



Recent Progress in Heliogyro Solar Sail Structural Dynamics

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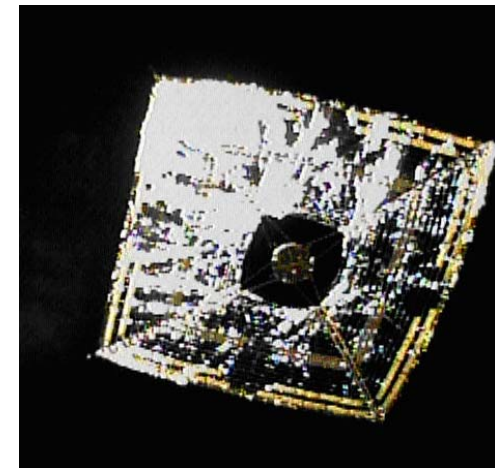
Background: The *Heliogyro* Solar Sail (MacNeal, 1967)



- The *heliogyro* is a helicopter-like spinning solar sail concept, conceived by MacNeal in the 1960s and studied by JPL in the 1970s.
- The heliogyro is a *mission-enabling* technology:
 - Membrane solar sail “blades” are compactly stowed on reels and easily deployed.
 - No elaborate management of large, 2-D membranes structures needed, so architecture may be scaled to very large sizes. $F \sim \text{Area of sail}$
 - Lightweight due to centrifugal stiffening. $a = F/m$
- Despite these advantages, development has lagged heavier, square-rigged solar sail designs (e.g., *Sunjammer*) due to the difficulty of full-scale ground testing.
- *Dynamics need to be validated by (validated) analysis, followed by an affordable flight demonstration, to advance the maturity of heliogyro solar sailing technology.*



A 15 km diameter heliogyro solar sail was the preferred concept for a proposed JPL Comet Halley rendezvous mission in 1977.



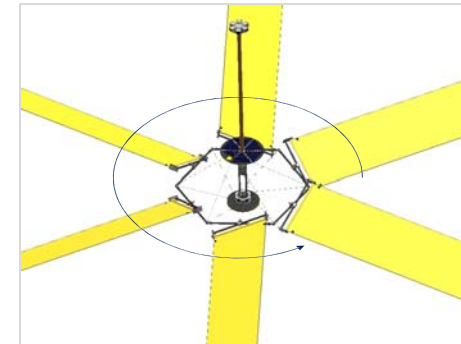
JAXA IKAROS (2010) is a 14 m spinning solar sail, but 2-D acreage management of sail limits scalability.

Presentation Overview



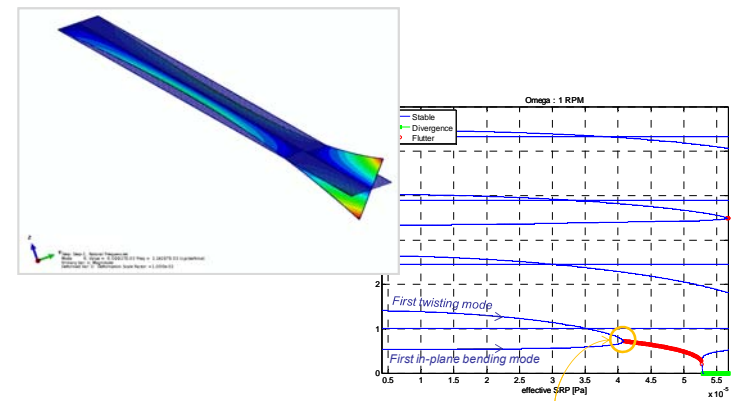
1. Overview of HELIOS, our heliogyro technology demonstration mission reference concept:

- *HELIOS is being used as a reference mission concept for our heliogyro technology development activities.*



2. Summary of current heliogyro structural dynamics and control studies being conducted at NASA:

- *Integrated finite element modeling;*
- *Solarelastic stability studies;*
- *Blade dynamics and control studies;*
- *Ground validation experiments;*



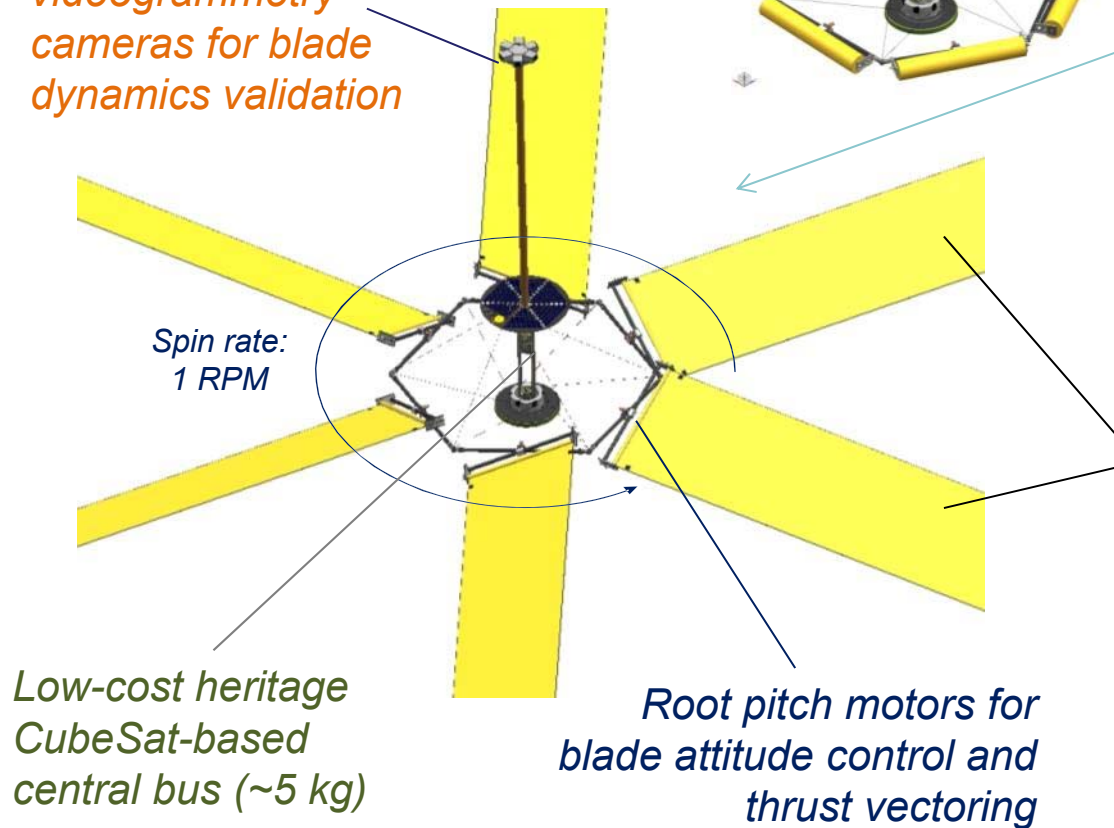
3. Conclusions and future work

HELIOS is our low-cost heliogyro reference concept



HELIOS* Heliogyro Solar Sail Technology Demonstration Mission

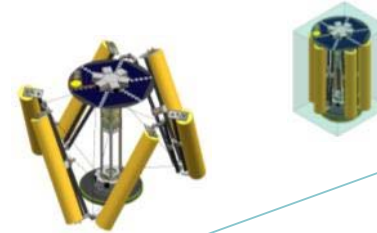
Deployable videogrammetry cameras for blade dynamics validation



Spin rate:
1 RPM

Low-cost heritage
CubeSat-based
central bus (~5 kg)

Root pitch motors for
blade attitude control and
thrust vectoring



HELIOS
deployment
sequence

Centrifugal stiffening makes the heliogyro lighter and faster than conventional rigid-structure solar sails.

Six (6) **centrifugally stiffened** 2.54 μm x 0.75 m x 220 m aluminized Mylar solar sail "blades".

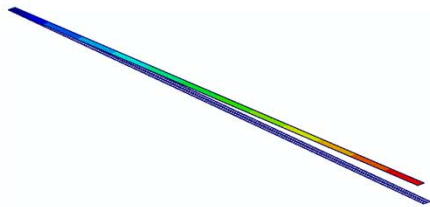
- Total solar sail vehicle mass: ~18 kg
- Power: ~40 W
- Orbit: 1400 km dawn-dusk sun-synch
- Characteristic acceleration: ~0.46 mm/s²
- ESPA-class rideshare payload

* HELIOS – High-Performance, Enabling, Low-Cost, Innovative, Operational Heliogyro Solar Sail [Ref: Wilkie, W. K., et al. "The Heliogyro Reloaded." JANNAF 5th Spacecraft Propulsion Subcommittee Joint Meeting, December 2011.]

