**The Heliopause Electrostatic Rapid Transit System (HERTS) Design, Trades, and Analyses Performed in the First Year of a Two Year Investigation.**

***Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov***
***NASA-MSFC--Advanced Concepts Office—256-797-1448***

The Heliopause Electrostatic Rapid Transit System (HERTS)[1] was one of the seven total Phase II NASA Innovative Advanced Concepts (NIAC) that was down-selected in 2015 for continued funding and research. In Phase I we learned that a spacecraft propelled by an Electric Sail (E-Sail) can travel great astronomical distances, such as to the Heliopause region of the solar system (~100 to 120 AU) in approximately one quarter of the time (10 years) versus the time it took the Voyager spacecraft launched in 1977 (36 years). The current work within the Phase II NIAC effort builds upon the work that was done in the Phase I NIAC and is focused on:

1) Testing of plasma interaction with a charged wire in a unique MSFC test chamber,
2) Development of a Particle-in-Cell (PIC) models that are validated in the plasma testing and used to extrapolate to the E-Sail propulsion system design.
3) Further down select of a wire deployment and control approach from those narrowed down in the Phase I effort.

This paper will document the findings to date (June, 2016) of the above focused areas.

The motivation for this revolutionary propulsion technology comes from the National Research Council: Solar and Space Physics 2012 Heliophysics Decadal Survey. The Heliophysics Decadal Survey, Section 10.5.2.7 states in part; "… recent in situ measurements by the Voyagers, combined with all-sky heliospheric images from IBEX and Cassini, have made outer-heliospheric science one of the most exciting and fastest-developing fields of Heliophysics... The proposed Interstellar Probe Mission would make comprehensive, state-of-the-art, in situ measurements…required for understanding the nature of the outer heliosphere and exploring our local galactic environment." It goes on to say, ***"The main technical hurdle is propulsion. Advanced propulsion options should aim to reach the Heliopause considerably faster than Voyager 1 (3.6 AU/year)… It has high priority for the Solar and Heliospheric Physics (SHP) Panel that NASA develops the necessary propulsion technology for visionary missions like The Solar Polar Imager (SPI) and Interstellar Probe to enable the vision in the coming decades."***

The concept investigated has been named the Heliopause Electrostatic Rapid Transit System (HERTS) by the MSFC team. The HERTS is a revolutionary propellant-less propulsion concept that is ideal for deep space missions to the Outer Planets, Heliopause, and beyond. It is unique in that it uses momentum exchange from naturally occurring solar wind protons to propel a spacecraft within the Heliosphere. The propulsion system consists of an array of electrically positively-biased wires that extend outward 10 to 20 km from a rotating (one revolution per hour) spacecraft as shown in Figure 1. The recent investigations have focused on a wire lengths up to 20 km primarily based upon past Space Shuttle Tether Satellite System experiments.

[1] *The HERTS is one of the seven down-selected 2015 Phase II NIAC investigations awarded in July, 2015*

**The Heliopause Electrostatic Rapid Transit System (HERTS) Design, Trades, and Analyses Performed in the First Year of a Two Year Investigation.**

*Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov*
*NASA-MSFC--Advanced Concepts Office—256-797-1448*

*Figure 1: Notional Electric Sail*

The results obtained in Phase I included trip times to various outer planets based upon the spacecraft mass and are shown in Figure 2. In addition to these trip times, trip times to Pluto would be on the order of five to six years. A comparison of trip times to a distance of 100 AU enabled by the E-Sail and other advanced propulsion systems is shown in Figure 3.

| Notional Trip Times to Outer Planets Enabled E-Sail Propulsion System Enables Rapid Trip Times to the Outer Planets [1] | | | | |
|---|---|---|---|---|
| **Destination** | **Distance** | **Spacecraft Mass (kg)** | | |
| | | 500 | 1000 | 1500 |
| **Jupiter** | 5.2 AU | 1.0 yr | 1.6 yr | 2.5 yr |
| **Saturn** | 9.6 AU | 1.7 yr | 2.8 yr | 4.6 yr |
| **Uranus** | 19 AU | 3.1 yr | 5.3 yr | 9.6 yr |
| **Neptune** | 30 AU | 4.6 yr | 8.0 yr | 15.0 yr |

