THE HELIOGYRO RELOADED

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ABSTRACT

The heliogyro is a high-performance, spinning solar sail architecture that uses long - order of kilometers - reflective membrane strips to produce thrust from solar radiation pressure. The heliogyro's membrane "blades" spin about a central hub and are stiffened by centrifugal forces only, making the design exceedingly light weight. Blades are also stowed and deployed from rolls; eliminating deployment and packaging problems associated with handling extremely large, and delicate, membrane sheets used with most traditional square-rigged or spinning disk solar sail designs. The heliogyro solar sail concept was first advanced in the 1960s by MacNeal. A 15 km diameter version was later extensively studied in the 1970s by JPL for an ambitious Comet Halley rendezvous mission, but ultimately not selected due to the need for a risk-reduction flight demonstration. Demonstrating system-level feasibility of a large, spinning heliogyro solar sail on the ground is impossible; however, recent advances in microsatellite bus technologies, coupled with the successful flight demonstration of reflectance control technologies on the JAXA IKAROS solar sail, now make an affordable, small-scale heliogyro technology flight demonstration potentially feasible. In this paper, we will present an overview of the history of the heliogyro solar sail concept, with particular attention paid to the MIT 200-meter-diameter heliogyro study of 1989, followed by a description of our updated, low-cost, heliogyro flight demonstration concept. Our preliminary heliogyro concept (HELIOS) should be capable of demonstrating an order-of-magnitude characteristic acceleration performance improvement over existing solar sail demonstrators (HELIOS target: 0.5 to 1.0 mm/s^2 at 1.0 AU); placing the heliogyro technology in the range required to enable a variety of science and human exploration relevant support missions.

INTRODUCTION

Solar sails require no on-board propellant and derive thrust directly from momentum transfer of solar photons.[1] NASA's In-Space Propulsion Technology Roadmap identifies solar sail systems as a mission- enabling technology for continuous thrust applications and high delta-V destinations otherwise unreachable with chemical or solar electric propulsion (SEP).[2] Relevant science applications include solar weather early warning sentinels, high-inclination solar polar observers, and deep space probes to the heliopause and interstellar space. "Gravity tractors" for asteroid deflection have also been proposed.[3]

This work was performed under internal funding.

Human spaceflight-relevant missions include NEO robotic precursor spacecraft and Earth-to-Mars cargo prepositioning.[4]

As solar radiation pressure is extremely small (4.6×10^{-6} Pa at 1.0 AU) very large reflective surfaces must be used to generate appreciable thrust. Mass of the large reflective surfaces, which, with the mass of any spacecraft bus and scientific payload, is the total sail craft mass, must also be minimized in order to develop overall accelerations sufficient to conduct missions within a reasonable timeframe. These two fundamental requirements; large area and low mass (or areal density) to first order are sufficient to quantify the overall performance of any solar sail vehicle.

CANONICAL SOLAR SAIL ARCHITECTURES

Solar sail architectures have traditionally fallen into three broad categories. The first, and most studied architecture, is the kite-like, “square-rigged” solar sail design. Notable recent examples include the two 20-meter ground demonstration test articles, developed for the NASA In-Space Propulsion Technology Program (ISPT), ca. 2005.[5] (Figure 1.) Several small, CubeSat-class examples also exist, including NanoSail-D, which, to date, is the only spaceflight example.[6,7] Autonomous deployment of solar sail structures is generally perceived to be the highest risk element present with solar sail technology. The primary advantage of square-rigged sail designs is that their primary structures, including deployment, are testable on the ground prior to space flight, which to a large extent helps mitigate this risk, at least for small size solar sails.

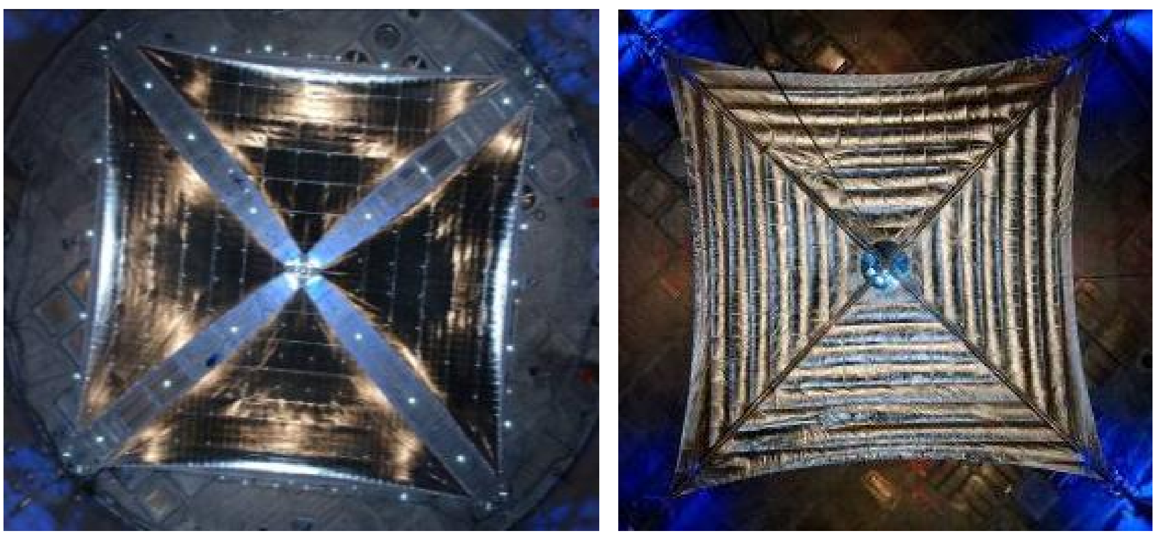

Figure 1. NASA solar sail technology ground test demonstrators (2005): ATK 20-m demonstrator (left); L’GARDE 20-meter demonstrator (right).

The chief drawback of the square-rigged architecture is that the mass of supporting structures, generally booms or deployable trusses, begins to dominate the overall mass of the sail system for very large area sails. Since propulsive thrust is only derived from the reflective membrane elements of the sail system, square-rigged designs become impractically heavy at very large scales. An additional complicating factor is acreage management of the very large, and delicate, square, or triangular, sail membrane gores. Manufacture, ground handling and packaging of very large area sail membranes, on the order of μm in thickness, is extremely difficult. Likewise, deployment of the packaged, often intricately folded, membranes is also a delicate and risky operation. Attitude control schemes include controlling center-of-mass offsets with respect to the sail solar radiation center of pressure, which permits pitch and yaw control. Roll control may be accomplished with actuators at the boom tips to develop a pinwheel-like torsional warping in the sail. Alternatively, large reflective membrane vanes at the boom tips, controlled in pitch, may be used to generate three-axis controllability. As the tip vanes produce the required control torques through radiation pressure, they may themselves become quite large and present additional complications for deployment.

