(Preprint) AAS 17-142

CONCEPTUAL DESIGN OF AN ELECTRIC SAIL TECHNOLOGY DEMONSTRATION MISSION SPACECRAFT

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There is great interest in examining the outer planets of our solar system and Heliopause region (edge of Solar System) and beyond regions of interstellar space by both the Planetary and Heliophysics communities. These needs are well documented in the recent National Academy of Sciences Decadal Surveys. There is significant interest in developing revolutionary propulsion techniques that will enable such Heliopause scientific missions to be completed within 10 to15 years of the launch date. One such enabling propulsion technique commonly known as Electric Sail (E-Sail) propulsion employs positively charged bare wire tethers that extend radially outward from a rotating spacecraft spinning at a rate of one revolution per hour. Around the positively charged bare-wire tethers, a Debye Sheath is created once positive voltage is applied. This sheath stands off of the bare wire tether at a sheath diameter that is proportional to the voltage in the wire coupled with the flux density of solar wind ions within the solar system (or the location of spacecraft in the solar system. The protons that are expended from the sun (solar wind) at 400 to 800 km/sec are electrostatically repelled away from these positively charged Debye sheaths and propulsive thrust is produced via the resulting momentum transfer. The amount of thrust produced is directly proportional to the total wire length.

The Marshall Space Flight Center (MSFC) Electric Sail team is currently funded via a two year Phase II NASA Innovative Advanced Concepts (NIAC) awarded in July 2015. The team's current activities are: 1) Developing a Particle in Cell (PIC) numeric engineering model from the experimental data collected at MSFC's Solar Wind Facility on the interaction between simulated solar wind interaction with a charged bare wire that can be applied to a variety of missions, 2) The development of the necessary tether deployers and tethers to enable successful deployment of multiple, multi km length bare tethers, 3) Controllability of the spacecraft via a voltage bias to steer itself through the solar system to destinations of discovery. These activities once demonstrated analytically, will require a technology demonstration mission (TDM) around the year2020 to demonstrate that all systems work together seamlessly before a Heliophysics Electrostatic Rapid Transit System (HERTS) mission could be initiated. A notional TDM spacecraft that meets the requirements of such a mission will be showcased in this paper.

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INTRODUCTION

The Heliopause Electrostatic Rapid Transit System (HERTS), investigated under a previous Phase I NIAC award and further funded in a follow-on two year Phase II NIAC awarded in September 2015, is a revolutionary propulsion concept that is ideal for deep space missions to the outer planets, the Heliopause, and beyond. It is revolutionary in that it uses an Electric Sail (E-Sail) to obtain momentum from the hypersonic solar wind and can provide propulsion throughout the heliosphere, as shown schematically in Figure 1. Consistent with the concept of a "sail," no propellant is needed as electrostatic interactions capture a small amount of thrust from the solar wind that can, over a period of months, accelerate a spacecraft to enormous speeds—on the order of 100-150 km/s (~ 20-30 AU/year). Accordingly, the HERTS would enable a spacecraft to reach the Heliopause in less than 15 years.

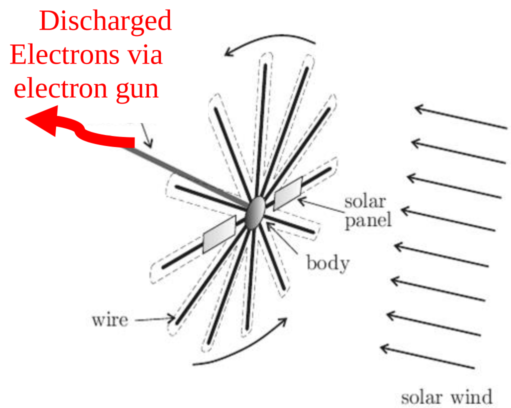


Figure 1. E-Sail Model

The basic principle on which the HERTS propulsion system operates is the exchange of momentum between an "electric sail" and solar wind, which continually flows radially away from the sun at speeds ranging from 300 to 700 km/s (Figure 2). The "sail" consists of an array of long, charged wires which extend radially outward 10 to 30 km from a slowly rotating spacecraft (Figure 1). Momentum is transferred from the solar wind to the array through the deflection of the positively charged solar wind protons by a high voltage potential applied to the wires.