HELIOS Deployment Animation

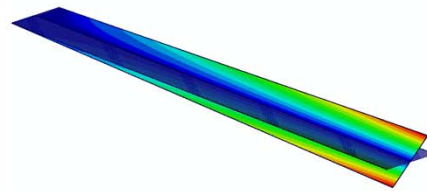


The structural dynamics of HELIOS are being studied using ABAQUS nonlinear finite element analysis



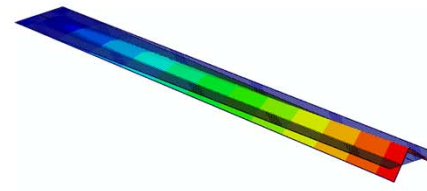
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Mode 1: $\omega/\Omega = 1.00$



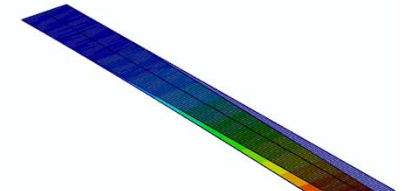
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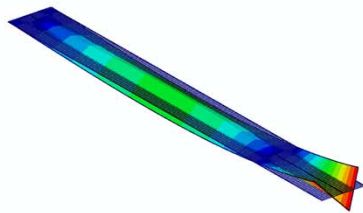
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Mode 3: $\omega/\Omega = 1.53$



Y Axis: Mode 4, Natural Frequency
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Mode 4: $\omega/\Omega = 1.70$



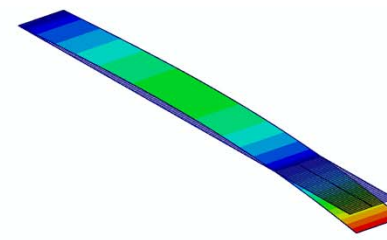
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Mode 5: $\omega/\Omega = 2.01$



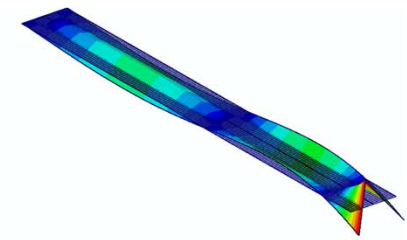
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Mode 6: $\omega/\Omega = 2.24$



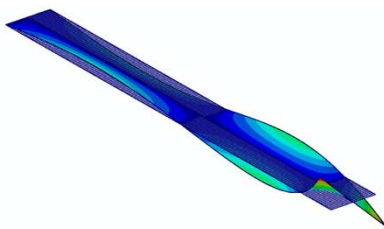
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Mode 7: $\omega/\Omega = 2.46$



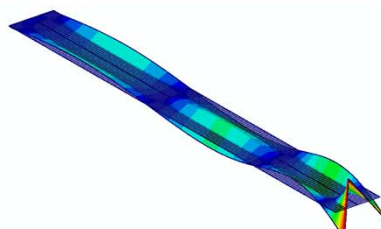
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Mode 8: $\omega/\Omega = 2.67$



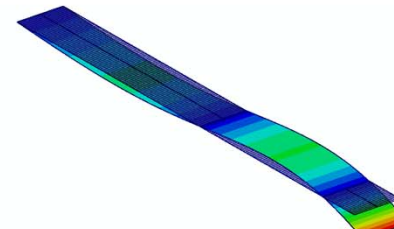
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Mode 9: $\omega/\Omega = 3.32$



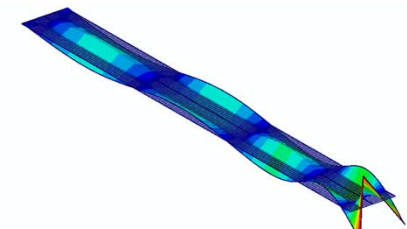
Y Axis: Mode 10, Natural Frequency
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Mode 10: $\omega/\Omega = 3.40$



Y Axis: Mode 11, Natural Frequency
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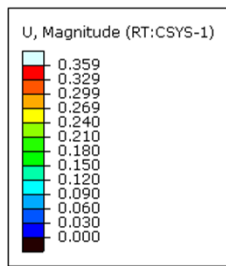
Mode 11: $\omega/\Omega = 3.88$



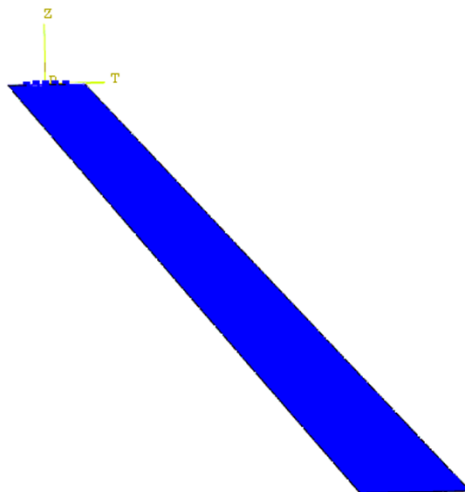
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Mode 12: $\omega/\Omega = 4.18$

ABAQUS may also be used for fully coupled time domain dynamics simulations of HELIOS



Step: Step-2 Frame: 1
Total Time: 240.500000



4 wide Uniform Heliogyro Blade, Spinning Analysis, with SRP
ODB: UnifBlade_4wide_Dynamic_1p000rpm_pbar0p00094_pitch-20_1rev.odb Abaqus/Standard 6.11-1 Tu

Step: Step-2, Add SRP to rotating flat blade
Increment: 14; Step Time = 0.5000
Primary Var: U, Magnitude (RT:CSYS-1)
Deformed Var: U (RT:CSYS-1) Deformation Scale Factor: +1.000e+00

Step: Step-2 Frame: 1
Total Time: 240.500000

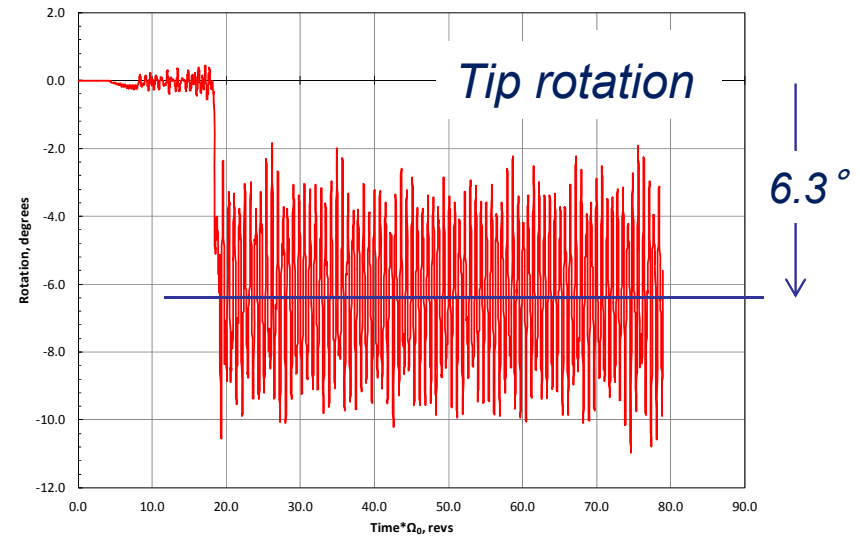
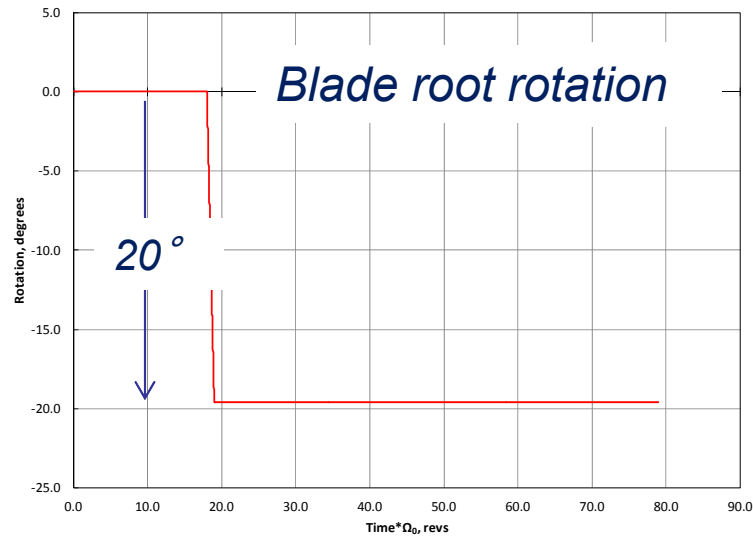


4 wide Uniform Heliogyro Blade, Spinning Analysis, with SRP
ODB: UnifBlade_4wide_Dynamic_1p000rpm_pbar0p00094_pitch-20_1rev.odb Abaqus/Standard 6.11-1 Tu

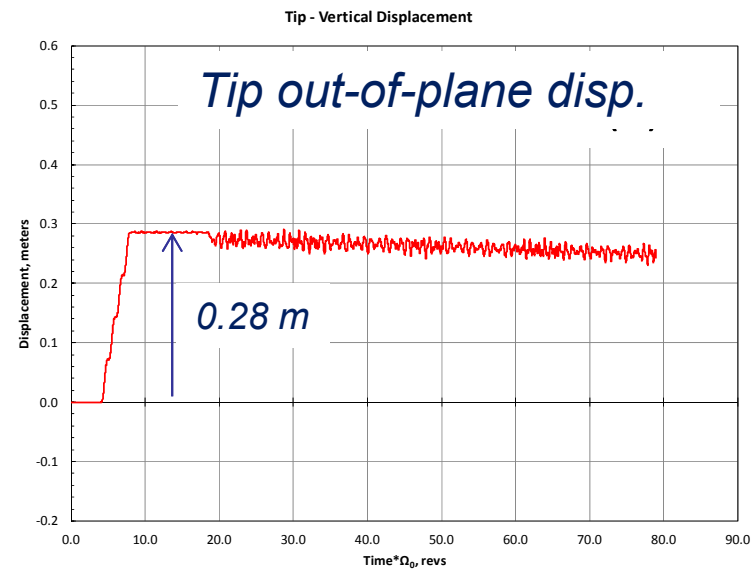
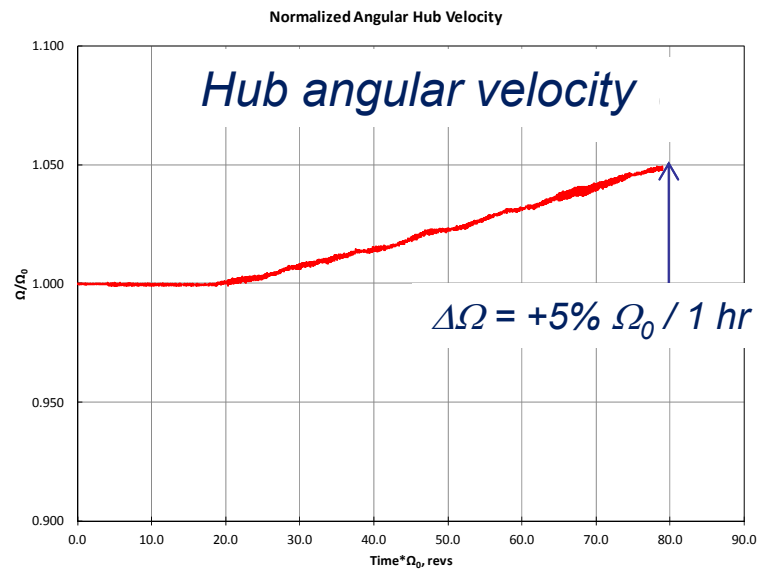
Step: Step-2, Add SRP to rotating flat blade
Increment: 14; Step Time = 0.5000
Deformed Var: U (RT:CSYS-1) Deformation Scale Factor: +1.000e+00

