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Electric Sail Design Sensitivities

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Abstract:

Electric Sails (E-Sails) are a promising propulsion technology that seek to enable high characteristic propellentless acceleration for spacecraft to reach distant and/or difficult to reach orbits such as rapid transit to heliopause. The E-Sail system exchanges momentum by using positively charged electrostatic tethers to repel solar wind photons to push it through space. This concept was first theorized by Pekka Janhunen in 2004 with further developments occurring including a NASA Innovative Advanced Concepts Phase 1 and Phase 2 hosted out of NASA's Marshall Space Flight Center (MSFC) [1]. These developments led to further maturation of the overall system, and this paper is designed to help identify different design sensitivities of an integrated Electric Sail system. To approach this, a small team at MSFC took an in-house developed three degrees of freedom (3DoF) simulation tool and a trajectory modelling tool to look at different design parameters and to determine a potential ideal E-Sail configuration.

An E-Sail system has different design architectures including a barbell design, hub and spoke design, and a potential hybrid solution. The barbell design features two equally massed satellites that spin around a central point in the tether system. The hub and spoke design features a large central spacecraft with small end spacecraft to aid in formation control of the overall E-Sail system. Leveraging elements from both the hub and spoke, and barbell design, a hybrid option exists where one could have a larger central mass and one or two tethers extended to a smaller end mass [2]. In summary, the hub and spoke design is the ideal configuration for E-Sail with tethers spanning kilometers to achieve the designed design characteristic acceleration of at least one mm/s^2 with this architecture being the focus of this study.

Different key design parameters were varied as part of this study. These parameters include the total number of tethers, the length of the tethers, spin rate, relative spacecraft mass, tether voltage, inertia per tether, and impact of slew rate changes. These results started from an internal MSFC technology demonstration mission design and then the parameters were varied with engineering judgement to ensure that the results were consistent with expected results. These were varied in the MSFC 3DoF tool and compared to baseline results to generate a candidate ideal E-Sail design system. These results were then used to help inform the mission analysis design for the system.

The 3DoF trajectory optimization was performed in the Astrodynamics and Space Science Enabling Toolbox (ASSET) and utilized collocation optimization of control vector pointing with the objective function being transfer duration. A representative model of the E-Sail force was derived as a function of the Sun-pointing vector direction. This model was initialized with a zero Sun Incidence Angle (SIA) trajectory for the initial guess generation, then with a portion of the mission optimized SIA time history for fast outbound transfers. After the trajectory is hyperbolic relative to a heliocentric frame, the SIA is maintained at 0 degrees except for any needed trajectory correction maneuvers. This trajectory optimization looked at different characteristic acceleration values to analyze the impact it had on mission performance.

As a result of this study, the team can best inform mission designers and technology development efforts to mature the E-Sail system. This study will allow mission designers to have defined rules-of-thumb to design an E-Sail system to meet desired mission needs as well as providing several sample mission profiles. These design drivers will inform maturation efforts on which design requirements to consider for an integrated E-Sail design.

Nomenclature

ASSET	Astrodynamics and Space Science Toolkit
AU	Astronomical Unit
DRM	Design Reference Mission
DRV	Design Reference Vehicle
E-Sail	Electrostatic Sail or Electric Sail
FOSS	Free and Open Source
HERTS	Heliopause Electrostatic Rapid Transit System
NASA	National Aeronautics and Space Administration
NIAC	NASA Innovative Advanced Concepts
ROSES	Research Opportunities in Space and Earth Sciences
SIA	Sun Incidence Angle
SPI	Solar Polar Imager

I. ELECTRIC SAIL SYSTEM OVERVIEW

Electric Sails are a propellentless propulsion system that creates propulsive force from the momentum exchange of positively biased electrostatic tethers and the protons found in the solar wind. Different configurations of tethers exist with the focus of this paper being on the hub and spoke design.

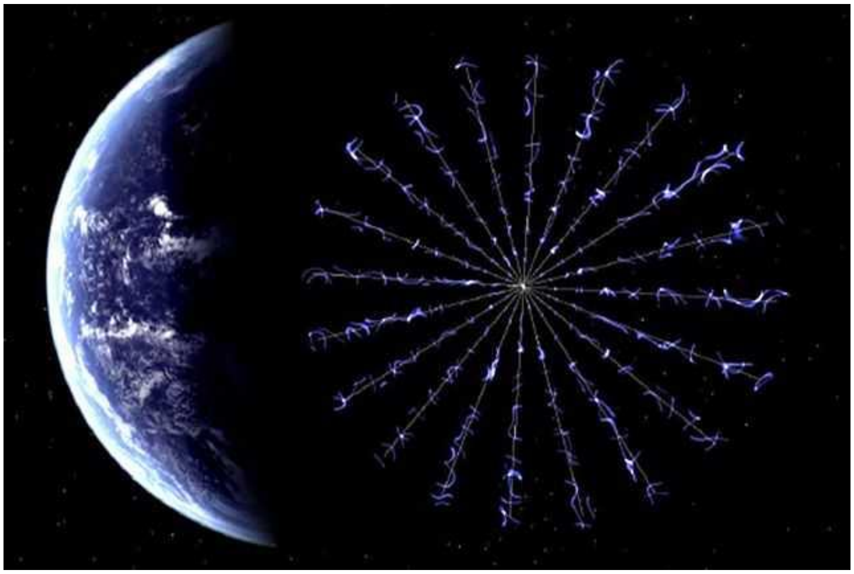

Figure 1. Electric Sail Hub and Spoke Design [2]

An artistic visualization of the hub and spoke can be seen in Figure 1. These tethers spanning from the central hub extended in the distance of kilometers even for a small spacecraft to create an effective sail area for propelling through space. This sail area is formed through a plasma sheath forming around the charged tethers [2]. The sail shape created from the combined tether sheaths is vital for creating a uniform shape to propel it through space.

