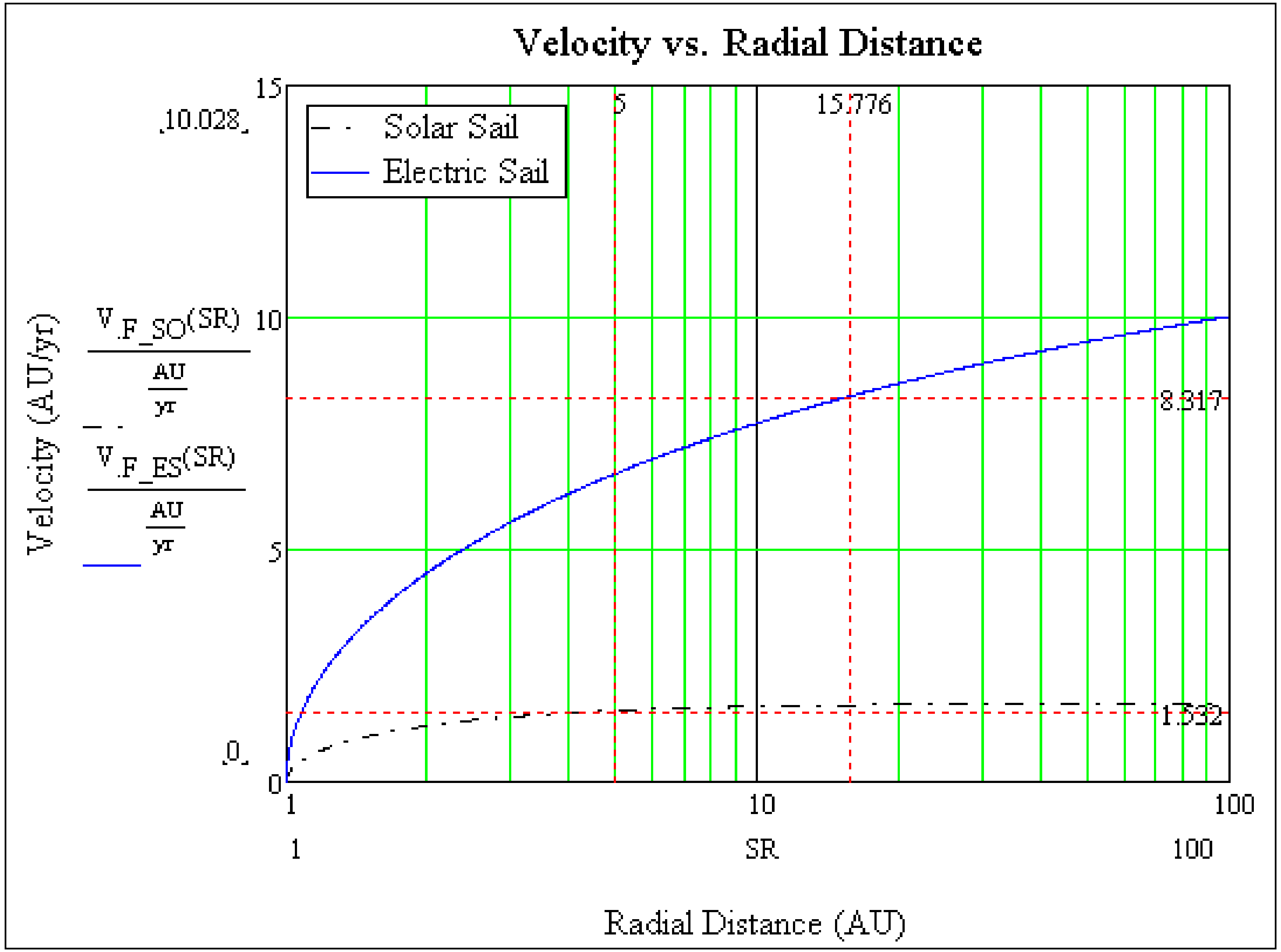


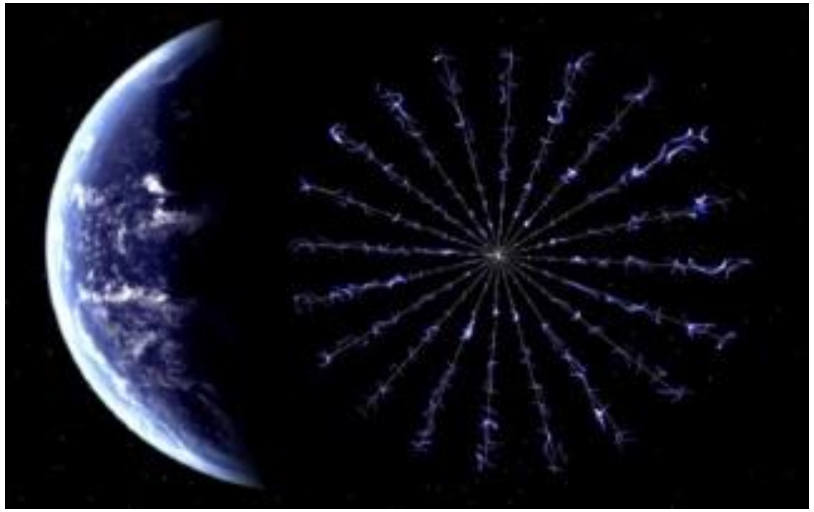
Electrostatic Sail (E-Sail): Operational Principles

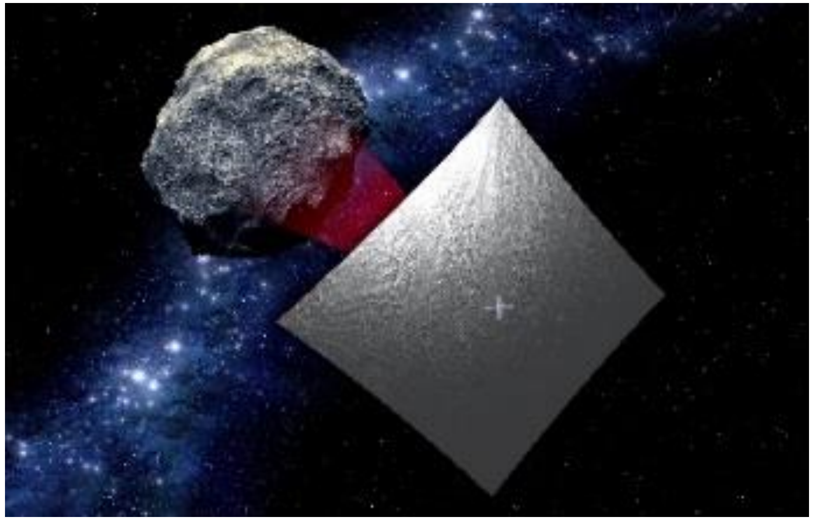
- As the E-sail moves away from the sun and the plasma density decreases (as $1/r^2$), the electric field around the wires gradually expands (to 180 m at 5 AU), partially compensating for the lower plasma density by increasing the relative size of the 'virtual' sail.
  - The thrust therefore drops only as ~ $1/r$, instead of $1/r^2$
- An electron gun is used to keep the spacecraft and wires in a high positive potential (~kV).
- Wire length and voltages are mission specific and determine the total ΔV available