The second-most studied solar sail architecture is the spinning disk sail. The disk sail relies upon centrifugal forces only to deploy and flatten the sail membrane structure, making these sail designs, in principal, the most efficient and lightest of all solar sail structures. Chief disadvantages are, as with large square-riggers, the deployment and packaging issues associated with the very large reflective membranes and, unique to the disk sail, the problem of attitude control of the spinning sail membrane itself. Many spinning disk solar sail conceptual designs exist in the literature, but, to date, only one successful spaceflight example: the JAXA IKAROS solar sail; launched in 2010.[*] (Figure 2.)[8] In addition to being the world's first propulsive solar sail spacecraft, IKAROS successfully demonstrated an innovative spinning membrane control approach, using thin film liquid crystal elements integrated into the perimeter of the sail membrane.[9] Low electric fields applied to the liquid crystal films permit switching of the local reflectivity of the sail membrane between diffuse and specular states; changing the resulting solar radiation pressure acting on those portions of the sail. Synchronizing switching of the reflectivity control elements with the sail spin rate allows net, two-axis control torques to be generated on the entire sail vehicle.

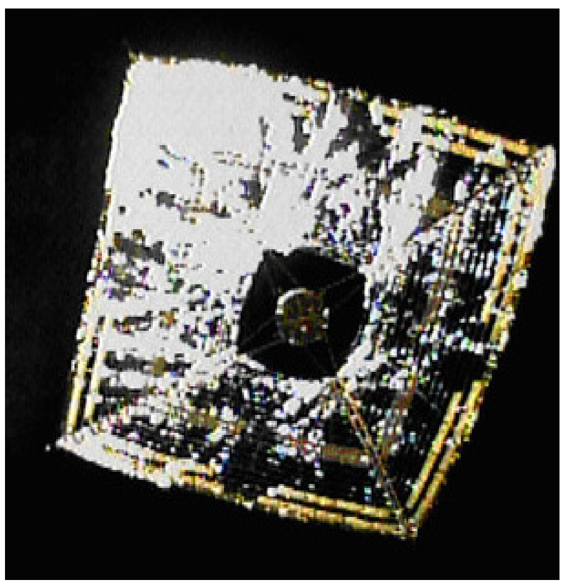

Figure 2. JAXA IKAROS 20-meter (diagonal) spinning solar sail (JAXA, 2010).

The third "canonical" solar sail architecture is the *heliogyro*.

THE HELIOGYRO

The heliogyro is a helicopter-like, spinning solar sail. It was first advanced by MacNeal in the 1960s.[10] Heliogyros possess the primary advantage of the spinning disk sail, namely low weight, while avoiding many of the difficulties associated with stowage and deployment of large membrane areas. The

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[*] Although technically a spinning *square* solar sail, the fundamental flight characteristics and structural dynamics of IKAROS are identical to a spinning disk sail.

sail elements of the heliogyro are long – up to order of kilometers – high aspect ratio reflective membrane strips. These membrane strips, or "blades", spin about a central spacecraft hub and are stiffened by centrifugal forces only, thus making the design exceedingly light weight. Blades are stowed and deployed from reels; eliminating deployment and packaging problems associated with handling extremely large, and delicate, membrane sheets proposed with most traditional square-rigged or spinning disk solar sail designs. Attitude control is accomplished by pitching the blades at the root to change their orientation with respect to the sun. This may be performed collectively, to generate torques about the spin axis, for example to spin up or spin down the heliogyro, or cyclically, in a per-revolution fashion, to generate thrust components in the plane of rotation. Combinations of collective and cyclic pitch create overturning moments. Attitude control may thus be accomplished about all six axes using blade pitch actuation alone.

Despite these compelling advantages, very few heliogyro designs exist in the literature. The most in-depth heliogyro study, and one of the most detailed studies of any solar sail concept, was that conducted in 1977 by JPL for an ambitious Comet Halley rendezvous mission.[11] The mission study considered both a heliogyro and a large square-rigged solar sail design (850 m x 850 m), with the heliogyro selected as the preferred approach. The final heliogyro design featured a dozen blades in two counter-rotating tiers. (Figure 3.) Each blade was nominally 8 meters wide and 7500 meters long. Both concepts would have required the full cargo bay of the Space Shuttle; which, at that time, was still several years away from flight. The heliogyro proposal included a sub-scale (6 blades, 4.1 m wide by 2838 m long!) flight demonstration using an Arianne launch vehicle.[12] Ultimately, a solar electric propulsion approach was selected over the heliogyro, due primarily to the perceived overall high risk associated with unproven solar sail technology.[†]

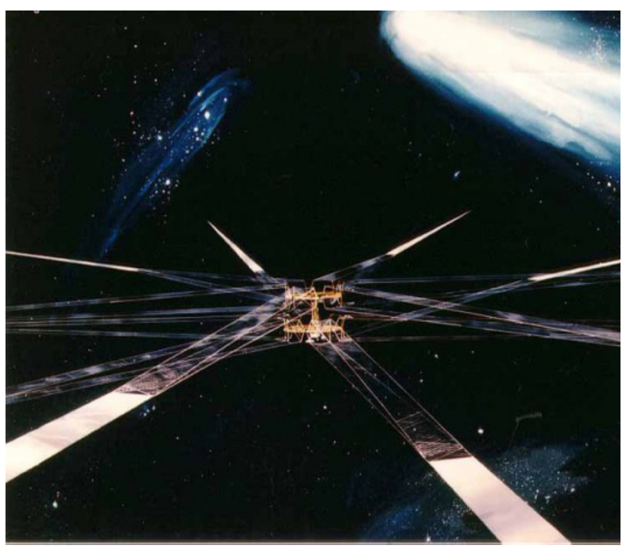

Figure 3. JPL Comet Halley Rendezvous Mission heliogyro concept (1977).

Heliogyro conceptual studies since 1977 have been very rare, with the most notable example being a 1989 small heliogyro study performed by a MIT design team as an entry into a solar sail race to Mars proposed by the Columbus Quincentenary Commission.[13] The MIT team proposed a very small, 8-bladed, 200 meter diameter heliogyro. To minimize mass and complexity, blade pitch control was accomplished using an innovative, solid-state piezoelectric torsional actuation system at the root of each

[†] Ultimately, the solar electric propulsion Comet Halley rendezvous mission recommended to NASA was cancelled.

blade.   Further heliogyro solar sail development since the MIT study has been almost nonexistent, with the exception being some analytical heliogyro control and dynamics investigations by Blomquist; one of the original MIT design team members.[14]

CHALLENGES FOR SOLAR SAIL TECHNOLOGY ADVANCEMENT

The romance of solar sailing has, for many decades, contained considerable appeal with both technologists and the public. However, advancement of solar sail technology to where it is considered to be a viable propulsion alternative for space mission managers and designers will require, at a minimum, two things: requirements derived from compelling science or exploration missions that are *enabled*, or significantly enhanced, by solar sail technology; and a credible technology development pathway to achieving those solar sail enabled mission requirements. Macdonald and McInnis examine this issue by considering the distribution of two fundamental solar sail performance metrics; sail system loading and sail area; for a representative selection of recent mission studies where solar sails either dramatically enhance overall mission capability, or there are no feasible propulsion alternatives other than solar sails. [15] (Figure 4.) From this data, they derive a “mean applications trend line”. Solar sail systems with properties on or near this trend line are thus within the approximate application space for solar sail enabled or enhanced missions.