E-Sails can be used for various missions with the primary use case being rapid transit to the outer solar system and reaching heliopause. Currently, only the Voyager 1 and Voyager 2 probes have passed this threshold into interstellar space which took them up to 40 years to reach that threshold. Previous design studies into this transit with electric sails expected approximately a 10-year transit time. This value has been circulated as the ultimate design goal of Phase 1 and Phase 2 for NIAC developments of the electric sail system. In addition to this mission, other missions of interest utilizing this high characteristic acceleration include a solar gravitational lens, rapid transit to outer planets, solar storm monitoring. Another mission of consideration is a multiple aperture telescope which utilizes the hub and spoke design of the electric sail to distribute multiple sensors in a large form factor. These two design attributes, characteristic acceleration and formation integrity form the basis of this study and how changes in the system design impact those attributes.

II. ELECTRIC SAIL TRADE SPACE

To create this trade study, several different design parameters were selected to vary as part of this study. These design parameters were chosen as these are part of design choices that one will have to make when creating an electric sail configuration. The goal of the trade study is to demonstrate on how tuning these parameters impact the overall performance with a focus on the characteristic acceleration of the system and formation integrity during a sample slew maneuverer. In addition, some of these factors may couple together and cause coupled improvements or detractions from performance.

The parameters varied were the following: length of tethers, spin rate, relative mass between the central body and the outer end satellite masses, and tether voltage. The number of tethers for different sized electric sail spacecraft varies with concepts for a small hub and spoke spacecraft design having four tethers and larger one such as the HERTS spacecraft concept featuring twenty tethers spanning radially [3]. Spin rate of the overall system can be tuned based on deployment methods but specifics on how to achieve this final spin rate are beyond the scope of this study. Ratio of mass between the end masses and the central spacecraft are part of the design process as the end masses are small spacecraft that help maintain the formation control of the overall tether array. Tether voltage changes the voltage potential on the tethers which this tether potential is what help creates the momentum exchange between the solar wind and the sailcraft, propelling it through space. The tether inertia is a function of the chosen tether material and the weaving of it with designs such as the Hoyt tether to provide protection against micrometeoroids and other small space debris.

In addition to varying these unique parameters, some of these parameters may couple together and provide constructive benefit or may inhibit when looking at different combinations. Due to the short turnaround nature of this study, coupling parameters candidates were identified for study but were not able to be completed as part of the study such as coupling between the spin rate and tether inertia. Other candidate parameters that were considered for study were the tether voltage transients which impacts the change rate of tether voltage and thrust values for the end mass thrusters. These parameters were not pursued due to time constraints.

III. TRADE SPACE METHODOLOGY

The trade space was studied by modeling, simulating, and analyzing the performance of design variants in an attitude and formation dynamics and control simulation environment in MATLAB.

The design variants were generated using by varying each of the variable design parameters over a range of values to assess the effects on, and sensitivities of, key performance metrics. Each design parameter was varied about a baseline value corresponding to a Design Reference Vehicle (DRV) that was derived from a previous study as a vehicle which could achieve transit time objectives for a Solar Polar Imager (SPI) Design Reference Mission (DRM) while exhibiting decent controllability for slewing, formation keeping, and spin control [3]. The ranges of values over which the design parameters were varied are shown in Table 1. Each design variant corresponds to a single simulation case, all under the same scenario as a basis of comparison.

Table 1: Electric Sail Parameters Varied

Parameter Varied	Design Reference Value	Lowest Value	Highest Value
Length of Tethers	8000 meters	5000 meters	11000 meters
Spin Rate	0.005 rad/s	0.0005 rad/s	0.05 rad/s
Mass Ratio between Central Point and End Mass	Each End Mass is 16% of the Central Mass	Each End Mass is 4% of the Central Mass	Each End Mass is 34% of the Central Mass
Tether Voltage	6000 Volts	3000 Volts	12000 Volts

The simulation involves a slew from normal sun incidence to 45 degrees of sun incidence angle (SIA) to assess slew capabilities while also stressing the non-ideal tether dynamics, such as deflection of the end satellites and tethers out of the spin plane, that impact formation keeping and spin rate control. This slew maneuver is representative of a realistic mission scenario where the end satellites are deployed, spun up, and powered on in a sun-facing orientation to maximize power generation, then turning to the SIA which maximizes thrust in the velocity direction for orbit raising and lowering maneuvers. As the intent of this study was to assess the dynamics and controls of a fully operational E-sail, the simulations were initiated from a fully deployed, spun-up, and powered-on state.

The spacecraft bodies (i.e., the central hub and the end satellites) were modelled as point masses. The tethers were modelled as simple linear springs with axial tensile stiffness based on material properties and geometry of a realistic tether [2] and no compressive or bending stiffness, nor damping. With this tensile stiffness and root boundary conditions that allow the tether to rotate relative to the hub spacecraft body, the first-order effects of the solar wind exerting a lateral force on the tethers [2] and causing them to deflect. The centripetal forces acting on the tethers due to the spin of the E-sail and their impact on the out-of-plane dynamics were also captured. A slewing approach described in [4] involving varying tether voltage as a sinusoidal function of the orientation of the tether relative to the inertial axis of rotation of slew, was employed.