Velocity vs. Radial Distance Comparison for Equal Mass Spacecraft



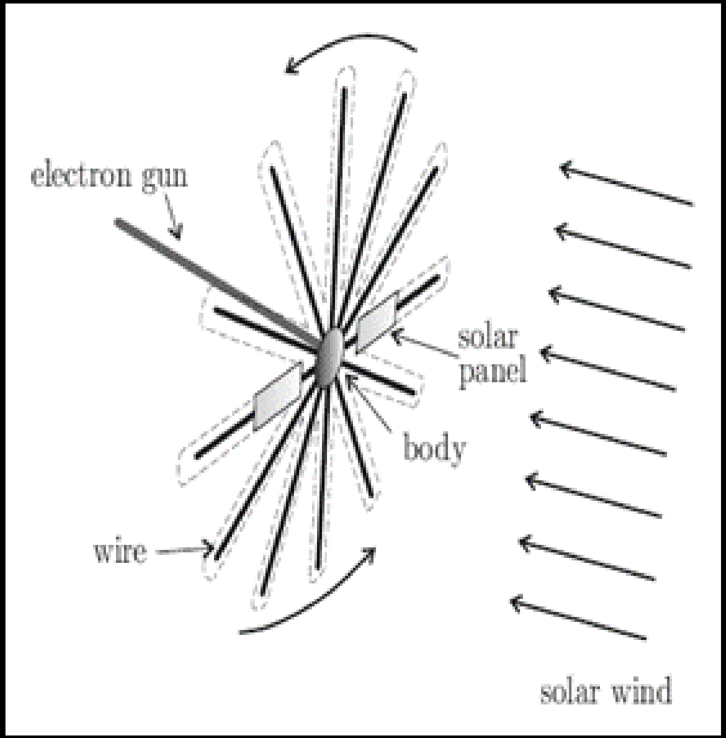




Electrostatic Sail (E-Sail): Operational Principles

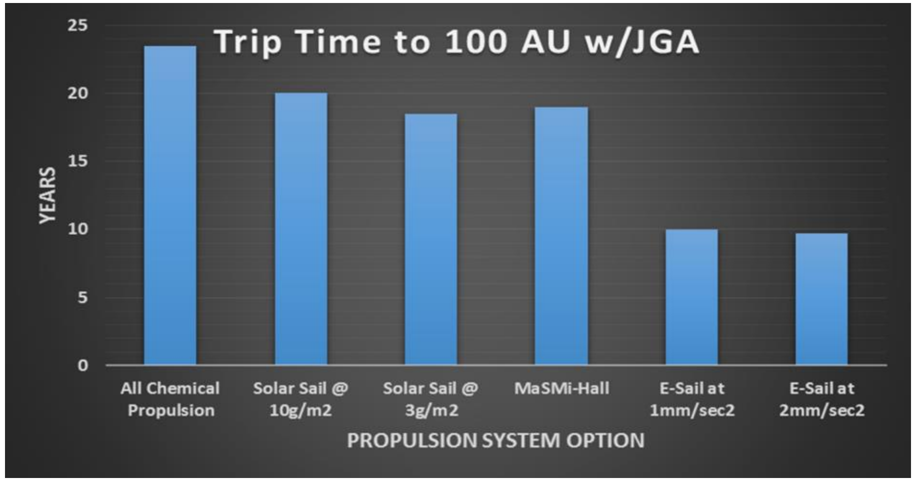
Characteristic accelerations of 1 – 2 mm/sec²

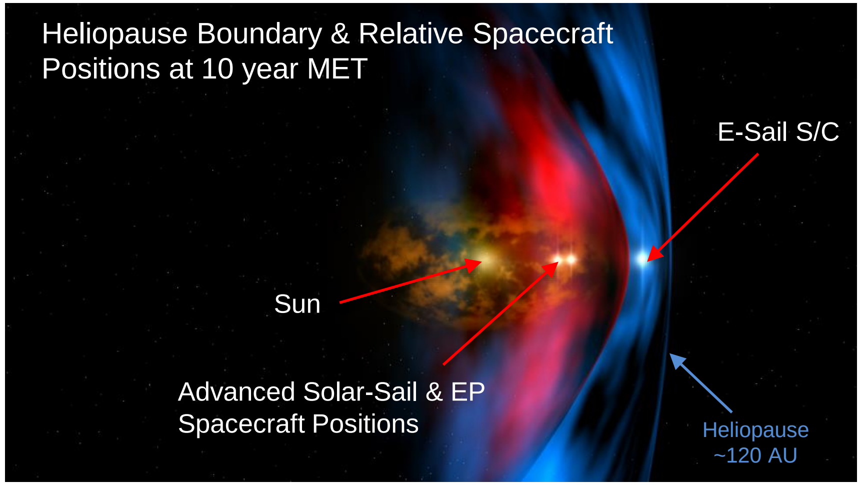
Spacecraft velocities of 12 – 20 AU/year possible (3X -4X faster than Voyager)



Heliopause and Beyond Mission Capture

- **The Electrostatic Sail Propulsion enables Heliopause Missions**
  - Findings from the Phase I & Phase II NIAC studies indicate that a science spacecraft could reach the Heliopause region in ~10 to 12 years
    - This is faster than alternative propulsion such as Solar Sail or Electric Propulsion (EP) systems
      - EP systems are limited to maximum total hours on thruster and propellant load