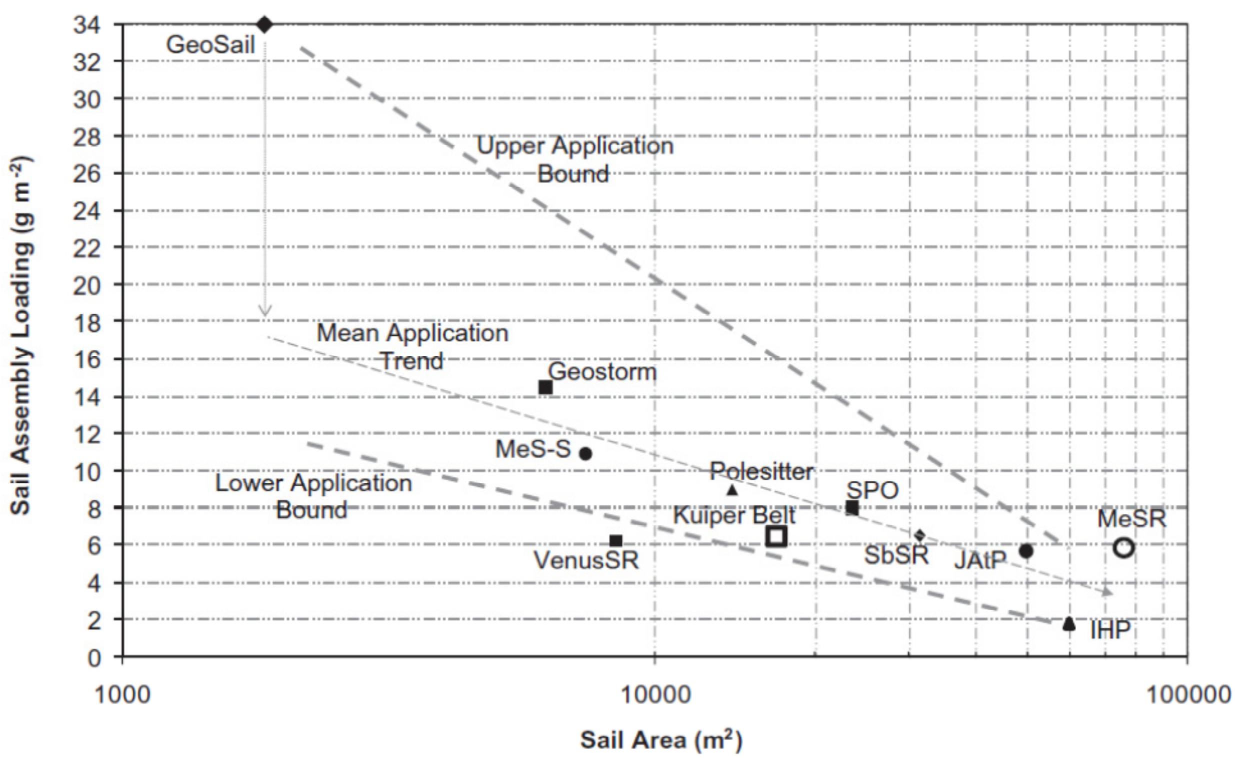

Figure 4. Solar sail mission application technology requirements. (Macdonald, McInnes. 2011)

A similar examination of solar sail mission trends is shown in Figure 5, where solar sail characteristic acceleration, a_c, defined as the ratio of solar radiation derived thrust to the total mass of the sail system plus all other spacecraft systems, e.g., science instruments, etc., is plotted against total sail area for a variety of representative mission studies. This plot roughly bounds regions of application space for the main canonical sail architectures. In particular, it can be seen that for the highest performance applications (a_c >0.5 mm/s^2, area > 10000 m^2), both high characteristic acceleration and large area preclude the use of square-rigged architectures, and spinning sails become necessary. For these missions, heliogyro architectures offer the most practical approach, provided the required deployment and flight control technologies can be convincingly developed and demonstrated.

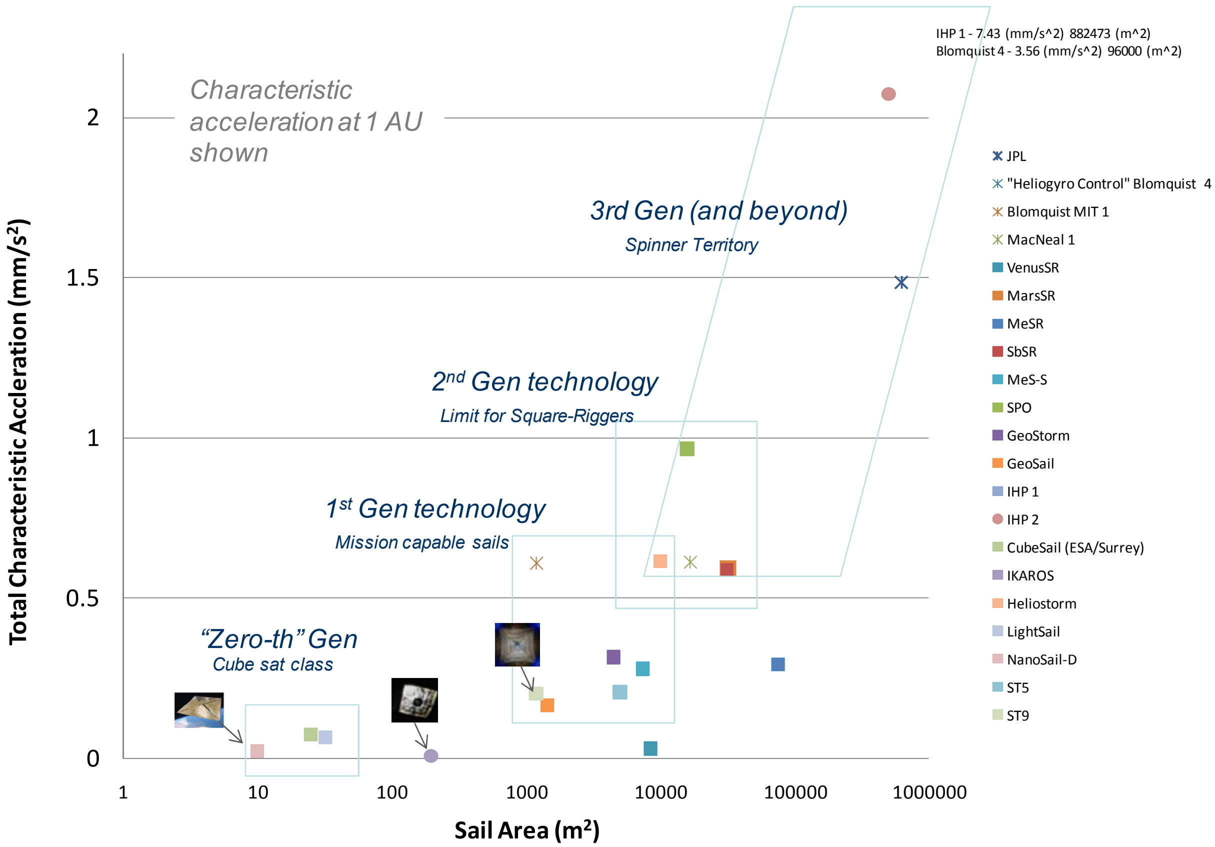

Figure 5. Solar sail mission characteristic acceleration versus sail area.