Thus, using these models, the variable design parameters described below in Table 2 result in different slew, spin, and out-of-plane tether deflection dynamics, which can be used as indicators of the state of health of the design from a guidance and control perspective. The key performance metrics used for assessing the design variants and sensitivities to the design parameters are listed and defined in Table 2.

Table 2**:** Key Performance Metrics

Key Performance Metric	Description	Ideal Performance
Characteristic Acceleration	Characteristic acceleration is the acceleration achieved by the sailcraft at 1 AU	Higher values are better than lower values
Cone Error	Deflections of the sail plane perpendicular to the direction of travel	Close to 0 degrees is ideal
Formation Error	Error between different end masses laterally	Close to 0 degrees is ideal
Slew Performance	Integrated sailcraft performance performing a slew	Smoothness of slew curve

A visualization of what cone error looks like can be found in Figure 2.

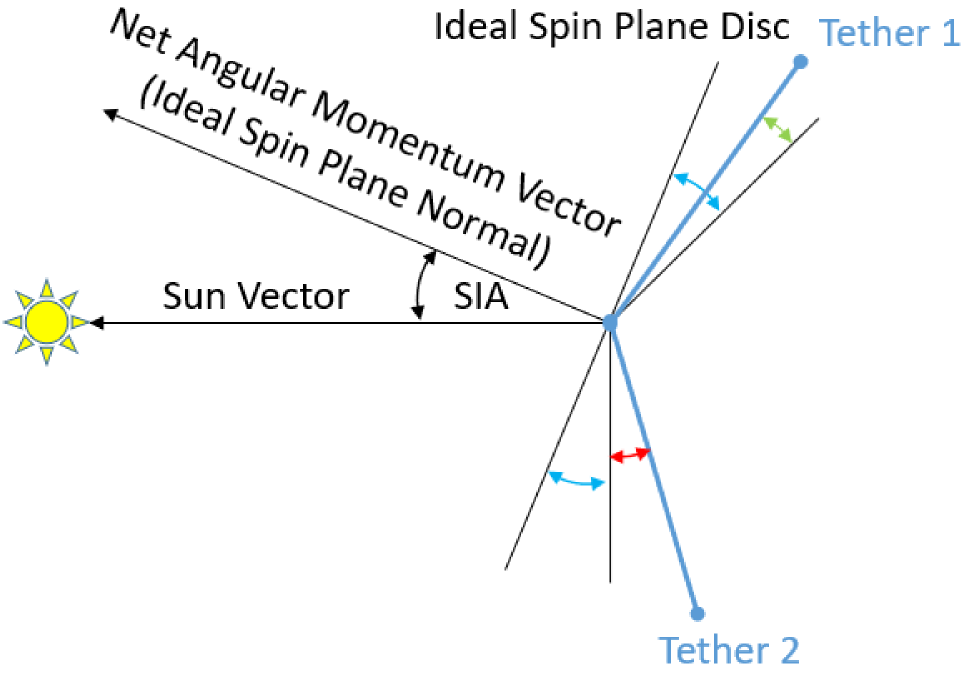

Figure 2. Visualization of Cone Error

Cone error can be seen with the blue line showing the average cone error while the green and red arrows refer to the local cone error. The overall tether dynamics are more complicated than rigid bars with the tethers flexing and bending because of the different forces on the sail. The ideal cone error forms a flat sail plane equal to the SIA.

A visualization of what formation error looks like can be found in Figure 3.

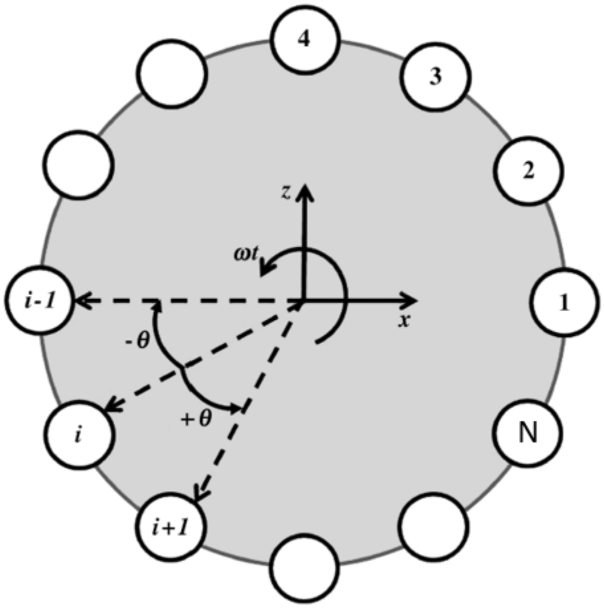

Figure 3. Visualization of Formation Error

The visualization presented in Figure 3 shows plus and minus theta values which are the angles in relation to the tether i. These thetas are to formation error are the delta between theta and number of tethers divided by 360 degrees or two pi radians. As this error closes to zero, that creates a uniform sail which helps minimize the disturbance torques for the integrated sailcraft system.

IV. Trade Space Results

A. Length of Tethers

The length of tethers in the electric sail system impacts all the key performance parameters outlined in table 2. The longer the tether increases the overall system inertia and increases the overall sail area.