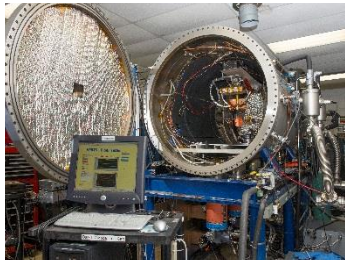


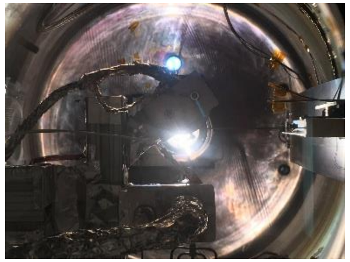
The Electrostatic Sail Propulsion technology enables Heliopause missions to be completed in < 12 years and also enables Interstellar Probe Missions. Since no propellants are needed these missions can be launched on an ELV.

Plasma Testing was Key to Advancing Knowledge of Space Plasma Physics

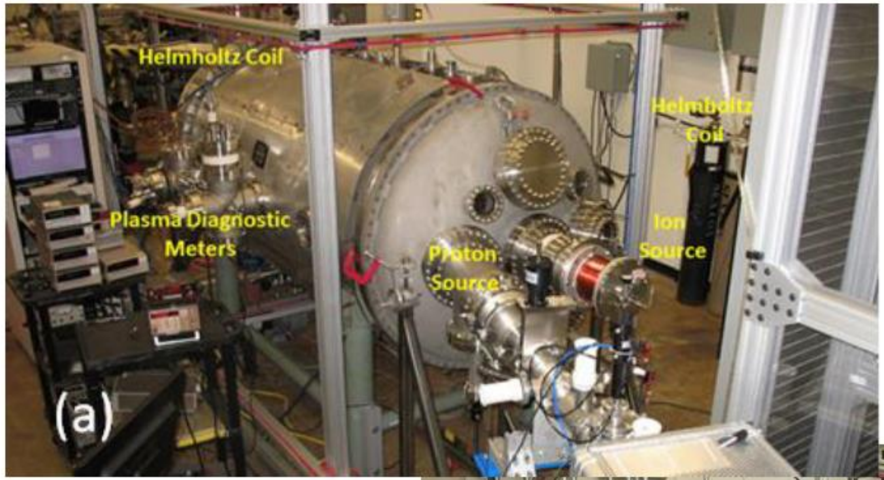
- **The Phase II experimental testing enabled a 'knowledge bridge' to be constructed from the testing performed > 30 years ago on negative biased objects operating in a space environment to recent testing on positive biased objects operating in a similar space environment**

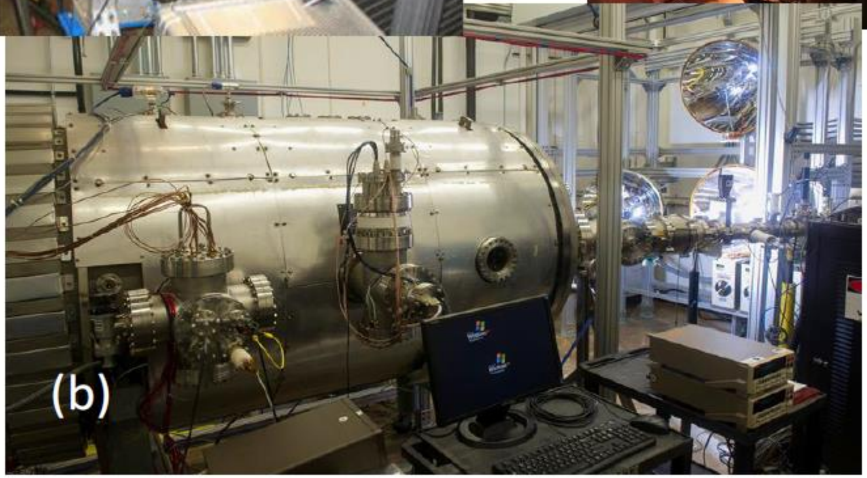
- **Phase II experimental results were a combination of:**
  - Extensive plasma chamber testing, and
  - Rigorous analysis of data collected on positive biased objects for an appropriate set of dimensionless space plasma parameters under the condition of Debye length (λd) < tether diameter
    - Normalized Potential (Φb)
    - Mach Number (S)



