SOLAR SAIL PROPULSION SENSITIVITY TO MEMBRANE SHAPE AND OPTICAL PROPERTIES USING THE SOLAR VECTORING EVALUATION TOOL (SVET)

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ABSTRACT

Solar sail propulsive performance is dependent on sail membrane optical properties and on sail membrane shape. Assumptions of an ideal sail (flat, perfect reflector) can result in errors which can affect spacecraft control, trajectory analyses, and overall evaluation of solar sail performance. A MATLAB® program has been developed to generate sail shape point cloud files for two square-architecture solar sail designs. Simple parabolic profiles are assumed for sail shape under solar pressure loading. These files are then input into the Solar Vectoring Evaluation Tool (SVET) software to determine the propulsive force vector, center of pressure, and moments about the sail body axes as a function of sail shape and optical properties. Also, the impact of the *center-line angle*, due to non-perfect optical properties, is addressed since this constrains sail force vector cone angle and is often overlooked when assuming ideal-reflector membranes. Preliminary sensitivity analysis using these tools aids in determining the key geometric and optical parameters that drive solar sail propulsive performance.

INTRODUCTION

Solar sail propulsive performance is dependent on sail membrane optical properties (e.g., reflectivity) and on sail membrane shape (*e.g.*, billow). Assumptions of a flat, perfect reflector can result in errors which can affect spacecraft control, trajectory analyses, and overall evaluation of solar sail performance. Accurate models are required which incorporate the "non-ideal" characteristics of the sail in order to understand their realistic behavior. The shape and optical properties of the solar sail are the primarily characteristics affecting the propulsive performance. The work presented in this paper had multiple purposes. One was the evaluation of the Solar Vectoring Evaluation Tool (SVET) software[1], developed by SRS Technologies for NASA MSFC. Some software bugs were identified and repaired so now SVET is ready for use in further analyses. A second purpose was to develop a MATLAB®-based model which simulates the shape of two different square-architecture solar sail designs. Given a solar sail shape, SVET can then calculate the resulting propulsive force vector, the center of pressure, and moments about the sail body axes. This non-finite-element approach provides quick examination of the effects of changes in sail shape necessary for conducting sensitivity analyses in a timely manner. And lastly, once the SVET software was debugged and the solar sail models developed, some preliminary sensitivity analysis was done to demonstrate the capability of using the two tools together.

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SOLAR SAIL MODEL DEVELOPMENT

A MATLAB® program has been developed which generates point cloud files simulating the deflected shape of two square-architecture solar sail designs; one developed by ATK-Able and the other by L'Garde Inc.. Both designs have four separate sail quadrants with the ATK-Able design utilizing a 3-point suspension of each quadrant and L'Garde utilizing a striped net suspension system. Parabolic profiles are assumed for sail shape under solar pressure loading which is adequate for *deflection/sail-edge-length* << 1^2. For the model of the 3-point design, the sail quadrant has parabolic deflection along both the support boom edge and the outer sail edge resulting in the maximum deflection occurring in the central part of the quadrant. For the model of the striped-net design, each stripe (or chord) of the net has a parabolic profile with a linearly increasing depth from the sailcraft hub out to the sail edge. Additionally, with the striped-net model, the sail sags between each of the chords in a parabolic fashion at constant depth for each of the "troughs". This results in the maximum deflection occurring at the outer edge of the sail membrane. All of these geometric parameters are variable inputs in the program. The figures below show point clouds generated by the MATLAB® program representing the two sail designs. The striped-net model is further along in development since this design has been recently selected for a NASA Phase A study for a 1600-m^2 solar sail flight validation.

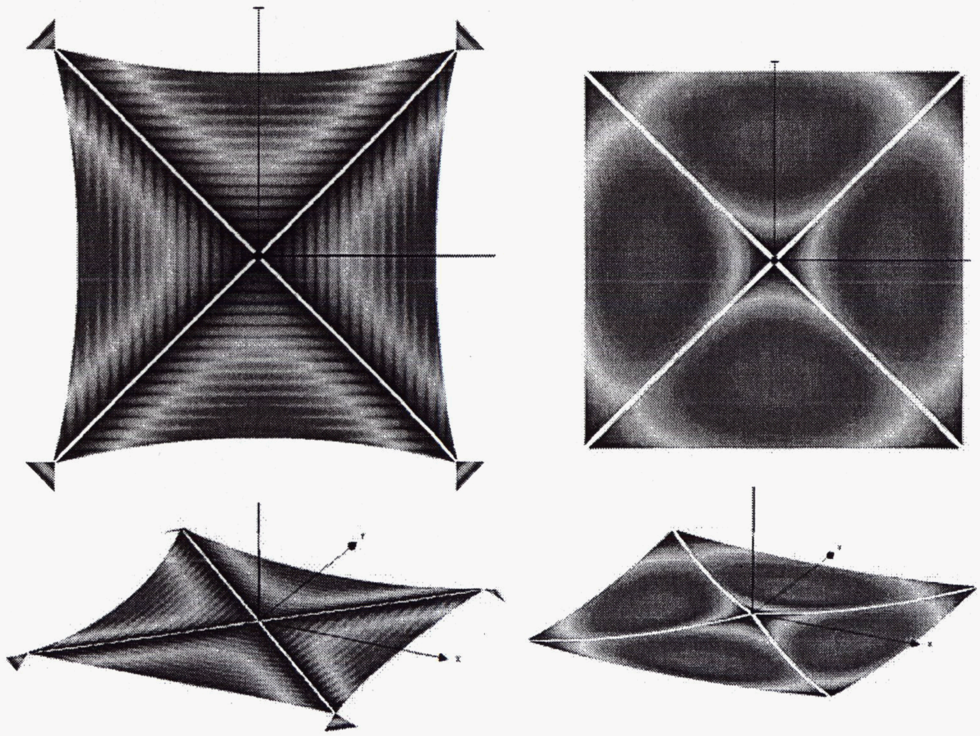


Figure 1. Models of the striped-net (left) and 3-point (right) solar sail designs with color representing billow depth. Maximum deflection occurs at the outer edge for the striped-net quadrant and at the central area for the 3-point quadrant.

SENSITIVITY ANALYSIS

<u>STRIPED-NET MODEL USED</u>

To be further studied under a NASA Phase A program, the striped-net model shown in Fig. 1 represents a slightly more developed model than the 3-point version. A 6% edge scallop and four tip vanes have been added to more closely represent the actual design. A more accurate model of the 3-point design would also include edge scallops on all three sides of each of the four sail quadrants. The striped-net model representing the design submitted by L'Garde in response to a NASA Research Announcement[3] will be used for the analyses discussed in this paper. The model is of the 1600-m^2 class solar sail and is a 44-meter (tip-to-tip) solar sail comprised of 18 stripes (~1.2 m stripe width) per quadrant with a 3% (of sail size) hub-to-edge slope resulting in a maximum billow deflection of 1.3 m. Additionally, there is a several centimeter sag of the membrane between each support-net chord which gives a multi-trough appearance. The actual design also has a center circle cutout, approximately 2-m diameter, where the spacecraft bus would be located but this is not currently represented in the model (relatively small affect due to small area/moments). The model also contains four, 5-m^2 control vanes located at the tip of each boom statically canted back 30-degrees in their "passive-stability" configuration. However, for the purposes of this most of this analysis, the vanes, have been removed. For comparison, a flat, square solar sail of the 1600 m^2 class was used, both in and "ideal" configuration (flat perfect reflector) and a "non-ideal" configuration (flat with non-ideal optical properties). Commonly, the ideal configuration is assumed in general discussions of solar sail performance but, as will be shown, this assumption leads to errors in evaluating realistic propulsive performance. Table 1 shows the characteristics of the solar sails used in this analysis.