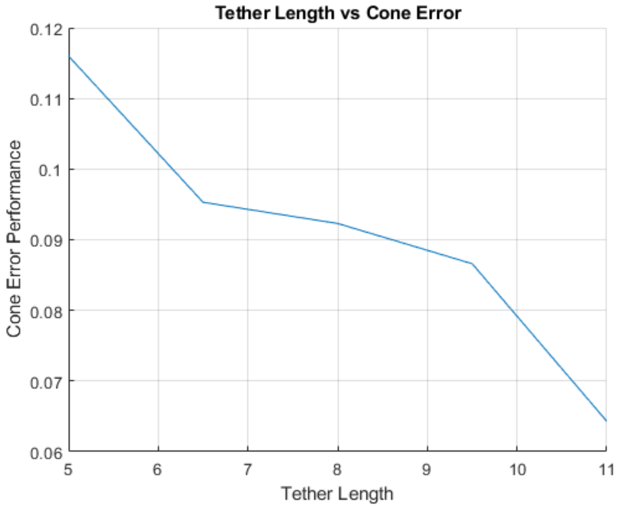

Figure 4. Tether Length vs Cone Error

Figure 4 shows the impact of increasing tether length versus cone error. Longer tethers lead to a smaller cone error in the system.

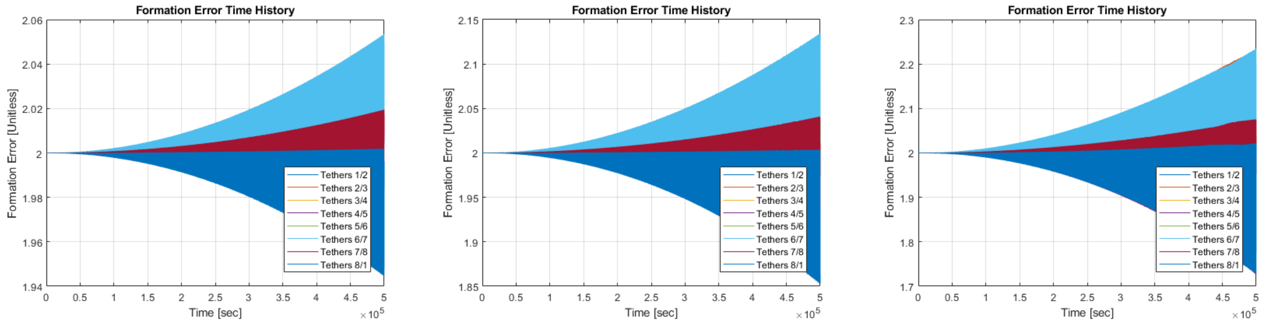

Figure 5. Formation Error with Increasing Tether Lengths from Left to Right

Figure 5 shows the opposite effect of cone error where it causes increasing formation error with longer tethers having larger errors.

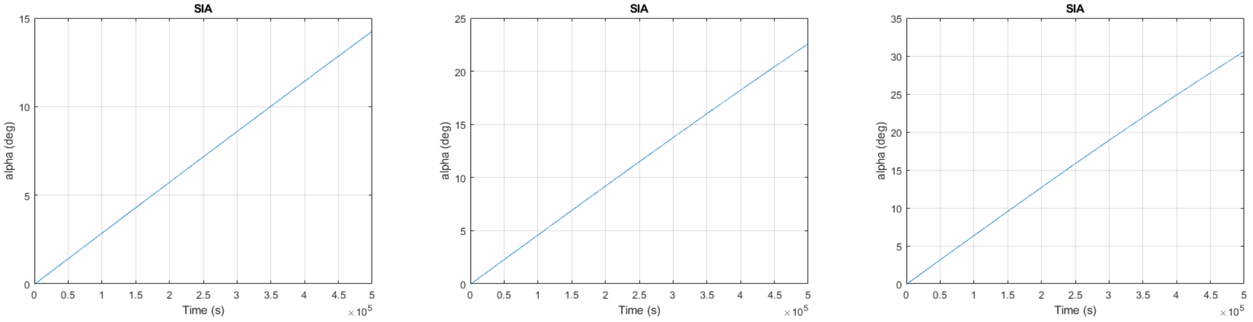

Figure 6. Slew Performance with Increasing Tether Lengths from Left to Right

Figure 6 shows the slew angle with a commanded 45 degree slew and the longer tethers causing a faster slew rate. This increase in slew performance is due to the increased sail area.

B. Spin Rate of the Electric Sail System

The spin rate of the system impacts the passive stability with cone error, formation error, and the slew performance. This parameter does not impact the characteristic acceleration due to it not impacting the sail size or the plasma sheath forming the effective sail area.

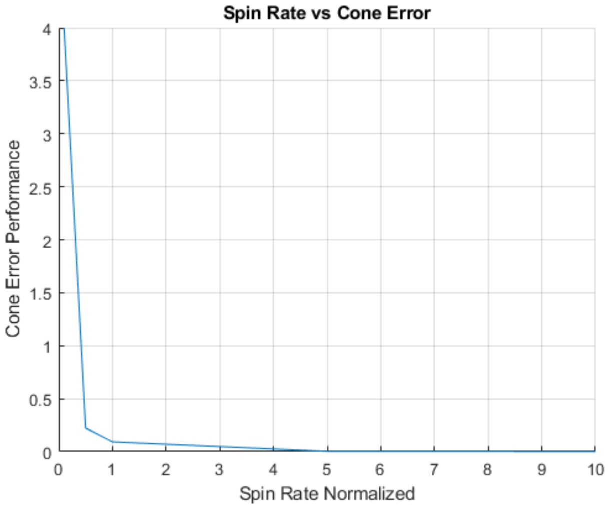

Figure 7. Spin Rate Versus Cone Error

Figure 7 shows the spin rate versus cone error with the spin rate normalized around 0.005 rad/s. The slower spin rate shows a high cone error but rapidly approaches zero with increased spin rates.