HELIOS uniform reference blade; 4 x 220 M3D4 membrane element mesh, no battens or edge reinforcement: $\Omega_0 = 1$ RPM, 0.1% ζ ; 0.85 reflectivity; 1.0 AU; $\gamma = 180^\circ$

ABAQUS simulations include solar radiation pressure and hub degrees of freedom



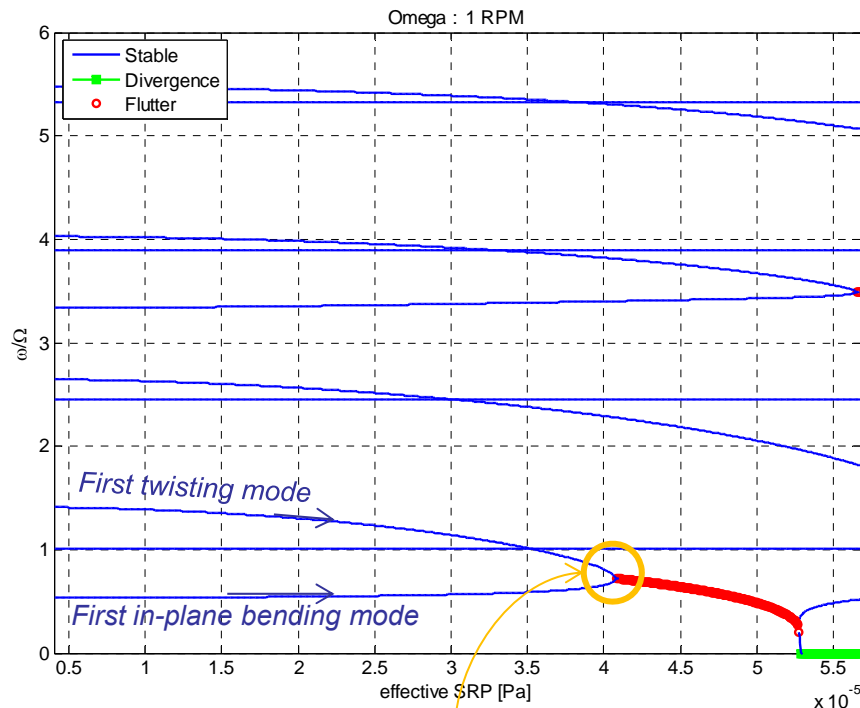
HELIOS uniform reference blade: $\Omega_0 = 1 \text{ RPM}$, 0.1% ζ ; 0.8 reflectivity; 1.0 AU; $\gamma = 0$ □



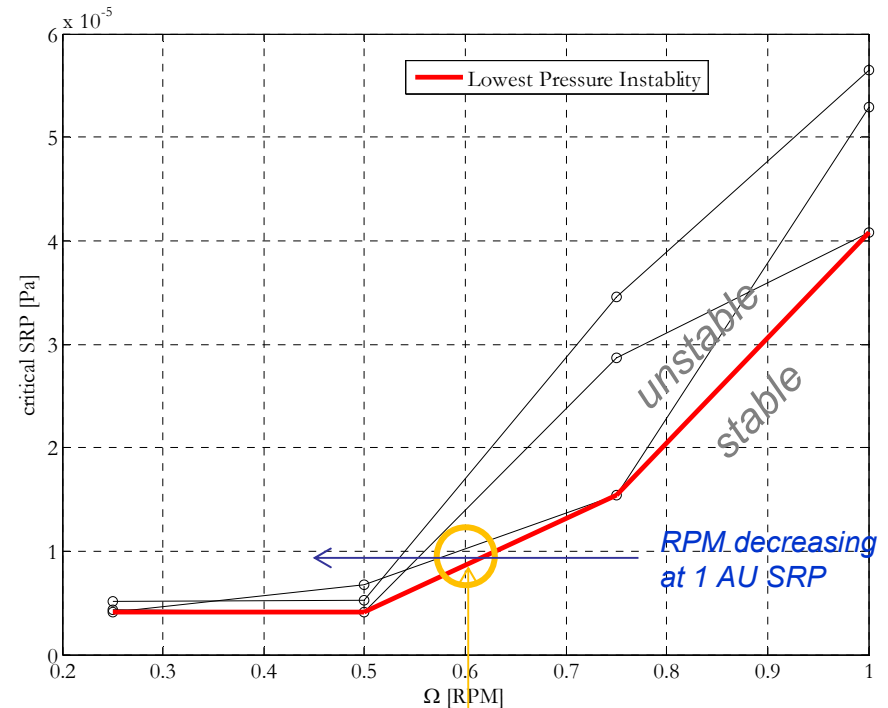
Solarelastic dynamic stability is being studied using fully coupled nonlinear beam equations (ref: Gibbs, Dowell, 2013)



- Approach based on Natori (1989)
- Uses beam equations of motion developed for rotary wing (Hodges, Dowell)
- Valid for small elastic deflections and zero coning angle.

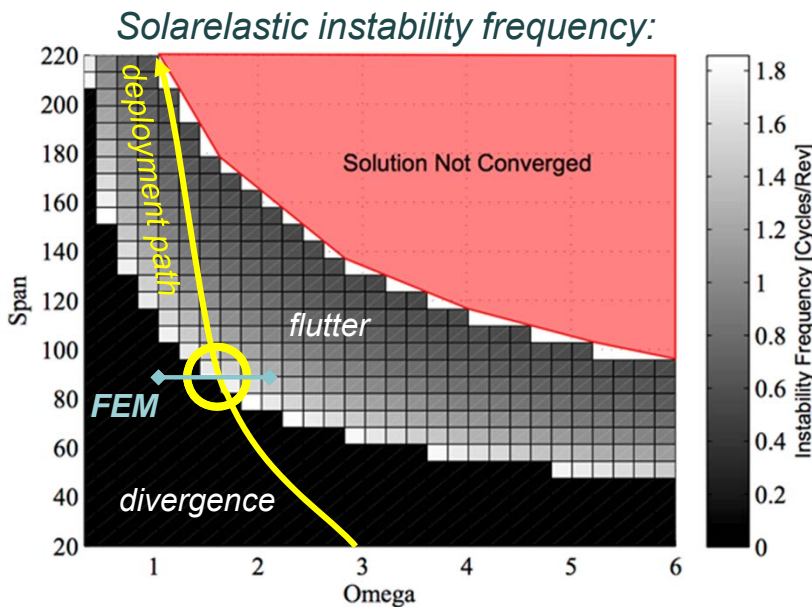
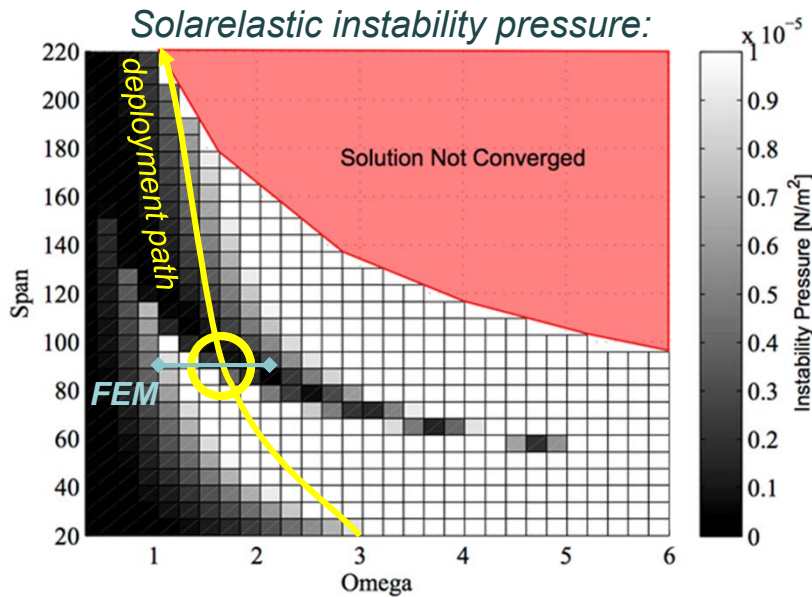


