

## DEVELOPMENTS OF THE SOLAR BLADE SAIL

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### Abstract

The Solar Blade Heliogyro Solar Sail has the appearance of a Dutch windmill and employs sail control akin to a helicopter. Four solar reflecting blades, each 40 meters long by 1 meter wide and constructed from ultrathin polyimide film, are attached to a central spacecraft bus and are pitched along their radial axis. Embedded Kevlar and battens provide added stiffness and resistance to tears. The satellite uses collective and cyclic pitch of these solar blades relative to the sun's rays to control attitude and thrust. The spacecraft weighs less than 7 kilograms, and, when stowed, is a package approximately the size of a golf bag. Total launch mass, including stowage carriage, is 35 kilograms.

The satellite will demonstrate attitude precession, spin rate management, and orbital adjustments, after which it will sail out past the orbit of the moon. The development and successful flight of Solar Blade will enable dwelling at sub-L1 LaGrange points, hovering over a planetary pole, and travel to distant reaches of the Solar System.

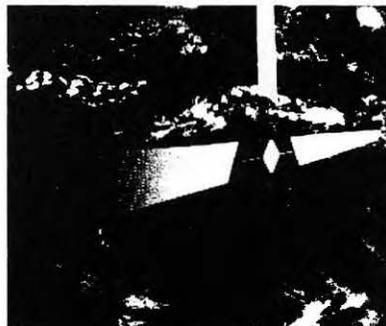
### Introduction/Project Overview

Launch of the Solar Blade spacecraft, the first heliogyro solar sail in space, will herald a revolution in spacecraft propulsion by eliminating the need for fuel. The Solar Blade Nanosatellite utilizes reflected solar radiation pressure as its only means of propulsion and attitude control. The continuous force generated by photons striking the windmill-like sail is sufficient to

boost the craft out of Earth's gravity well and, eventually, out of the solar system.

Solar sail concepts have existed for decades, but their implementation has been elusive; to date, no true solar sail craft have flown in space. The primary difficulty with solar sails has been the need for great sail surface area relative to the payload mass. Also, the cost associated with manufacturing very large sails and the risks of deploying such structures in space has hindered their development. For example, early solar sail spacecraft designs with payloads weighing hundreds of kilograms in mass led to sails with dimensions of kilometers. Carnegie Mellon University is employing miniaturization technology to dramatically reduce spacecraft payload mass, which shrinks the size of the sail and overall spacecraft mass. This reduction of size and weight makes the Solar Blade heliogyro design eminently more practical and flyable than previous solar sails.

The promise of solar sailing in space is in the continuous propulsion derived from natural solar pressure. Solar sailing makes possible exotic missions once thought impractical due to their large propellant requirements. Such missions include dwelling at Lagrange points, hovering over an Earth pole, cruising to asteroids, and flying to nearby stars.



## **Solar Blade Mission**

The Solar Blade Heliogyro has the appearance of a Dutch windmill and employs sail control akin to a helicopter. Four solar reflecting blades, 40 meters long by 1 meter wide and constructed from ultrathin polyimide film, are attached to a central spacecraft bus and are pitched along their radial axis. Embedded Kevlar and battens provide added stiffness and resistance to tears. The satellite uses collective and cyclic pitch of these solar blades relative to the sun's rays to control attitude and thrust. The spacecraft weighs less than 7 kilograms, and, when stowed, is a cylindrical package 0.4 meters in diameter and 1.2 meters high. The total launch mass, including the stowage vehicle, is 35 kilograms.

The Solar Blade and its accompanying stowage vehicle launch as an integrated package. After release from the launch vehicle, a propulsion unit on the stowage vehicle detumbles the spacecraft and points it toward the Sun. While maintaining a lock on the Sun, the blade roll holders deploy, and the propulsion unit spins up the spacecraft to 60 revolutions per minute. Then, the blades feed out in a controlled, balanced manner. During deployment, Solar Blade slows to its operating spin rate of 1 rpm.

A panospheric camera mounted on the stowage vehicle films the entire deployment. Then, the stowage vehicle and Solar Blade separate, leaving the stowage vehicle to slowly deorbit. The spacecraft will demonstrate attitude precession, spin rate management, orbital adjustment, and station keeping in Earth orbit for a month. Then Solar Blade will attempt an outward spiral trajectory.