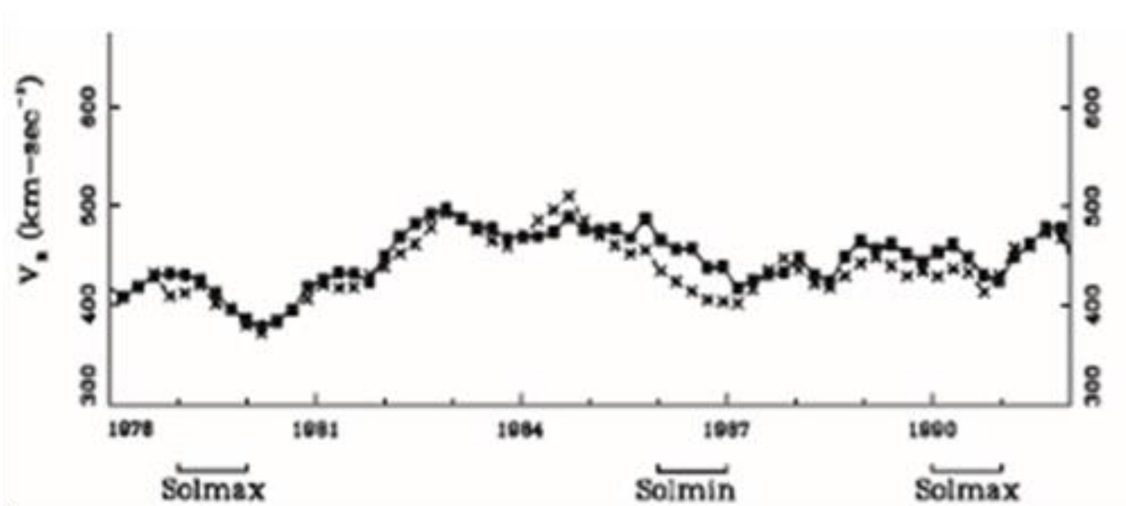


Figure 2. Solar Wind Velocity over Time

Electric sail propulsion has been explored and recently published in the open literature, primarily by Dr. Pekka Janhunen, of the Finnish Meteorological Institute (FMI). The Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) performed a top level feasibility study in 2013 which indicated a HERTS propulsion system can accelerate a spacecraft to velocities as much as three to four times that predicted by any realistic extrapolation of solar electric and solar sail propulsion systems. The results of the Phase I NIAC study found the concept to be feasible from a mission design perspective and identified technical issues for further study. Since most of the E-Sail propulsion system components already have a flight heritage, it can be reasonably expected that a HERTS system capable of reaching the Heliopause in less than 15 years could be developed within a decade and provide meaningful Heliophysics Science in the 2025-2030 timeframe. Furthermore, the propulsion system can be used to explore any of the major planets or their moons with transit times significantly less than any other concept.

BENEFITS TO SPACE EXPLORATION

The E-Sail concept presents an inherently scalable system. There is considerable flexibility in how the spacecraft is configured and operated. If the theoretical predictions from the plasma testing and PIC modeling are consistent with the current models, then the system will be scalable down to a CubeSat in the 6U to 12U formats. One of the more significant risk of the E-Sail is the amount of current required to energize the electrostatic sheath. If there are large amounts of electrons captured, the concept will still work, however the larger current draws will limit the ability to scale down to CubeSat scales.

Deep space exploration is going to be governed by the ability to power the satellite and by the distances needed to communicate the data back to earth. Obviously there are numerous other drivers, but these two are driven by the distance from the sun. For missions closer to the sun the use of photovoltaic arrays to generate electricity will be practical. Once distances expand beyond serval AU the size of the solar arrays will become a major portion of the mass and volume of the spacecraft. At some point the mission designers are forced to use nuclear power sources which tend to drive up the mass of the spacecraft. The E-Sail is scalable for any of these configurations, and if the power demands are as projected, the CubeSats become viable to explore many of the planets and their moons. Mars transfers are very practical as well as missions to the various liberation points.

The E-Sail propulsion system could allow CubeSats to travel to the inner-planets as well as distances greater than the asteroid belts. One mission that has been proposed is an asteroid belt mapping mission where an E-Sail is used to propel the spacecraft to the Asteroid belt and then the ability to steer by modulating the electrostatic sheaths would be used to inspect the asteroids and map the ones of interest for later missions. This exciting mission would be of interest to planetary scientists as well as commercial interests that plan to mine the asteroid belts.