In addition to these mission and technological requirements, a third consideration becomes important: that of the prospects for funding credible technology demonstrations. Deployment of solar sail systems with these key mission-enabling characteristics; i.e., very light weight and very large area; become impossible to validate on the ground. Credible, and most of all, affordable, spaceflight technology demonstrations will be thus required if solar sail technology is to be adopted as a realistic space propulsion option.

Recent developments in CubeSat bus technology are potentially enabling for very small solar sails. In particular, these small satellite technology breakthroughs, coupled with an increase in the opportunities for inexpensive "rideshare" launch opportunities, may make an affordable, high-performance, heliogyro solar sail flight demonstration possible. In this paper, we will present a small-scale heliogyro solar sail technology demonstration concept, based, in large part upon the small MIT heliogyro conceptual design proposed in 1989. We will also discuss ongoing heliogyro structural dynamics and controls investigations. We will conclude with an outline of future heliogyro development work, with the near-term goal of achieving a low-cost, small satellite heliogyro technology demonstration mission.

RESULTS AND DISCUSSION

NASA 2011 SMALL SAT HELIOGYRO (RE-)ASSESMENT

The goal of our preliminary heliogyro design study was to re-evaluate the feasibility of the 1989 MIT 200-meter heliogyro concept in light of recent small sat and CubeSat innovations, the successes of the 2010 IKAROS spinning solar sail flight demonstration, and the increased likelihood of low-cost secondary payload "rideshare" launch opportunities. Requirements necessary to qualify as an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adaptor (ESPA) rideshare payload were adopted for this study.[16] From a design perspective, the ESPA stowed volume and dimensional restrictions had the largest influence on the heliogyro configuration as they placed an upper limit on the maximum length of the heliogyro blade deployment reels, and hence blade chord. Other requirements were to maintain or exceed the nominal characteristic acceleration performance of the MIT concept; approximately 0.5 mm/s^2; and if possible, look for opportunities to reduce mechanical complexity and deployment risk, for example, by reducing the number of blades. The original MIT design parameters are compared with our updated, "working concept" heliogyro properties in Table 1.

Table 1: Comparison of parameters for the 1989 MIT heliogyro and the 2011 NASA heliogyro working concept.

	MIT (1989)	**NASA (2011)**
Total sail craft mass (kg)	18	8.4
Characteristic acceleration, a_c (mm/s^2)	0.6	1.0
Sail material	Kapton (7.62 μm); aluminum (0.1 μm)	Mylar (2.54 μm); aluminum (0.1 μm)
Sail reflective area (m^2)	1200	960
Non-sail mass (kg)	5	5
Number of sail blades	8	6
Blade chord (m)	1.5	0.8
Blade length (m)	100	200
Rotational period (minutes)	3	3
Blade root stress (Pa)	8650	34000
Blade root allowable stress (Pa)	55 M	55 M
Blade root tension load (N)	0.1	0.07

The most significant differences between the NASA working concept and the MIT design are 1) the reduced blade chord from 1.5 m to 0.8 m, necessitated by ESPA payload envelope restrictions; 2) the reduction of the number of heliogyro blades (from 8 to 6); and 3) the lightweighting of the sail system by use of thinner 2.54 μm commercial aluminized Mylar. JAXA's recent success using liquid crystal reflectivity control aboard the IKAROS solar sail inspired us to replace MIT's original piezoelectric root pitch blade control with a reflectivity modulation based twist control approach using liquid crystal thin film elements located at the tip of each blade. A sketch of the overall NASA concept is shown in Figure 6.

Packaging and deployment of the core blade reel hex truss is slightly different from that proposed for the octagonal blade reel truss in the original MIT study. Our deployment is based upon a "spoked-wheel" concept developed in the 1970s for deploying large area solar arrays.[17] A schematic of the deployment sequence is shown in Figure 7.

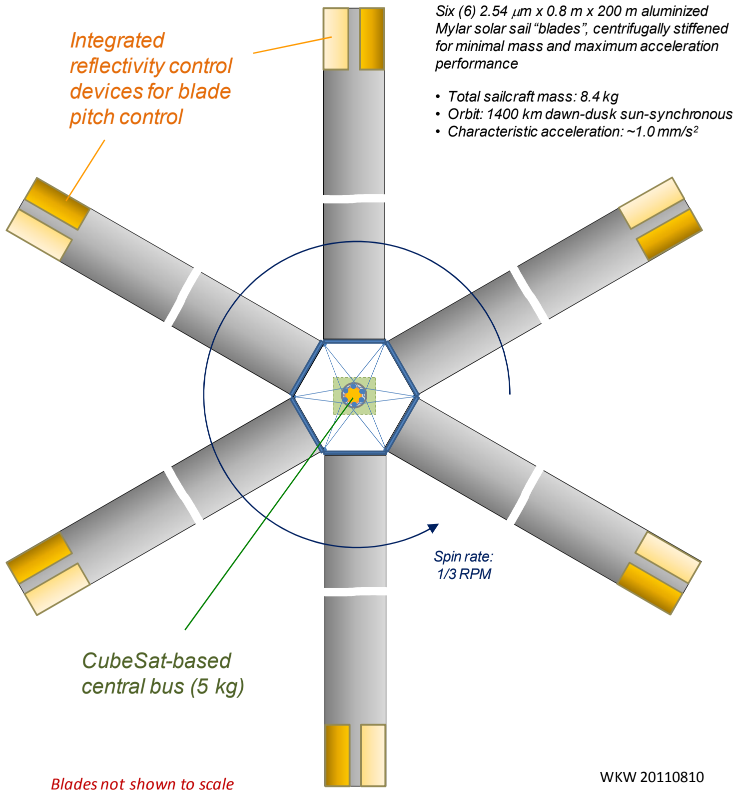

Figure 6. General configuration of the 2011 NASA heliogyro working concept.