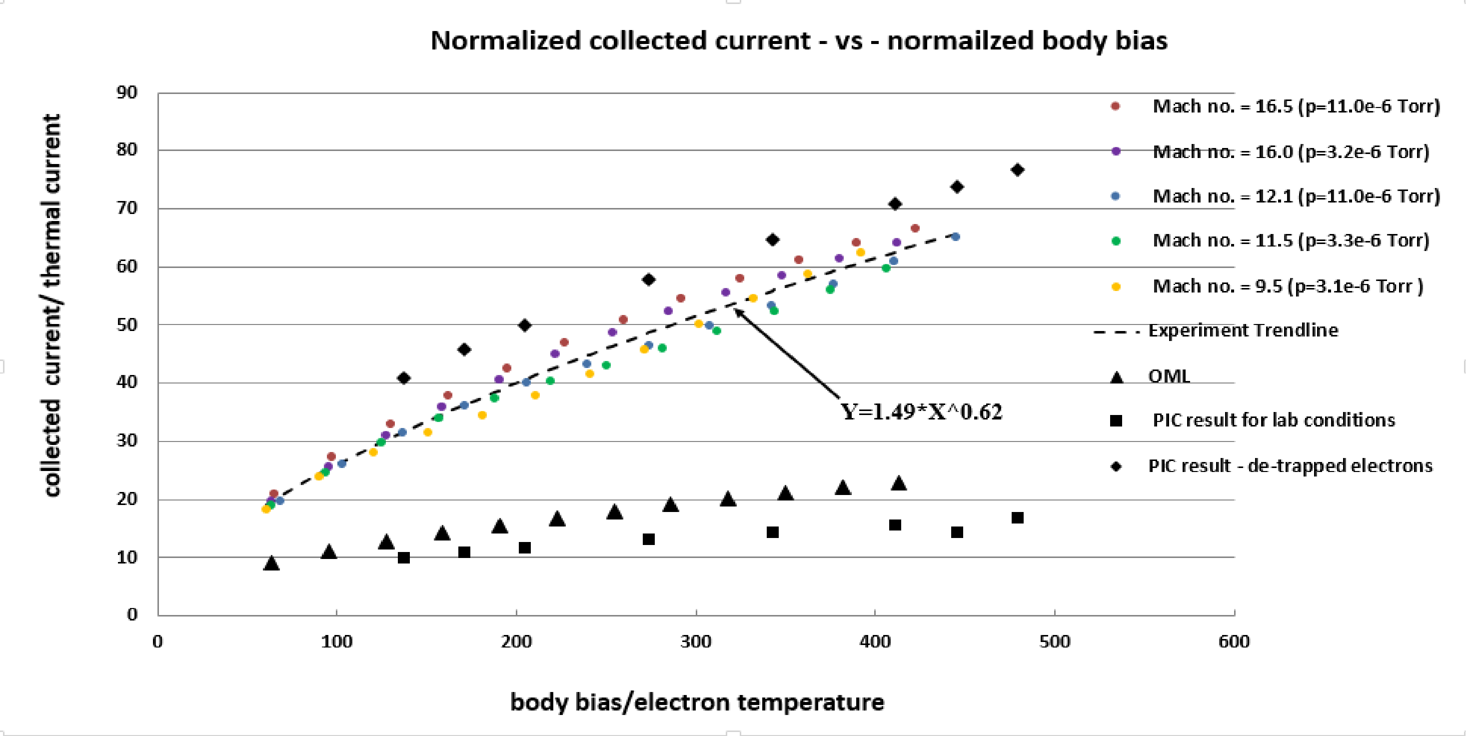


E-Sail Plasma Physics Testing at MSFC



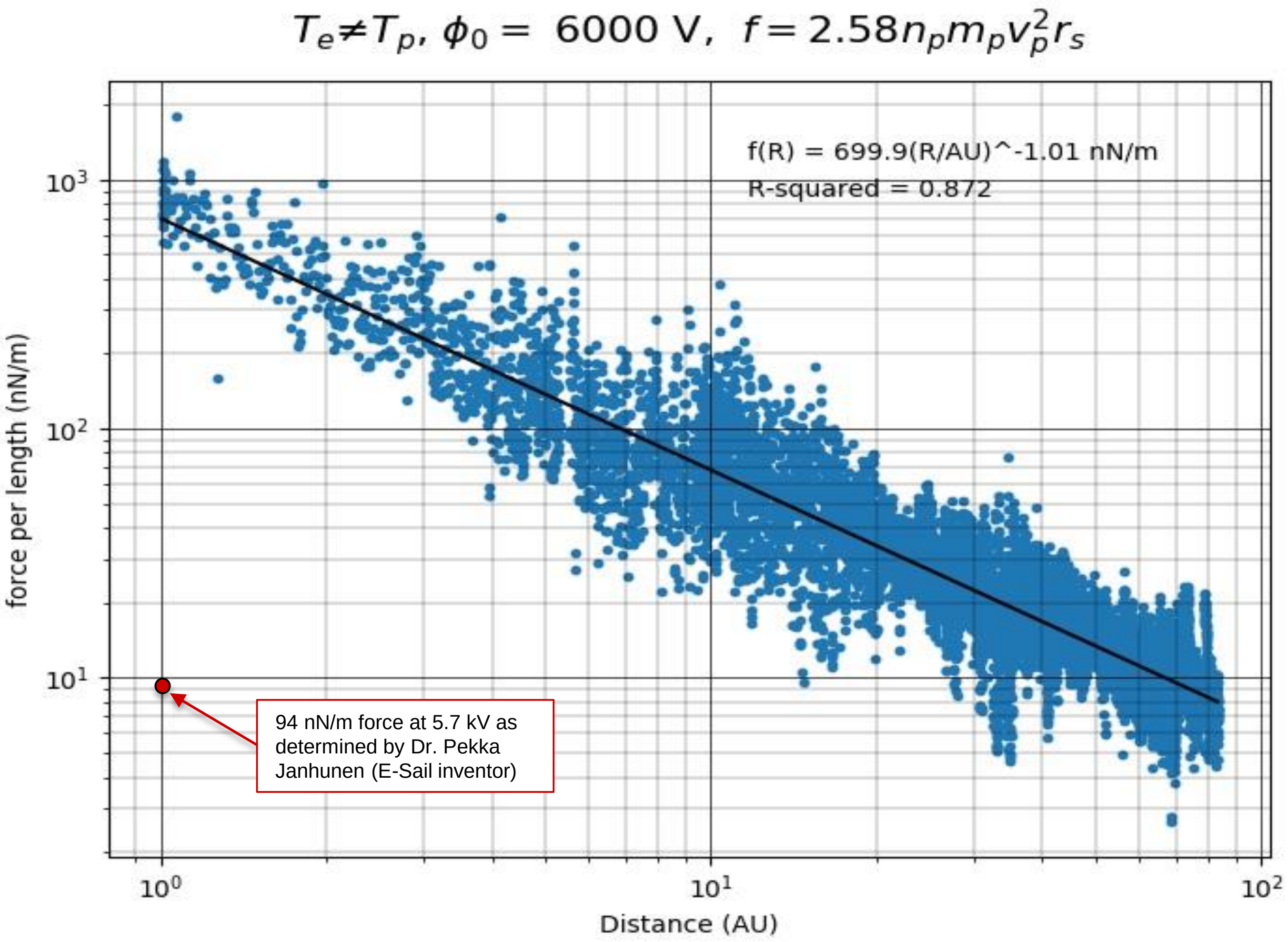


Current Collected by E-Sail



- **The normalized experimental results on current collected are identified by the dashed line and the amount of current collected was much greater than expected from the Orbit Limited Motion (OML) model**
- **The maximum current collection potential (PIC model result) is shown by the diamonds and represents the hypothetical case where all the electrons jump onto the positively charged wire (No trapped electrons)**
    - This is the limiting case that the spacecraft system must be designed for