The lifetime of a satellite propelled by the E-Sail is driven only by the endurance of the hardware since no propellant is required. A small CubeSat could circle through the Asteroid belts for years continuing to map the belts and obtain detailed surveys across the entire belt. Very few if any other propulsion system offers this kind of endurance and performance.

TECHNOLOGY DEMONSTARTION MISSION OBJECTIVES

Before any future Heliopause exploratory spacecraft or Interstellar spacecraft, which is to be propelled through space via an electric sail propulsion system is funded and built by any space fairing nation, the basic principles of propulsion via an electric sail propulsion system must first be demonstrated in deep space. The deployment of the required electric sail conductors must occur outside of the Earth's magnetosphere, since the electric sail produces thrust through the momentum exchange created by electrostatic repulsion that is present between the solar wind positively charged solar wind protons and a positively charged space conductor/s. Therefore, our team believes that a Technology Demonstration Mission (TDM) must be developed and flown in deep space to prove the principles of electric sail propulsion.

Our proposed TDM mission concept (Figure 3) would utilize future NASA Space Launch System (SLS) ride share opportunities in the early 2020's with the TDM spacecraft being jettisoned from the SLS upper stage once the Orion Module safely has separated from the launch stack in the Cis-lunar region of space. The overall focus of the TDM spacecraft investigation was to determine if all of the components necessary for an electric sail propelled TDM spacecraft could be packaged within the volume allocated for a single 12U spacecraft.

Before a representative electric sail TDM spacecraft could be conceptually developed, one key driving requirement (KDR) had to be set by the team, as this unique KDR set the systems design for the propulsion, power and thermal subsystems. This unique KDR is the characteristic acceleration value. The chosen characteristic acceleration was set to be equal to, or greater than 0.6 mm/sec^2. This value was selected as it is an order of magnitude greater than the NEA Scout solar sail spacecraft characteristic acceleration value of 0.06 mm/sec^2 (figure 4). It was our team's philosophy that this TDM shall demonstrate an acceleration potential that is close to the minimal characteristic acceleration required by the HERTS spacecraft, which is 1 mm/sec^2 as determined by the NASA HERTS team during the Phase I NIAC study. A comparison of characteristic accelerations of the NEA Scout to other spacecraft that have flown can also be seen in Figure 4.

The primary goals of the TDM as designed are to develop a CubeSat that can: 1) Deploy a 16,500 m conductive tether in deep space, 2) Charge the tether to a 6000V DC positive bias, 3) Accelerate the spacecraft, and 4) Steer the spacecraft. The secondary goal of the TDM is to collect meaningful science data either in route to a final destination or at the final destination.

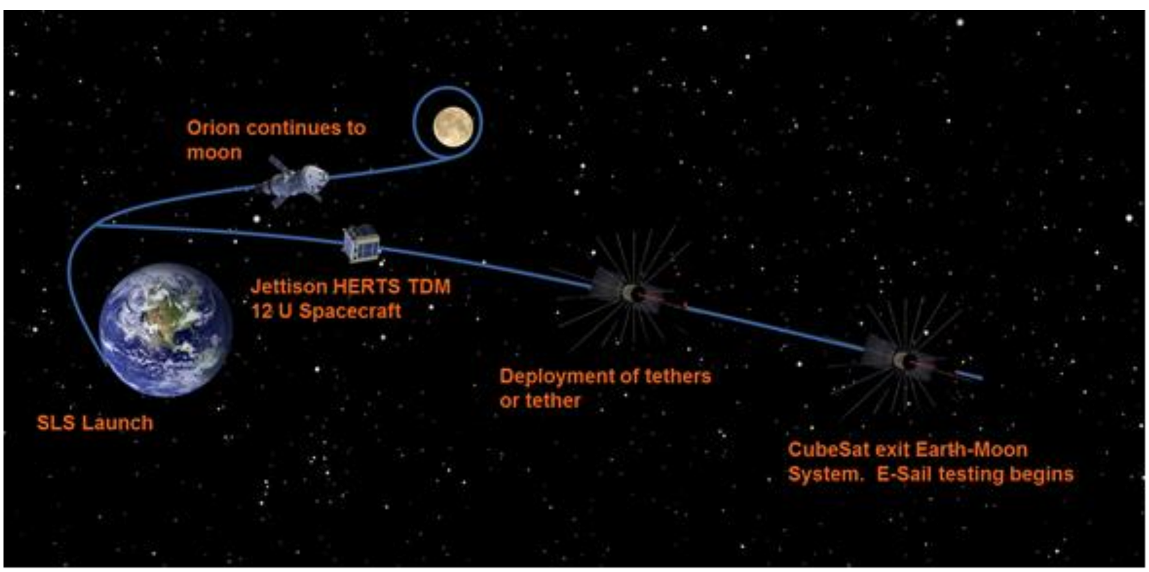


Figure 3. Overall Concept of Operation for the E-Sail Technology Demonstration Mission Spacecraft C1onfiguration