The Laboratory of Atmospheric and Space Physics (LASP), located at the University of Colorado Boulder, provides the satellite detumbling, Sun-acquisition, and spin-up design, which consists of a bank of cold gas

thrusters, a Sun presence diode, a Sun crossing diode, and bang-bang control logic incorporated in a PC board [1,2]. Their system resides on the stowage vehicle. Solar Blade and the stowage vehicle utilize amateur radio band frequencies in the range of 1 to 10 GHz, at a power of up to 10 Watts.

The Solar Blade spacecraft can accommodate adapters from various launch vehicles, as long as the interface is similar to commercially available interfaces. It does not require a telemetry passthrough, but will use it if it is available. Solar Blade is currently designed to be compatible with an Ariane secondary payload fairing. The program's initial financial backers are USAF, NASA, the Space Studies Institute, The FINDS Foundation, Radio Shack, and Carnegie Mellon University.

### **Program Constraints**

The Solar Blade Project is a university project. As a result, resources are limited. Highest consideration is given to maximizing use of these resources. Furthermore, the mission design is driven toward simplification, to minimize costs as well as to minimize time to launch.

CMU researchers and students carry out the work related to the solar sail innovations. They also lead the mission design and implementation. Corporate partners and other university researchers provide added support and expertise regarding the more traditional aspects of the project.

### **Solar Blade Reference Design**

#### **Payload Characteristics**

The Solar Blade Mission demonstrates technology. Every component onboard is necessary for the basic operation of the spacecraft. Solar Blade, therefore, does not contain a traditional payload. Its  $4\pi$  steradian camera does have a dual purpose, however; along with sensing celestial

objects for attitude and position determination, it supplies images of space for purposes other than operations. Periodically, Solar Blade will store a  $4\pi$  steradian image and relay it to Earth.

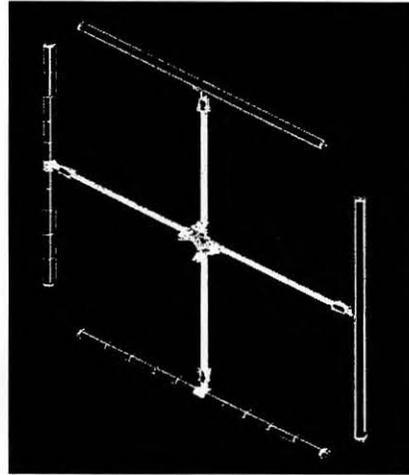
#### Spacecraft Characteristics

The Solar Blade spacecraft consists of four 40 m x 1 m rolls, or blades, of 1.27  $\mu\text{m}$ -thick CP1 polyimide material attached to a central bus, or core, through 4 blade roll holders and 4 struts. The picture below shows the support structure of Solar Blade, with the avionics box removed and the blades rolled up onto their spindles.

The central bus contains all of the avionics except for the hard-wired Sun acquisition system. Included in the bus avionics are the radiation-hardened microcontroller, transceiver, eprom, memory, and GNC system. Wiring extends out to the 4 blade roll deployment motors mounted on the blade roll holder and the 4 blade pitch motors connected at the blade roll holder yokes. Refer to the Structure subsection for labeled drawings.

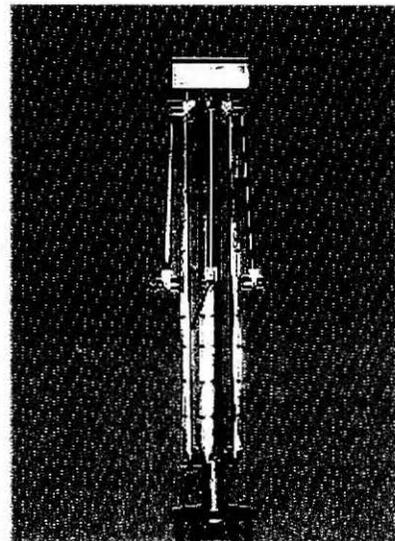
Nearly all of the support structure is machined Al 7075-T7. All actuating surfaces are hard anodized. Parts that actuate only once are also dry lubed with dicronite or a similar material. Parts that actuate repeatedly require a flight-worthy liquid lubricant such as Brayoil, Braycoat 601 or Braycoat 604.