Table 1 Comparative Sails used for Sensitivity Analysis

	Flat Square		Striped-net	
	Ideal	Non-ideal	Non-ideal	w/Vanes
Area (m^2)	1600 m^2	1600 m^2	1627 m^2	1647 m^2
Sail size (side length)	40 m	40 m	44 m	44 m
Control vanes	none	none	none	4 @ 5 m^2
Maximum billow (m)	0 m	0 m	1.3 m	1.3 m
Solar flux at 1 AU	1400 W/m^2	1400 W/m^2	1400 W/m^2	1400 W/m^2
Reflectivity (front)	1.00	0.90	0.90	0.90
Absorptivity (front)	0	0.10	0.10	0.10
Emissivity (front)	0	0.05	0.05	0.05
Emissivity (back)	0	0.55	0.55	0.55

CENTER-LINE ANGLE EFFECT AND SOLAR SAIL PERFORMANCE

To demonstrate the capability of using these tools to conduct sensitivity analyses, a brief examination of a few key parameters associated with solar sail propulsion were examined as a function of sun angle (pitch). Following a similar approach as presented by McInnes[4], Fig. 2 defines the geometry and key parameters used in discussing solar sail performance. Since a non-ideal sail is not a perfect reflector, the direction of the thrust vector will not be normal to the sail due to absorption of photons resulting in a transverse component of thrust. This causes the thrust vector to be biased in the direction of the incident radiation. This is further complicated by the sail having shape (billow). The *center-line angle* ϕ, which is the angle between the thrust vector and the sail normal, is given by $\tan\phi = Ft/Fn$ where *Ft* and *Fn* are the transverse and normal components of thrust respectively. For an ideal sail, $\phi = 0$ and the cone angle equals the sun angle ($\theta = \alpha$) since no transverse component of thrust is generated.

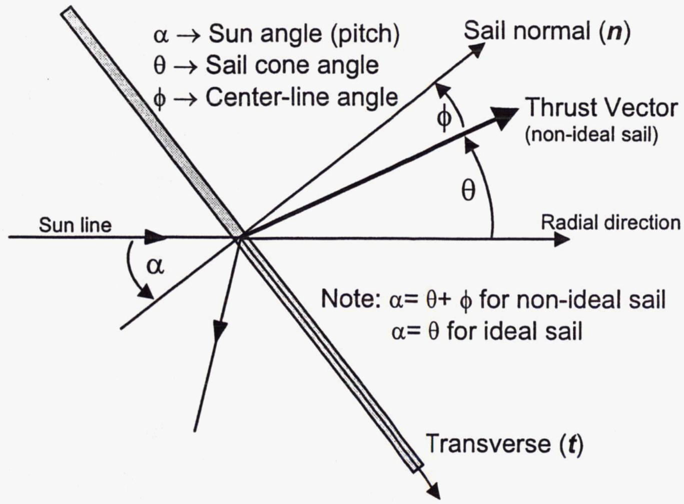


Figure 2. Angle geometry schematic for a non-ideal solar sail. For an ideal solar sail, the thrust vector and the sail normal are coincident.

Given the shape from the MATLAB®-based model shown in Fig. 1 and the input optical properties from Table 1, SVET can calculate the resulting solar force (thrust) vector, center of pressure, and resulting torques. Basically, this is done through mesh generation and summation over each triangular surface element. Figure 3 shows the thrust magnitude as a function of sun angle using these models and the SVET software. Again, the square sail is a perfectly flat sail used for comparison purposes versus the striped net model which has a complex billow shape.

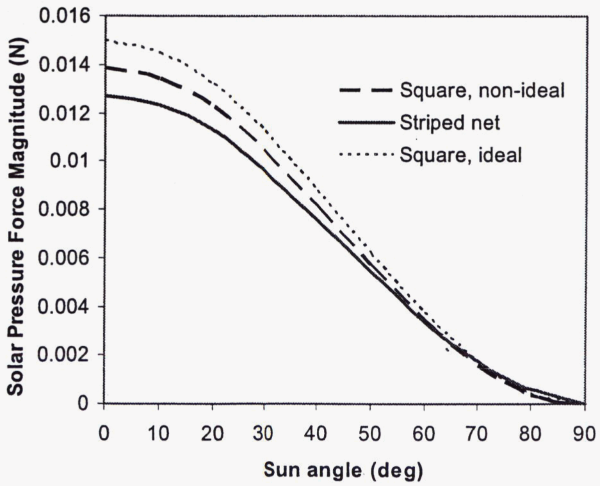
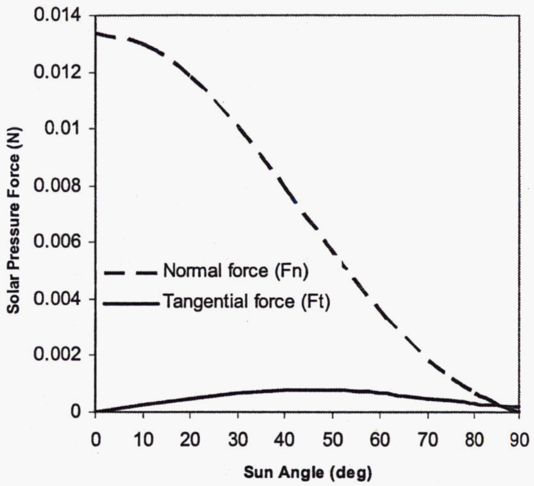


Figure 3. Thrust magnitude as a function of sun angle. Non-ideal optical properties reduce thrust (dashed line) and an additional reduction is seen due to sail billow (solid line) except at high sun angles where it actually crosses over slightly.

However, in looking at the thrust magnitude in this way, a vital piece of information has been lost; the direction of the thrust. In looking at Fig. 3, it appears that the sail can provide useful thrust all the way up to a 90° sun angle – albeit, decreasing smaller. Upon closer examination, this is not the case since the tangential component contributes an increasingly significant portion of the total thrust at the higher sun angles as seen in the left-side graph of Fig. 4. This is more evident when the center-line angle is plotted as a function of sun angle (right-side graph of Fig. 4). Note the significant increase of the center-line angle beyond $\alpha = 70°$. The effect of shape can also be seen here with the striped-net model showing approximately twice the angle over most of the range as compared to the non-ideal square solar sail model (recall that an ideal sail does not exhibit this effect). The center line effect is quite significant since this limits the operational range of the sailcraft; limited in the sense of producing thrust normal to the sail surface.