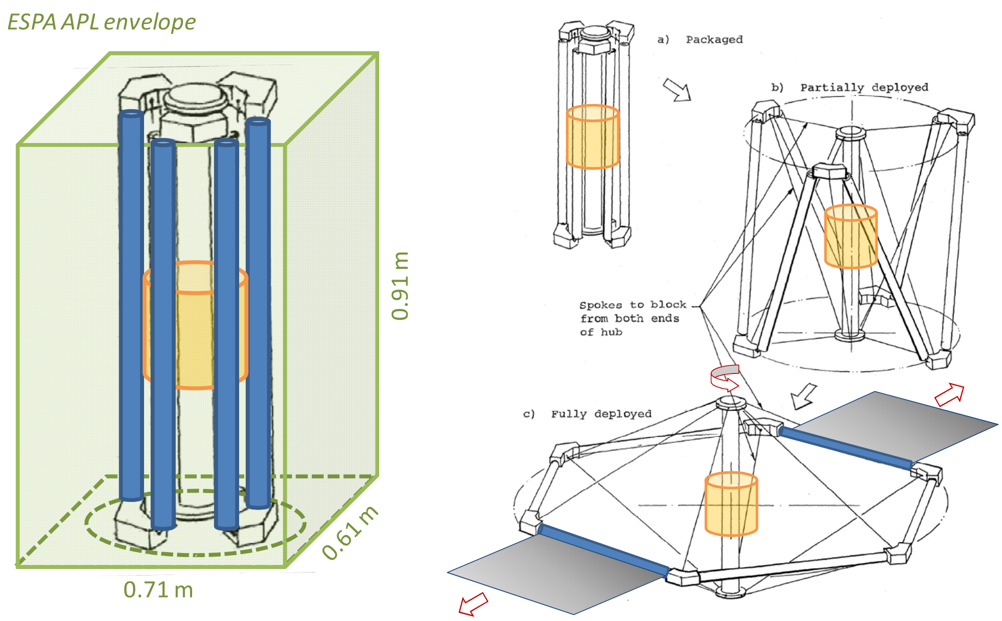

Figure 7. Deployment sequence for the 2011 NASA working concept (based on Crawford, Hedgepeth, Preiswerk. 1975). Stowed working concept within the ESPA payload envelope is shown at the left.

Characteristic acceleration performance of the NASA working concept heliogyro and the MIT baseline heliogyro are shown as a function of blade radius in Figure 8. An initial 8-bladed, ESPA configuration, using 7.54 mm Kapton blade material (same as the MIT reference design) is also shown. It is worth noting that increasing blade radius does not produce proportional increases in characteristic acceleration, as the ultimate performance of the heliogyro, or any solar sail, asymptotes to that of the membrane structure sail performance alone as sail area approaches infinity. The greatest performance gains are realized by lightweighting the sail membrane material, as was done for our final working concept, by adopting thinner, 2.54 μm Mylar over the thicker, and heavier, 7.62 μm Kapton employed on the MIT reference design.

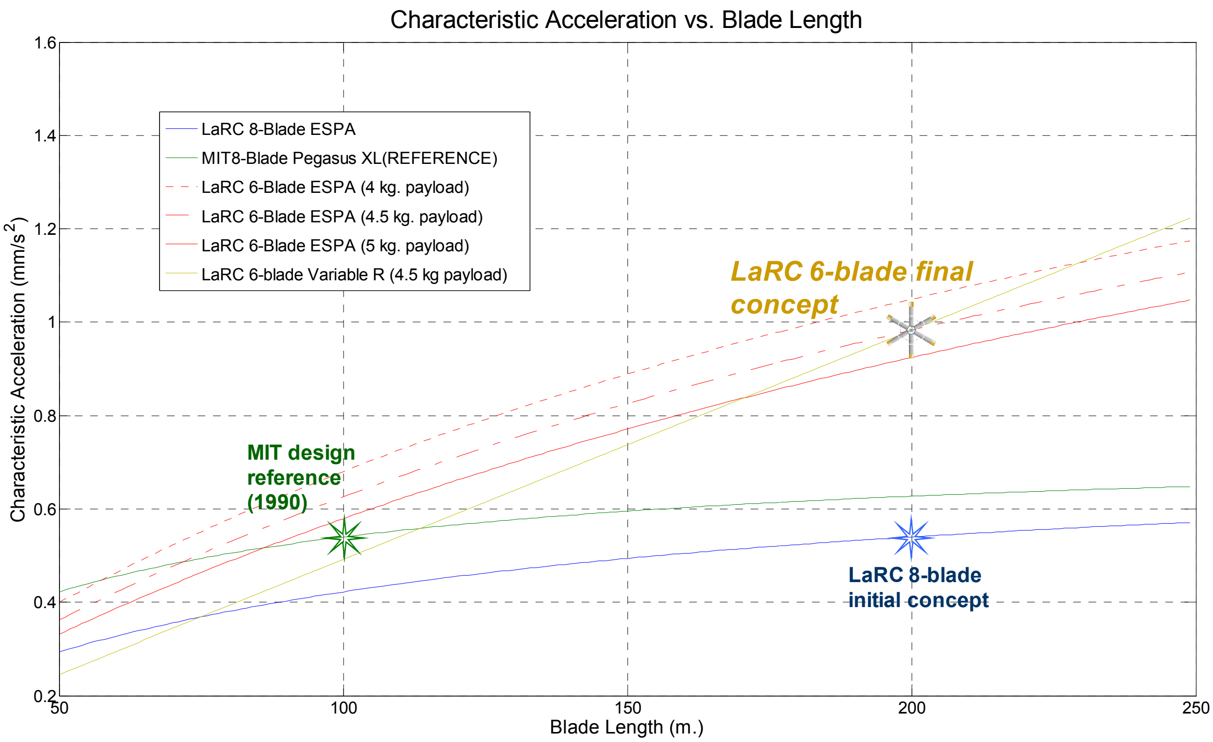

Figure 8. Heliogyro characteristic acceleration performance trends. Performance curves as a function of blade radius are shown for the MIT design reference (green), an 8-bladed early NASA-LaRC concept (blue), and the final NASA-LaRC heliogyro concept (red). Dashed red lines show performance trends for differing payload masses. The yellow line indicates performance of the final NASA-LaRC heliogyro working concept at intermediate deployed radii.

Encouraged by the results of the preliminary heliogyro assessment, a more detailed mission and systems analysis was performed. Key details from this study (dubbed HELIOS, for **H**igh-Performance, **E**nabling, **L**ow-Cost, **I**nnovative, **O**perational **S**olar Sail) are described below.

HELIOS: A HELIOGYRO TECHNOLOGY DEMONSTRATION MISSION

HELIOS is intended to be a low-cost, CubeSat technology based heliogyro technology flight demonstration; based on the preliminary working concept. Primary objectives are: 1) validation of critical heliogyro deployment technologies; 2) demonstrate controlled heliogyro solar sail flight at mission-enabling characteristic accelerations, defined here as $a_c > 0.5$ mm/s^2; 3) validation of heliogyro structural dynamics and solar sail flight models; and 4) demonstration of orbit changing capabilities, specifically orbit raising and orbit lowering. To minimize aerodynamics drag effects, a 1200-1400 km altitude, initially dawn-dusk sun-synchronous orbit is desired with minimal eclipsing, to avoid potential complications of thermal-elastic transient dynamic effects. Nominal mission duration is approximately four months; with de-orbit at mission end-of-life.

