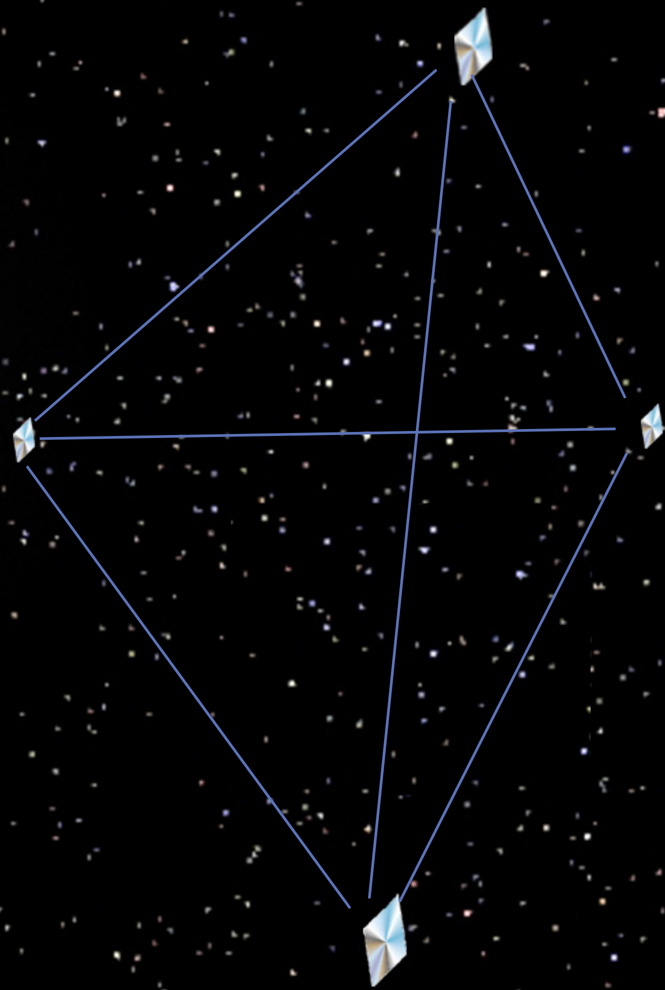
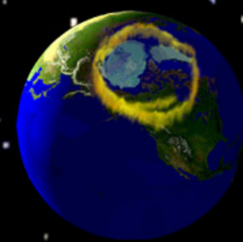
Factoring Force Uncertainty into Solar Sail Mission Planning



6th International Symposium
on Space Sailing
(ISSS 2023)



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City University of New York
5 - 9 June, 2023

Topics

- Describe difference between “Ideal” sail and “Realistic” sail thrust/force performance.
- Review areas where these differences need to be addressed in Solar Sail mission definition and development.
  - Identify activities that address approaches.
- Recommend solar sail “calibration” activities that would be beneficial for upcoming Solar Sail demonstration and/or operational missions.

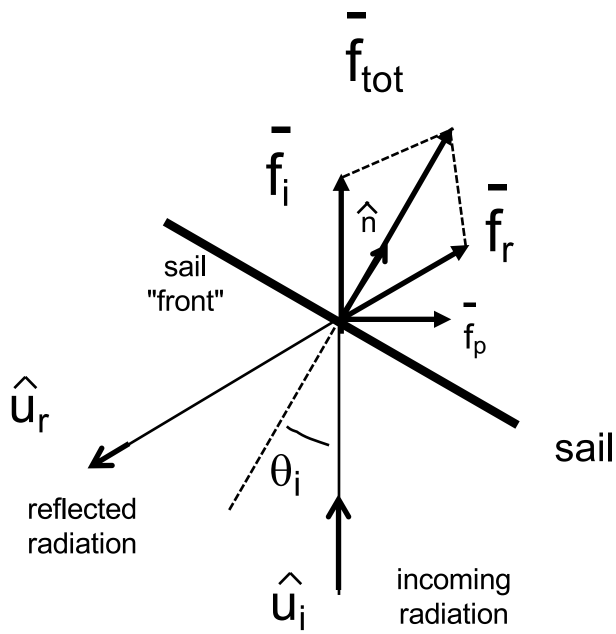
The Need

- Many solar sail mission development groups use the concept of "ideal" solar sails for initial mission concept proposal.
  - This may be appropriate for very early feasibility sizing (< 100-m sail maybe, > 200-m sail maybe not), however some concepts may be presenting overly optimistic capabilities for solar sail missions.
- Use of a more "realistic" solar sail model, addressing both thrust performance and sailcraft trajectory control, would ensure that concept feasibility and required developments and potential mission success are better reflected.

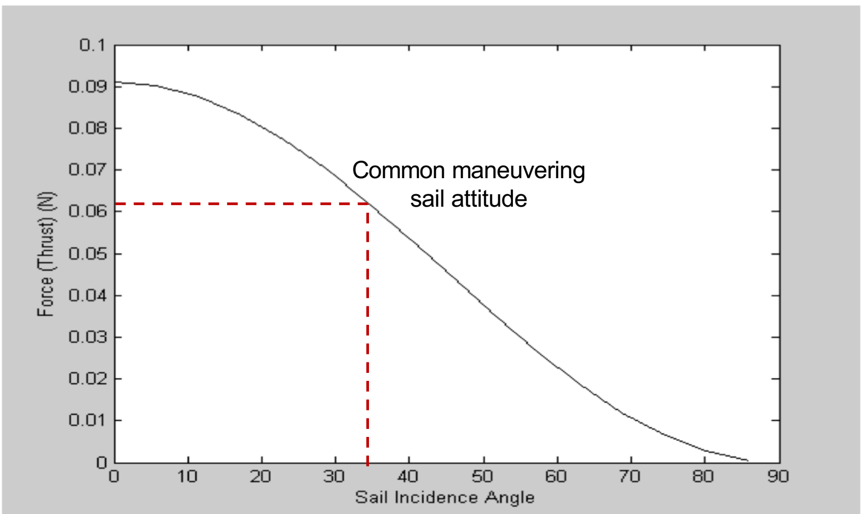
Ideal Solar Sail Thrust

- Reflection of Solar Radiation Photons (P_I = local SRP)
  - Complete reflection off "ideal" surface.
  - Resulting force normal to sail (flat) surface.
  - Force magnitude a function of distance from Sun, sail area, and sail surface angle to the Sun.

$$\bar{f}_{tot} = 2P_I A(\cos\theta_i)^2 \hat{n}$$



Solar Radiation Pressure Force



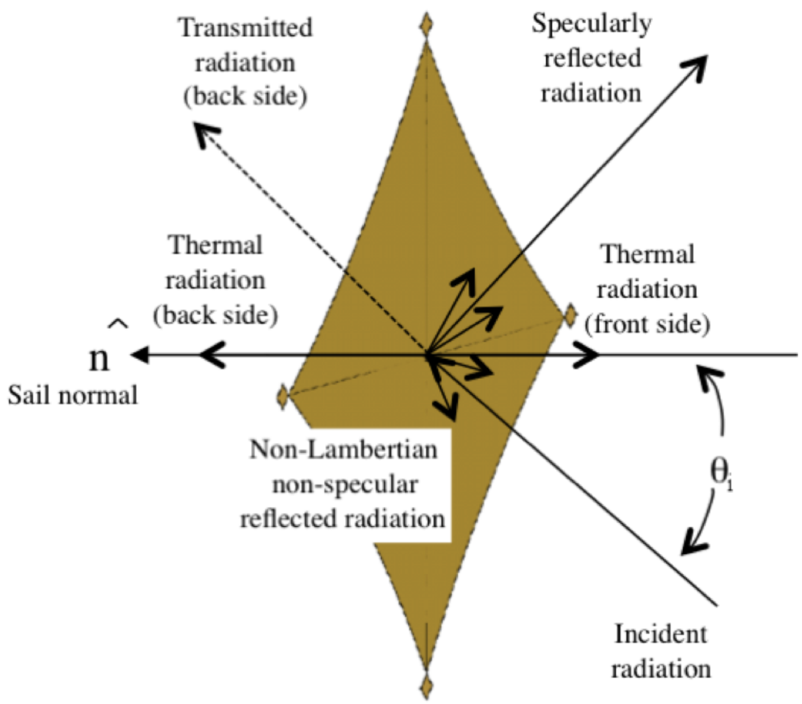
Solar Sail Total Force (Thrust) Vs. Sun-Incidence Angle
(For a 100 x 100 meter perfect sail @ 1 A.U.)

Non-Ideal Solar Sail Thrust

- Non-ideal optical properties.
- Non-ideal sail shape.
    - Flatness, billow, droop, actual projected area, asymmetry.
    - Wrinkles, crinkles and creases.
    - Center of Pressure (C_P) location uncertainty.
- Resulting force NOT simply normal to sail surface.
    - Direction potentially difficult to predict accurately.
- C_P and actual force direction potentially changing with sail attitude.

Non-Ideal Optical Properties

- Transmissivity, Absorptivity, Reflectivity, Specularity, Emissivity, Lambertian.
  - Note: due to manufacturing processes, these properties likely change over the surface of the solar sail material.



