Solar & Electric Sailing Overview
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Acknowledgments

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Solar sails use photon “pressure” or force on thin, lightweight, reflective sheets to produce thrust.
Solar Sail Missions Flown (as of April 11, 2018)

- **NanoSail-D (2010)**
  - NASA
  - Earth Orbit
  - Deployment Only
  - 3U CubeSat
  - 10 m²

- **IKAROS (2010)**
  - JAXA
  - Interplanetary
  - Full Flight
  - 315 kg Smallsat
  - 196 m²

- **LightSail-1 (2015)**
  - The Planetary Society
  - Earth Orbit
  - Deployment Only
  - 3U CubeSat
  - 32 m²

- **CanX-7 (2016)**
  - Canada
  - Earth Orbit
  - Deployment Only
  - 3U CubeSat
  - <10 m²

- **InflateSail (2017)**
  - EU/Univ. of Surrey
  - Earth Orbit
  - Deployment Only
  - 3U CubeSat
  - 10 m²
Planned Solar Sail Missions (as of April 11, 2018)

CU Aerospace (2018)
Univ. Illinois / NASA
Earth Orbit
Full Flight
3U CubeSat
20 m²

LightSail-2 (2018)
The Planetary Society
Earth Orbit
Full Flight
3U CubeSat
32 m²

Near Earth Asteroid Scout (2019)
NASA
Interplanetary
Full Flight
6U CubeSat
86 m²
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 m² 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
NEA Scout Flight System
NEA Scout Hardware Overview
NEA Scout Full Scale Successful Deployment
NEA Scout – Mission Overview

System Performance:
0.06 mm/sec²
25 g/m²
Ground to space laser illumination of a solar sail to impart measurable $\Delta V$

Provide a sail in a mid-inclination orbit and we can make it happen!
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)
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?

- 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.

Figure credit: Mengali, et al., J. Spacecr. Rockets, 45, 122-129, 2008.
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 $\sim 1/r$, instead of $1/r^2$

• An electron gun is used to keep the spacecraft and wires in a high positive potential ($\sim$kV).

• Wire length and voltages are mission specific and determine the total $\Delta V$ available
Velocity vs. Radial Distance
Comparison for Equal Mass Spacecraft

Velocity vs. Radial Distance

- Solar Sail
- Electric Sail

Velocity (AU/yr)

Radial Distance (AU)
Electrostatic Sail (E-Sail):
Operational Principles

Characteristic accelerations of $1 - 2 \text{ mm/sec}^2$

Spacecraft velocities of $12 - 20 \text{ AU/year}$ possible (3X - 4X faster than Voyager)
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 ($\lambda_d$) < tether diameter
    - Normalized Potential ($\Phi_b$)
    - Mach Number ($S$)
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 $T_e \neq T_p$)

\[ T_e \neq T_p, \quad \phi_0 = 6000 \, \text{V}, \quad f = 2.58 n_p m_p v_p^2 r_s \]

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

94 nN/m force at 5.7 kV as determined by Dr. Pekka Jänhunen (E-Sail inventor)
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.
The E-Sail propulsion system for a proposed spacecraft was designed with a characteristic acceleration rate $\dot{a}_{1\text{AU}}$ of ~10 times greater than the NEA Scout Solar Sail.
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.

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