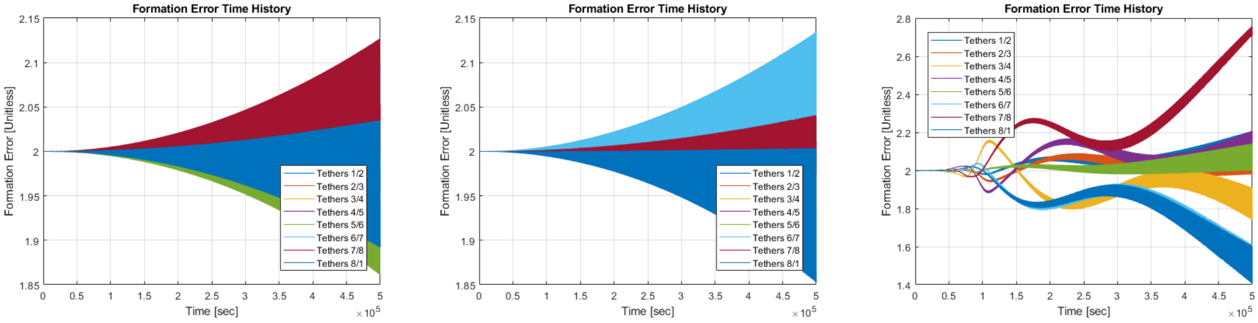

Figure 8. Formation Error with Increasing Spin Rate from Left to Right

Figure 8 shows the opposite effect where the formation begins falling apart as the spacecraft proceeds through the slew manuever that it is conducting. Formation error is slightly larger in the nominal but has a significantly smaller cone error in comparison to the slower rotational speed. Additionally, challenges may occur with trying to get the system up to the desired spin rate.

C. Mass Ratio Between Central Spacecraft and Tether End Spacecraft

The mass ratio between the outer spacecraft at the end of the tethers and the central spacecraft of the electric sail system is a crucial part of the dynamics of the integrated system. With this parameter changing the overall mass of the system and not impacting the momentum exchange effect other than reducing the acceleration, only cone error, formation error, and slew performance are impacted by this sensitivity study.

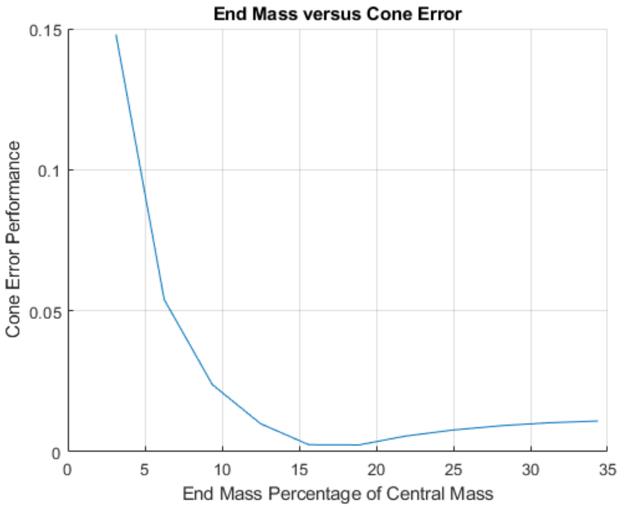

Figure 9. Cone Error as a Function of End Mass Percentage of Central Mass

Figure 9 shows how the end mass percentage changing impacts the average cone error. Due to the tether dynamics, a local minimum is reached between fifteen and twenty percent of the central mass and going outside of that window leads to increased cone error.

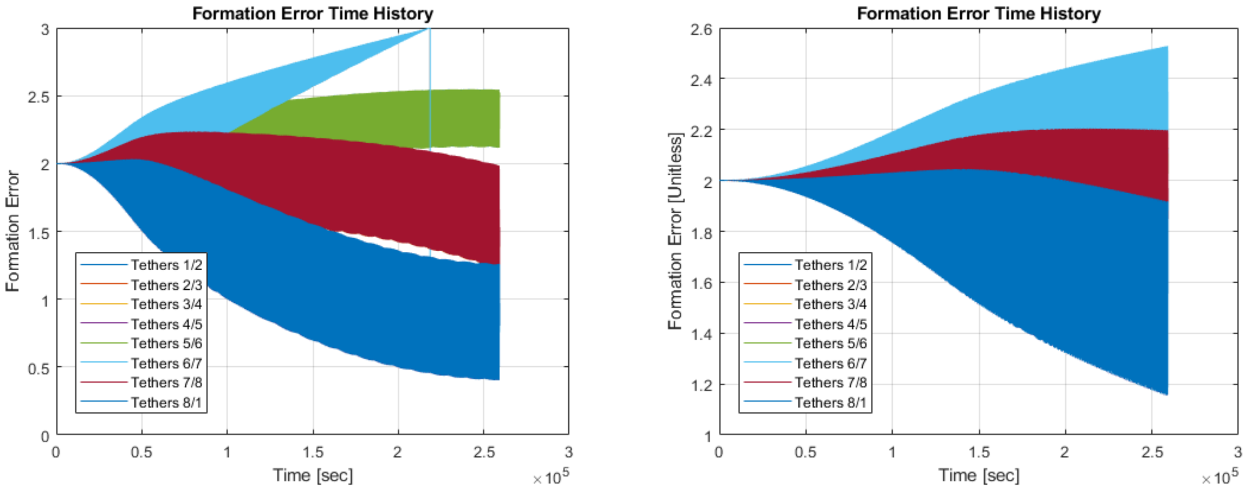

Figure 10. Formation Error at 6% End Mass Percentage (Left) and Formation error at 18% End Mass Percentage (Right)

As the mass percentage increases for the end mass, it reduces the overall formation error as shown in figure 10. Ideal formation error as indicated by these plots is two but it is a unitless form factor. Increasing mass further reduces this error but increasing mass has the trade off of leading to lower characteristic acceleration and increased cone error.