In its deployed configuration, the support structure takes up a volume equal to a box 1.35 m on a side and 12 cm high. To better fit available secondary payload slots, and to brace against launch loads, the spacecraft folds into a cylindrical envelope 40 cm (dia) by 1.2 m.



*Figure 1 Primary Structure of Solar Blade.*

A stowage vehicle supports Solar Blade during launch. It consists of a cylindrical tube running from the bottom of the avionics box to the tips of the blade rolls, a blade roll latch system, a propulsion system used for Sun acquisition and initial spin-up of Solar Blade, a solar panel, a panospheric camera for filming deployment, batteries, and a stowage vehicle/Solar Blade release device. (See pictures of the Stowage Vehicle below.) The spacecraft mounts to its launch vehicle through the base of the stowage vehicle.



*Figure 2 Mechanical Prototype of Solar Blade Spacecraft.*

### Avionics- Schematic

Solar Blade uses a centralized architecture to link each subsystem directly to a Mongoose-V flight computer. The Sun Acquisition System is hardware-driven, and automatically starts its task after release from the launch vehicle. It sends an indication to the Central Processor when it has begun and when it has acquired the Sun. The other subsystems are slaves of the CPU.

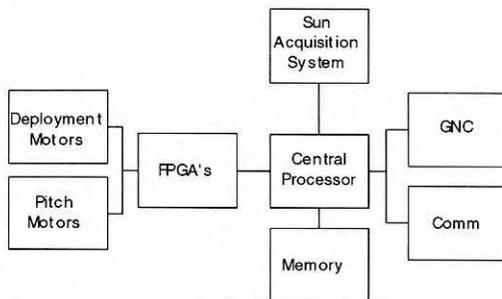


Figure 3 Avionics Schematic.

### Communications

A transceiver package integrates into the flight computer. Two antennas transmit data. A two-meter long flexible metal tape omniantenna is rolled up in the space between the Solar Blade and the stowage vehicle. After separation, the antenna unrolls on its own, and acts as the sole antenna for Solar Blade. Prior to separation, a toroidal tube antenna, part of the spine of the stowage vehicle, operates at higher power to quickly send back deployment image sequences and initial spacecraft data. Batteries in the stowage vehicle boost transmit power before separation.

### Power

The power system capability is based on the early phases of the mission while Solar Blade is near the initial transfer orbit (1000 km x 35786 km). The primary power system drivers are the power required to operate the vehicle during sunlight and eclipse, length of time in eclipse, as well as battery capacity, mass, and volume. The

eclipse time at these altitudes is about 40 minutes per orbit. The power requirements for the Solar Blade when in direct sunlight and when in eclipse are shown below in Table 1.

Vehicle	Sunlight Power (W)	Eclipse Power (W)
Solar Blade	20 ave.	3
W/ Stowage Vehicle	45 max, 27 ave.	4

Table 1. Required Vehicle Power

### Solar Array

Since the Solar Blade lifetime is expected to be as long as 2 years, using only primary batteries for power generation is not an option. The Solar Blade power system will need to have solar arrays and secondary batteries. Mounted atop each blade strut is a 966 cm<sup>2</sup> (23 cm x 42 cm) thin film solar array supplied by the Air Force Research Laboratory. The cells operate at 10% efficiency, resulting in approximately 50 Watts of unregulated power. After power regulation, and taking into account system losses, approximately 35 Watts are available for the spacecraft. See the overall spacecraft drawings and the support strut assembly drawing in the Solar Blade Structure section for illustrations of the mounting scheme.

### Batteries

Solar Blade uses rechargeable lithium-ion batteries at an assumed power density of 70 W-hr/kg. Given a required 9 W-hr charge capacity, the battery should weigh less than 150 grams.

### Thermal

During its mission, the Solar Blade spacecraft will remain in a relatively consistent thermal environment, ranging from a maximum of 2 hours in eclipse to many hours in direct sunlight, always approximately 1 AU from the Sun. The spacecraft can rely solely on passive

measures such as thermal blankets and thermal coatings to control the temperature. Components will be placed such that their temperatures remain within allowable limits.