Packaging of the HELIOS heliogyro spacecraft as an ESPA auxiliary payload permits a number of rideshare launch options, depending on intended orbits of the primary vehicles. The DoD Space Test Program Mission S26 (STP-26) provides a particularly attractive launch scenario well suited to HELIOS mission requirements.[18] STP-26, launched from the Kodiak Launch Complex in November 2010, carried fourteen payload experiments on seven separate spacecraft carried into orbit using a single Minotaur IV launch vehicle. The Minotaur IV configured with the Multi-Payload Adapter (MPA) is capable of accommodating four ESPA class payloads. STP-26 also demonstrated a dual-orbit capability using the Hydrazine Auxiliary Propulsion System (HAPS), which achieved a secondary orbit of 1200 km altitude. The stowed HELIOS spacecraft, with ESPA payload envelope indicated, is shown in a potential launch configuration on a Minotaur IV MPA atop HAPS in Figure 9.

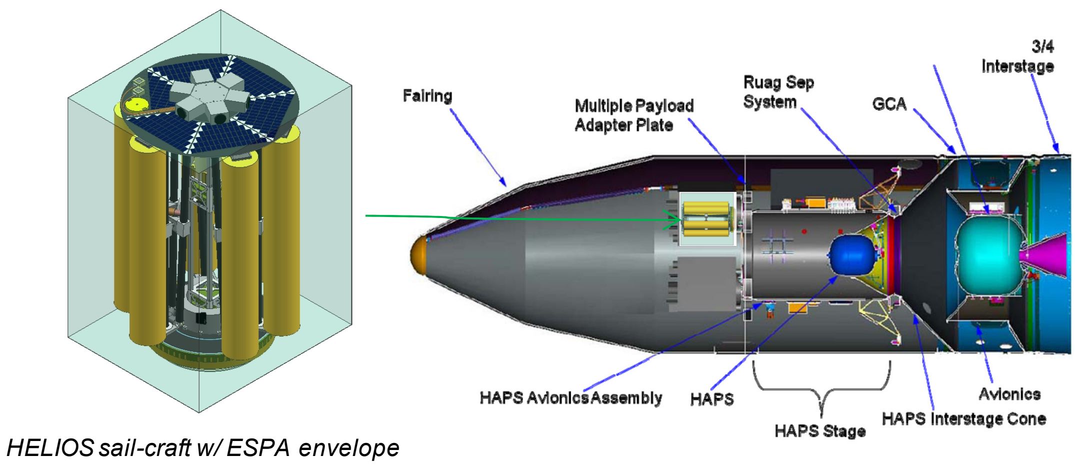

Figure 9. HELIOS stowed payload, with potential Minotaur IV HAPS launch configuration shown.

The HELIOS spacecraft determines its attitude via sun sensors (4 pi steradian coverage) and magnetometers. Attitude control of the core vehicle is accomplished using magnetic torque coils with large loop areas. HELIOS separates from the launch vehicle with push-off springs (via a Light Band separation system) and will be tumbling. The spacecraft must first acquire a sun pointed attitude, deploy the blade reel hex truss, and spin-up prior to deployment of the sail blade membranes. The blade reel truss must be deployed prior to spin-up to establish the deployed axis of symmetry as the primary axis, with appropriate margin. The complete HELIOS deployment sequence (Figure 10) is as follows:

- separate from LV in unpowered state;
- separation switch powers up spacecraft and initiates deployment sequence;
- detumble;
- acquire sun;
- deploy blade reel “hex truss”;
- spin-up/checkout;
- controlled sail blade deployment.

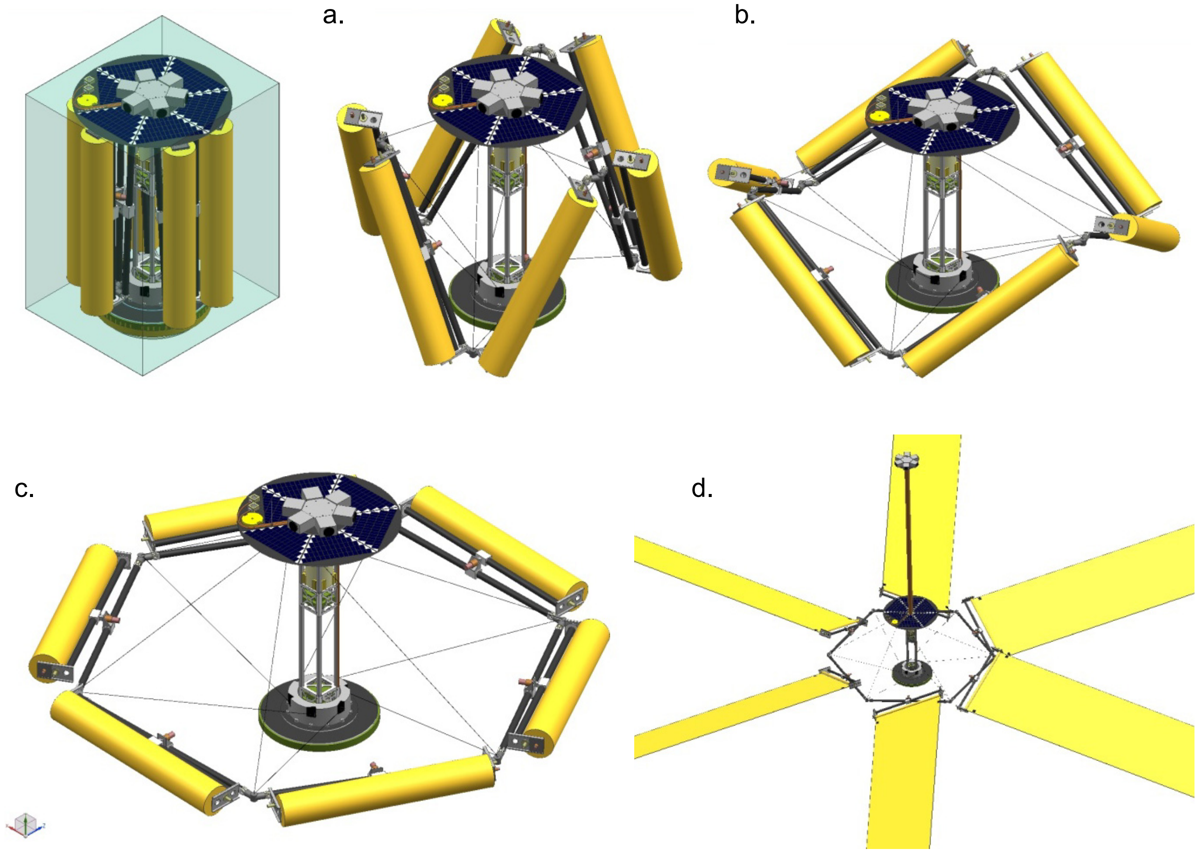

Figure 10. HELIOS deployment sequence: After detumble, acquisition and orientation to the sun (along the spin axis in the +X direction) blade reels are released via a burn wire (a). Deployment is actuated via strain energy stored in blade reel hex truss vertex springs (b). Tensioned cables connect the deployed truss to the central spacecraft bus. Once the blade truss is deployed (c), magnetic coils are used to spin up the core spacecraft to the nominal pre-blade deployment spin rate. After a systems checkout, a synchronized, controlled blade deployment is intiated. The blade camera mast is deployed at an intermediate blade deployment radius, and blade pitch control is activated to manage overall spin rate via solar radiation pressure induced torque (d).