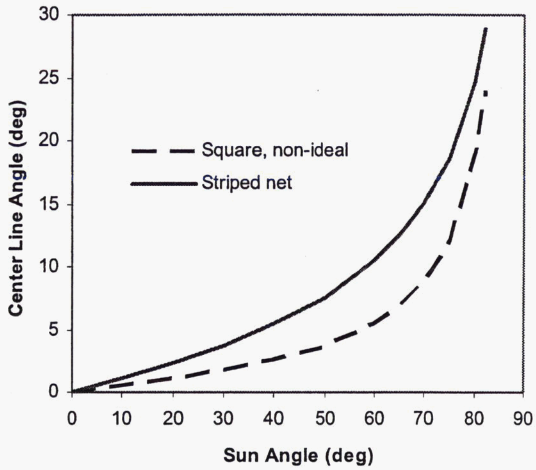


Figure 4. Normal and tangential components of thrust for the striped-net solar sail (left). Center-line angle as a function of sun angle.

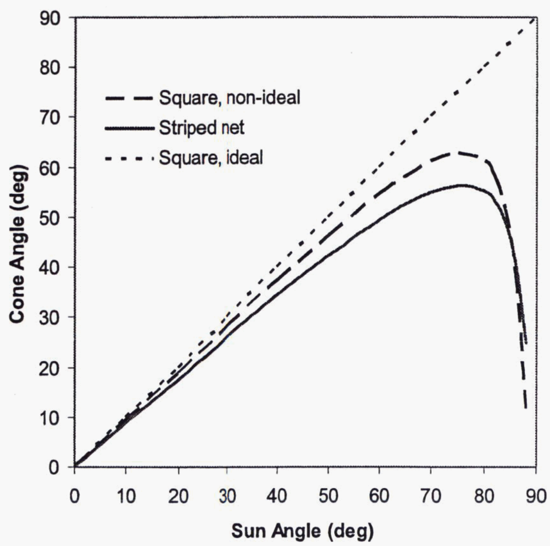


Figure 5. Cone angle θ as a function of sun angle α. For an ideal sail, $\theta = \alpha$. Note that for non-ideal sails, the cone angle has a maximum and then drops off quickly which constrains the useful operational range of the solar sail.

The *cone angle* θ, defined as the angle between the thrust vector and the incident radiation, is a commonly used parameter in solar sail thrust analysis. Figure 5 shows the cone angle for the compared sails including the ideal case. Figure 5 is directly related to Fig. 4 since $\alpha = \phi + \theta$. The significant feature to point out here is that the cone angle reaches a maximum for the non-ideal solar sails. The maximum cone angle for the striped-net model is about $\theta = 55°$ corresponding to a sun angle around $\alpha = 75°$. This is basically saying that at this sun angle, useful (normal to sail) thrust falls off rapidly; some thrust remains at the higher sun angles but it is oriented transversely, in the plane of the sail. Figure 6 also reveals this maximum cone angle behavior as well as the expected decreasing trend of the thrust as a function of cone angle. This center-line-cone-angle effect is significant since it is in contrast to the "ideal sail" idea that the thrust vector is always oriented normal to the sail surface and can be in principle operated up to a 90° sun angle.

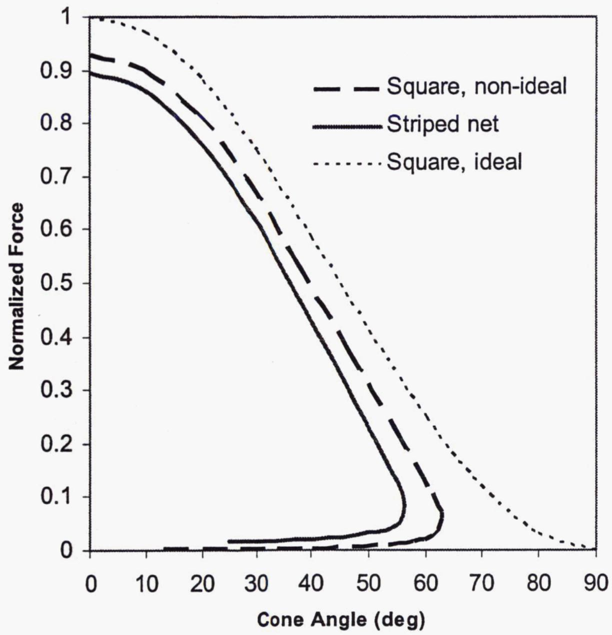


Figure 6. Solar sail thrust (normalized to an ideal sail) as a function of cone angle θ showing again how the cone angle reaches a maximum and then decreases rapidly. The ideal sail curve shown in this figure is equivalent to Fig. 3 since cone angle is equal to the sun angle in this case.

SOLAR PRESSURE TORQUES ON THE SAILCRAFT

Shown here briefly is the additional capability of using these tools to calculate torques about the body axes (left side of Fig. 7) and the center of pressure, *CP* (right-side of Fig. 7). This type of data can be useful when looking at sailcraft control issues. The torques are shown for the striped-net design with and without the tip vanes (see Fig. 1). As can be seen in this figure, the addition of the four tip vanes has a significant impact on the torques produced on the sailcraft. These torques are produced as a result of shifts in the center of pressure which can be quite large at high sun angles. This behavior directly impacts sailcraft control authority designs which need to ensure that the sailcraft can compensate for this *CP*-shift induced torque. Although not thoroughly examined yet, the small rise in the torque at α >75° is thought to be due to the rapidly increasing shift in the center of pressure at these larger sun angles (*i.e.,* small force but large moment arm). It is non-intuitive behaviors such as this which supports the use of these tools so that “non-ideal” solar sail spacecraft can be analyzed and understood so that real, flyable solar sails can be designed and flown with reduced risk.

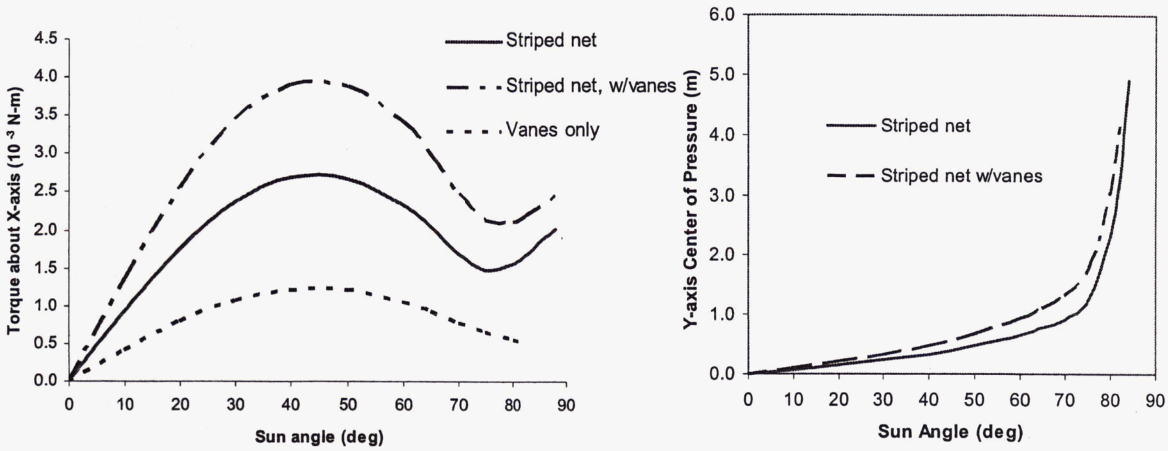


Figure 7. Torque produced about the X-axis (left) due to the shift of the center of pressure along the Y-axis of the solar sail.