*Figure 2: Trip Times to the Outer Planets*

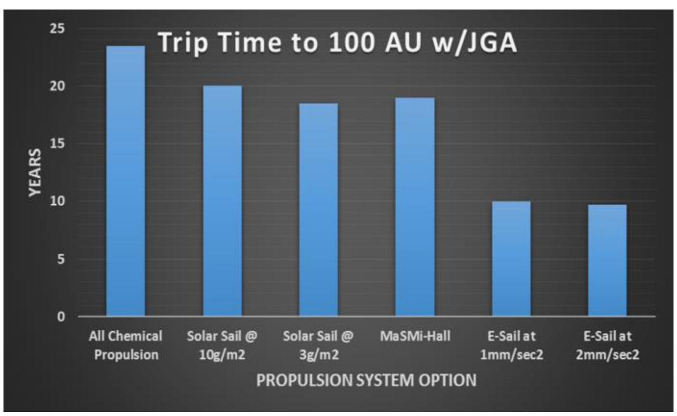


*Figure 3: Trip Times to Heliopause via E-Sail and Other Advanced Propulsions Systems*

The underlying beauty of this revolutionary technology is that most of the subsystems required are at a high Technology Readiness Level (TRL) and a Technology Demonstration Mission (TDM) could be done in the 2020-2022 timeframe. This envisioned TDM would blaze the path for a Heliophysics Mission to the Heliopause and beyond in the 2025 to 2035 timeframe.

The performance of the HERTS and its suitability as a Heliospheric propulsion system is critically dependent upon how it interacts with the solar wind plasma. The thrust is determined by repulsion of solar wind protons by the high positive bias on the wires, and the operational

***Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov***
***NASA-MSFC--Advanced Concepts Office—256-797-1448***

power is determined by the corresponding collection of electrons that must be ejected back into the solar wind to maintain the required positive bias voltage on the wire array. Previous calculations of E-Sail performance have been based on the simple Orbit-Motion Limited (OML) model. However, the Phase I study uncovered issues that bring into question the use of the OML model as a viable approximation for either proton or electron interactions. **Therefore, one of the main objectives of the Phase II study is to resolve the interaction issues and establish physically correct and accurate models for proton repulsion and electron collection from which the engineering design parameters thrust per unit length of wire and system power can be calculated.**

## Plasma Chamber Testing:

One issue discovered during Phase I is centered on the use of the OML model. A discrepancy exists between the calculated force per unit length on a charged wire based on the OML model, and a similar calculation based on empirical data obtained from previous experimental studies of satellite-space plasma interactions carried out at MSFC.

Thrust based on the experimental data (≈2.5 μN/m) was about 3.5 times greater than the OML-based calculation. However, the satellite-space plasma interaction experiments involved spherical and short cylindrical test bodies that were biased negatively—attractive for positive ions. Use of the data, therefore, assumes that the attractive force on positive ions is equal in magnitude to that of a repulsive force, and that the differences in body geometry will not have a significant effect. Neither of these assumptions may be correct and require further study. Therefore, the first objective of the Plasma Chamber Testing will be to repeat the interaction experiment, using the same diagnostics, but with a positive bias applied to a long thin cylindrical test body, which will be more representative of the biased E-Sail wires.

The results of the experimental Plasma Chamber Testing performed at the MSFC Solar Wind Facility (Figure 3) will be documented in this paper and are also used to benchmark the numerous numeric models being developed to support this investigation.