An absolute worst-case steady state analysis for the solar arrays shows their temperature range to be  $-69^{\circ}\text{C}$  to  $+80^{\circ}\text{C}$ . This is acceptable for solar arrays. The actual coldest and hottest temperatures will be higher and lower, respectively, due to transient effects. With MLI blankets, the core temperature range will be much narrower than that for the solar arrays. A more detailed analysis will confirm the validity of a completely passive system. If further work shows active heating is necessary, some of the excess power generated from the solar arrays will be put into strip heaters. This will impact the secondary battery power storage requirement.

#### Wiring

Ultralight flex cable will be used throughout the spacecraft. This reduces weight, but increases fabrication costs. The pitch and deployment motor wiring will run through the struts and along the blade roll holder. A slip ring will interface the wiring from the strut to the wiring on the blade roll holder, to allow the blades to continuously spin during emergency reacquisition maneuvers. Wiring weight is typically 1% to 4% of the total spacecraft dry mass, which for Solar Blade will amount to 0.05 to 0.2 kg total. Assume 0.1 kg average.

#### Guidance, Navigation, and Control

The Solar Blade vehicle is essentially an autonomous vehicle with ground monitoring and override capabilities. Attitude and position determination is strictly done onboard, using a hybrid of a special  $4\pi$  steradian imager being developed at Carnegie Mellon and Microcosm's MANS autonomous navigation system. Our method of Instantaneous Celestial Attitude and Location determination (ICAL) requires the identification of the direction vectors to the

Sun, Earth and Moon in the spacecraft reference frame, as well as the apparent size of the Earth or Moon as seen by the  $360^{\circ}$  field-of-view ICAL imager. To find the Sun and planet center locations, we will derive a compact algorithm using a series of computer techniques such as edge finding, segmentation, and so on. Our algorithms will take into account occlusion, terminator location, albedo, color, and size to distinguish between bodies. To test the algorithms, we will develop a breadboard imager and a planet simulator consisting of lighted spheres precisely placed. We will specifically check the case that hindered MANS on its 1994 flight: partial occlusion of the Sun by the Moon. With planet locations accomplished, we will use Microcosm's MANS algorithm as a starting point to determine the attitude and position of the spacecraft-mounted camera.

The mission trajectory plan is preprogrammed into the spacecraft, as well as the behaviors necessary to maneuver the spacecraft. Performance of the spacecraft is downlinked, and necessary or desired changes to the trajectory plan are uplinked.

#### Structure

Solar Blade is made primarily of 7075-T7 Aluminum. Anodized coating, synergistic dry/wet lubricants, Teflon-impregnated materials, and high-strength steels will be used where necessary. Illustrations of Solar Blade appear below.