SUMMARY AND CONCLUSIONS

Solar sail propulsive performance is dependent on sail membrane optical properties and on sail membrane shape. Assumptions of an ideal sail (flat, perfect reflector) can result in errors which can affect spacecraft control, trajectory analyses, and overall evaluation of solar sail performance. A MATLAB® program has been developed to generate sail shape point cloud files for two square-architecture solar sail designs which are then input into the Solar Vectoring Evaluation Tool (SVET) software to determine the propulsive force vector, center of pressure, and moments about the sail body axes as a function of sail shape and optical properties. Sensitivity analysis using these tools aids in determining the key geometric and optical parameters that drive solar sail propulsive performance. Some basic analysis has been done on the striped-net architecture solar sail primarily to demonstrate the application of these tools. Included in the analysis was examining the impact of the *center-line angle* ϕ which significantly constrains the sail force vector cone angle directly impacting solar sail thrust performance. The center-line effect is often overlooked when assuming ideal-reflector membranes and can lead to significant errors in evaluating propulsive performance. For the striped-net model, the cone angle reaches a maximum near $\theta = 55°$ corresponding to an operational limit, where thrust is no longer produced normal to the sail, to a sun (pitch) angle of around $\alpha = 75°$. This is in contrast to the “ideal sail” idea that the thrust vector is always oriented normal to the sail surface and can be in principle operated up to a 90° sun angle. Upon examining the solar pressure torques, it was found that the center of pressure shifts significantly at large sun angles possibly attributing to the unexpected increase in torque at these higher sun angles. It is non-intuitive behaviors such as this which supports the use of these tools to understand “non-ideal” solar sail spacecraft behavior so that real, flyable solar sails can be designed, manufactured and flown with reduced risk.

ACKNOWLEDGMENTS

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2. Greschik, G. and M. M. Mikulas, "Design Study of a Square Solar Sail Architecture." J. of Spacecraft and Rockets 39(5): 653-661 (2002).
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Solar Sail Propulsion Sensitivity to Membrane Shape and Optical Properties using the Solar Vectoring Evaluation Tool

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Purpose of the Work

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- Solar sail propulsive performance is dependent on sail membrane shape and optical properties.
- Assumptions of an ideal sail (flat, perfect reflector) can result in errors affecting evaluation of solar sail performance.
- A MATLAB® program has been developed to generate sail shape point cloud files for realistic solar sails.
- Solar Vectoring Evaluation Tool (SVET) software is then used to determine the propulsive force vector, center of pressure, and moments as a function of sail shape and optical properties.
- Conducting sensitivity analyses aids in determining the key geometric and optical parameters that drive solar sail propulsive performance.

Outline

- Introduction
- Solar Sail Model Development
  - Striped-net solar sail
  - MATLAB® model
- Solar Vectoring Evaluation Tool (SVET)
- Sensitivity Analysis – Propulsive Performance
  - Center-line angle effect
  - Cone angle limitation
  - Solar pressure torques
- Summary
- Acknowledgements

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Introduction

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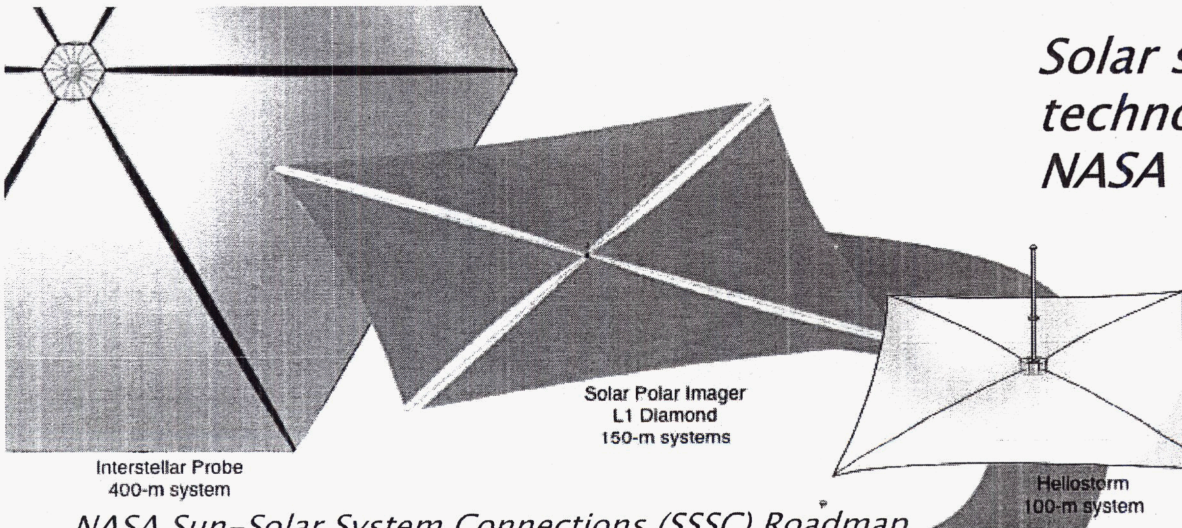


NASA Sun–Solar System Connections (SSSC) Roadmap

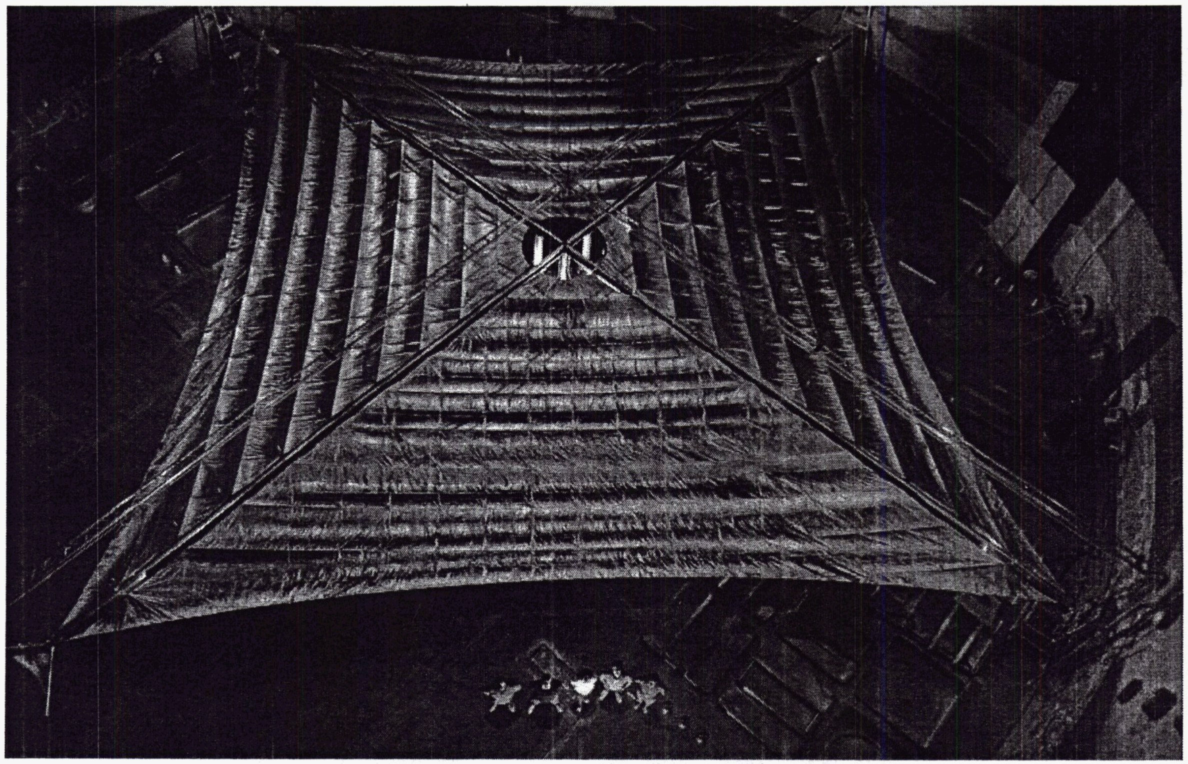
Solar sails are an enabling technology for future NASA science missions