Solar Sail Optical Properties

Ideal and Non-Ideal Solar Sail Optical Properties

	t_r	a_b	r_f	s	ε_f	ε_b	B_f	B_b
Ideal sail	0	0	1	1	0	0	2/3	2/3
Non-ideal JPL sail	0.02	0.1	0.88	0.94	0.05	0.55	0.79	0.55

"Table 3-1"

t_r	Transmissivity (≅ 0)	s	Specularity (non-spec = 1-s)
a_b	Absorptivity (≅ 1-r_f)	$\varepsilon_{f,b}$	Emissivity (front and back)
r_f	Reflectivity	$B_{f,b}$	Lambertian (front and back)

Non-Ideal Optical Properties

- Non-Ideal Optical Properties Affect Both Sail Force Magnitude and Direction.

<u>Normal Force</u>

$$\bar{f}_n = P_l A\left[\left(1+r_f s\right)\cos^2(\theta_i)+B_f(1-s)r_f\cos(\theta_i)+\left(1-r_f\right)\frac{\varepsilon_f B_f-\varepsilon_b B_b}{\varepsilon_f+\varepsilon_b}\cos(\theta_i)\right]\hat{n}$$

<u>Tangential Force</u>

$$\bar{f}_t = P_l A\left(1-r_f s\right)\cos(\theta_i)\sin(\theta_i)\hat{t}$$

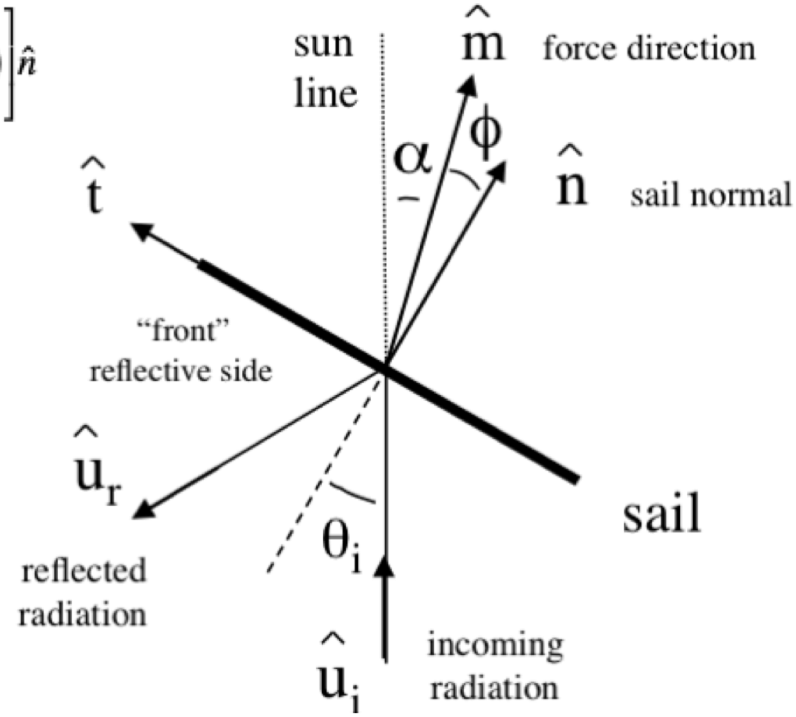
<u>Total Force</u>

$$f_{tot} = \left(f_n^2+f_t^2\right)^{1/2}$$

θ_i Sun-incidence angle

ϕ Centerline angle = $\tan(\phi)=\frac{f_t}{f_n}$

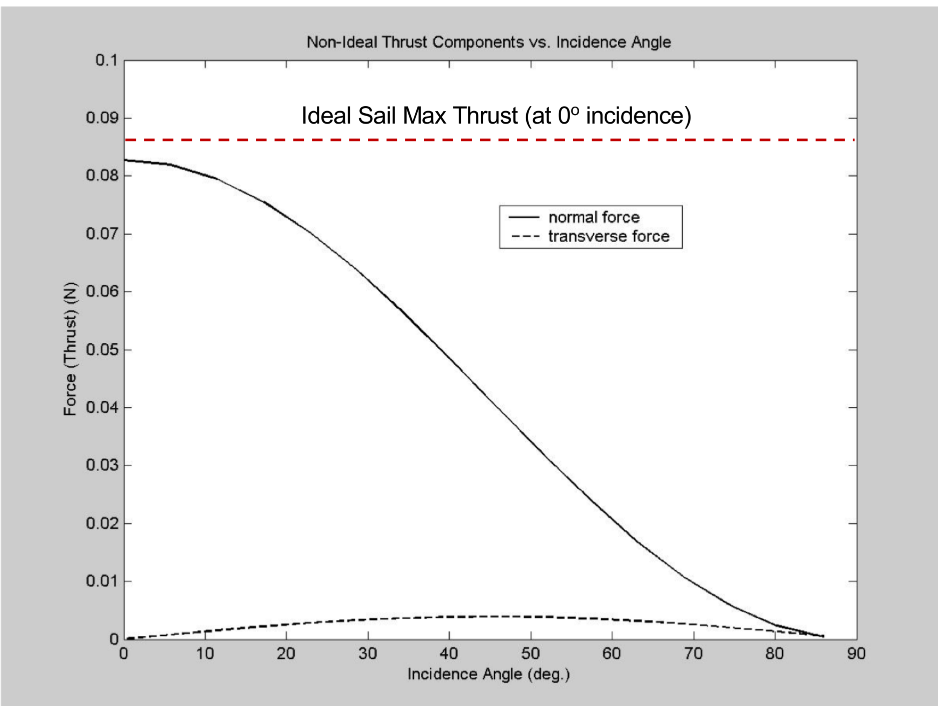
α Cone angle = $\alpha=\theta_i-\phi$



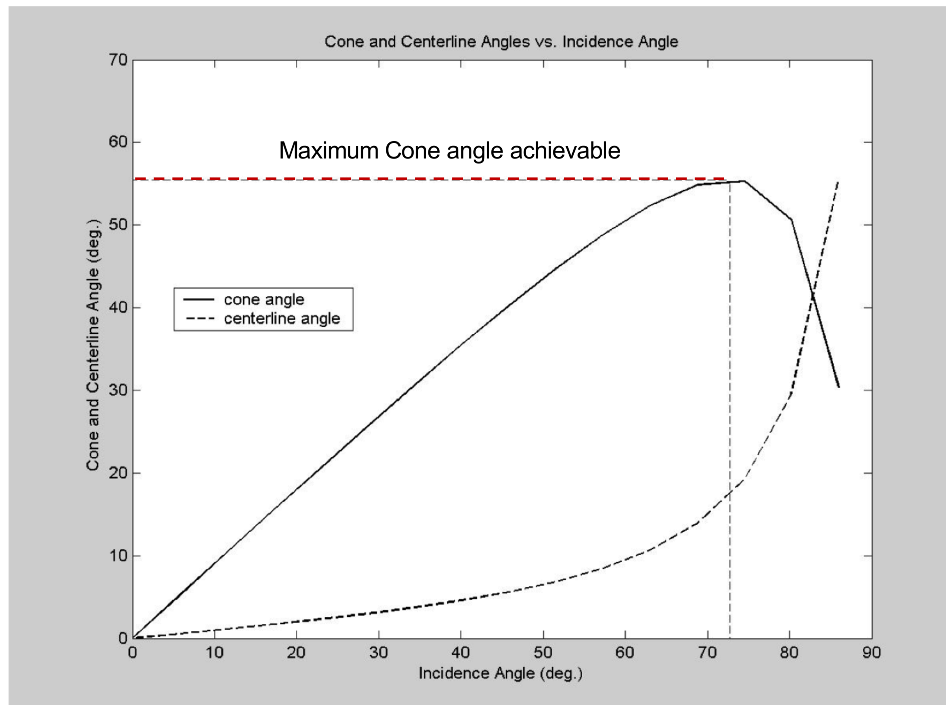
Non-perfect Reflector Force Direction

Thrust Effect of Non-Ideal Optical Properties (only)

- Total sail thrust less than Ideal sail
- Limits maximum Cone angle
  - Force direction from sun-line limited



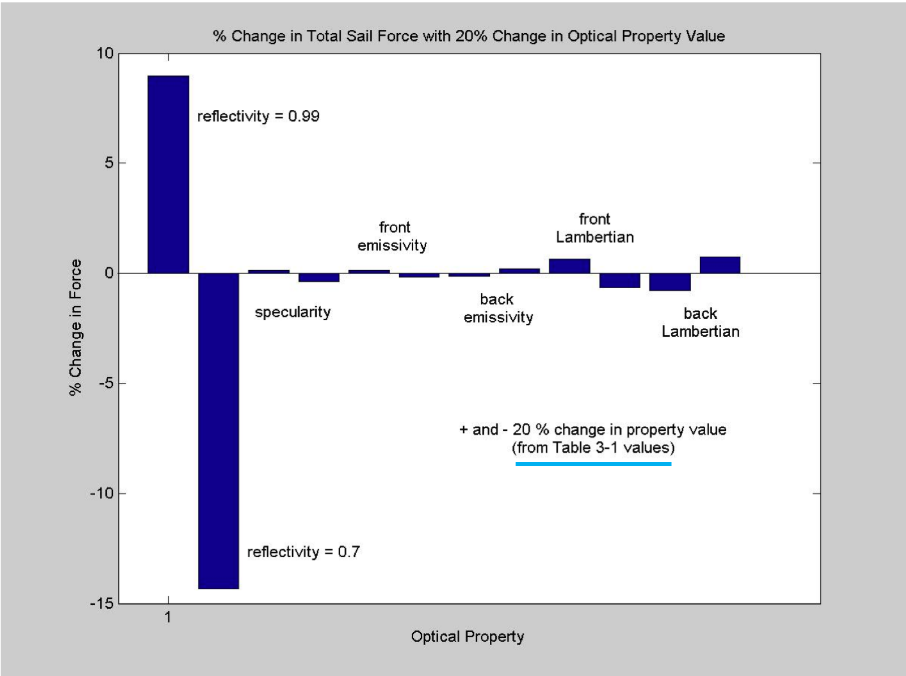
Normal and Tangential Force Components Vs. Sun-Incidence Angle
(For a 100 x 100 meter non-ideal sail @ 1 A.U.)