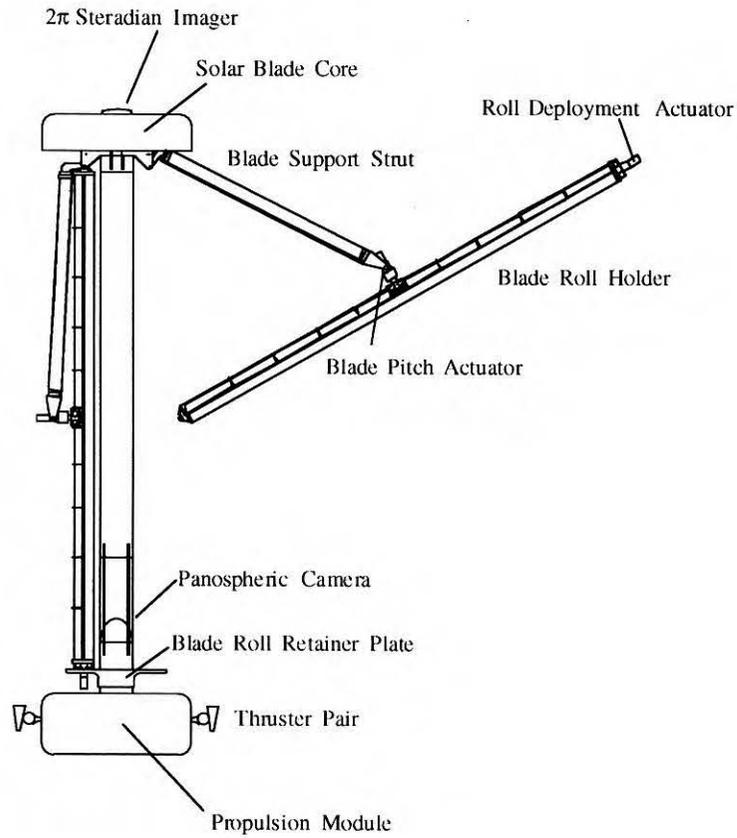


Figure 4. Solar Blade/Stowage Vehicle Package with Major Components Labeled.

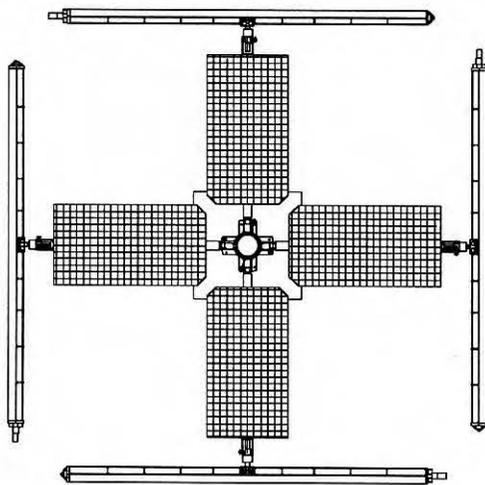


Figure 5. Face-on View of Solar Blade Core After Deployment. For Clarity, the Blades are not Shown Unfurled.

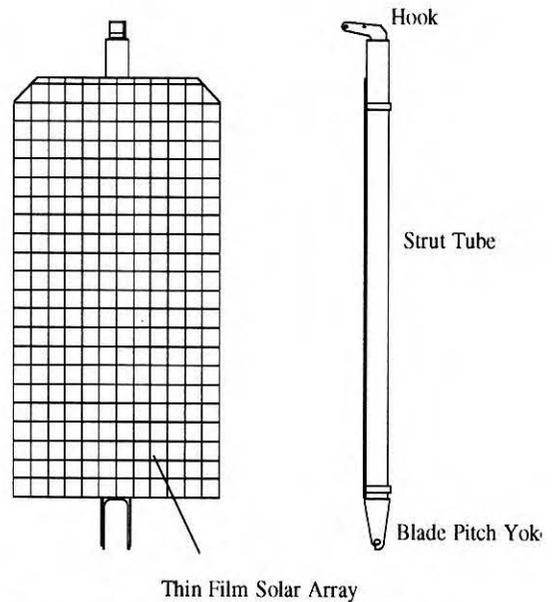


Figure 6. Blade Roll Support Strut Assembly.

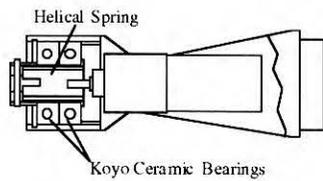
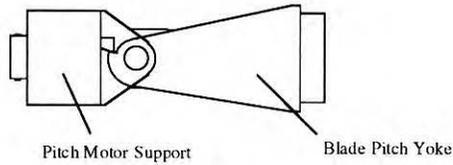
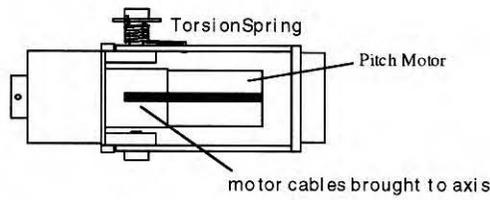


Figure 7. Blade Pitch Assembly. Bottom View is Partially Cut Away to Reveal Details.