For the $\Omega = 1$ RPM nominal rotor speed, HELIOS will encounter a pitch-lag flutter instability at $\sim 4 \times 1$ AU solar radiation pressure (~ 0.5 AU)

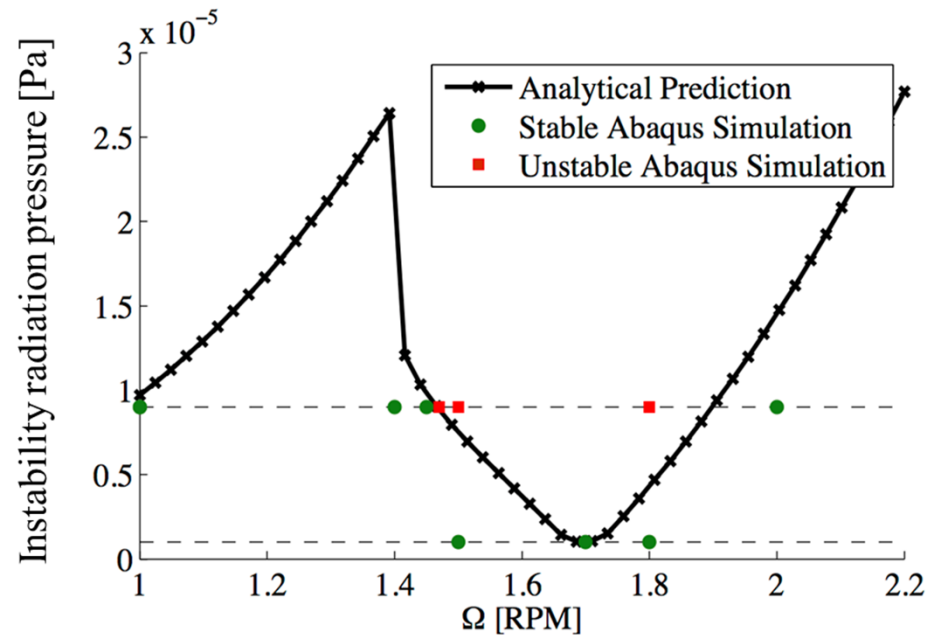


For operations at 1 AU, HELIOS will encounter a flutter instability for $\Omega < 0.6$ RPM.

Solarelastic stability during blade deployment



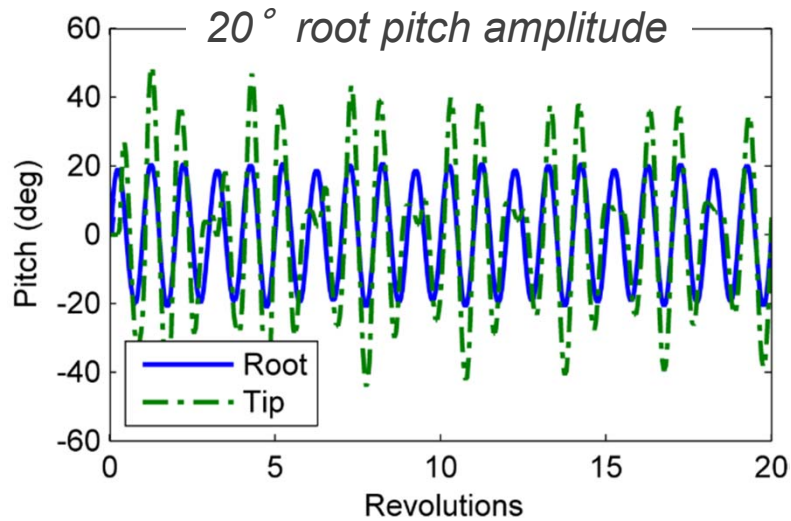
- Fixed rotation speed models indicate a low solar radiation pressure instability region will be encountered during blade deployment (left).
- FEM model confirms instability for fixed speed rotation case (below)
- FEM shows instability disappears for free-wheeling hub (actual in-plane b.c.)



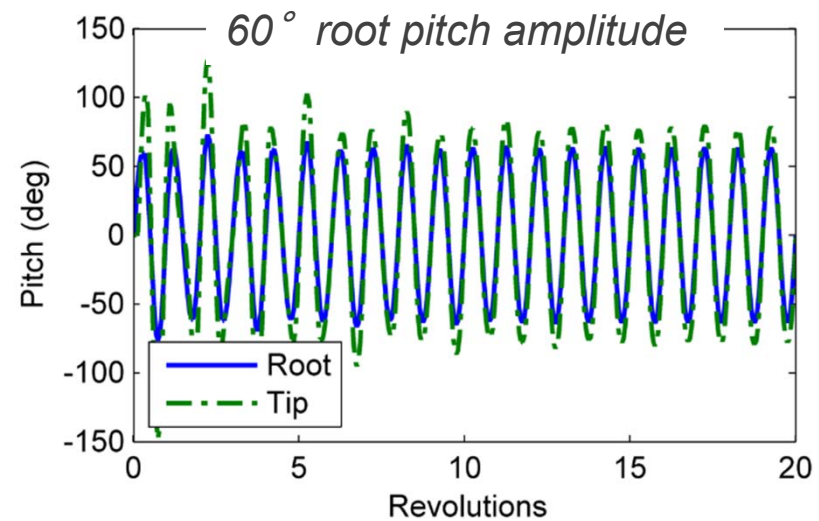
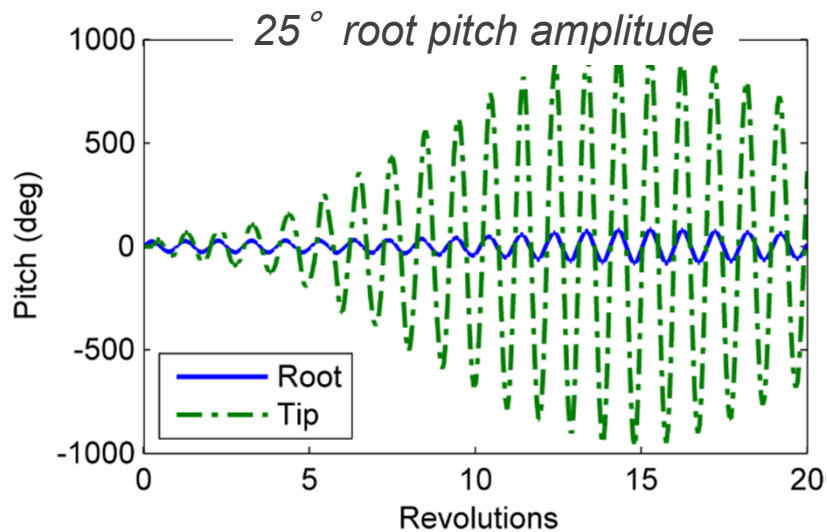
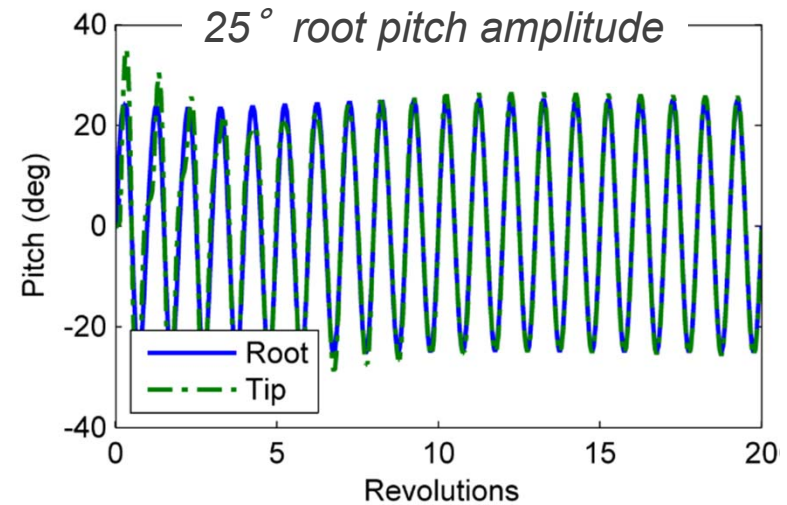
Nonlinear Cyclic Pitch Stability of Blades