- Need to develop accurate models and analysis tools to aid in the design and evaluation of realistic, “non-ideal” solar sails.
- Sensitivity analyses help determine critical design parameters such as sail shape and optical properties which affect propulsive performance.

Solar Sail Model Development

Striped-Net Solar Sail

- L'Garde Inc. 20-m solar sail deployed at Plum Brook July 2005
- Chosen as sail provider for NMP-ST9 Phase A Study Report
- Inflatable, rigidizable boom w/striped-net supporting aluminized Mylar®



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Solar Sail Model Development

MATLAB® Model

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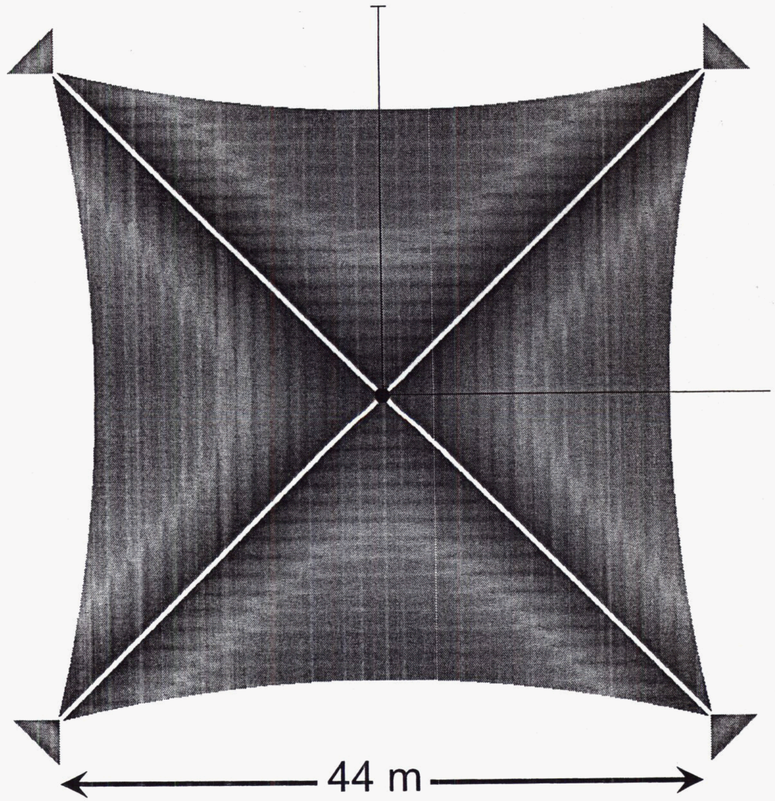
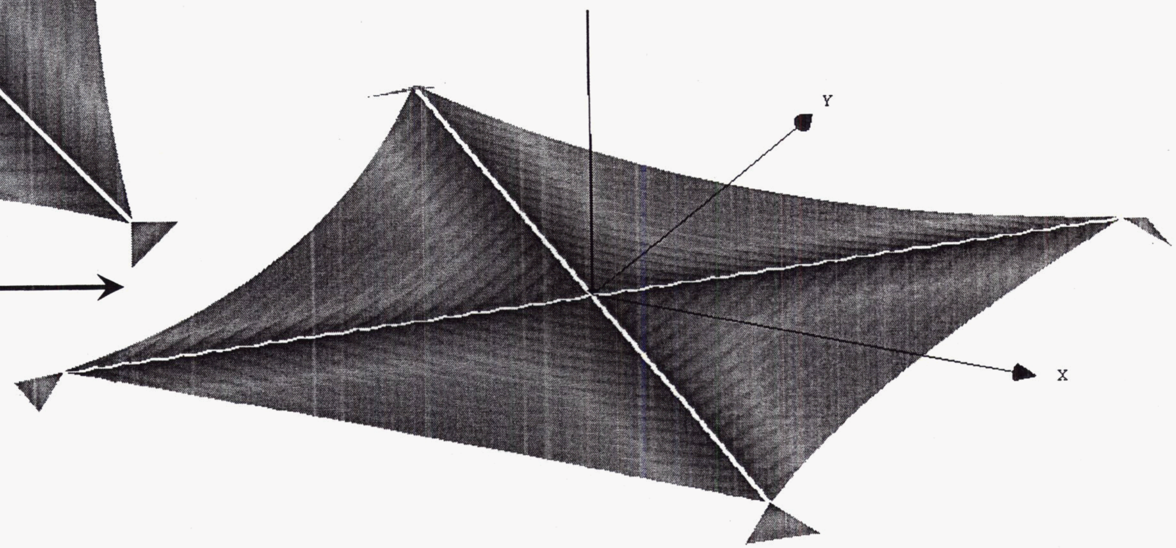


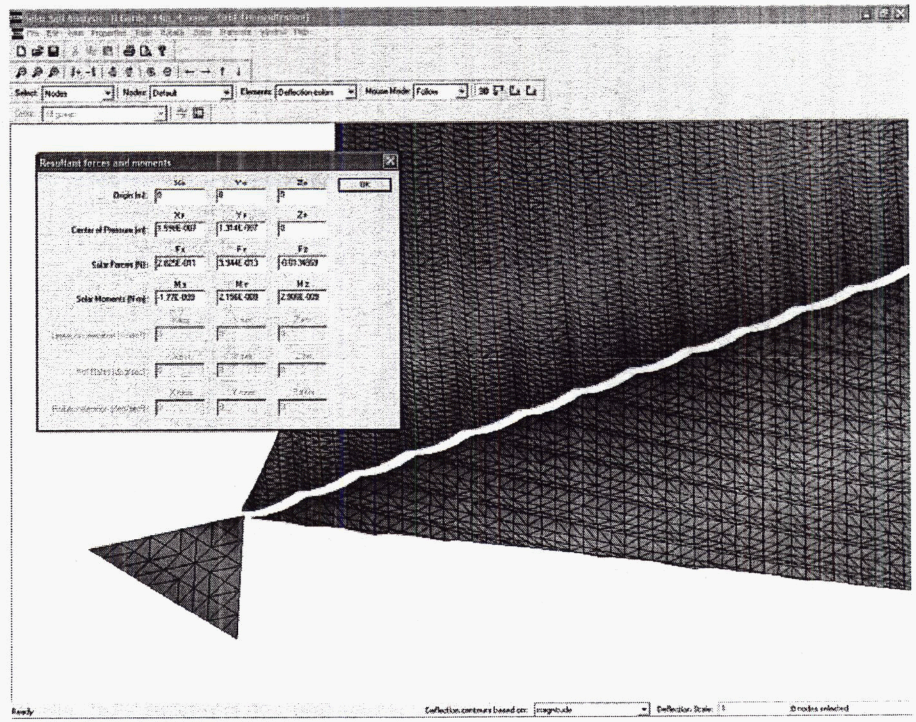
- MATLAB® model generates shape
- 44-meter, with four 5-m^2 control vanes
- Parabolic profile on net/membrane
- 3% (sail size) hub-to-edge linear slope
- 6% (sail size) edge scallop