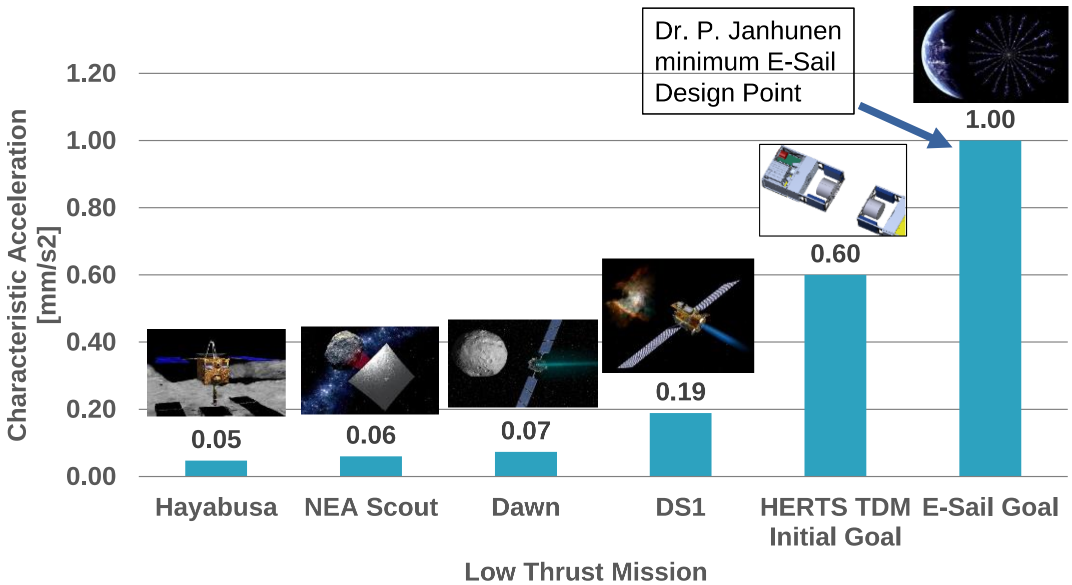


Figure 4. Comparison of E-Sail Acceleration to Other Spacecraft

SCIENCE MISSION OBJECTIVES

Our team has determined that the possible deep space locations and destinations for an electric sail TDM are constrained by two spacecraft attributes, notably the electrical power production methodology and communication system architecture. Since this mission is to be a low risk mission the electrical power system must use photovoltaic arrays as the source of electric power. This decision limits the destinations to < 5AU distances. The communication design requires electrical power to drive the spacecraft transponders and at distances > 1 AU total distance from the Earth, the physical demands (size mass, and power) of a communications system outgrow the space allocated for such a system in a CubeSat architecture. Therefore, the team limited the reference maximum distance away from Earth to a 1 AU range.

Upon looking at these constraints the team determined that the best scientific return would be a Heliophysics mission that took Heliophysics sensors out of the solar system ecliptic plain. Figure 5 shows the effects of an electric sail spacecraft's initial characteristic acceleration versus the total inclination out of the solar systems ecliptic plain achieved over a three year mission. This propulsion technology will enable small scientific spacecraft to get to many locations outside the ecliptic plain in order to investigate the sun and its affect upon space weather better.