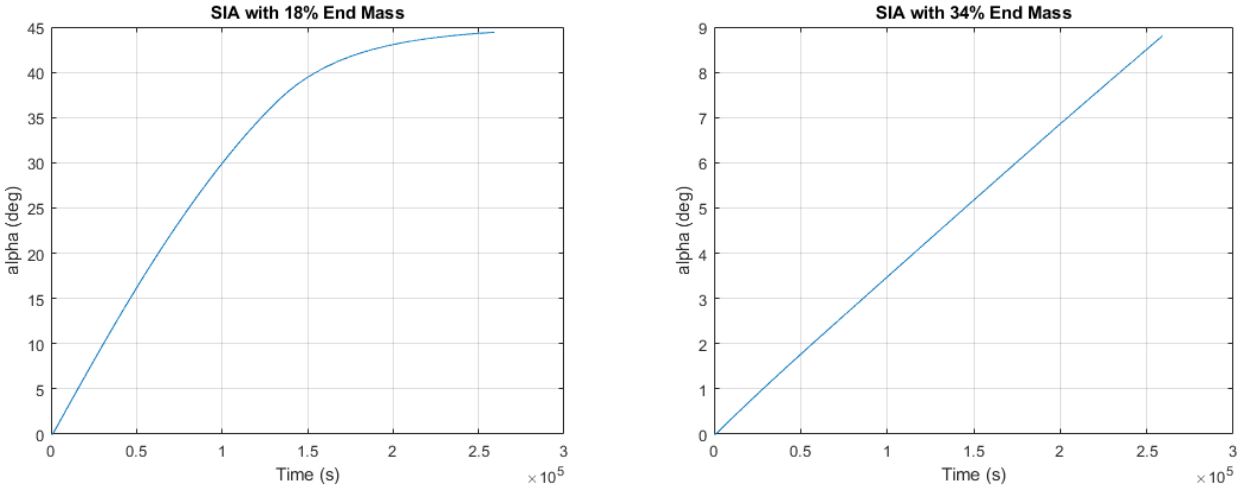

Figure 11. Formation Error at 18% End Mass Percentage (Left) and Formation error at 34% End Mass Percentage (Right)

As seen in Figure 11, as the mass percentage increases for the end mass, it reduces the slew performance of the system. This result results the end mass for the electric sail system to be optimized between fifteen and twenty percent of the central spacecraft.

D. Tether Voltage

Varying the tether voltage maximum is a function of the tether material selected for an electric sail system. Modulating the voltage can help improve system performance by creating a larger plasma sheath for momentum exchange and thus creating a larger characteristic acceleration.

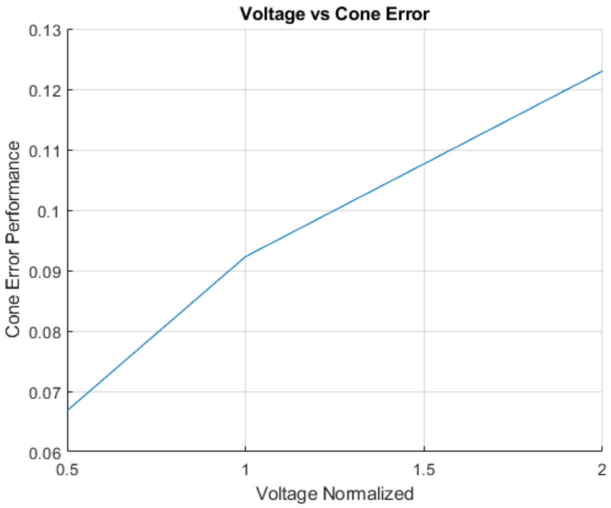

Figure 12. Cone Error as a Function of Tether Voltage Normalized

Figure 12 shows that the increase in voltage across the tether ends up leading to a larger cone error but it is not as significant as other factors such as the end mass ratio to central spacecraft mass.

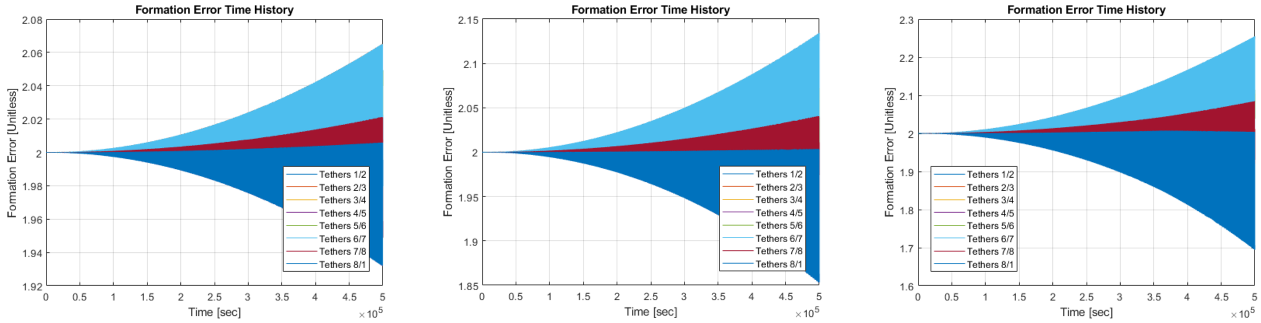

Figure 13. Formation Error with Increasing Spin Rate from Left to Right

In figure 13, changing the voltage does not have a significant impact to the formation error but higher voltage leads to a slight increase in formation error.

