The Conceptual Design of an Electric Sail Technology Demonstration Mission Spacecraft

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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
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.
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 to 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/s² 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

- 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.
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
• **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

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

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

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.

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.

MSFC Plasma Chamber (Top View)

Conductor (0.18 cm, SS, Tube)

Measurement Region (10 cm x 50 cm)

Ion Source

Plasma chamber height (L)

1/3 L

1/3 L

1/3 L

Charged section
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
A Sample of Plasma Chamber Data

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

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):
    \[
    \vec{a} = a_0 \left( \frac{R_E}{r} \right)^{c_1} \cos^{c_2}(\alpha) \vec{n}
    \]
    \[
    \bar{a} = \text{acceleration}
    \]
    \[
    a_0 = \text{characteristic acceleration defined as thrust/mass at normal incidence (}\alpha=0\text{) at 1 AU}
    \]
    \[
    R_E = \text{constant of 1 AU}
    \]
    \[
    r = \text{distance from sun}
    \]
    \[
    c_1 = \text{constant of radial variation (typically either 7/6 or 1)}
    \]
    \[
    c_2 = \text{constant of angular variation (typically between 1 and 2)}
    \]
    \[
    \alpha = \text{incidence angle to solar wind of body vector to reference plane of E-sail}
    \]
    \[
    \vec{n} = \text{thrust/acceleration reference frame of E-sail}
    \]
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 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):
    • Deploy a 16,000 m conductive tether
    • Accelerate the spacecraft, &
    • Steer

• Secondary goals of mission:
  • Collect meaningful science data
The conceptual design of an E-Sail propulsion system for a proposed TDM was designed with a characteristic acceleration that is 10 times greater than 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

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

### Diagrams

- **"Hub and Spoke"**
  - 4 km tether
  - 12 U units

- **"Hybrid"**
  - 8 km tethers
  - 10 U units
  - 1 U units

- **"Barbell"**
  - 16 km tethers
  - 6 U units
  - 6 U units
### Down-Selected Tether Material Options for Further Study

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

<table>
<thead>
<tr>
<th></th>
<th>Miralon (CNT)</th>
<th>Copper</th>
<th>Aluminum</th>
<th>AmberStrand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass [kg]</strong></td>
<td>0.60</td>
<td>6.69</td>
<td>2.02</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>Tensile Load at Yield [N]</strong></td>
<td>40.72</td>
<td>3.17</td>
<td>12.49</td>
<td>40.48</td>
</tr>
<tr>
<td><strong>Voltage Drop [V]</strong></td>
<td>2,431.5</td>
<td>51.1</td>
<td>80.6</td>
<td>902.4</td>
</tr>
</tbody>
</table>

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)**

**HERTS TDM (12U)**

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

**NEAS Components Used**
- Avionics
- Communication
- Reaction Control
- Power
- Attitude Control
Animation of Proposed E-Sail TDM (2023)
Before a Tech Demo Mission can be done, NASA must first prove the successful deployment of multiple tethers in an experiment on Earth, or in the upper atmosphere, or in LEO.
Backup Slides Follow
MSFC Plasma Chamber
(Top View)

Ion Source

Conductor (0.18 cm, SS, Tube)

Measurement Region (10 cm x 50 cm)

1.2 m

1.57 m

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