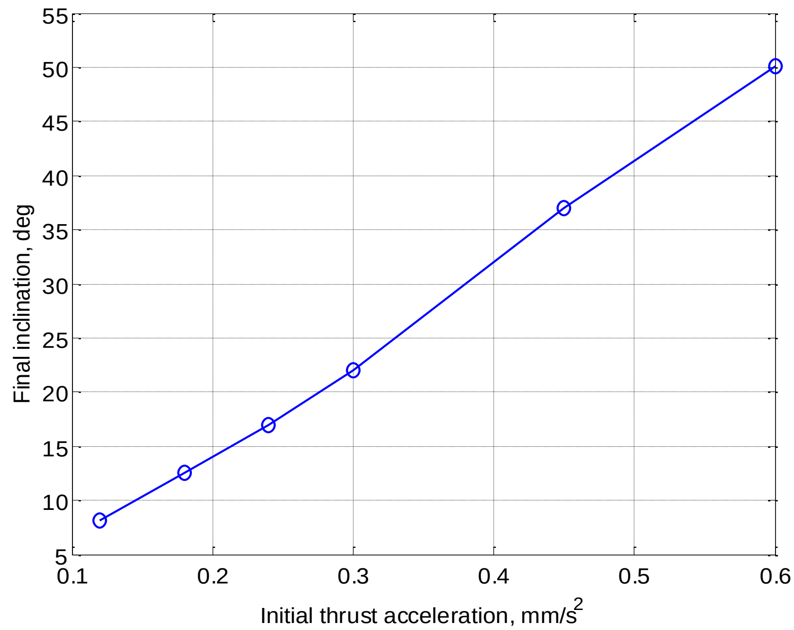


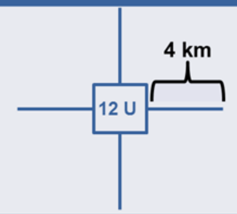
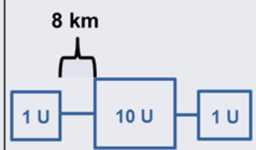
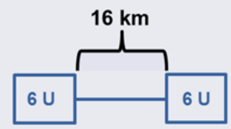
Figure 5. Inclination from Ecliptic Plane vs. Characteristic Acceleration over Three Year Trip

TDM CONFIGURATION TRADES

Trades were conducted to determine the best spacecraft architecture for deployment of the 16,500 m of conductor/s required to meet the TDM spacecrafts characteristic acceleration specification. The configurations that were traded are shown in Table 1 and include the Hub and Spoke, Hybrid, and Barbell. Initial approaches attempted to duplicate the large HERTS class spacecraft which used a hub and spoke configuration. The desire was to mimic the HERTS conductor/tether configuration as close as practical. The constraints of mass, volume, and propulsion to deploy the systems quickly eliminated the hub and spoke concept as infeasible at this scale or with a small number of conductor wires deployed.

This paper will use the terminology “conductors” and “tethers” interchangeably the long conductor wires are essentially deployed as tethers. In reality a tether is considered a device to connect two objects and in the E-Sail propulsion systems, the outer object is simply an end mass. While tethers can be used to describe this, some of our team use conductors. We will focus on conductors for the remaining portion of the paper.

Table 1: TDM E-Sail Configurations

	"Hub and Spoke"	"Hybrid"	"Barbell"
			
Tether Length	4 Tethers, each 4 km length	Two tethers, each 8 km length	Single 16 km tether
Steering Capability	Different tether voltages	Different tether voltages	Insulator/switch at center

The total thrust is detemined primarily by the charge on the conductor and the total length that is deployed. Table 2 presents the total conductor length required to obtain the desired accleration for the TDM. This table also presents the rotation rate required to deploy the conductor if a single conductor configurations is selected. In the TDM case, 16 km was selected as the conductor length for a goal of demonstrating acceleration ten times greater that that obtained by the NEA Scout solar sail mission. The number was selected as a challenge to the team, and since new technology performance is inversely related to the maturity of the technology, a factor of ten was selected as simple enough for acceleration to make the E-sail viable in systems trades. This can be a single tether that is 16 km long or 50 conductors that are 320 meters long each. Interaction between sheaths is largely unknown at this time, so we desire to minimize that overlap intially. Multiple conductors are required to provide steering, so in the case of a single condcuctor, a node or switch / potentiometer is required at the center to allow the condcuctors' voltages to be modulated to provide steering. It is postulated that sheath to sheath overlap may provide better performance, but no analysis has been conducted at this time.