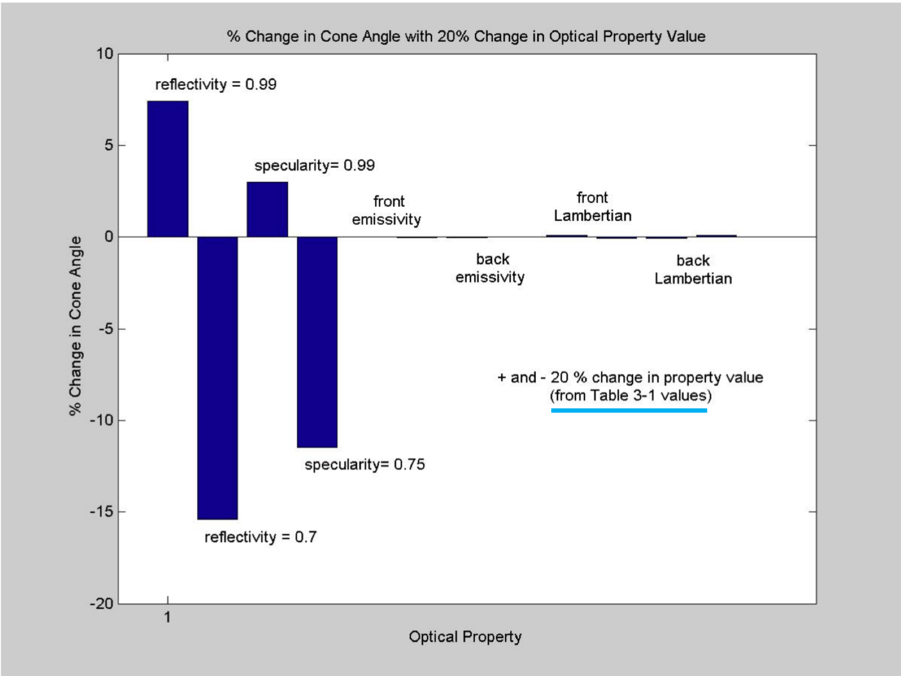
Cone and Centerline Angles Vs. Sun-Incidence Angle
(For a 100 x 100 meter sail @ 1 A.U.)

Relative Effects of Non-Ideal Optical Properties

- Reflectivity most important performance parameter.
  - For both thrust magnitude and direction.
- Specularity has significant effect on thrust direction.



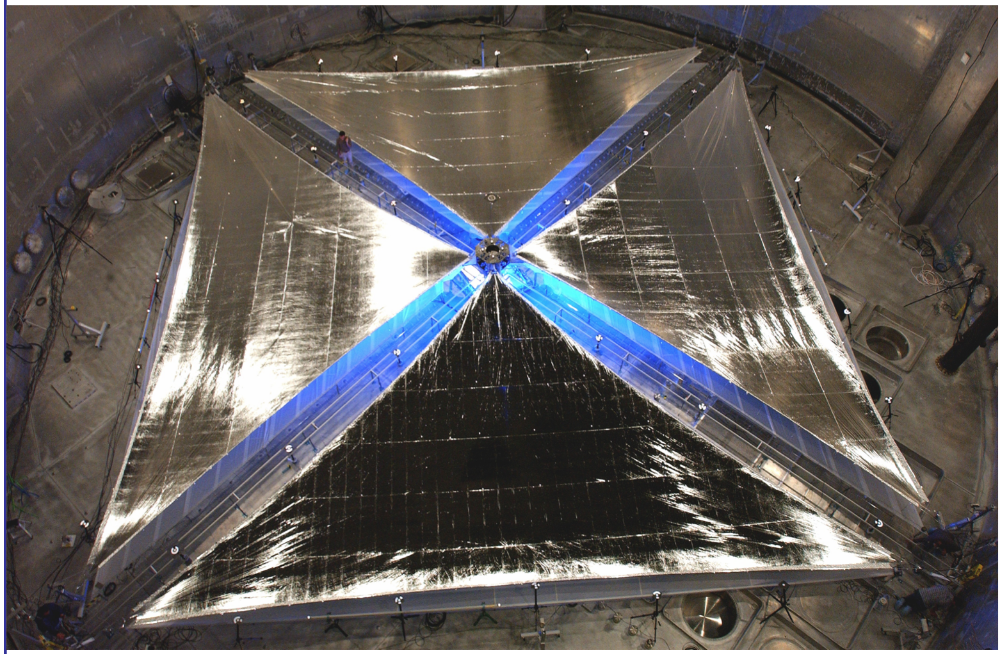
Relative Effects of Optical Properties on Sail Thrust Magnitude



Relative Effects of Optical Properties on Sail Thrust Direction

Non-Ideal Sail Shape

- Non-flatness, billow, droop, actual projected area, asymmetry all affect sail thrust and direction.
- Examples of two different sail test articles:

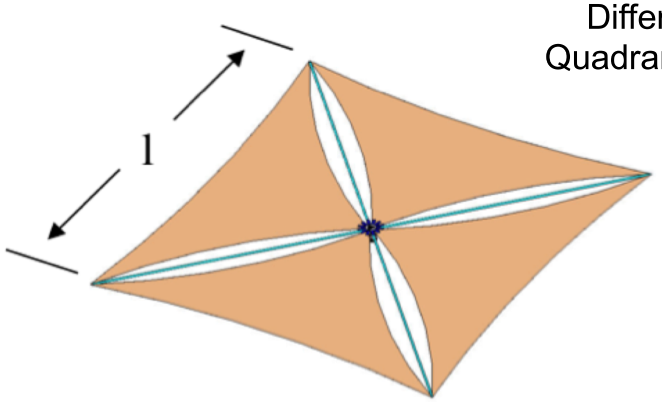


CP1 Tensioned Sail (NASA/ATK)

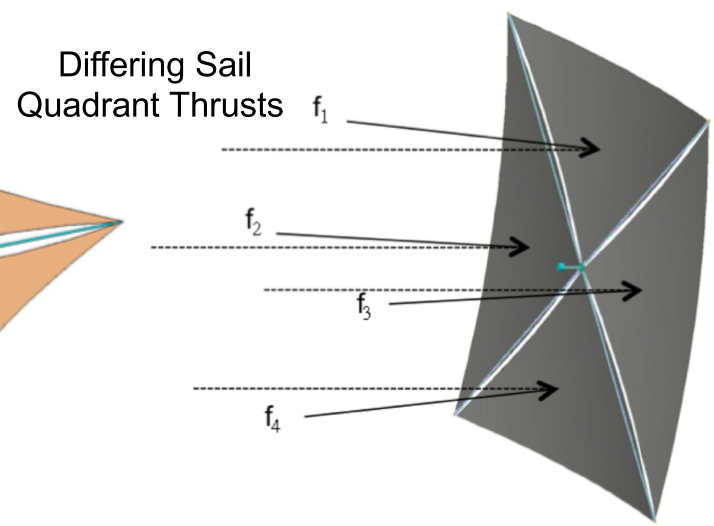
Mylar Draped Sail (NASA/L'Garde)

Non-Ideal Sail Shape

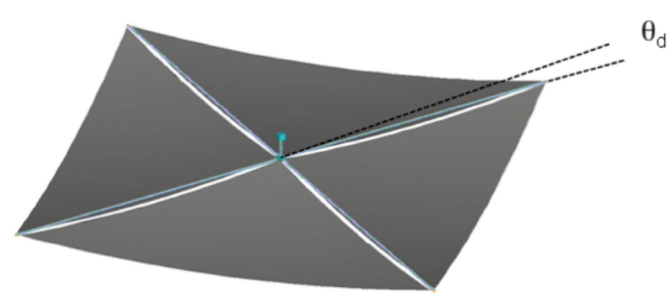
- Area projected in direction of sun (thrust area) affected by sail construction/configuration and non-flatness (billow, droop, etc.).
- Asymmetry of sail quadrants (both shape and optical) can also affect sail thrust, direction and stability.
  - All these characteristics may change with sail/sun attitude.



Projected Sail Area



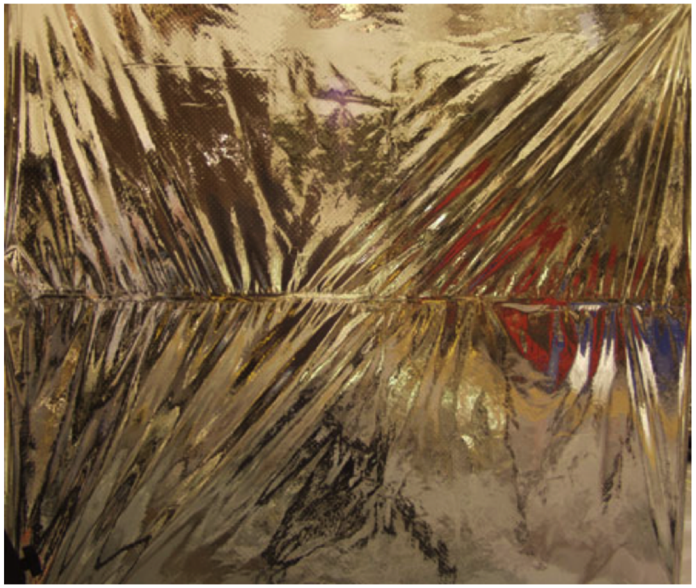
Solar Sail Billow



Sail Droop Angle

Other Sail Surface Properties

- Solar sail construction and handling can (does) create significant surface imperfections.
  - Wrinkles (long period), crinkles (short/random period), and creases (along sail material joints, rip stops, and folds) impacts sail specularity and associated thrust magnitude and direction, and may contribute to thrust asymmetry over the whole sail surface.