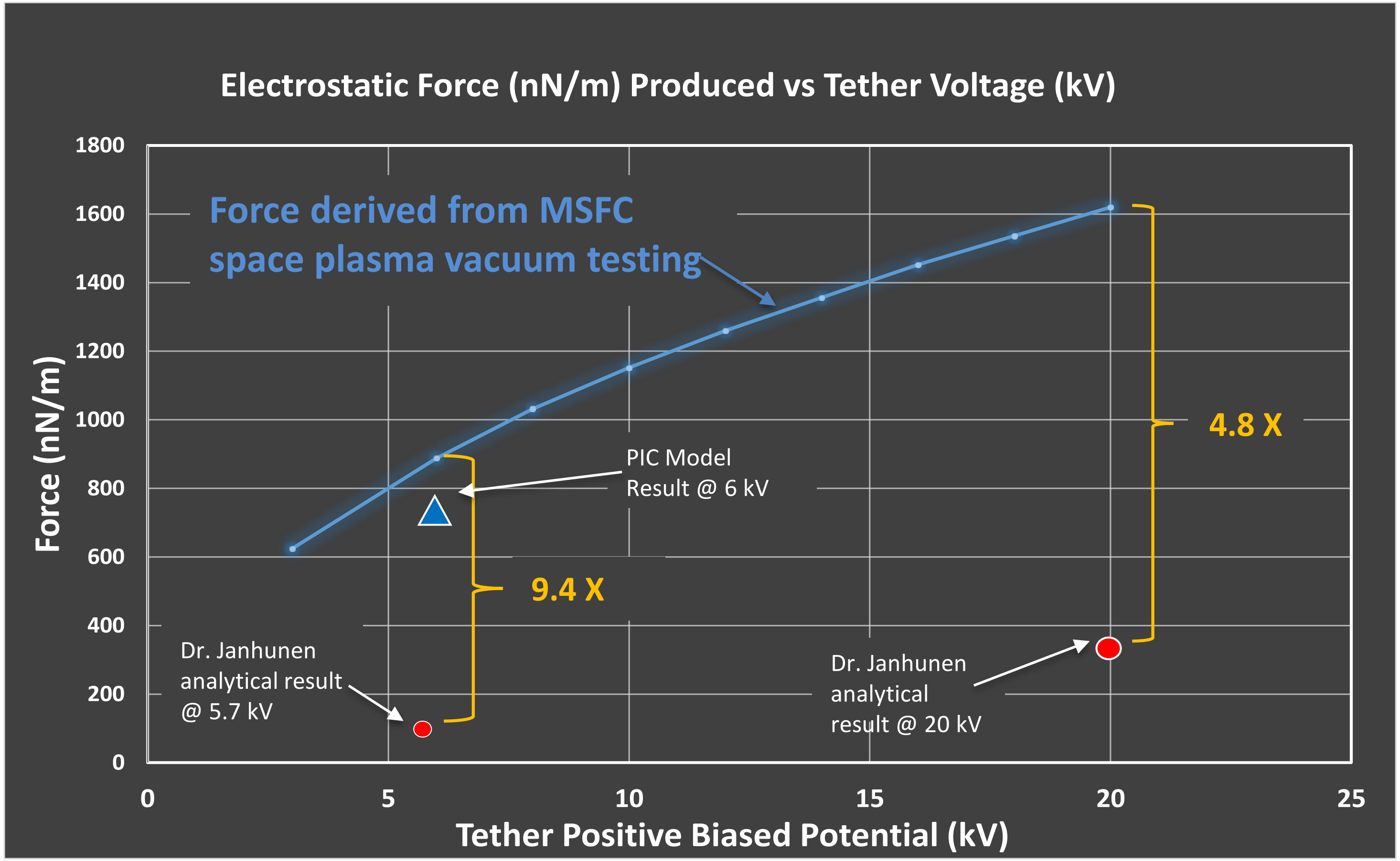
E-Sail Thrust Force at a 6 kV Bias vs AU Distance (where Te ≠ Tp)



The electrostatic sail thrust force created as derived from the experimental plasma chamber testing decays at the rate of: $1/r^{1.01}$