Table 2. Characteristic Acceleration Rates vs. Total Conductor Length

E-Sail TDM (mm/s2)	S/C Mass (kg)	Total Wire Length (m)	Length of Each Wire (4 wires total)	ω_2 (Rev/sec)	l_2/l_1	ω_1 (Rev/min)
0.06	24.0	1,655	413.79	0.00010	61,927	**356**
0.12	24.0	3,310	828	0.00010	381,256	**2,192**
0.18	24.0	4,966	1,241	0.00010	1,158,317	**6,660**
0.24	24.0	6,621	1,655	0.00010	2,593,440	**14,911**
0.3	24.0	8,276	2,069	0.00010	4,886,952	**28,097**
0.6	24.0	16,552	4,138	0.00010	36,241,861	**208,370**
1.0	24.0	27,586	6,897	0.00010	162,501,675	**934,291**
2.0	24.0	55,172	13,793	0.00010	1,268,305,111	**7,292,024**

The simplest deployment would be a spin and deploy where the spacecraft is spun up to the desired angular momentum folled by deploying the conductors. This would result in the conductors being deployed by the centrifugal forces created from the spin and would end after deployment with the spacecraft in its final configuration. The configuration in deep space would conserve angular momentum, so if a rotation rate of 3 to 5 rotations per day was desired then that defines the total angular momentum for the system. The final rotation rate is required to maintain 5 to 10 times the total thrust on each condcuctor. If the conductors were not rotating then the thrust would swing the conductors upwind over time and eliminate the thrust on the vehicle. The final geometry of the conductor has not been clearly defined, but the wire will assume a hyperbola or similar shape that will cause some losses due to a cosine effect of the angle between the sheath and the solar winds. The impact of that has not been clearly defined at this time.

To use a spin deployment presents a challenge to the spacecraft to both provide the initial anlgular momentum in a compact volume and to design a vehicle that can take very high initial angular momentums. It is clear by examining Table 2 that the rotation rates and G levels on the spacecraft using a spin deployment is infeasible unless the extended length of the conductor is relatively short. To make the hub and spoke feasible in deployment of conductors, a large number, approaching 50 or more, of individual conductors may be required, and these architectural affects must be investigated more thoroughly. Spinning up any spacecraft will require both propulsion and fuel which takes up a volume allocation of the total volume available.

The use of propulsion to deploy the conductors is part of the trade space. A quick assessment shows that there is a large trade space within the use of the propulsion for deployment. Since this technology demonstration flight will be a secondary payload, the use of propellants will be restricted. Cold gas systems are considered as well as ion thrusters in some cases. The spin up on a small body to very high angular momentum requires a large amount of propellant if the initial spin up is done room the stored configurations. Figure 6 presents the total impulse required for deploying a hub and spoke configuration from a stored configuration. The x axis of Figure 6 is the value of total conductor length to be deployed whereas, the y axis is the total number of tethers. The lines on the chart represent the required propulsive impulse required (N-s) to deploy a variety of tethers of length L vs the total number of tethers present in the system. A quick inspection of this figure shows that the propellant requirements are very large for long tethers. Clearly the propellant requirement favors short conductors. Taking the trade to the next logical step is to assess the impact of using propellants on long arms or at the end of the conductors to provide the spin up. As the leverage arm increases the required propellant, the mass goes down.

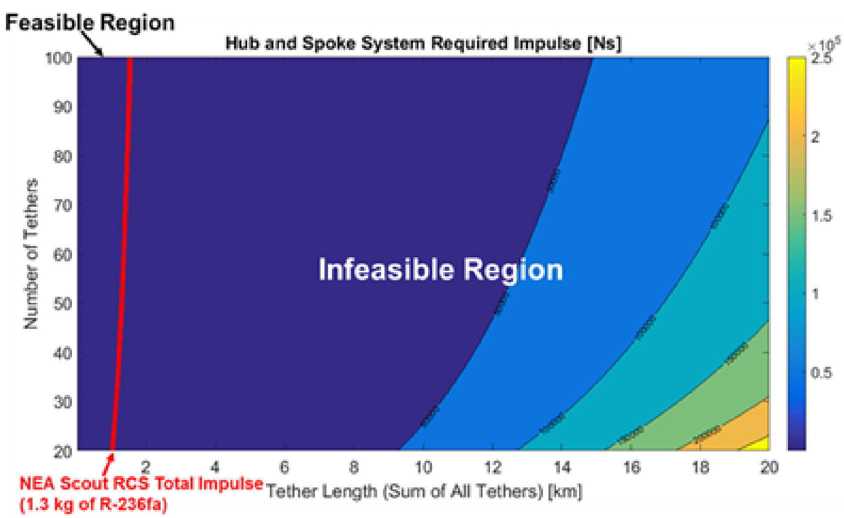


Figure 6. Total Impulse Required for Tether Deployment vs Total Tether Length

The current baseline approach for the large HERTS class satellites is to use several ion thrusters at the end of a deployable arms to provide the energy to spin up the vehicle. To further complicate the issue, we must consider on large spacecraft the presence of an auxiliary conductor that connects the conductors in a ring at some distance from the center. This auxiliary line is not likely to be used to conduct current, but rather to connect the conductors mechanically. In the cases where the vehicle modulates the current on individual conductors to provide steering, the concern is that the conductors will move out of place unless the conductors are mechanically restrained. The studies are underway to assess if this is required since the conductors, once deployed, are very large distances apart. For the TDM mission, we are not considering these auxiliary lines due to their complexity in the deployment and the fact their need is not firmly established at this time.