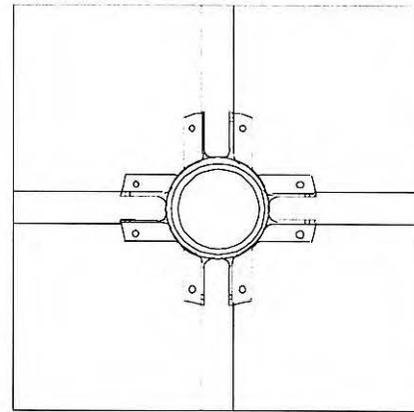
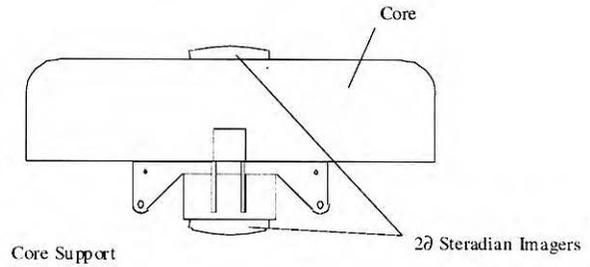


Figure 9. Core Drawing. The Two Cameras Mounted on Top and Bottom Constitute the  $4\pi$  Steradian Sensor.

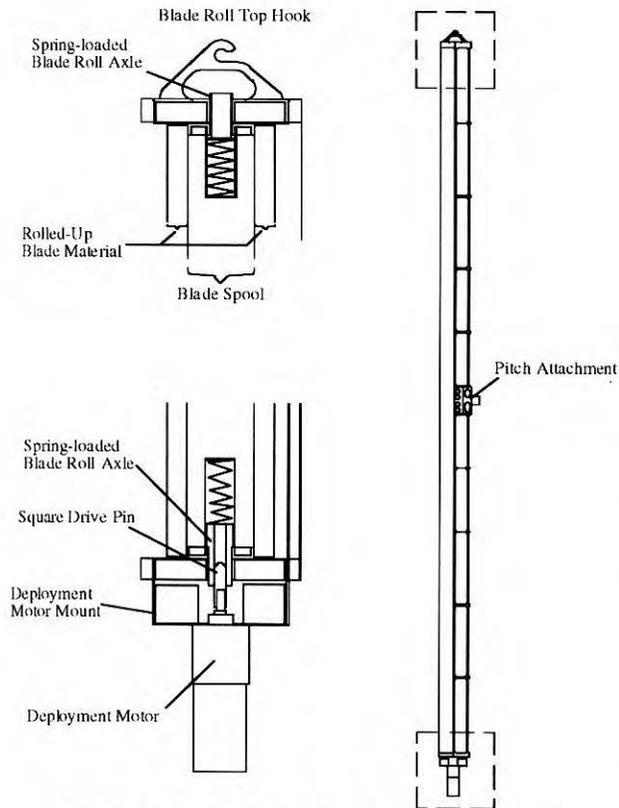
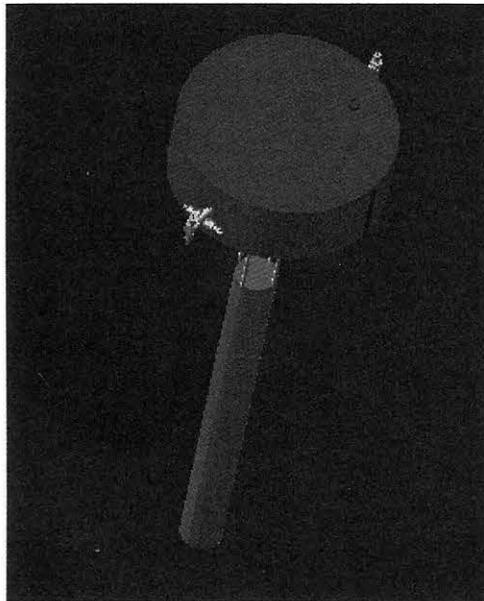
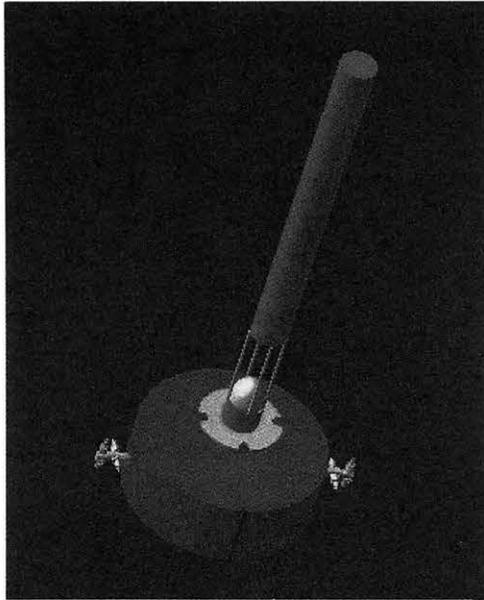


Figure 8. Blade Roll Holder Assembly. Cut-Away Views on Left, Top and Bottom.