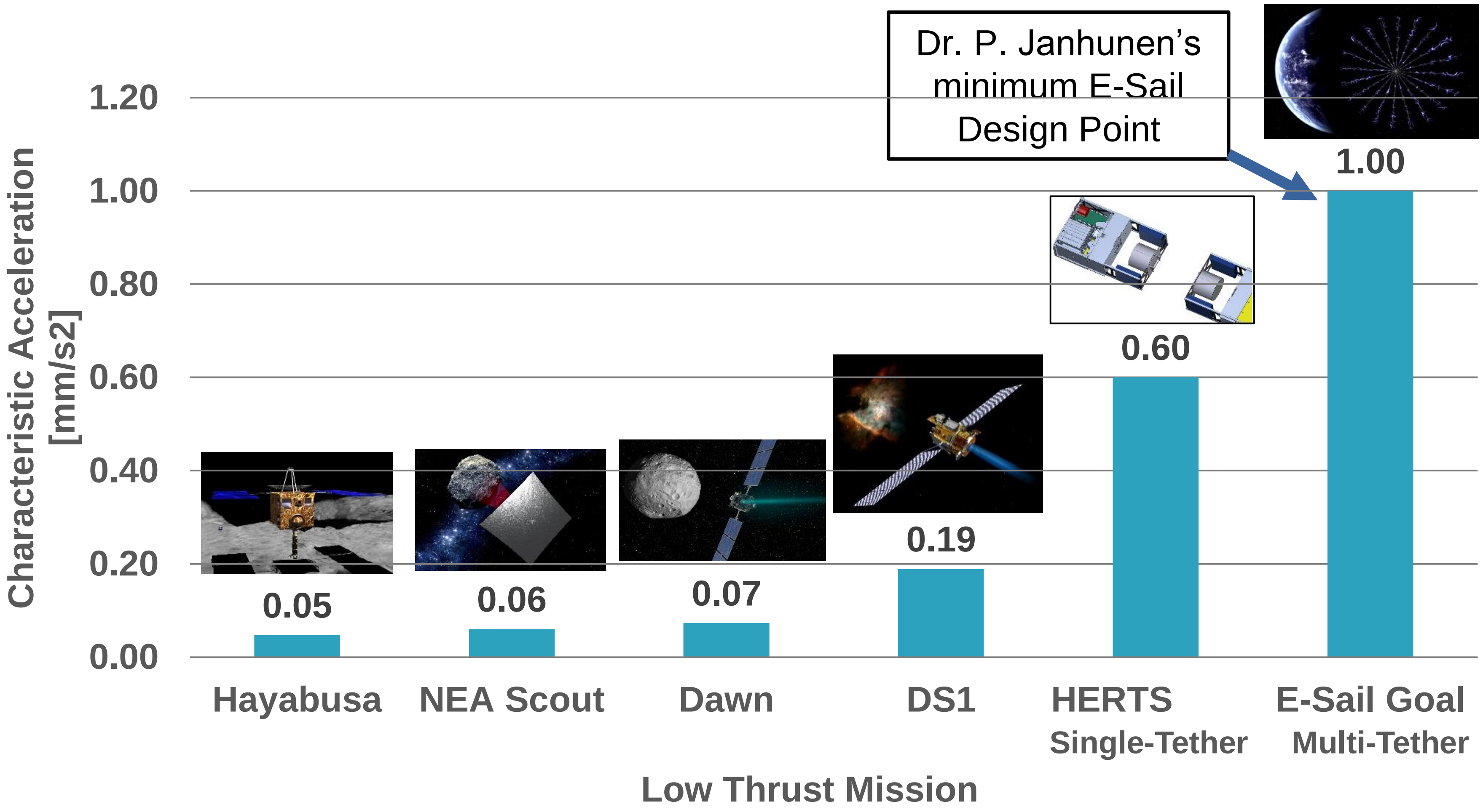
E-Sail Thrust Force Produced at 1 AU

- **Results of the HERTS Electrostatic Thrust Force Produced**



There is good agreement between the thrust as calculated from the PIC Model and the derived thrust from experimental vacuum chamber tests at the 6 kV bias

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



The E-Sail propulsion system for a proposed spacecraft was designed with a characteristic acceleration rate$_{1\ AU}$ of ~10 times greater than the NEA Scout Solar Sail

E-Sail Technology Readiness Levels

- **The highly successful STMD NIAC project successfully advanced E-sail system technology from TRL 2 to TRL 4**
- **Many individual subsystem TRL's are higher than TRL 4, based on the NIAC Phase II TRL assessment**
- **MSFC Plans to reassess system TRL's in FY18**

Subsystem	TRL
Tether Deployment Subsystem	4/5
Electron Emitter	4
New Tether Materials	4
State of Art (SOA) Tethers	5
High Voltage Power Supply	5
High Voltage Switching	5
Command, Control & Comm. (NEA Scout Heritage)	7
Power Generation	7

BACKUP