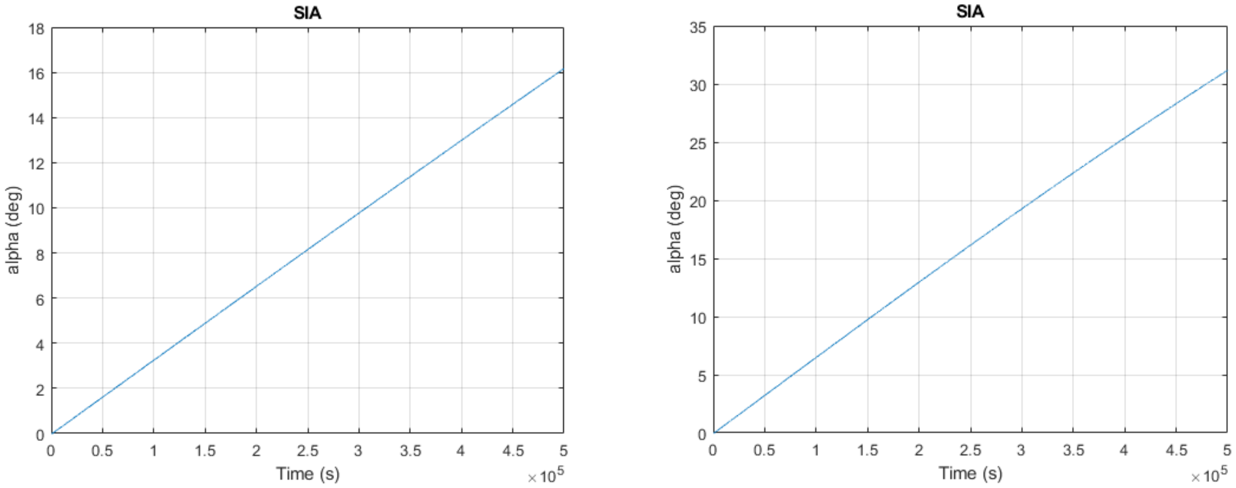

Figure 14. Slew Performance with Low Voltage (left) and Slew Performance with High Voltage (right)

Figure 14 shows the impact of changing the voltage with slew performance with the qualitative stability remaining similar but the higher voltage resulting in a much higher slew rate compared to the lower slew rate.

V. MISSION DESIGN RESULTS

Mission design and modeling of e-sail enabled trajectories were generated and optimized using the Astrodynamics and Space Science Toolkit (ASSET) [5]. ASSET is a free and open-source software (FOSS) funded by a NASA ROSES grant and was developed by the Astrodynamics and Space Research Lab at the University of Alabama. Due to the code based, vector functionality of ASSET, an e-sail force model with user defined characteristic acceleration can be appended to any gravitational force model. A Sun centric, two body model was used for all preliminary e-sail trajectory optimization.

In the ASSET implementation of e-sail dynamics, a vector functional description of the sail is defined. The sail model computes the expected acceleration based upon: user defined characteristic acceleration, distance from the Sun, and a sail pointing control vector. The sail pointing control vector, *u*, is a three-dimensional cartesian vector that ASSET can manipulate during optimization routine calls. This control vector *u* is constrained to have a magnitude between 0 and 1 and gets multiplied by the scaler acceleration value computed in the sail model. When *u* is at vector magnitude 1, it represents the e-sail being fully on. Conversely, a magnitude for *u* that is less than 1 represents using less than the maximum power in the e-sail. This ability to throttle the acceleration is a distinct advantage that e-sails have compared to conventional, reflective solar sails. When the e-sail acceleration has been computed for a given state/time step, the acceleration vector is added into the Sun centric two body model used in this analysis.

The purpose of the mission design analysis as a part of this study is to determine an estimate of how long an e-sail enabled spacecraft would take to reach the solar system heliopause. For this analysis, the heliopause is considered to be at exactly 100 astronautical units (AU) away from the Sun. Additionally, a Sun centric two body model is used, hence no other planetary gravitational perturbations nor flybys are used. Finally, the e-sail mission design does not make any assumptions about the spacecraft mass. Instead, all analysis is conducted for a fixed characteristic acceleration of the sail. As such, the results do not speak to the required sail power nor the spacecraft mass, but instead the total acceleration the e-sail system must be able to produce.

When using ASSET as an optimizer, all optimization phases require an initial guess trajectory to seed the computation. For this analysis, the initial trajectory is fixed as an Earth launch inwards towards the Sun. The spacecraft position starts at 1 AU, has the velocity of a circular orbit, and is rotated toward the Sun by 45 degrees. The resulting elliptical trajectory can be seen below in Figure 15. This Sunward launch was selected to enable the sail to leverage the acceleration scaling that happens when the e-sail gets closer to the Sun. The initial guess for optimization propagates the spacecraft with the e-sail turned off (*u* vector magnitude of 0) until perihelion of the trajectory is reached. After reaching solar closest approach, the e-sail is turned on. This initial guess uses a 0 degree SIA, where the sail it pointed directly at the Sun. The initial guess trajectory is then optimized in ASSET, where the control variables are: coast time until turning on the e-sail, sail magnitude, and sail pointing direction. In almost all optimization runs, the sail maintained 0 degrees SIA for the entire duration of the flight. While there is a possibility that this is a sub-optimal pointing history, the control law would be beneficial during operations due to its simplicity.