The final configuration selected was the barbell as shown in Table 1. The barbell configuration provides simplicity and meets all of the requirements as well as providing mitigation for most of the key technology issues identified for the HERTS class propulsion system. A hub and spoke configuration would have increased the similarity to HERTS class missions, but the added complexity and costs made it a less desirable approach for a TDM flight. The concept of operations of the barbell configuration is to use small cold gas thrusters to separate the two 6U spacecraft deploying the single 16,500 m conductor (8,250 m contained in each 6U spacecraft) as the two spacecraft separate (See Figure 7).

Each spacecraft is identical and carries half of the conductors required. The center of the conductor contains a small switch that allows the conductor to be connected as a single conductor if required. The baseline configuration would be to deploy with the switch in the off position since each spacecraft is capable of providing the current required. After the initial deployment is complete the thruster at then used to spin up the bodies. Since the leverage arm is 8 km from the center of the mass the propellant requirements are very modest. The use of redundant spacecraft provides a degree of redundancy that most CubeSats cannot afford.

The electric sail propulsion system's success is highly dependent upon the conductor material chosen. Therefore, much work has been focused into identifying the best potential conductor materials to investigate for further analysis and testing. Table 3 showcases the variety of tether/conductor materials that are being evaluated including various synthetic materials and metallic materials. The current reference conductor material the team is using is the Amberstrand material. This is due primarily to the low density of the material coupled with its tensile strength properties. Whereas the metallic materials (copper or aluminum) offer much better electrical conductivity values, this comes with a much larger mass to the system and much lower tensile strength properties.

Table 3: Tether/Conductor Materials Being Investigated

	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

DOWN-SELECTED SPACECRAFT CONCEPT

Marshall Spaceflight Center Advanced Concepts organization developed a concept of the TDM spacecraft. Since the mission must be conducted outside the Earth's geomagnetic field, the avionics and subsystems must be compatible with the radiation environment of deep space. Typically these components are more complex and expensive.

Another MSFC team in conjunction with JPL is developing the Near Earth Asteroid (NEA) Scout vehicle which is a 12U CubeSat expected to fly on the first SLS mission. The NEA Scout is a solar sail demonstration flight that will travel to a near earth asteroid and survey the asteroid from a very close range. The NEA Scout spacecraft bus design offered a very close fit to the E-Sail TDM requirements. Therefore, the NEA Scout became the obvious point of departure for the bus design.

The overall concept of operations is shown in Figure 3 and targeted for a future flight of the SLS program. Other deep space missions on expendable rockets will be considered as well. The exact concept of operations will depend on the primary payload mission requirements. Shown in Figure 3 is a concept using the second flight of the SLS with crew on-board. In this lunar bound flight, the spacecraft is ejected during the trans-lunar flight phase, and once separated a safe range from the Orion module the spacecraft will begin the deployment of the 16,500 m of the conductors / tethers. The spacecraft will then energize the conductor to a positive biased voltage of 600V dc. It has been calculated that such a positive bias will create a Debye sheath of 50 m to 100 m in diameter around the energized conductor. This energized sheath will then reflect and deflect the protons that occur in the solar wind electrostatically thus producing thrust. Once the conductor is energized and thrust is produced, the testing of the E-Sail propulsion system will commence. Once initial testing is complete over a multiple day period, the spacecraft will begin to exit the ecliptic place to conduct the solar observations described in the Science Mission Objectives.

The function that the NEA Scout bus provides is a very close match to the E-Sail requirements. The primary issue yet to be address from the bus perspective is the communications requirements. The E-Sail TDM trajectory will be different than the NEA Scout, but the final trajectory has not been defined so no changes to the RF system have been addressed. JPL is developing the NEA Scout avionics hardware and the design is fairly mature. The flight is still several years away so modifications are possible. The E-Sail TDM assumed little of no changes to the NEA Scott for the preliminary concept. The hardware largely maps over one to one but the specific layout and positions of each subsystem differs in some degree due to the E-Sail propulsion interfaces and the use of two identical buses.