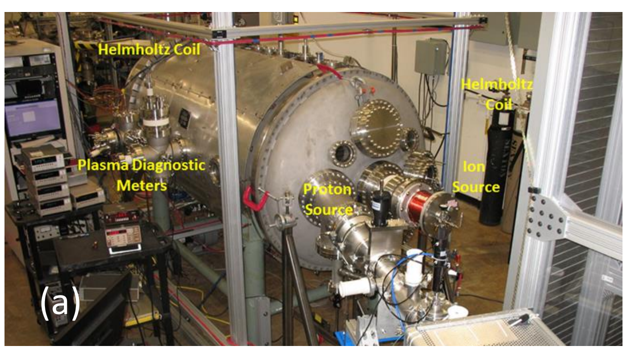


*Figure 4: The MSFC Plasma Chamber Test Facility*

## Development of a Particle-in-Cell (PIC) models:

The PIC model is a numerical computational tool that allows the simulation of a complex phenomenon—or, mathematically speaking, it is a method of solving a set of coupled partial differential equations that describe the phenomenon. In our case, that of a charged wire in a magnetized flowing plasma, a complex interaction is created where the distribution of solar wind protons and electrons are affected by the electric field around the wire and, conversely, the electric field and (to a lesser extent) the solar magnetic field imbedded in the solar wind are affected by the presence and movement of the charged particles. Magnetic effects can be ignored because the plasma flow is normal to the wire and the plasma sheath surrounding the wire is much smaller than the gyro-radius of solar wind protons. A system of five coupled, nonlinear partial differential equations is required to describe this interaction. The PIC method simplifies the problem by dividing the space around the wire (between the wire and the plasma sheath boundary) into a mesh of small elemental volumes, or "cells," and tracking the plasma particles through this mesh.

Tracking a large number of protons and electrons through the entire mesh then results in a first order charge distribution—which is used in a Poisson solver algorithm in conjunction with the Maxwell's equations to arrive at a more accurate first order distribution for the electric field.

In the second iteration, the slightly different first order electric field distribution acts on a new set of charged particles that are tracked through the mesh—which results in a slightly different, second order particle distribution that is, in turn, used to recalculate the electric field, and so on. As the process is continued, the solutions for the electric field and the proton and electron distributions should converge to a stable solution.

Results of the PIC Models as developed for this investigation will also be highlighted in this paper including comparison between the PIC Model results to the experimental results.

**Down Selection of Best Conductor Wire Material:**
The thrust-per-unit-length calculations from Phase I indicated that a 200 to 400 km of total length of conductive wires will be required to produce the desired spacecraft acceleration. This is significantly less than earlier concepts and is considered less of a challenge to develop. The total length required presents several engineering challenges such as minimizing potential resistance drop along the wire length, tensile strength limitations, keeping system mass low, survivability, and controlling system costs. Wire options investigated during Phase I are shown in Figure 5 and this paper will document the current trades and analysis performed to arrive at the best solution investigated in Phase II.

| | **Amberstrand** | | **CNT yarn** | | **Aluminum** | **Copper** |
|---|---|---|---|---|---|---|
| **Filament count, or wire size** | 66 | 166 | 1 | 4 | 35 ga | 35ga |
| **Diameter (µm)** | 230 | 370 | | | 142 | 142 |
| **Linear mass (g/km)** | 56 | 140 | 10 | 24 | 43 | 142 |
| **Each Tether length (km)** | 5 | 5 | 5 | 5 | 5 | 5 |
| **Tether mass (g)** | 280 | 700 | 50 | 120 | 260 | 860 |
| **Tether Strength (N)** | 41 | 105 | 15.00 | 36.00 | 1.96 | 8.04 |
| **Estimated material cost ($/km)** | 1300 | 1704 | 10000 | 25000 | 600 | 800 |
| **Est. Packed Volume @ 10 tethers (cc)** | 140 | 350 | 125 | 300 | 961 | 961 |
| | | | | | | |
| **Resistivity (ohms/m)** | 9 | 3 | 160 | 70 | 1.77 | 1.08 |

***Figure 5: E-Sail Conductor Options at Initiation of Phase II Investigation***

**The Heliopause Electrostatic Rapid Transit System (HERTS) Design, Trades, and Analyses Performed in the First Year of a Two Year Investigation.**

*Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov*
*NASA-MSFC--Advanced Concepts Office—256-797-1448*

In closing, this paper will document the knowledge gained during the first year of the two year Phase II NIAC investigation. The Heliopause Electrostatic Rapid Transit System (HERTS) fully supports NASA's vision to "lead advances in space" by providing a revolutionary, in-space propulsion system that can open the frontier of Heliophysics to new discovery. With the performance and benefits of a HERTS mission, the Heliospheric Physics community as well as the Outer Planetary interest groups will have at their disposal the ability to carry out Deep Space Missions with one-way Earth to Heliopause trip times of less than 10 years.

**The Heliopause Electrostatic Rapid Transit System (HERTS) Design, Trades, and Analyses Performed in the First Year of a Two Year Investigation.**

*Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov*
*NASA-MSFC--Advanced Concepts Office—256-797-1448*

**The Heliopause Electrostatic Rapid Transit System (HERTS) Design, Trades, and Analyses Performed in the First Year of a Two Year Investigation.**

*Bruce M. Wiegmann; bruce.m.wiegmann@nasa.gov*
*NASA-MSFC--Advanced Concepts Office—256-797-1448*