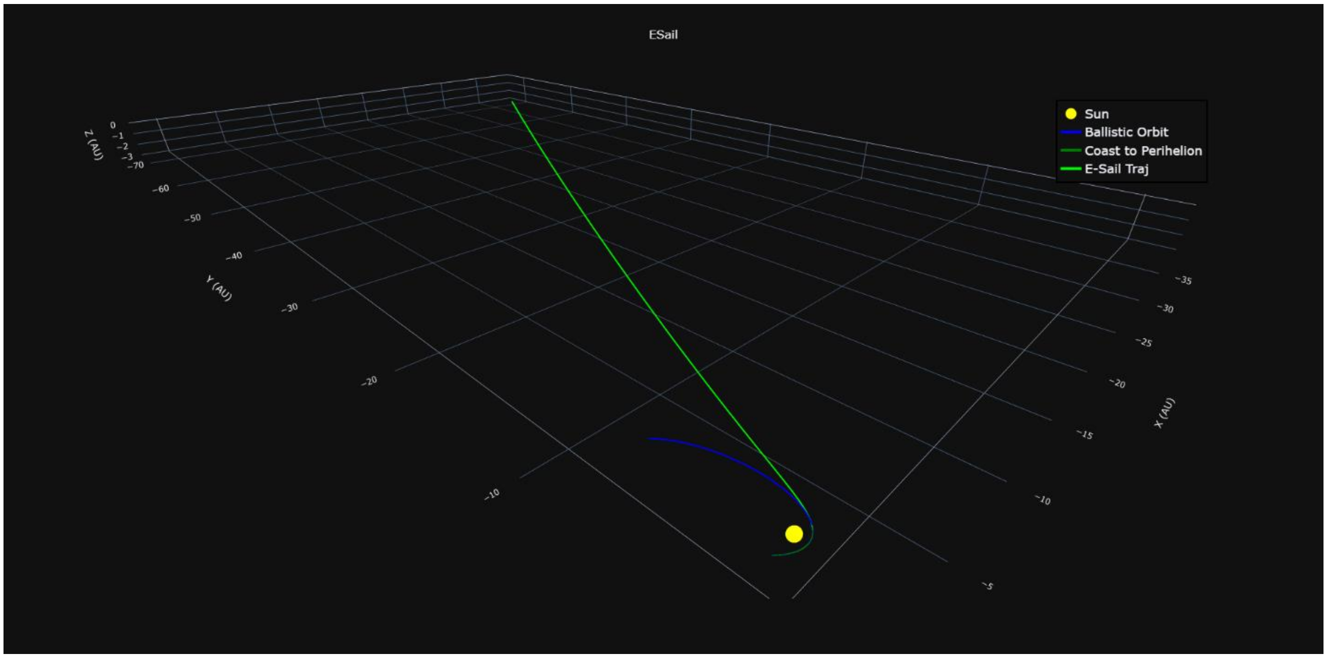

Figure 15. E-Sail Trajectory vs Ballistic Orbit

Using the same methodology described above, mission design analysis was conducted on three different characteristic acceleration values. All cases use the same optimal control methodology in ASSET, with the only difference between cases being the e-sail model. The resulting models, along with the time it the simulations take to reach heliopause, can be found below in Table 3.

Characteristic Acceleration (m/s)	**Time To Heliopause (years)**
0.002	10.5999
0.004	8.4576
0.006	8.1539

Table 3: Heliopause Transfer Times

These transit times indicate that it is possible for a transit time meeting the HERTS goal of ten years to heliopause and it is possible to do it without utilizing a Jupiter gravity assist.

VI. CONCLUSIONS AND FUTURE WORK

This study helped reveal the different sensitivities that the integrated electric sail system has as the system performance changes with design choices being made. The information gathered in this study can help potential mission designers A summary of the results determined in this study can be found in table 4 below.

Parameter	Cone Error	Formation Error	Slew Performance	Additional Notes
Length of Tethers	Longer tethers result in lower cone error	Longer tethers lead to slightly larger formation error	Longer tethers cause an increased sail area which results in increased slew performance.	Tether length is maximum is dictated by electric sail tether spools. Longer tethers also increase the effective sail area

Spin Rate	Higher spin rate results in lower cone error	Higher spin rate leads to larger formation errors and the system heading towards an unstable area	Spin rate causes instabilities with the slew performance	Ultimate spin rate is dictated by the deployment dynamics
Mass Ratio between Central Spacecraft and Tether End Spacecraft	Higher outer spacecraft mass reduces cone error but around 15% of the central spacecraft mass it reaches close to a minimum	Higher mass ratios lead to a reduced formation error	Heavier end masses will result in slower slew speed	Tether end spacecraft mass is dictated by system needs and will be designed to be lighter than the central spacecraft
Tether Voltage	Higher voltage leads to higher cone error but to a lessor degree than the other parameters	Higher voltages lead to a slightly larger	Higher voltages lead to a faster slew rate	Tether voltage depends on material selection and capabilities of the sailcraft's power system

Table 4: Summary of Study Results

This table can help serve as a quick reference for understanding the impact of dynamics with key performance parameters of the electric sail system. These can help with preliminary designs of e-sail systems for mission concept studies and the different desired performance attributes.

For follow on work to this study, further investigations into the impact of different performance parameters such as number of tethers with the system. This study was focused on a technology demonstration mission sized e-sail, not a full-sized science mission sail as outlined in [2] and [3]. As a direct follow-on work to this study, a new DRV and DRM would be required to determine unknowns with the system such as how much mass would be for the central spacecraft and the small spacecraft at the end of the tethers. This maturation of the system will help bring e-sails from its concept phase to a flight project.

VII. ACKNOWLEDGEMENTS

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