Because the spin-rate will decrease as the sail deploys, due to conservation of angular momentum, the spin-rate will initially be relatively high (order of 5 RPM). As some time may be required to achieve this spin-rate, a mass efficient approach using magnetic coils, with large loop areas distributed on the HELIOS bus, is used instead of heavier torque rods. For spin axis control the magnetic coil wraps around the circumference of the upper/lower deck. The precession coil/rod is mounted to the side of one of the cubes. Bus attitude determination and control are combined with sail pitch control in a dedicated CubeSat-like assembly.

In contrast with the piezoelectric control system used with the MIT heliogyro concept and the reflectivity control based system considered for our preliminary heliogyro concept, HELIOS sail blade pitch control is accomplished using conventional root pitch motors. Reflectivity control, although initially preferred as a simpler and lighter weight option, was deemed to be insufficiently mature to be used for primary blade pitch flight control, at least in the near term. Blade root pitch angle is measured with analog output potentiometers. Blade bending and torsion deflection will be measured by estimating the local compound sun angle using small photovoltaic sensors located at intervals along the length of each blade. Blades will also be monitored using a dedicated camera system positioned above the plane of rotation by a deployable mast, with imagery stored and periodically downlinked for analysis on the ground. As noted by MacNeal in his original studies, the thin membrane blades of the heliogyro possess near-zero damping in both the out-of-plane (flapping) and torsion (pitch) directions. On HELIOS, damping will be provided using information from the distributed photovoltaic sensors along the blades, and closed-loop actuation of the pitch control motors. As rotation rates are very low (3 minutes per revolution) blade dynamic time scales will be very long and easily within the control bandwidth of the blade root pitch motors. Hub vibration will also be sensed using a centrally located MEMS 3-axis accelerometer. Blade deployment operations will take place at very slow rates (order of mm/sec). Controlled collective pitching of the blades, to adjust spin rate, will also take place during deployment. Deployment will be paused periodically to evaluate over all spin balance, structural dynamics and flight control characteristics.

The science data for HELIOS consists of camera images (from 6 cameras) and vibration data (accelerometers) and photovoltaic sensors on the sail membrane. The data volume is much larger than most typical CubeSats. The higher orbit required by HELIOS also complicates communications. Typical CubeSats use VHF/UHF communications and commercial transceivers are available for this purpose. CubeSats with higher data rate requirements have used S-Band transmitters, which are also commercially available. Our approach is to combine VHF/UHF for all uplink and engineering downlink and use S-Band for high rate downlink. As the HELIOS bus configuration is not favorable for omni-directional antennas, antennas will be mounted on both the +X and –X deck faces, with a 3dB beam-splitter connecting the two. The S-Band antenna will be a patch antenna, which is commercially available and compatible with a 1U cube. The VHF/UHF antenna is a pop-up monopole antenna with the deck acting as a ground plane. The antenna configuration is shown in Figure 11.

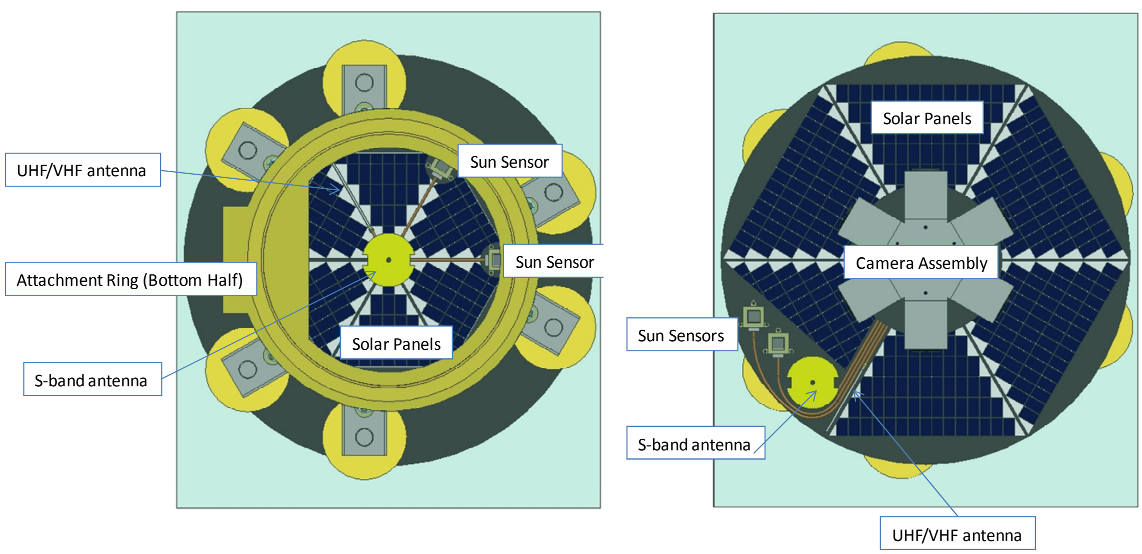

Figure 11. HELIOS antenna configurations: -X deck (left); +X deck right. Layout of the solar cells and blade monitoring camera system is also shown.

Table 2 provides a partial power budget for HELIOS. At 34 W, HELIOS power requirements are in excess of the largest advertised single CubeSat power supply, which is capable of 30W of power. The approach adopted here is to put a 20W supply in each cube, which has some advantages from an integration perspective. Solar cells on the +X deck provide 35W to 50W. The –X deck has half the cells as the +X deck to support launch operations.

Table 2: HELIOS Estimated Power Budget

Element	Power (W)
+ X Cube (bus systems):	*14*
OBC	5
VHF/UHF transceiver	2
S-band transmitter	2
Camera electronics	4
Power supply	1
-X Cube(sail systems):	*20*
ACS/Blade controller	5
Pitch motors and drivers	6
Mag torquers	5
I/O board	2
Power supply	2
Total	**34**

A preliminary mass budget for the HELIOS spacecraft, including the sail system, is provided in Table 3. The nominal spacecraft bus mass estimate is 4.5 kg with a maximum expected mass, including contingencies, of 5 kg. Unfortunately, the separation system scar mass, which must remain with the HELIOS sailcraft, is relatively heavy, at 785 gm. Mass of the blade deployment and control system is also somewhat heavy, at 8.4 kg, although component masses have not yet been optimized and some mass savings may be achievable in a more detailed design. Total sail membrane mass, including miscellaneous fittings, is book kept at 5.0 kg. Total mass of the complete HELIOS sailcraft is thus approximately 18 kg. Given the HELIOS sail area of 1000 m^2; slightly greater than the original working concept, this yields an approximate characteristic acceleration at 1.0 AU of 0.5 mm/s^2; which meets our nominal performance goal. It is notable that 18 kg is nearly identical to the original MIT small heliogyro mass estimate. Final HELIOS design parameters are summarized in Table 4.