Wrinkles and Creases

Crinkles

Sail Model Thrust Comparisons

- Four different sail models used (with same sailcraft):

<u>Ideal Sail Model</u>

- Flat, perfect reflector

<u>Non-ideal Sail Model</u>

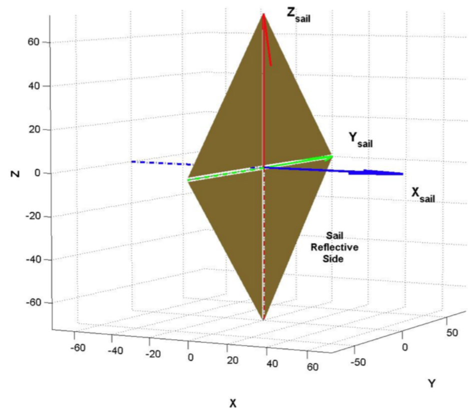
- Flat, non-perfect reflector

<u>Realistic Sail Model</u>

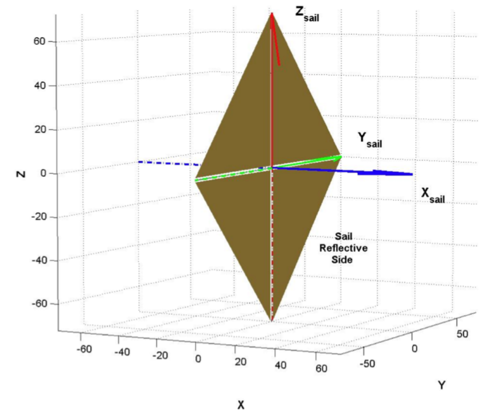
- Billowed, non-perfect reflector

<u>Striped Sail Model</u>

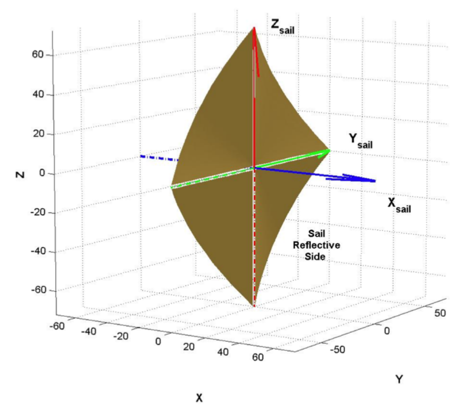
- Billowed, non-perfect reflector, striped (un-tensioned) material



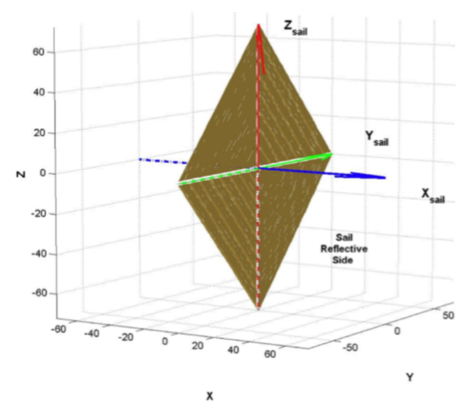
Sailcraft with Ideal Sail Model



Sailcraft with (Flat) Non-ideal Sail Model



Sailcraft with Non-ideal Billowed Sail Model



Sailcraft with Non-Ideal Billowed Striped Sail Model

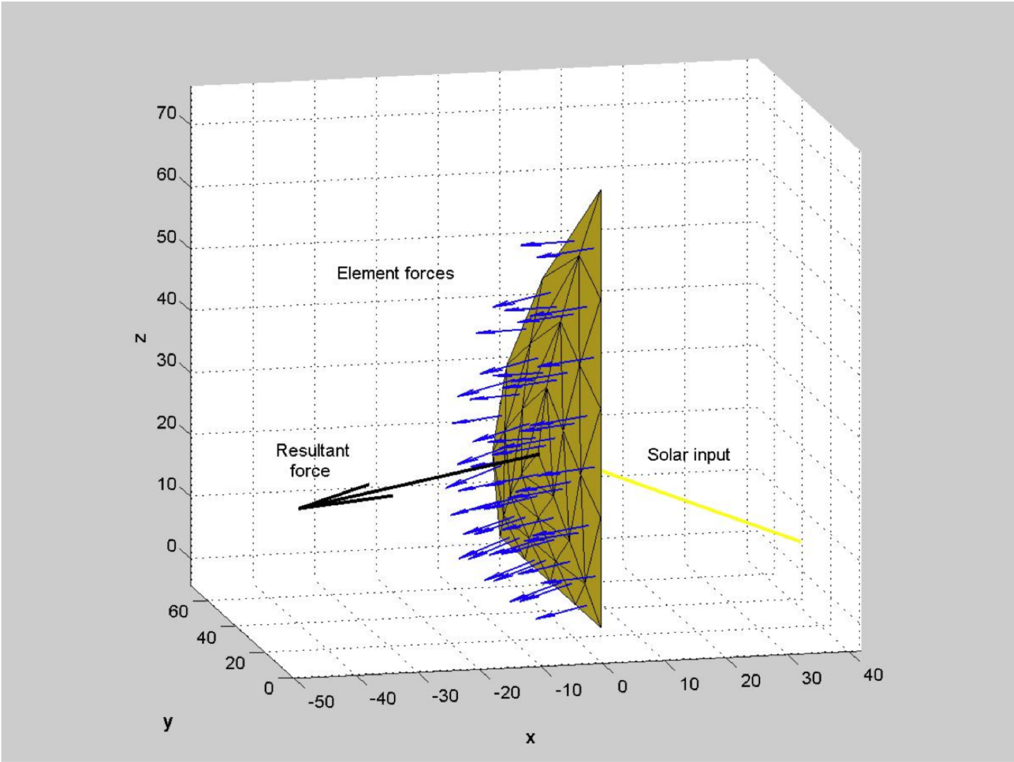
Sail Model Properties

- Model Characteristics:
- Optical properties as shown
  - Some differences associated with expected sail type properties
- Equal total sailcraft masses
- Equal sail (material) area
  - Projected area calculated by tool (billow, etc.)

	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
m_{sc}	300 kg	300 kg	300 kg	300 kg
m_s	60 kg	60 kg	60 kg	60 kg
m_p	240 kg	240 kg	240 kg	240 kg
A_{sail}	10,000 m^2	10,000 m^2	10,000 m^2	10,000 m^2
Billow (θ_b)	0	0	10^o	10^o
Droop (θ_d)	0	0	5^o	5^o
t_r	0	0.02	0.002	0.02
a_b	0	0.1	0.08	0.12
r_f	1	0.88	0.918	0.86
s_{act}	1	0.94	0.978	0.55
ε_f	0	0.05	0.02	0.03
ε_b	0	0.55	0.269	0.4
B_f	2/3	0.79	0.79	0.89
B_b	2/3	0.55	0.55	0.65

Sail Model Thrust Calculation

- Computational Method*:
  - Finite element model of each sail quadrant
  - Sail surfaces divided into many small areas
  - Billow modeled as circular cone section (incl. between stripes)
  - Solar radiation pressure force calculated for each individual area
  - Added vectorially for total thrust magnitude and direction