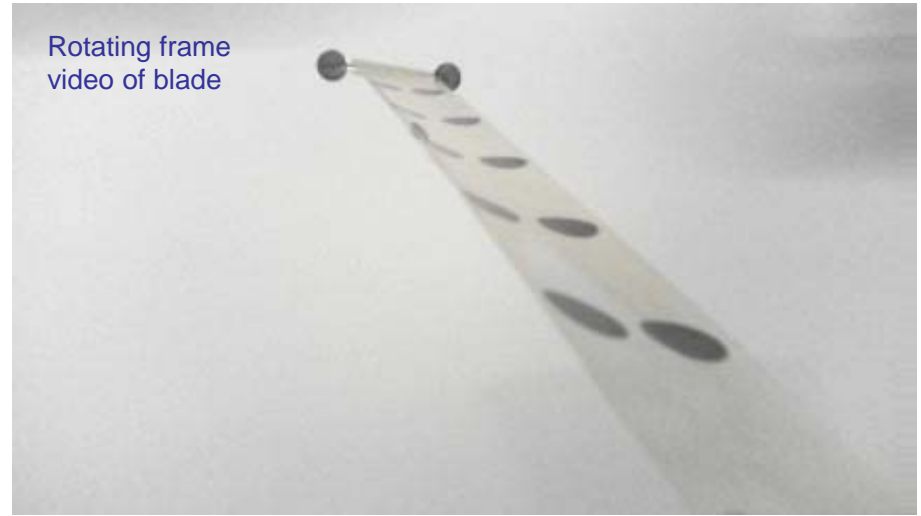
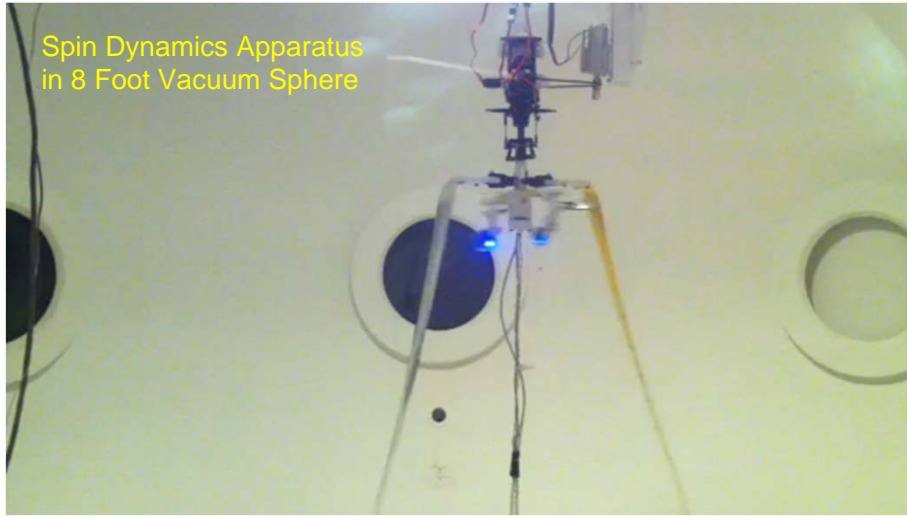
Uniform membrane sheet blade:



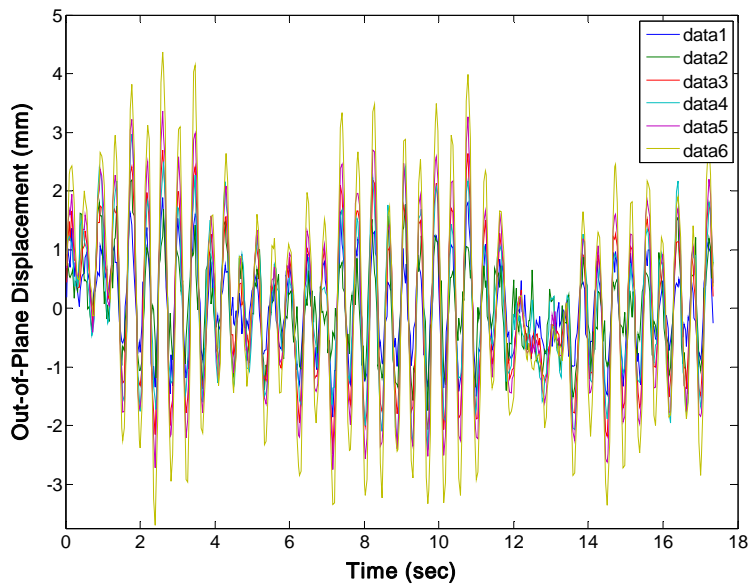
Edge-stiffened "rope ladder" blade:



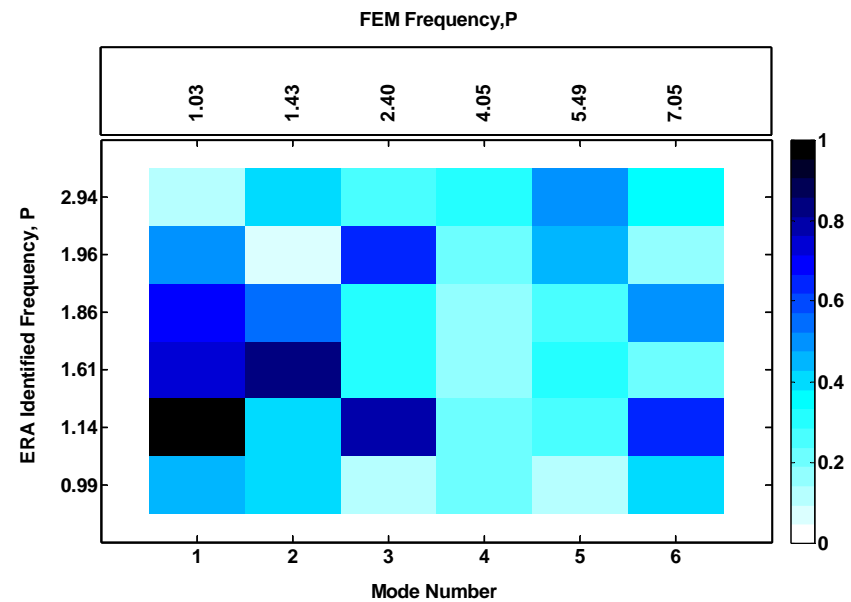
Dynamics of spinning membranes are being examined in vacuum chamber tests



Blade deflection data is measured via videogrammetry



Modal cross-orthogonality with FEM



Summary and Conclusions

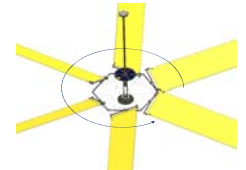


- Significant recent progress in understanding the structural dynamics of the heliogyro solar sail has been made, including:
 - Development of a fully coupled nonlinear finite element heliogyro structural dynamics modeling capability including solar radiation pressure;
 - Development of a computationally efficient analytical solarelasticity modeling capability useful for heliogyro stability studies, including stability during blade deployment;
 - Development of a small-scale heliogyro dynamics ground testing capability.
- We also conclude that:
 - Certain deployment instabilities seen when using fixed spin rate heliogyro blade dynamics models (e.g., MacNeal, Natori) are artefacts of the fixed spin rate assumption. These instabilities disappear when the central bus of the heliogyro is permitted to spin in response to blade forces.
 - Redirecting centrifugal tension loading to the blade leading and trailing edges, or adding tip mass to increase centrifugal stiffening, improves large-amplitude cyclic pitch response of the blades.

Future Work



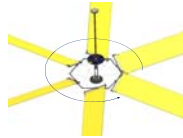
- Ongoing heliogyro technology development activities:
 - Further solarelasticity, structural dynamics and control investigations, and deployment dynamics simulation, including nonlinear system identification (NASA LaRC, Duke).
 - Blade damper and deployment mechanisms design, and hardware validation testing, particularly blade reels and deployable hex truss (JPL, NASA LaRC).
 - Advanced blade design, including materials, packaging, and scalability studies (NASA LaRC).
 - Heliogyro GNC and mission design. (CU, NASA LaRC, MSFC).
- Our ultimate goal is to enable a low-cost heliogyro technology development solar sail mission ca. 2020 timeframe.
 - Both ESPA and CubeSat heliogyro concepts in development.



Acknowledgements



- Many thanks to:



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Karen Lyle (NASA LaRC)

Justin Littell (NASA LaRC)

Christopher Savage (NASA, LaRC)

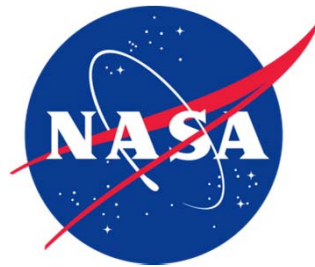
Wayne Matthews (NASA, LaRC)

Tom Walker (NASA, LaRC)

Paige Nardozzo (VMI)

Stephanie Lopez (UPR)

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Heliogyro technology lies on the *mean application trend line* for solar-sail-enabled missions