Table 3: HELIOS Estimated Mass Budget

System	Mass (kg)
Bus system:	*4.9*
+ X CubeSat (sun facing)	1.5
-X CubeSat (separation side)	2.3
Bus system integration hardware	1.1
Sail system:	*12.9*
Deployment structure and mechanisms	8.4
Sails	5.0
HELIOS total mass	**18.3**

ONGOING HELIOGYRO STRUCTURAL DYNAMICS AND CONTROL INVESTIGATIONS

Heliogyro blade pitch control may be accomplished using mechanical actuators or motors located at the blade root, although lighter weight "solid-state", active structures approaches may also exist. One approach, used notionally in the early LaRC heliogyro concept study, and currently being studied as lighter weight blade pitch control option for future designs, is to employ distributed liquid crystal thin film elements, similar to those successfully flown aboard the JAXA IKAROS solar sail in 2010, distributed along the blades to modulate local reflectivity. The liquid crystal films may be used to alternately switch the reflectivity of the underlying reflective sail membrane coating between diffuse (OFF) and specular (ON) reflective states using low electric fields. This changes the resulting radiation pressure acting on the coated region, which, in conjunction with a control scheme, may be used to generate trim control forces on the sail membrane. Modulating reflectivity can also be very effective for damping augmentation. Both novel electrochromic materials and active reflectivity control schemes are being studied for as a possible solid-state replacement for the current HELIOS mechanical root pitch control system.[19]

Detailed structural dynamics analysis of the giant JPL Comet Halley Rendezvous heliogyro was accomplished – successfully - using a specially modified, 1970s-era version of the NASTRAN finite element analysis program, although significant dynamic scaling of results was required to avoid many computational issues. Heliogyro analysis with modern day finite element software requires overcoming many of the same numerical challenges. Heliogyro blades achieve the membrane stiffness required to carry transverse solar pressure loads from the angular velocity of the spacecraft. Proposed heliogyro spacecraft designs have angular velocities at or below 1/3 RPM which results in very low bending stiffness for the blades. Convergence problems are encountered during conventional nonlinear quasi-static finite element analyses because the stiffness matrix is nearly singular and the resulting internal forces in the blade are very small. The finite element solver is forced to compare a nearly zero residual internal force to a nearly zero average internal force to obtain a converged solution. This results in numerical problems and ultimately leads to unreliable solutions. Nonlinear implicit dynamic finite element analyses will suffer from the same convergence problems as the nonlinear quasi-static analyses because an equilibrium check is performed for each time step. Long solution times are expected for nonlinear implicit dynamic analyses using well refined heliogyro blade meshes.

Modeling the deployment dynamics of heliogyro blades presents additional challenges. Heliogyro blade deployment and spacecraft maneuvering events can last for hours. Proposed low angular velocities will require many time steps per blade revolution, and many blade revolutions will be required to sufficiently analyze blade integrity and control issues during blade deployment and spacecraft maneuvering. Nonlinear explicit dynamic finite element analyses can help overcome initial stability issues and the associated convergence problems. However, explicit analyses are typically not used for long duration events because of small time steps and the tendency to accumulate error as time progresses. Time steps during a typical explicit analysis are on the order of $1x10^{-6}$ seconds. This means that solution times will be large and a significant amount of error can accumulate because a very large number of time steps will be needed for blade deployment and spacecraft maneuvering analyses. All of these challenges reinforce the need for an in depth look at using conventional finite element software for heliogyro analyses. Heliogyro blade dynamics and control are complex long duration problems that may ultimately require the use of heliogyro specific analysis software.

The blade reel truss deployment itself is likely one of the more tractable structural dynamics analysis tasks. Commercial multi-body dynamics codes, such as MSC-ADAMS, are generally well-suited to this problem. Preliminary analysis of strain-energy truss deployments using linear rotational springs at the blade reel vertices has already been conducted. A more elaborate, deployment analysis using nonlinear, self-locking, tape-spring like hinge flexures is also underway. In this approach, the detailed, nonlinear force-deflection behavior of the spring flexures is modeled using nonlinear, explicit LS-DYNA finite element analysis simulations. Characteristic force deflection characteristics derived with the LS-DYNA simulations are then used to define effective spring rate curves for use in the ADAMS blade reel truss deployment model. This methodology will ultimately be used to design the blade reel truss vertex spring-damper-latch mechanisms.

Table 4. Summary of HELIOS Sailcraft Parameters

	HELIOS
Total sail craft mass (kg)	18.3
Characteristic acceleration, a_c (mm/s^2)	0.5
Sail material	Mylar (2.54 μm), aluminum (0.1 μm)
Sail area (m^2)	1000
Non-sail mass (kg)	13.3
Number of blades	6
Blade chord (m)	0.765
Blade length (m)	218
Rotational period (minutes)	3
Blade root stress (Pa)	47000
Blade root allowable stress (Pa)	55 x10^6
Blade root tension load (N)	0.10

SUMMARY AND CONCLUSIONS

Heliogyro solar sails, although less studied than square-rigged and spinning disk architectures, possess many key advantages for future, mission-enabling solar sail designs. In particular, their straightforward deployment scheme and light weight make them a practical and higher-performance alternative to heavier, more difficult to deploy systems. As the large, spinning solar sails needed for the most compelling, solar sail enabled missions are not possible to test or validate on the ground, technology flight demonstrations will be required to demonstrate feasibility. The HELIOS heliogyro concept presented here is a potentially low-cost means of accomplishing this. HELIOS is designed using CubeSat bus technology, for low cost and low mass, and as a rideshare auxiliary payload to minimize launch costs. In addition to serving as a deployment validation flight experiment, performance characteristics of HELIOS are in the range required for meaningful solar sail missions. Characteristic acceleration of HELIOS, nominally 0.5 mm/s^2, is approximately three times the characteristic acceleration performance of the NASA ISPT program solar sail demonstrators, and 50 times that of IKAROS. Given a near term effort to advance the technology readiness of critical systems, most notably the blade deployment mechanisms, a HELIOS or HELIOS-like heliogyro flight demonstration could be ready for launch in as few as five years.

FUTURE WORK

Several tasks to develop heliogyro technology readiness are in work, or contemplated for the near term. Many of the critical blade deployment mechanisms are in principal testable on the ground. Blade truss deployment, which is accomplished via stored strain energy, can be tested via short duration drop tests. As blade root tensile loads are on the order of the gravity loads a vertically oriented section of the blade would experience under 1 g, blade deployment reel mechanisms may be validated by conducting deployment tests of short blade segments suspended vertically in a vacuum chamber. Flight dynamics models appropriate for heliogyro solar sails will also have to be developed, including algorithms for autonomous flight control. Blade structural dynamics will also require additional study, including investigations into possible aeroelastic instabilities such as blade flutter induced by unfavorable dynamic coupling of solar radiation pressure and blade deflections. Mechanical root pitch mechanisms may also be eliminated and replaced with more advanced, lighter-weight blade pitch control schemes. In particular, the promise of solid state pitch control via reflectivity modulation is particularly attractive, provided appropriate, light-weight and space durable reflectivity control materials can be developed.

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