Sail Quadrant Forces

* As used in the Princeton Satellite Systems (PSS) Solar Sail Module

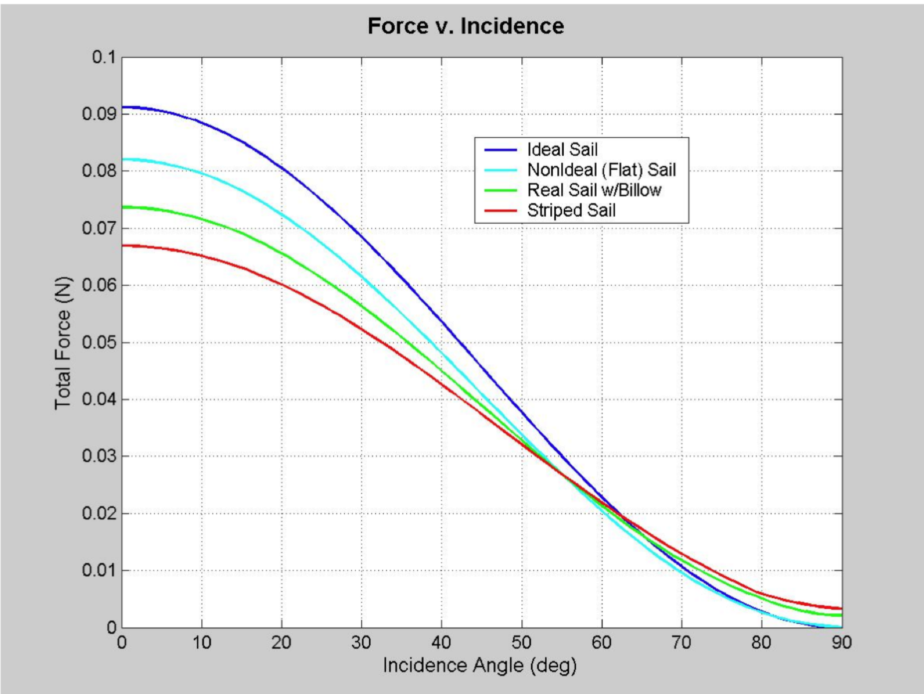
Sail Model Performance

Characteristic Acceleration Comparison

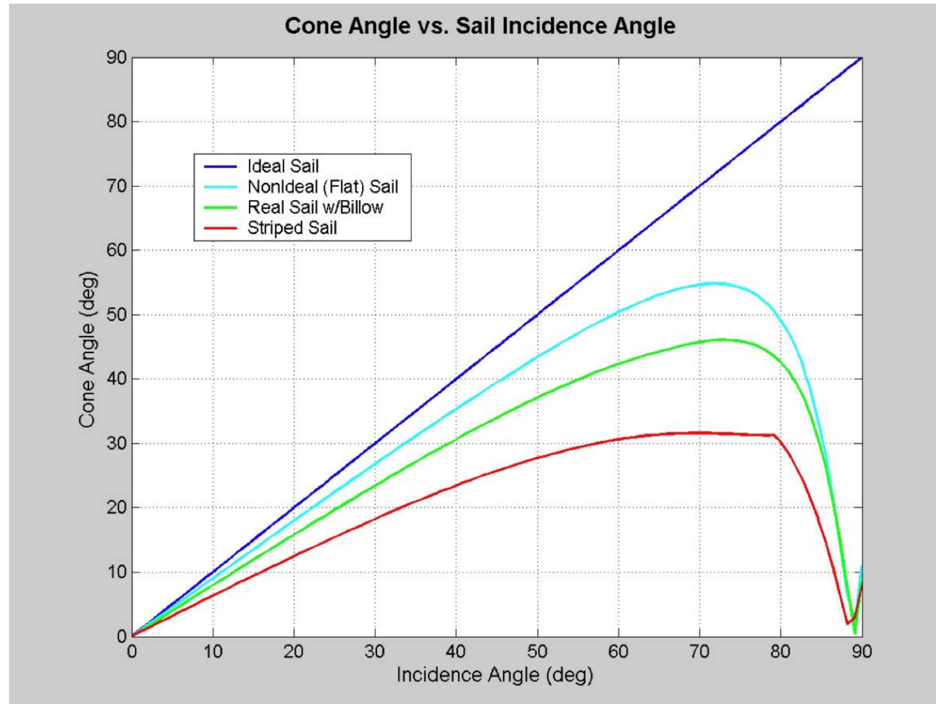
	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
a_C (mm/s²)	0.304	0.273	0.267	0.243
		-10.2%	-12.2%	-20.1%

Thrust Level Comparison

	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
0^{o} (N)	0.091	0.082	0.074	0.067
35^{o} (N)	0.063	0.056	0.053	0.048



Sail Forces Vs. Sun-Incidence Angle
(For a 100 x 100 meter perfect sail @ 1 A.U.)

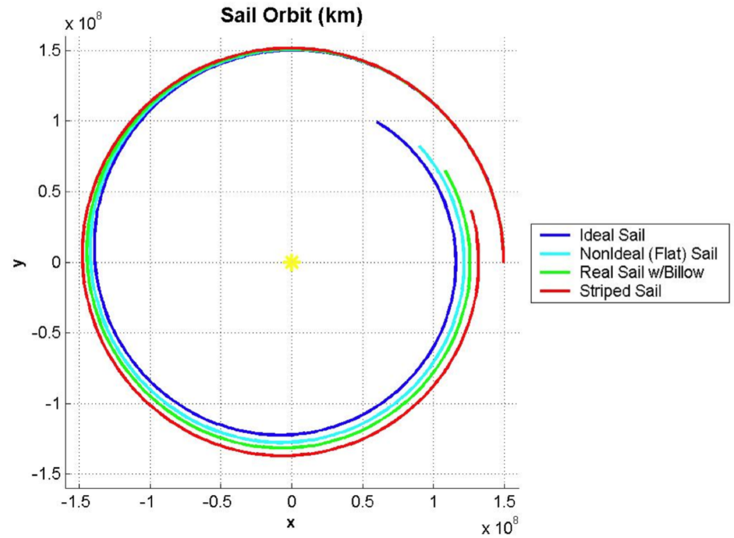


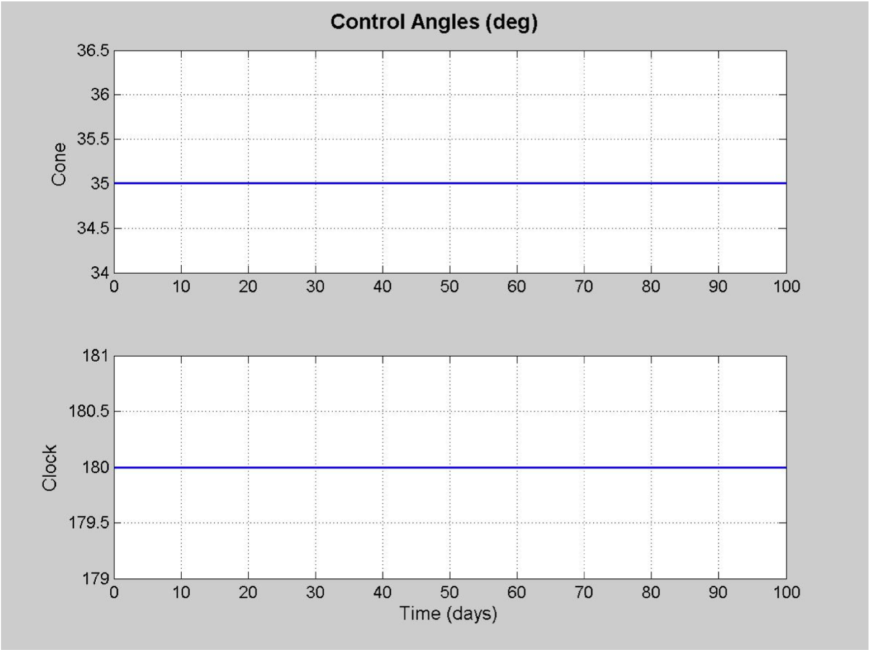
Cone Angles Vs. Sun-Incidence Angle
(For a 100 x 100 meter perfect sail @ 1 A.U.)

All results shown from Bruce Campbell Ph.D. dissertation "An Analysis of Thrust of a Realistic Solar Sail with Focus on a Validation Mission in a Geocentric Orbit", 2010

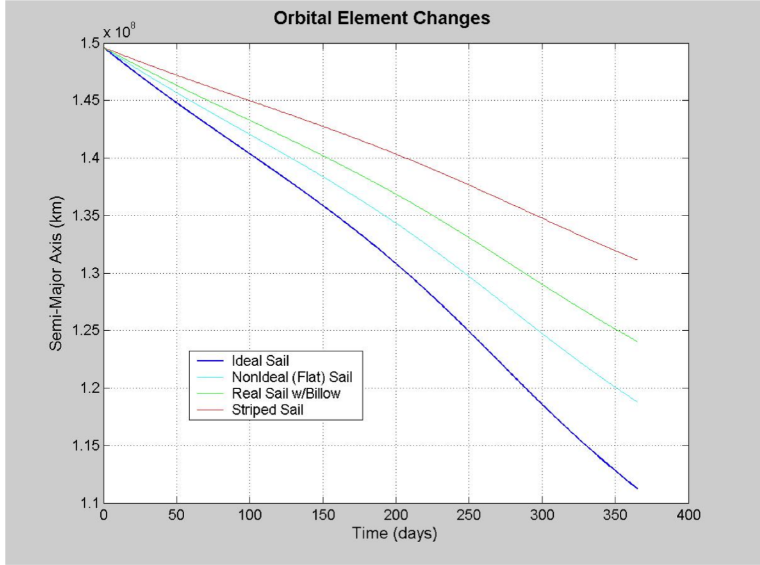
Simulation #1 – SMA Decrease

- 1 A.U circular heliocentric
- Fixed 35° cone angle and 180° clock angle
- 365 day simulation length