Sensitivity Analysis

Solar Vectoring Evaluation Tool (SVET)

- Software developed by SRS Technologies for NASA
- Input file formats (geometry)
  - *FEA (ALGOR/NASTRAN/MSC-PATRAN)*
  - *Point cloud files (x,y,z coordinates)*
- Optical property inputs
  - *Solar flux*
  - *Specular reflectivity*
  - *Solar absorptivity*
  - *Infrared emissivity (front/back)*
  - *Sun angle*
- Calculates
  - *Center of Pressure (X_p, Y_p, Z_p)*
  - *Solar pressure forces (F_x, F_y, F_z)*
  - *Solar pressure torques (M_x, M_y, M_z)*



Sensitivity Analysis

Design parameters

	Flat Square		Striped-net	
	Ideal	Non-ideal	Non-ideal	w/Vanes
Area (m^2)	1600	1600	1627	1647
Sail size (m)	40	40	44	44
Control vanes	none	none	none	4 @ 5 m^2
Maximum billow (m)	0	0	1.3	1.3
Solar flux at 1 AU (W/m^2)	1400	1400	1400	1400
Reflectivity (front)	1.00	0.90	0.90	0.90
Absorptivity (front)	0	0.10	0.10	0.10
Emissivity (front)	0	0.05	0.05	0.05
Emissivity (back)	0	0.55	0.55	0.55

Geometry

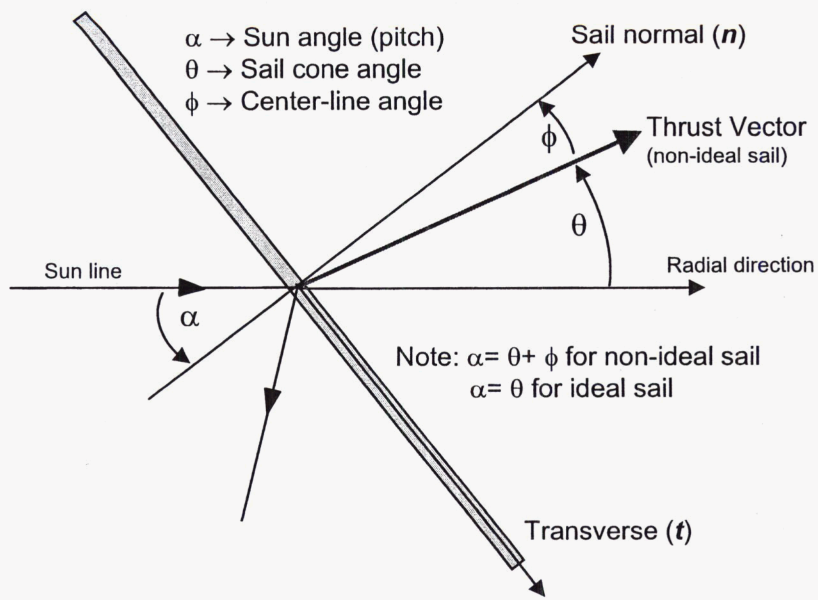
- size
- billow/shape
- control vanes

Optical properties

- reflectivity
- absorptivity
- emissivity

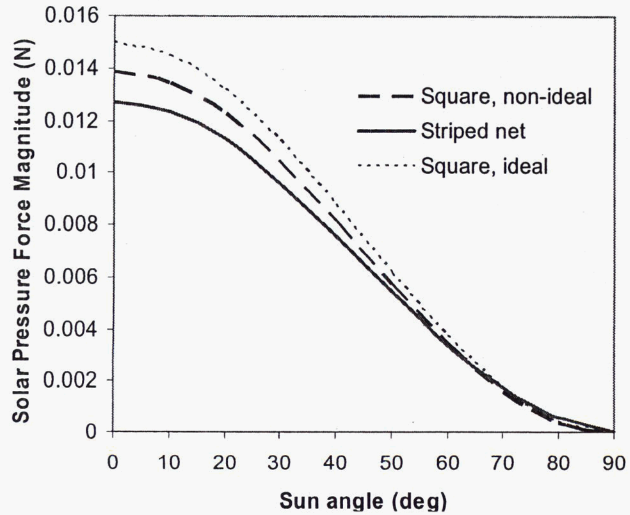
Sensitivity Analysis
Center-line Angle Effect

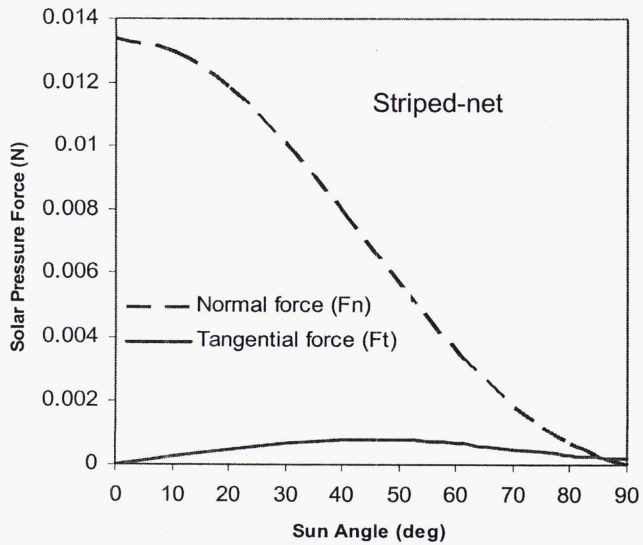
- Affects only non-ideal sails (reflectivity < 1)
- Causes thrust vector to bias towards incident radiation (sun line)
- For ideal sail, $\phi = 0$ ⇨ thrust is always oriented along sail normal