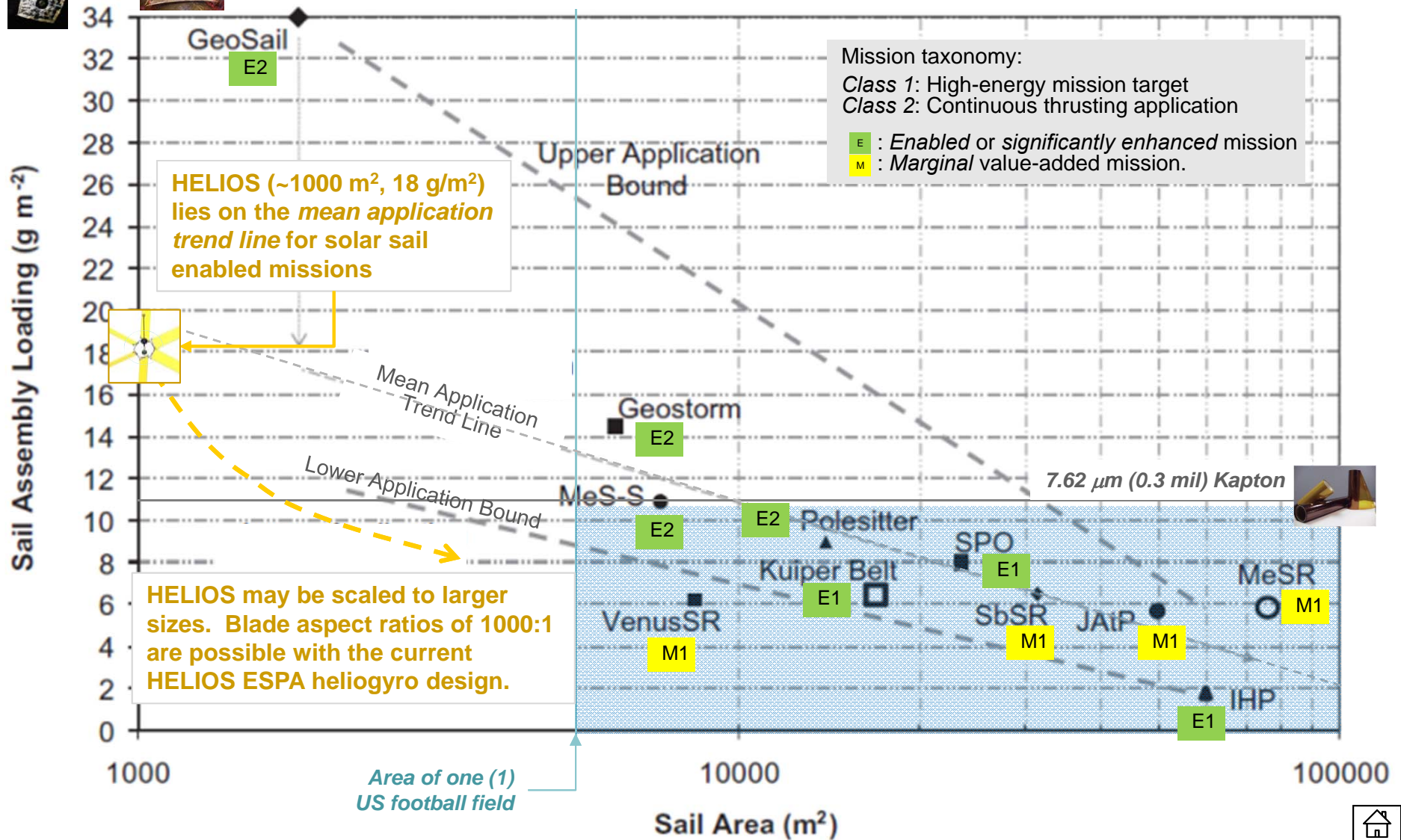
IKAROS (200 m², 75 g/m²)



Sunjammer (1200 m², 36 g/m²)



Ref: Macdonald, McInnes, 2011



HELIOS Heliogyro Technology Demonstration Reference Mission *(LaRC, JPL, CU, 2011)*



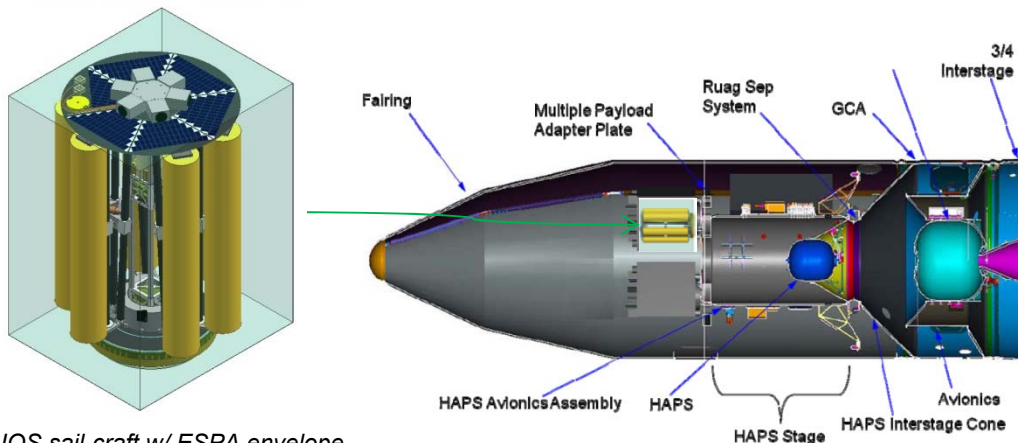
- Mission based on DoD Space Test Program Mission S26 (STP-26)
 - Minotaur-IV launched 19 Nov 2010 from Kodiak launch Complex
 - Carried 14 experiments on 7 separate spacecraft
 - Configured with Multi-Payload Adaptor (MPA) capable of carrying 4 ESPA class APLs
 - Dual orbit capability with Hydrazine Auxiliary Propulsion System (HAPS)
 - Capable of 1200 km secondary orbit.
- HELIOS Mission Objectives:
 - Demonstrate controlled heliogyro solar sail flight at mission-enabling characteristic accelerations ($a_c \approx 0.5 \text{ mm/s}^2$).
 - Validate critical deployment technologies scalable to mission-enabling solar sail architectures.
 - On-orbit validation of structural dynamics, solarelasticity, and thrust models.
 - Demonstrate orbit change capability (raising, lowering with de-orbit at EOL)
- HELIOS nominal orbit: 1200-1400 km sun-synchronous, dawn-dusk
 - Altitude >1000 km required to minimize aerodynamic drag.
 - Minimal eclipsing desired (thermal-elastic considerations)
- HELIOS mission duration: 4 months minimum, with de-orbit at EOL



Multi-Payload Adaptor



HAPS for dual-orbit capability

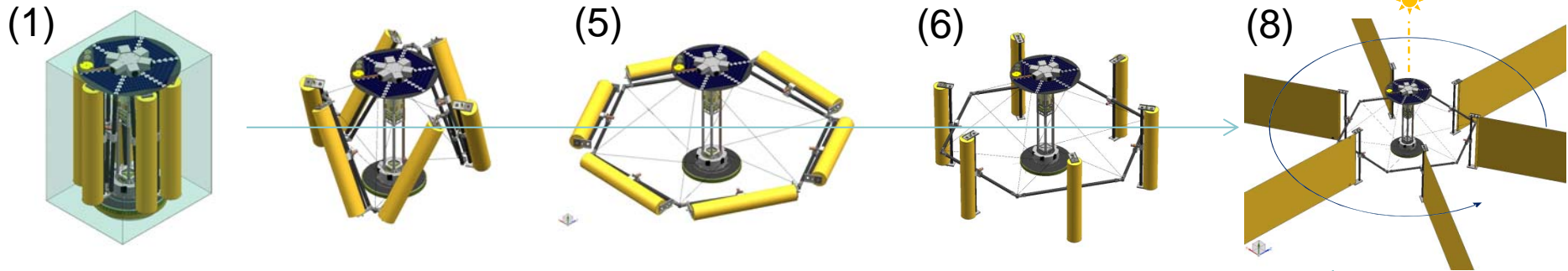


HELIOS sail-craft w/ ESPA envelope



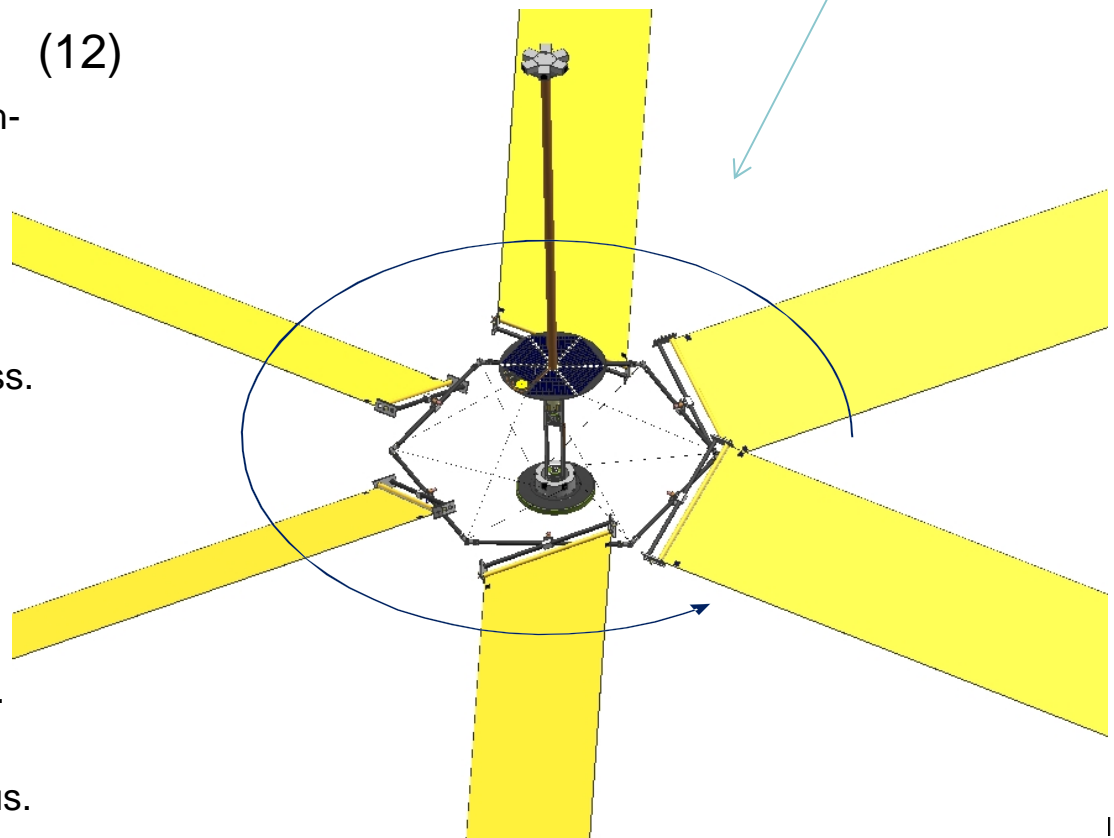
Minotaur-IV launch vehicle

HELIOS Deployment Sequence



HELIOS deployment sequence:

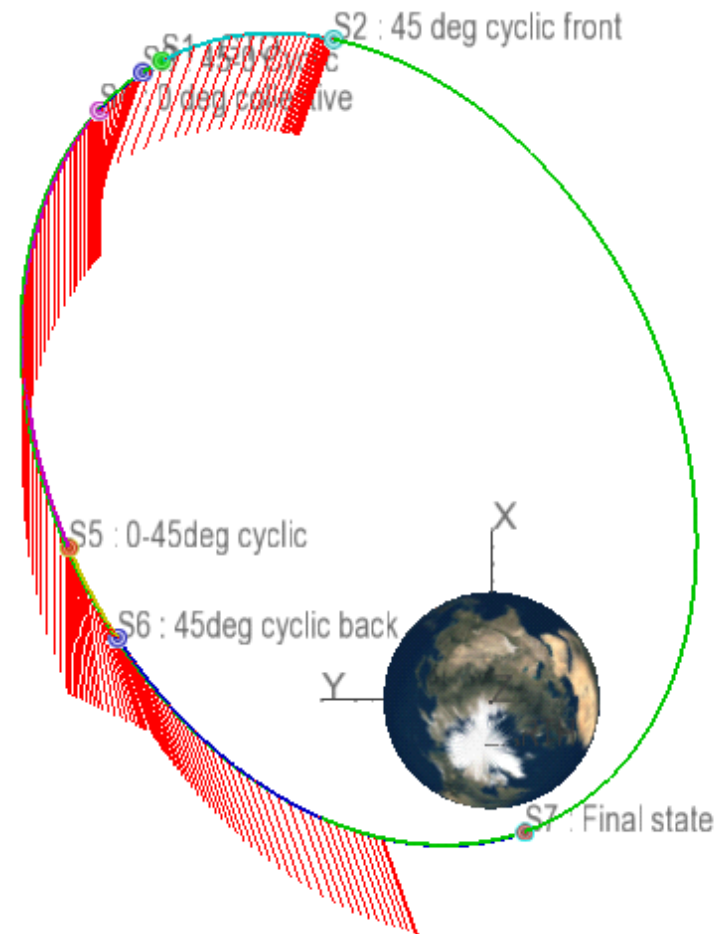
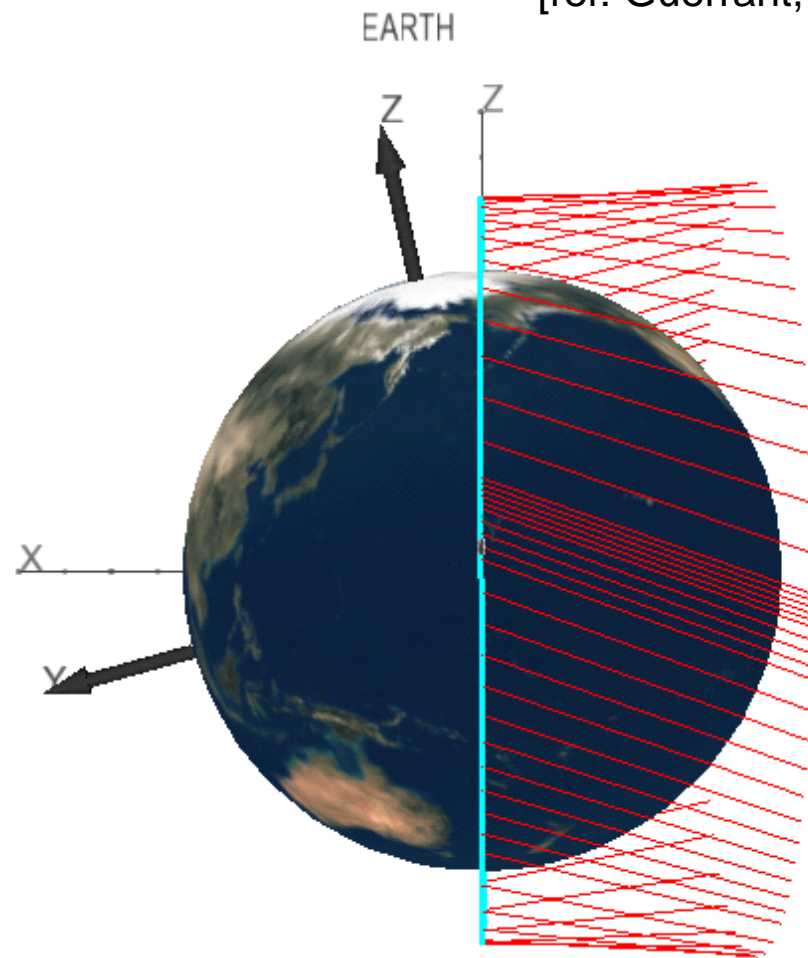
1. Separation from ESPA carrier via push-off springs. (HELIOS unpowered).
2. Sep switch powers on HELIOS.
3. Detumble via magnetic torque rods.
4. Acquire and point at sun.
5. Free deployment of blade reel hex truss.
6. Pitch blade reels to 90 degrees.
7. Spin-up with spin axis toward sun.
8. Initiate partial blade deployment.
9. Deploy camera mast.
10. Pitch blades down to engage solar radiation pressure for spin rate control.
11. Systems and flight control checkout.
12. Resume blade deployment to full radius.



Demonstrating orbit-raising capability will be one of the main objectives of the HELIOS mission



[ref: Guerrant, Lawrence, Heaton, 2013.]



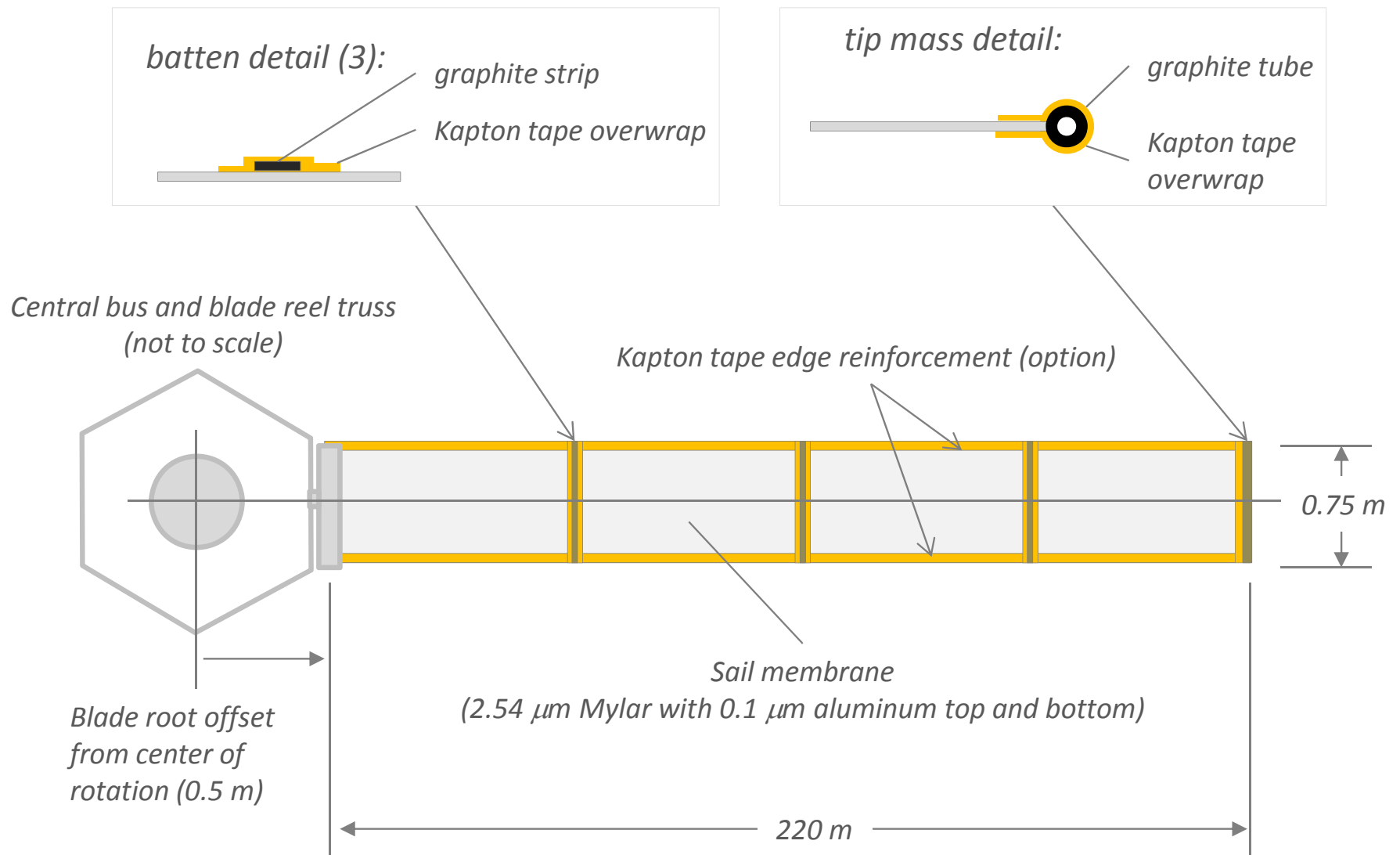
Mission Option A: Dawn-Dusk Sun Synchronous