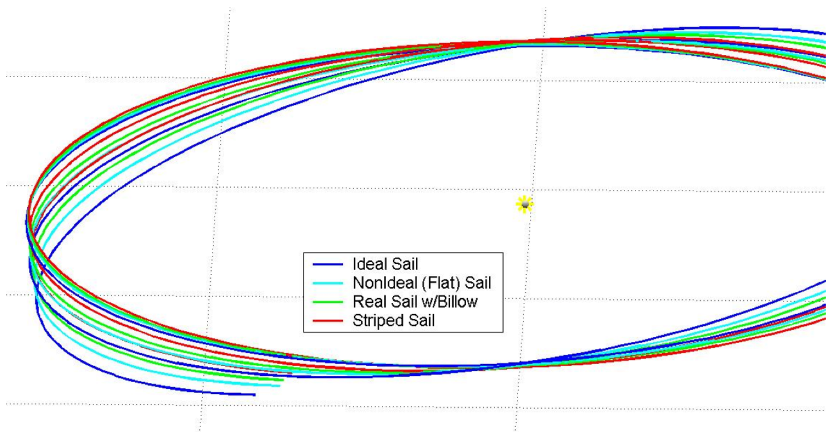


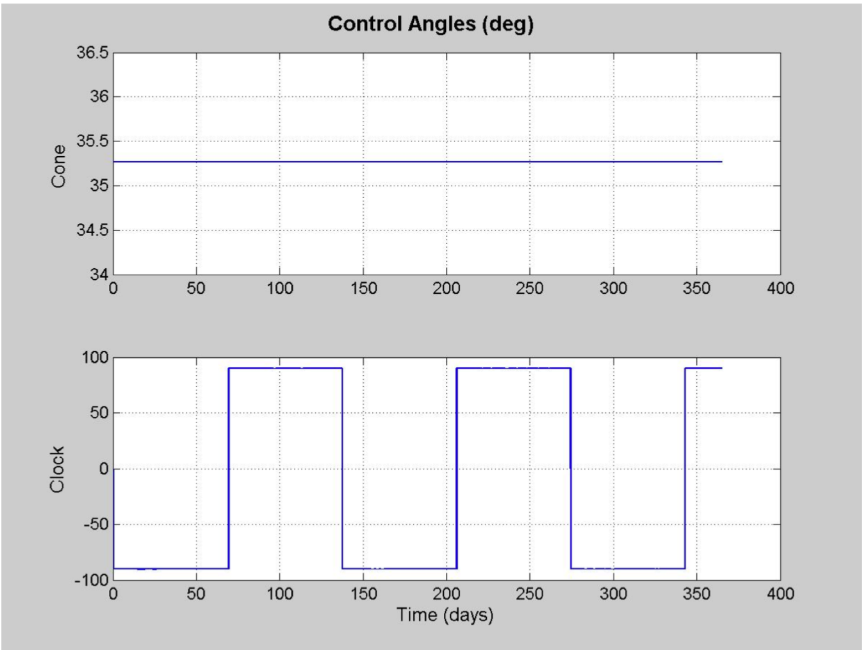
SMA Decrease Sailcraft Control Angles



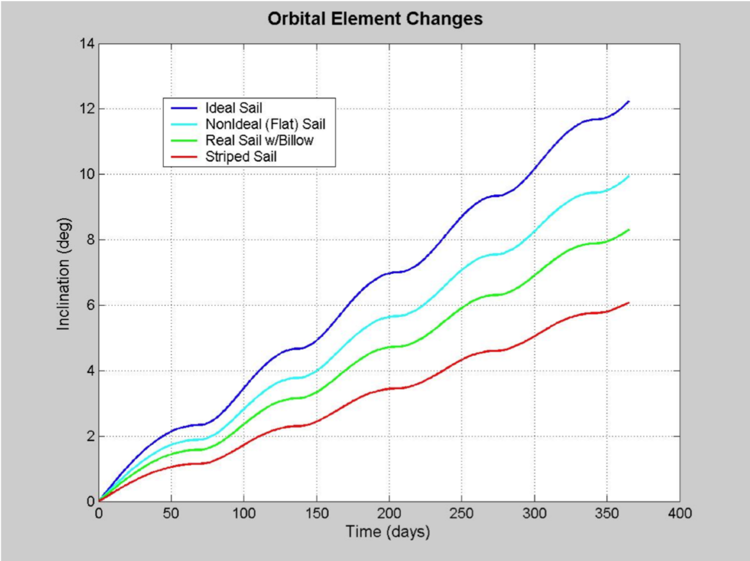
Simulation #2 – Inclination Increase

- 0.5 A.U circular heliocentric
- Fixed 35° cone angle and 180° "flipping" clock angle
- 365 day simulation length





Inclination Increase Sailcraft Control Angles



"Realistic" Solar Sail Mission Development

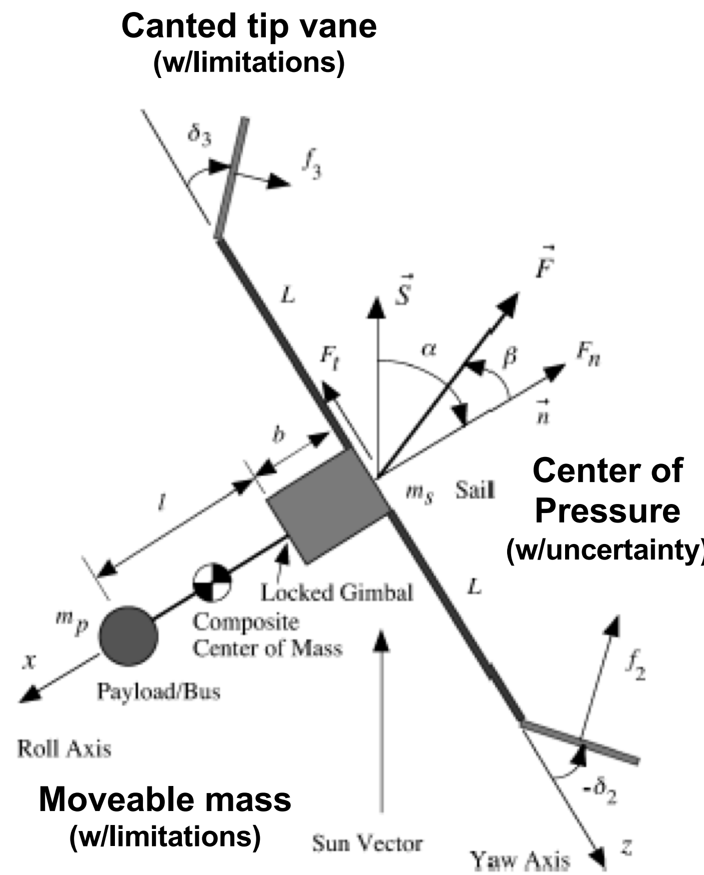
- <u>Attitude control is Trajectory control is Mission control</u>
- Process (solar sail GN&C systems required capabilities):
  - Determine optimal solar sail mission trajectory
    - Incorporate "realistic" solar sail force/thrust capabilities and profiles
    - Include "margin" for thrust and attitude control uncertainties
  - Determine associated (desired) sail attitude profiles
    - Also incorporate "realistic" solar sail ACS method (vanes, Cp/Cm offset, etc.) force/torque capabilities and profiles (attitudes)
    - Include "margin" for force and sailcraft/ACS response/dynamics uncertainties
  - Determine actual sailcraft position/trajectory and attitudes
  - Determine required sailcraft attitude (and associated ACS method configurations and commands) to correct trajectory
    - Ensure that solution remains within Sail and ACS method "realistic" capabilities
  - Rinse and repeat (at an optimal frequency)

ACS systems design!

GN&C systems design!

“Realistic” Solar Sail Attitude Control

- Solar Sail ACS method examples:
  - Tip Vanes
    - Small solar “sails” create torques about sailcraft Cp
    - Same uncertainties with “realistic” vane force magnitude and direction
    - Potential uncertainties with actual sail/boom shapes and coupled dynamics
    - Potential asymmetry between vanes and with changing sail and vane attitudes
    - Uncertain inherent sailcraft attitude stability
  - Cp/Cm Mass translation
    - Moveable mass creates Cm/Cp offset torques
    - Same uncertainties with “realistic” sail force magnitude and direction (Cp uncertainty)
    - Potential uncertainties with actual sail/boom coupled dynamics
    - Uncertain inherent sailcraft attitude stability



From Wie “Solar Sail Attitude Control and Dynamics, Part 2”

Solar Sail GN&C

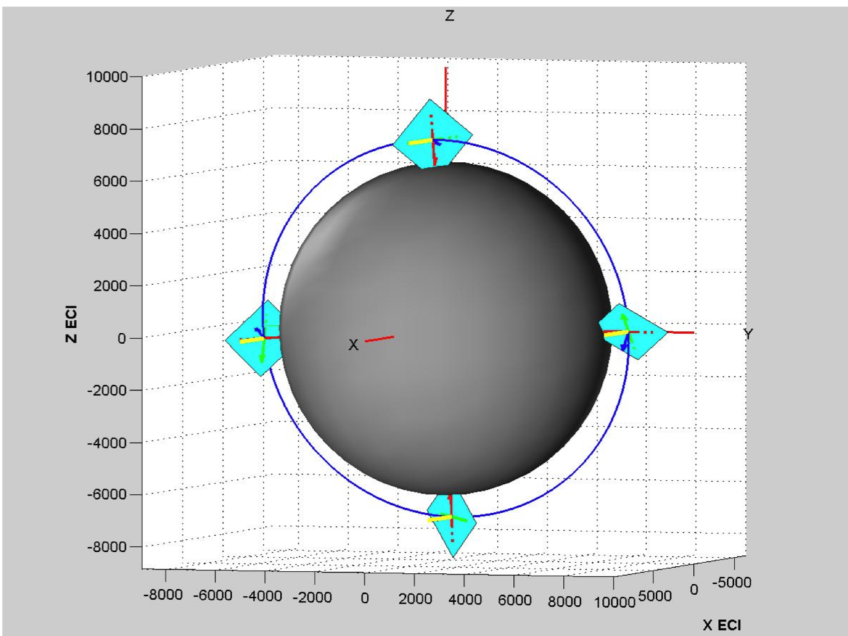
- Areas requiring incorporation of “realistic” sail properties:
  - Solar sail modelling
    - Optical properties, shape, dynamics
  - Solar sail trajectory modelling
    - Incorporating increased sail model fidelity
  - Solar sail attitude control modelling
    - ACS approach (vanes, Cm, surface manipulation [quadrant twist, reflectivity], etc.) modelling (including uncertainties)
    - Controller approach (PD/PID, bandwidth, etc.)
  - Solar sail manufacturing
    - No two alike