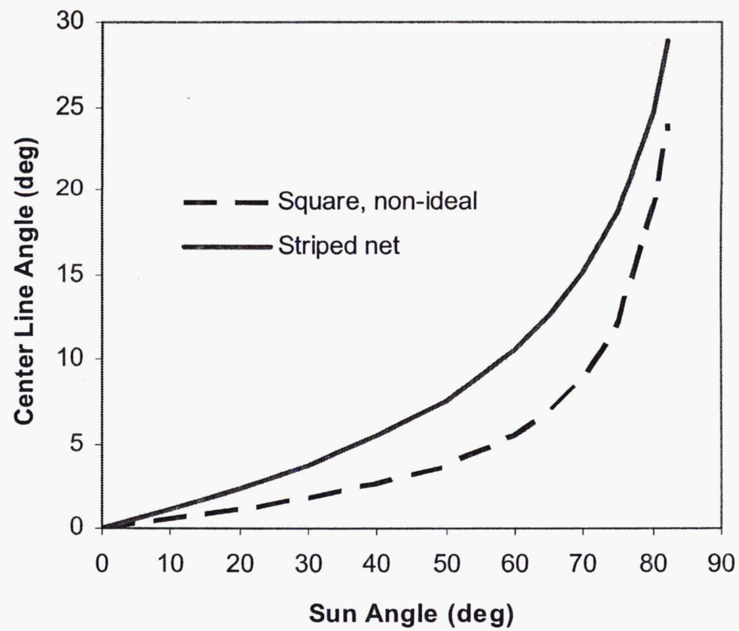
Sensitivity Analysis

Center-line Angle Effect





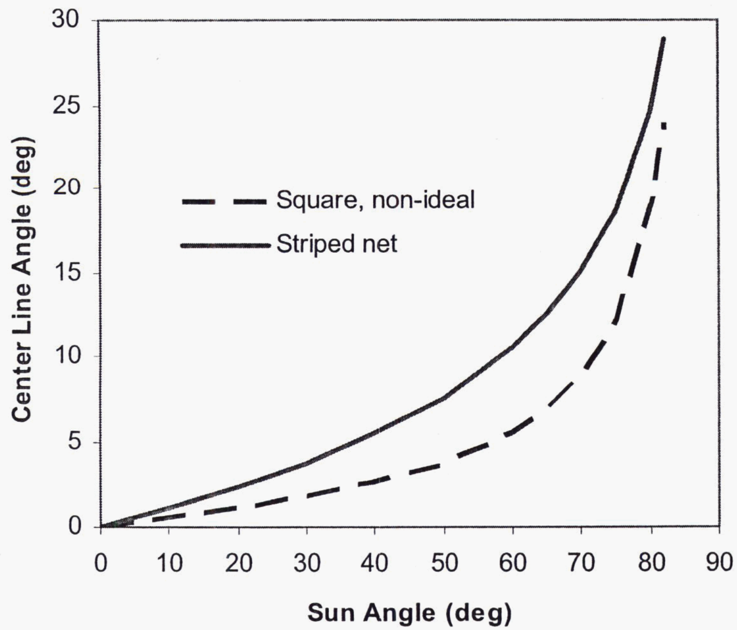
Center line angle: $\tan \phi = Ft / Fn$

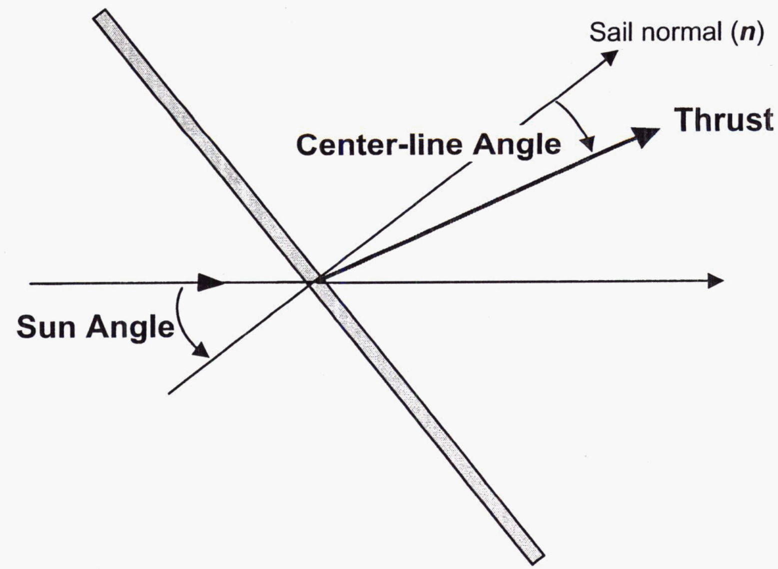


Sensitivity Analysis

Center-line Angle Effect

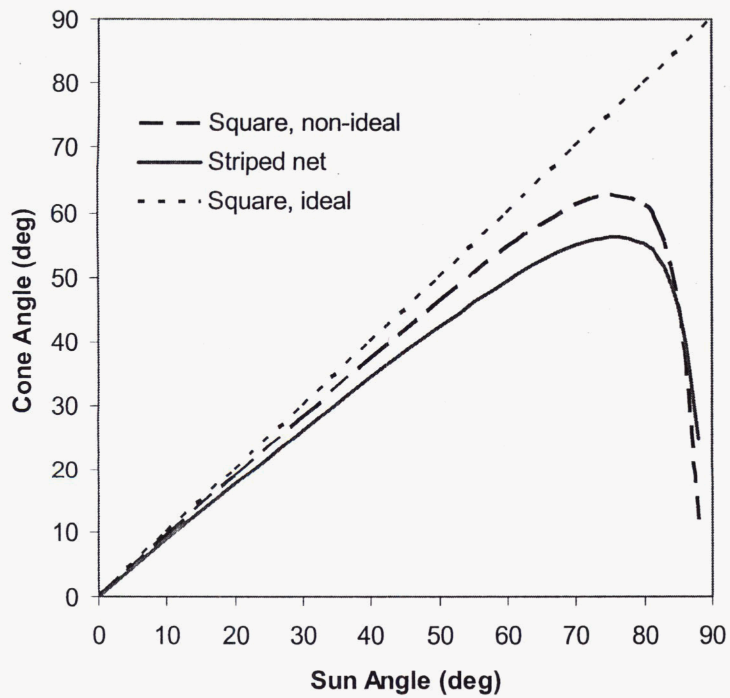
- As sun angle increases, thrust vector moves away from sail normal
- Affects the maximum usable thrust that "pushes" the sail