$a_{init} = 7878 \text{ km}; da/dt = 17 \text{ km/day}$

Mission Option B: Initial GTO

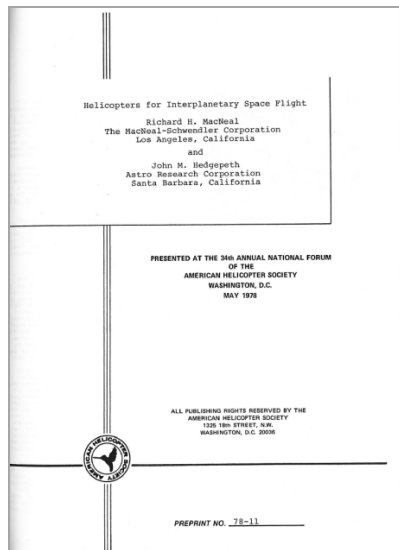
$a_{init} = 25021 \text{ km}; da/dt = 159 \text{ km/day}$

HELIOS reference blade design



Static twist distribution of edge stiffened heliogyro blade

(ref: MacNeal, Hedgepeth, 1978)



The differential equation for the twist of a straight rotor blade without elastic torsional stiffness is

$$-\frac{\partial}{\partial r} \left(J \frac{\partial \theta}{\partial r} \right) + I \left(\Omega^2 \sin \theta \cos \theta + \frac{\partial^2 \theta}{\partial t^2} \right) = m_{\theta} \quad (3)$$

where J is the second moment of spanwise tension stress about the midchord, I is the mass moment of inertia, and Ω is the rotational speed. The spanwise tension of the Heliogyro blade is concentrated in tendons at the leading and trailing edges, and the resulting torsional stiffness, J , is three times larger than it would be if the tension were uniformly distributed across the chord. Even so, the stiffness due to the nonlinear term in Eq. 3 (the so-called tennis racket effect) is significant.

Since Heliogyro blade pitch angles are not small, the nonlinear effects of the second term in Eq. 3 cannot be neglected. This is illustrated in Fig. 11, which shows the static blade twist for large pitch angles; and also in Fig. 12, where a reduction in torsional natural frequencies due to finite collective pitch is indicated.

$$-\frac{\partial}{\partial r} \left(J \frac{\partial \theta}{\partial r} \right) + I \left(\Omega^2 \sin \theta \cos \theta + \frac{\partial^2 \theta}{\partial t^2} \right) = m_{\theta}$$

- J : second moment of spanwise tension stress about midchord;
- I : mass moment of inertia

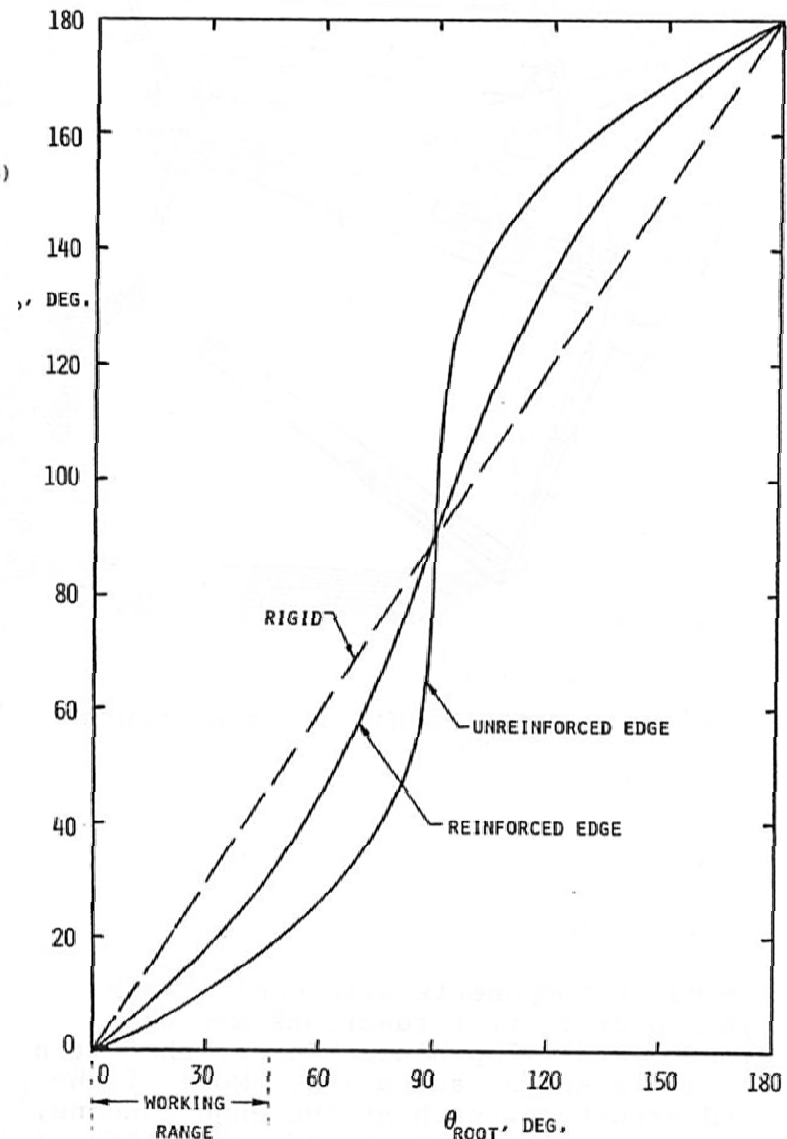
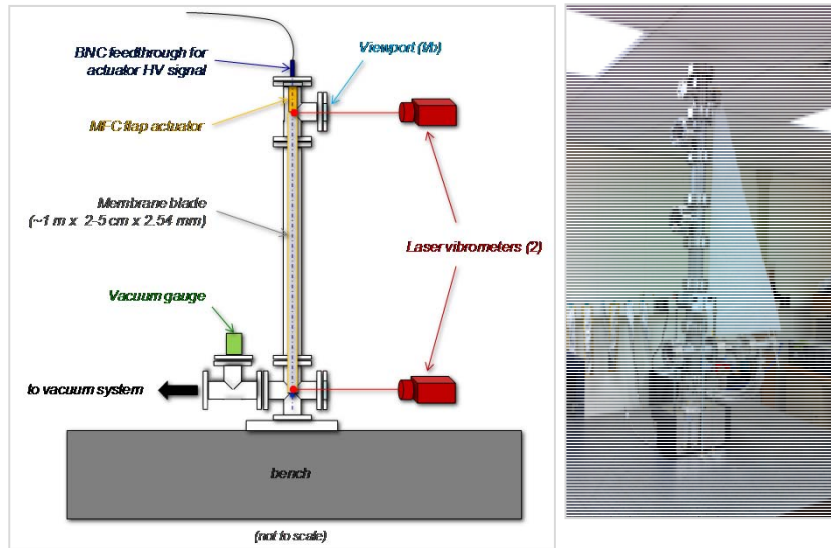


Figure 11. Static Twist of a Heliogyro Blade 2

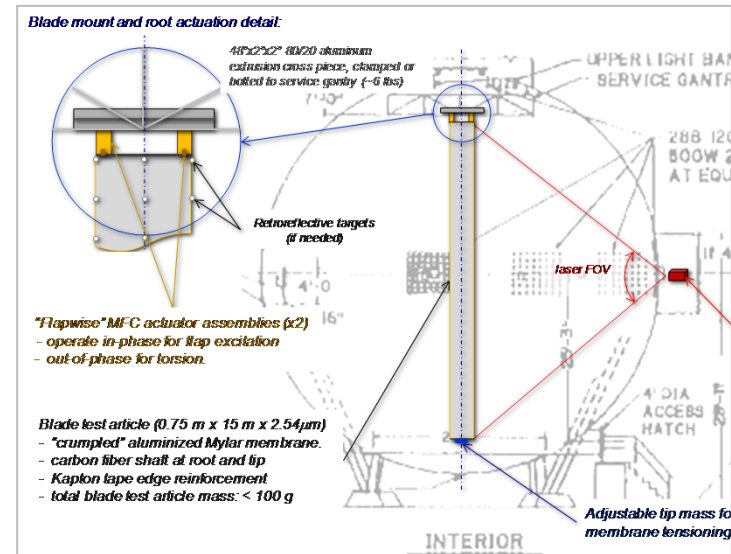
Heliogyro technology ground testing is underway



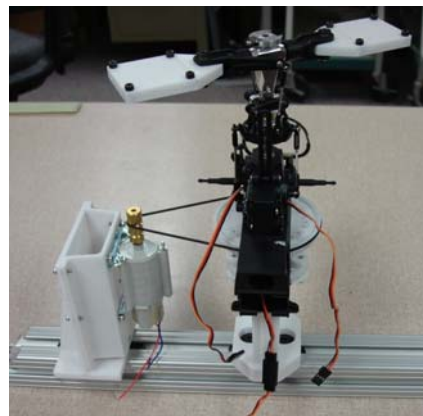
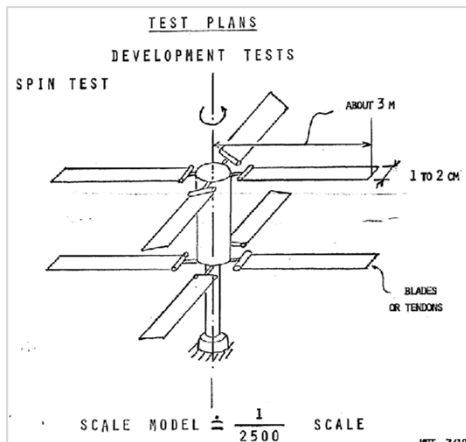
High Vacuum Membrane Damping Testing



60 Foot Space Simulator Control-Structures Testing



8 Foot Vacuum Sphere Membrane Spin Dynamics Testing



High Altitude Full-Scale Blade Deployment and Control Tests