A preliminary layout is shown in Figure 7, which reflects the NEA Scott avionics and the E-Sail propulsion system as currently defined. The two identical spacecraft would be launch on top of each other and would be deployed for the SLS vehicle as an assembly. After deployment to acceptable distances from the SLS / Orion vehicle the two spacecraft separate and begin deploying the conductor.

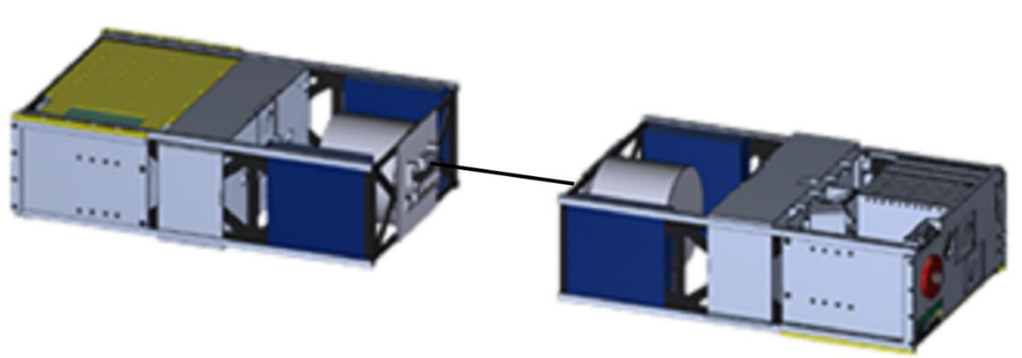


Figure 7: E-Sail TDM Spacecraft Configuration

FUTURE WORK

The electric sail work that our team is focused on is funded through September 2017, by the NASA Space Technology Mission Directorate (STMD). During these next months, a state of the art Particle-in-Cell (PIC) spacecraft model will be completed by a team member at the University of Alabama in Huntsville which will allow spacecraft designers the capability to determine the effectiveness of an electric sail propulsion system for future spacecraft of various sizes. Upon completion of this model, our team will re-evaluate the spacecraft designs for both the Heliopause mission and the TDM mission.

In addition, our team has been given internal MSFC 2017 Technology Investment Program (TIP) funding to demonstrate the tether deployment from two 6U satellite mockups on the MSFC Flat Floor Facility during the summer of 2017. This work is fundamental to proving the functionality of various electric-sail subsystems, including the tether deployer. Many recent space tether missions have failed, because of various tether deployment issues. This flat floor testing will be one of the risk reduction steps our team is taking.

The team has also submitted a proposal to fly a tether deployer system on an upcoming 2018 sub-orbital flight sponsored by NASA's STMD Flight Opportunities Program. The sub-orbital flights that are currently targeted in this solicitation may have up to 5 minutes of zero gravity time available. It is our team's belief that 200 m and possibly up to 1000 m of tether could be deployed in such a flight opportunity. However, the total amount of tether deployed is highly dependent upon the total zero gravity time, as well as the deployment speed of the as-built system. The lessons learned from the summer of 2017 flat floor testing will be integrated into the design of the sub-orbital flight hardware.

CONCLUSIONS

The fundamental research that is occurring at the MSFC in support of the Phase II NIAC project enumerated above will lead to a green, revolutionary propulsion system that may achieve travel speeds of up to 8-10 AU/yr. These spacecraft speeds are necessary for various future deep space missions of scientific discovery over the next 20 to 50 years. Before such elaborate missions can be fielded, an actual demonstration of this propulsion technology must be completed. The authors believe such a TDM can be commenced when the SLS EM-2 flight is launched in 2021, and the TDM will be completed after three years of operations, at which time the reference spacecraft may achieve an inclination of 50 degrees out of our solar system's ecliptic plane. At these locations, vast quantities of Heliophysics science data can be returned to scientists on Earth, thereby increasing our knowledge of the solar storms and resulting space weather phenomenon that eventually effect the Earth and many of the operational satellites in orbit about our planet.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the NASA MSFC Advanced Concepts Office for their work in performing the concept studies for the HERTS TDM spacecraft.

We also wish to thank NASA's Space Technology Mission Directorate, notably the NASA Innovative Advanced Concepts (NIAC) Program, which is led by Dr. Jason Derleth for continuing to fund the Phase II HERTS NIAC project.