Solar Sail "Calibration"

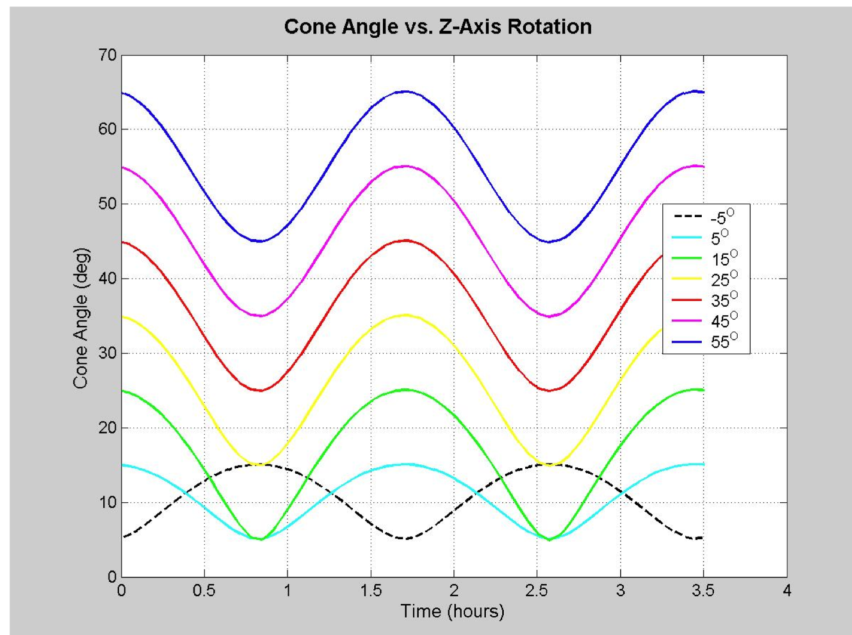
- Due to all the discussed uncertainties, and considering expected manufacturing differences, each solar sail flown will need to perform an in-space "calibration" program to establish performance characteristics and boundaries to allow updates to mission trajectories and control operations.
- This calibration may require non-mission systems and maneuvers to provide the needed information.
  - Sail-focused cameras/sensors for sail/boom shapes and dynamics.
  - Active attitude control mechanisms for stability.
  - A calibration maneuver profile to determine sail thrust and ACS performance.
    - Note that these systems could be part of the launch and deploy systems that could be designed for jettison before actual mission operations begin.

Example Calibration Operation (from ST-9)

- Dawn-Dusk Sun-Synchronous Circular Orbit @ 1,000 km
  - Local Vertical/Local Horizontal (LVLH) Attitude maintained
  - Steering Profile and Resulting Cone Angles
    - Steering profile holds set Z_{sail} rotation for many orbits (gravity gradient)
    - Cone angle (periodic) changes due to Sun-Earth-Sail (LVLH) relationships



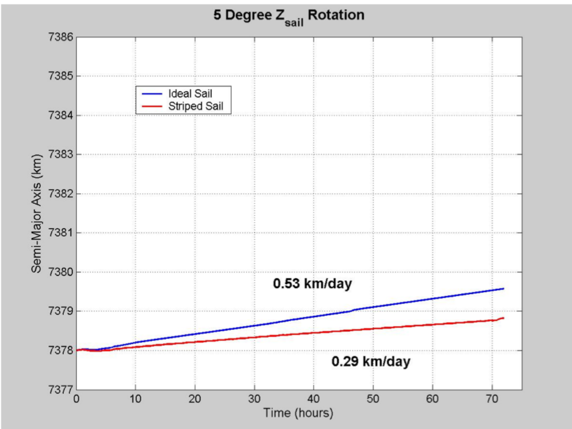
ST9 Simulation Steering Profile



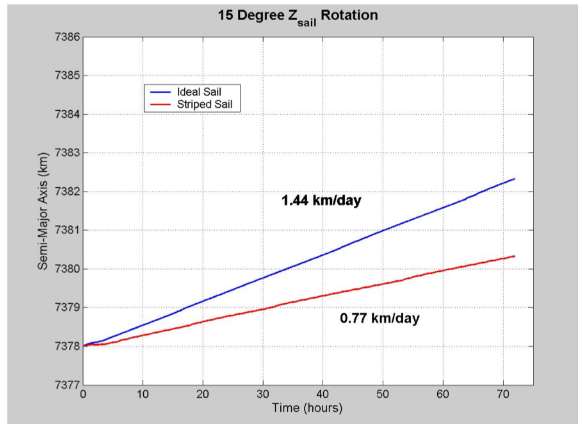
ST9 Simulation Cone Angles
for a Range of Fixed Z_{sail} Rotations

Simulated Orbit Raising Results (from ST-9)

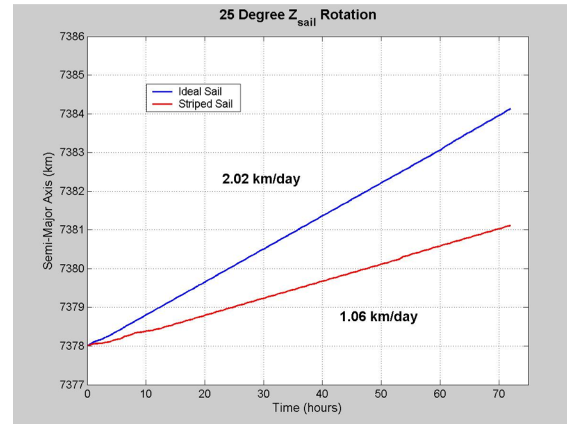
- Compares ST-9 “realistic” sail model to ideal model.