### Stowage Vehicle Structure

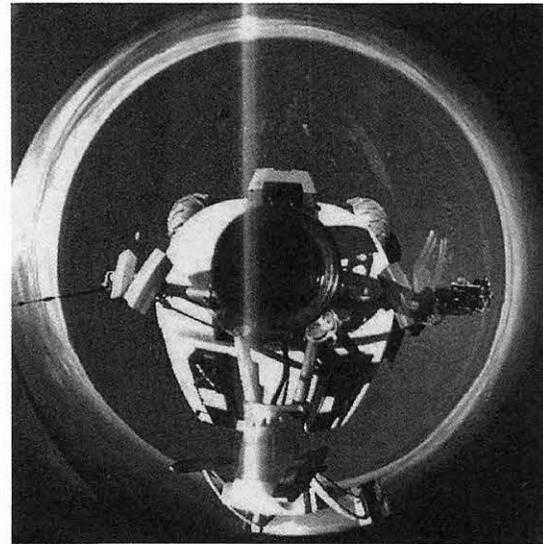
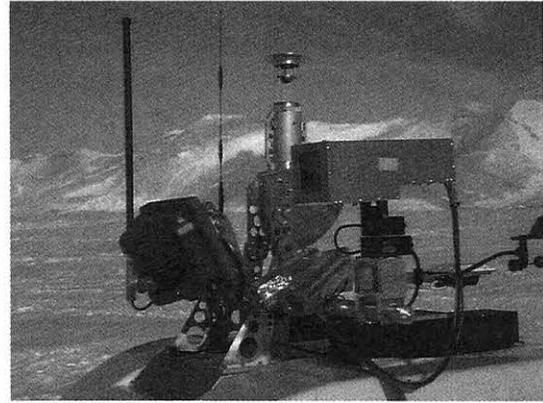
Illustrated in Figure 10 are the main components of the Stowage Vehicle. Shown are the panspheric camera, two banks of two thrusters, Sun-crossing diode, and Sun detector. Other components of the Stowage Vehicle reside inside the cylindrical portion of the structure.

To take pictures of the unfurling of blades, a panspheric imager resides in the Stowage Vehicle mast. It consists of a typical APS



*Figure 10. Stowage Vehicle Model. Top: Overall View of Stowage Vehicle; Bottom: Sun Detector Shown. This is the Side That Acquires the Sun.*

camera pointed toward an elliptical mirror, which allows for 360° image capture. The Panospheric Camera is based on proven designs used on CMU's Nomad rover, among other things. The first picture in Figure 11 shows a panospheric camera mast mounted on Nomad for an Antarctic trip; the second and third images show a raw image and a dewarped image, respectively, of



*Figure 11. Left: A panospheric Camera Mounted on a Mast Attached to the Nomad Rover During an Antarctic Field Trial; Right: Raw, Warped Image of Surrounding Atacama Desert Terrain Using a Panospheric Camera; Lower Right: Dewarped Image of Atacama Terrain.*

terrain encountered in Chile's Atacama Desert.

The Panospheric Camera can capture most of the blade deployment while the Stowage Vehicle stays attached to Solar Blade.

### Blade Actuation Subsystem Features/Implementation

The blade pitch actuation subsystem must be capable of 1 million cycles in space. The torque required to pitch the motors is less than .005 N-m and the maximum angle to be pitched is 90°. Nominal cycle time is 1 cycle per minute. The strawman actuators are Micromo 1525 brushless DC motors with a 16A 5000:1 gearbox. Each motor uses an absolute position encoder, spacecraft orientation, and computer commands for feedback control.