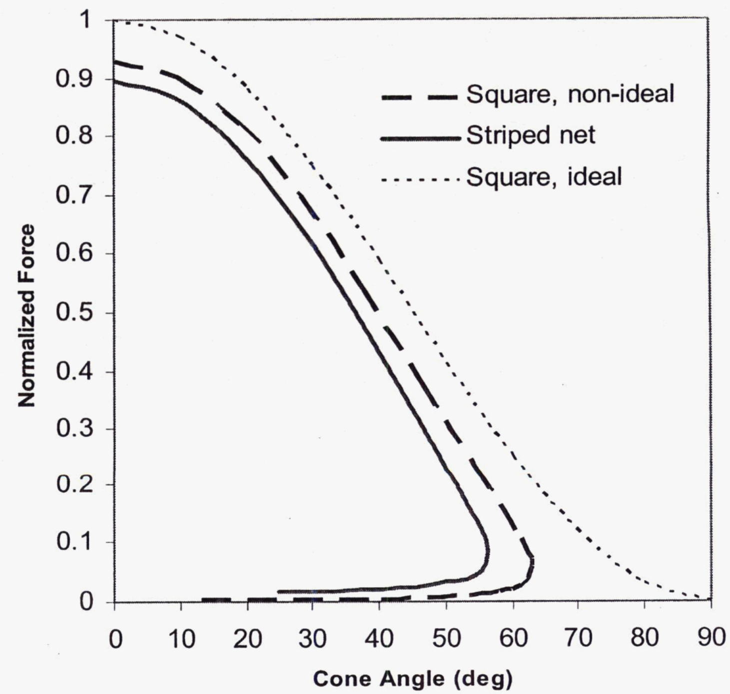




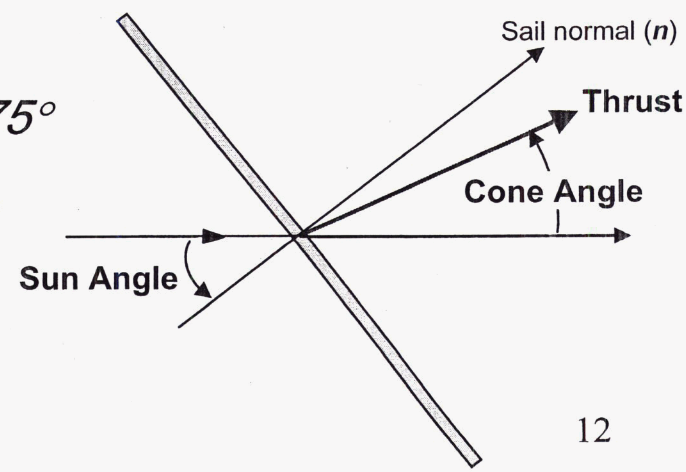
Sensitivity Analysis

Cone Angle Limitation



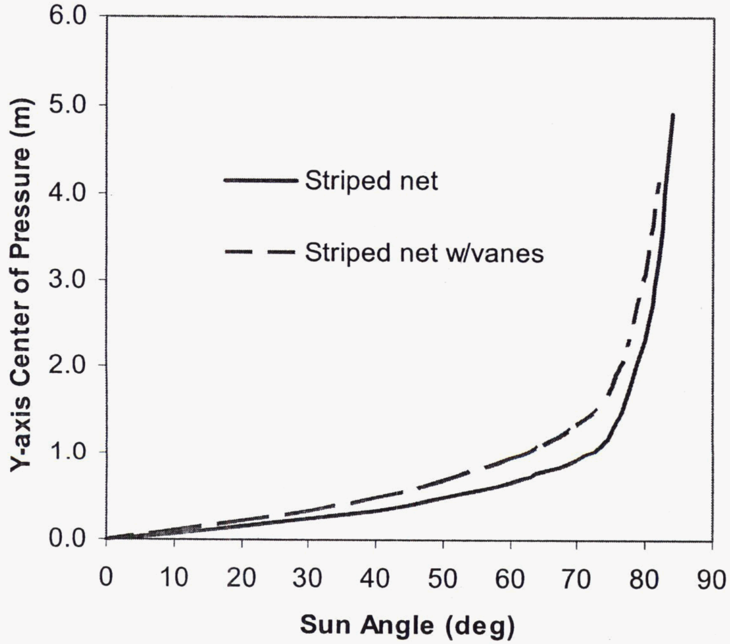


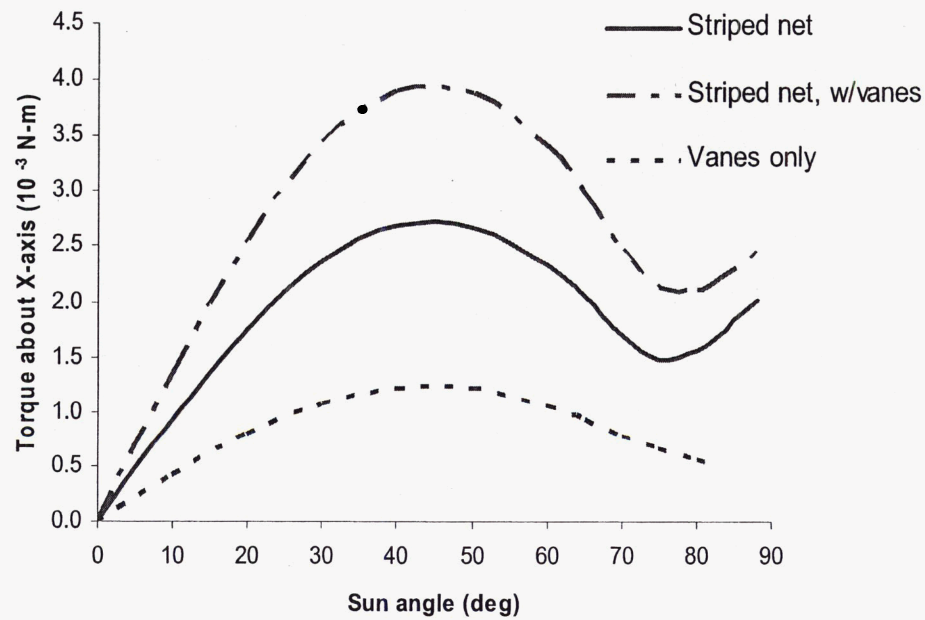
- Max cone angle ~ $\theta = 55^o$ ⇨ Sun angle ~ $\alpha = 75^o$
- Constrains useful (propulsive) operational range
- Significantly different than “ideal” behavior



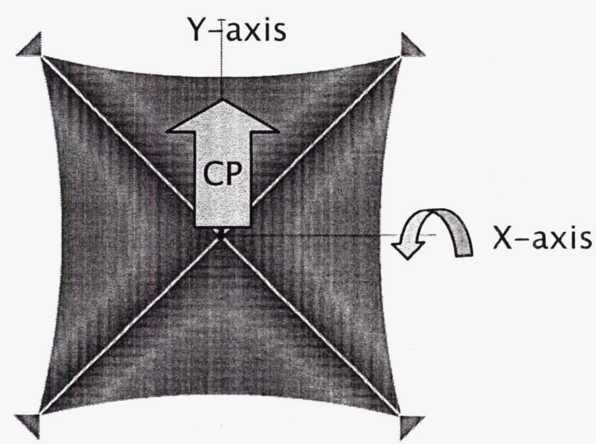
Sensitivity Analysis

Solar Pressure Torques





- Center of pressure (CP) shifts as sun angle increases
- Creates torque about x-axis ⇨ Control Authority issue
- Analysis can reveal possible anomalies



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Summary

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- A MATLAB® model has been developed to generate realistic sail shape profiles for the striped-net design as input into the Solar Vectoring Evaluation Tool software to determine the propulsive force vector, center of pressure, and resulting torques.

- Sensitivity analysis can be done using these tools to determine what key parameters drive solar sail propulsive performance.
  - ✓ *Center-line angle effect due to "non-ideal" properties*
  - ✓ *Cone angle limitation constraining operational range*
  - ✓ *Center of pressure shift and resulting torques affecting sailcraft control*

- Quick and easy toolset for use in understanding "non-ideal" solar sail performance as a function of geometric and optical parameters.

Acknowledgements

The work described in this paper was funded by the **In-Space Propulsion Technologies** Program, which is managed by NASA's Science Mission Directorate in Washington, D.C., and implemented by the In-Space Propulsion Technology Projects Office at Marshall Space Flight Center in Huntsville, AL.

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