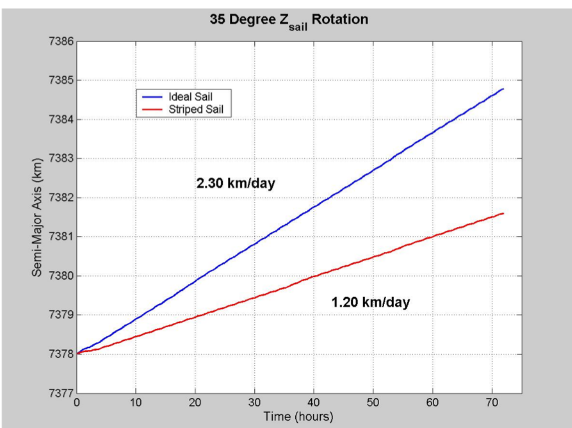
5° Z_{sail} Rotation



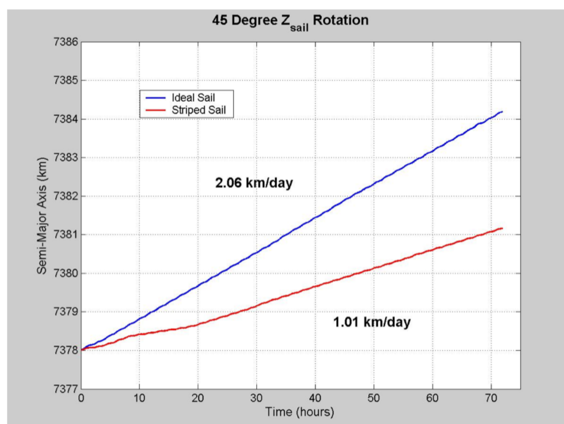
15° Z_{sail} Rotation



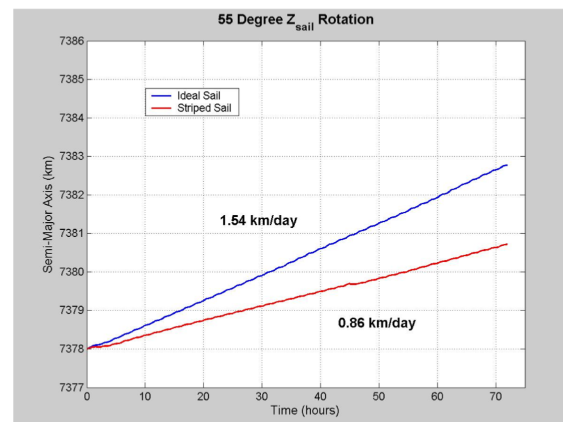
25° Z_{sail} Rotation



35° Z_{sail} Rotation



45° Z_{sail} Rotation

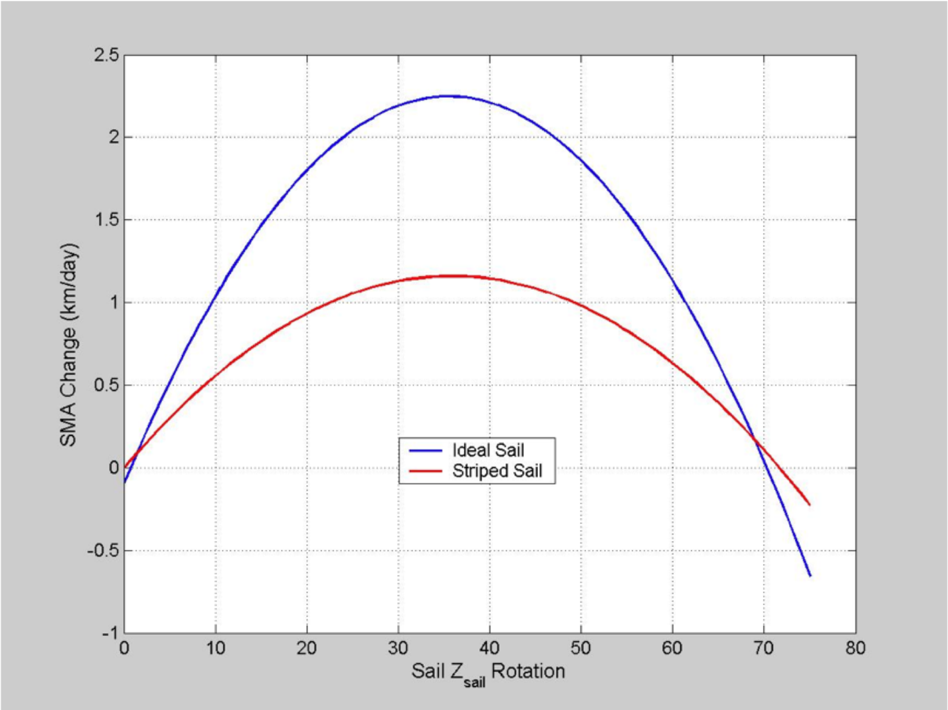


55° Z_{sail} Rotation

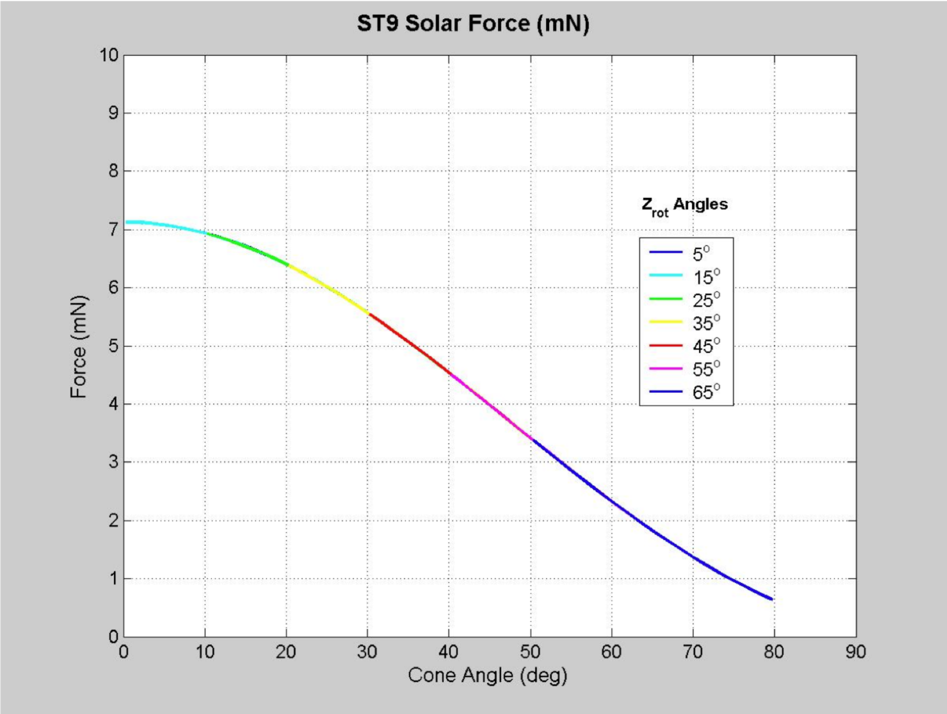
ST9 Simulation Ideal vs. Striped Sail SMA Increase Performance

Solar Sail Thrust Calibration (from ST-9)

- Plot of actual sail orbit maneuvers can be converted to the familiar Thrust vs. Cone angle curve for the actual (realistic) solar sail.



Simulated ST9 SMA Performance



ST9 Thrust vs. Cone Angle Curve
from “Simulated” Orbit Measurements

Conclusions

- Significant differences in performance between ideal, non-ideal (optically), and realistic sailcraft models.
  - Realistic sailcraft models are very much sail configuration dependent.
  - Sailcraft models and tools should incorporate the non-ideal/realistic characteristics and parameters described.
  - For best accuracy of sailcraft performance estimation and mission development requirements, actual sail characteristic measurements should be incorporated into concept developments.
  - Where this is not possible, best estimates of these characteristics for the particular sail configuration/construction should be incorporated, instead of using "standard" or ideal values.
- A solar sail validation flight should be flown as soon as possible. (Go ACS-3! Go GAMA?)
  - Will provide in-environment information for many solar sail characteristics, allowing validation of models and tools to allow more accurate estimation of future, important space missions only enabled by the use of solar sail propulsion.

Suggestion

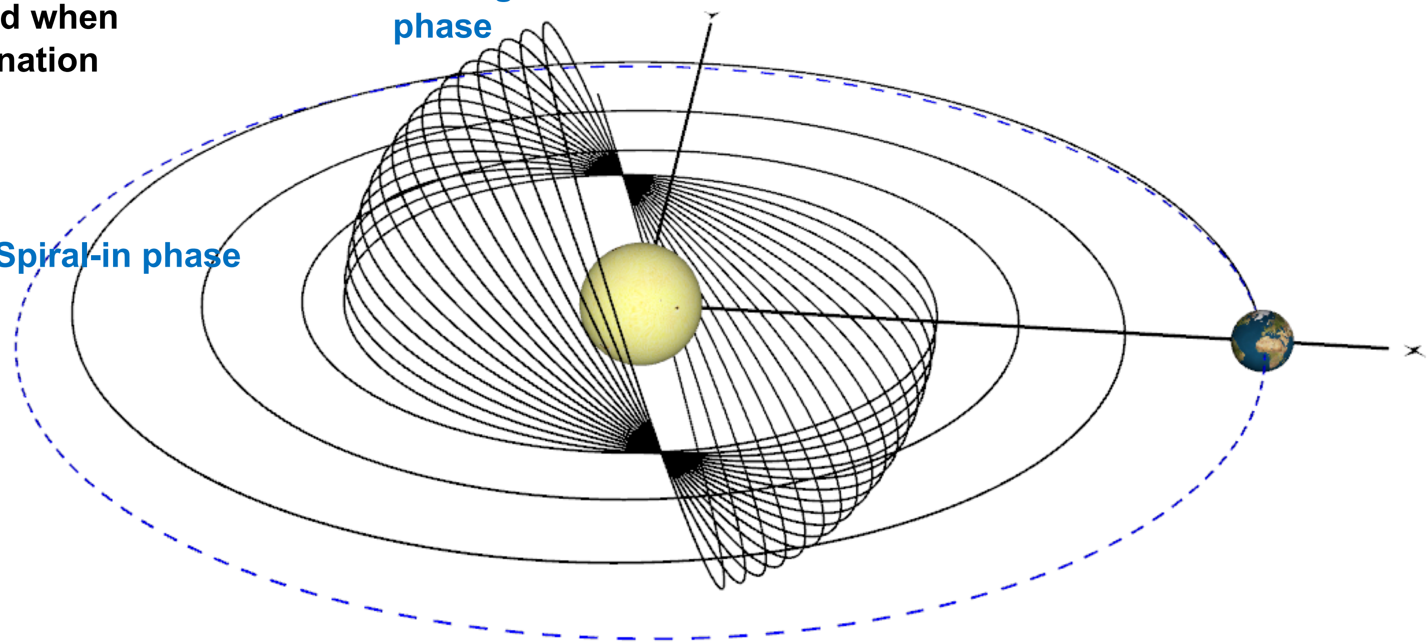
- Identify, and concentrate on a straight-forward solar sail science mission.
  - Will ACS-3 really provide the confidence to jump right to larger, complex solar sail missions requiring precise trajectories for mission success?
    - Planetary and other rendezvous missions needing to be at a certain place at a certain time.
    - Missions requiring frequent, precise attitude changes for trajectory or observations.
  - Perhaps, the first useful mission could primarily show the benefits of solar sail propulsion providing essentially unlimited ΔV capabilities compared to conventional and other newer approaches.
    - Several "Heliosphere Mapping Missions" have been envisioned that simply (and continuously) decrease the sailcraft semi-major axis (SMA) and/or inclination around the sun. (ex.: **High Inclination Solar Mission** [HISM], Heliospheric Meteorology Mission [HMM])
      - Such missions have much looser trajectory/steering requirements for full mission success.
    - Even a solar photonic assist mission, to show the ability to perform such a useful trajectory, has a very straight-forward (and somewhat loose) steering profile (similar to ISP).
      - Though not as comprehensive, such a mission could still have significant interest in the Heliophysics community.
  - There are likely many more relatively simple, but useful, missions that can allow solar sail propulsion to evolve and walk before we run.

Suggestion

- Straightforward Helio-mission Operations:

Clock angle "flip" by 180° only occurs during "cranking" each time the sailcraft passes through the solar ecliptic plane, and can be performed over hours or days

Cone angles relatively fixed when spiraling in, and when "cranking" the inclination



From Kobayashi, et. al "The High Inclination Solar Mission"

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Associated ISSS 2023 Presentations

- Controllability of Solar Sails – Herasimenka, et. al
- Solar-sail Steering Laws to Calibrate the Accelerations from Solar Radiation Pressure, Planetary Radiation Pressure, and Aerodynamic Drag - Carzana, et. al
- A Solar Sail Shape Modeling Approach for Attitude Control Design and Analysis - Gauvain, et. al
- Solar Sail Torque Model Characterization for the Near Earth Asteroid Scout Mission - B. Diedrich
- A Reduced-Order Model for the Dynamics of a Flexible Solar Sail - Tuzcu
- Uncertainty Quantification for Solar Sails in the Near-Earth Environment – Bonilla, et. al