### Sail

The blades of Solar Blade are made of CPI polyimide film. Embedded in the 5 micron film is 1.4 mil Kevlar rip stop material, laid out on a 1 inch grid. Fabricated by SRS Technologies of Huntsville, Alabama, the 40 stiffeners attached every 2.5 meters. Each stiffener consists of a thin strip of Kapton material with a residual deformation that causes it to roll up on itself to form a light, stiff tube. The strip unrolls and lays flat on the blade roll spool during stowage.

A commercial company will coat the front of each blade with 1500 Angstroms of aluminum and the back with 1500 Angstroms of Chrome.

### Sun Acquisition System

The Detumbling and Sun Acquisition System is a self-contained duplicate of a system designed, built and tested at the University of Colorado [1-3]. It is activated by a breakwire release signal during launch vehicle separation. Included in the system are two spinup thrusters, two precession thrusters, and two Sun sensors, as shown in Figure 9. The Sun acquisition logic resides solely in the electronic hardware. A state and logic flow diagram for this system is shown in Figure 12. The ADCS/Propulsion system must provide autonomous initial spinup, detumbling, and Sun acquisition in

an undeployed blade state, as well as a final spinup to 60 rpm for subsequent blade deployment.

The theory for the initial detumbling and acquisition maneuver is outlined in [2] along with techniques for conservatively estimating propellant mass consumption.

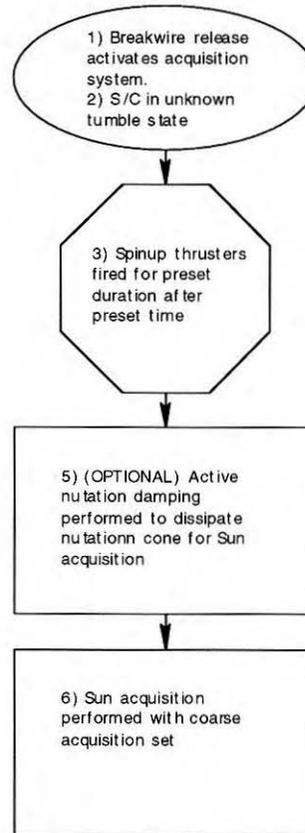


Figure 12. State and Logic flow diagram

A schematic of the initial ADCS/Propulsion system is shown in Figure 13.

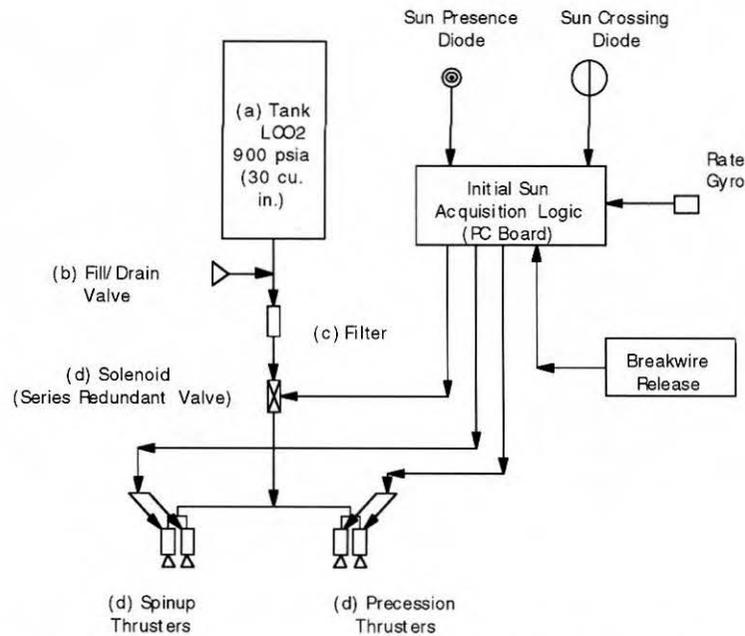


Figure 13. Initial ADCS/Propulsion system schematic [3].

### Operational Strategy

As a consequence of their flexibility, solar sails and other gossamer spacecraft demand surface activation and persistent control attention. Yet, control of the thin film material is an enigma. The nonlinear behavior of sails is difficult to analyze or predict. The effects of gravity and atmosphere on Earth make meaningful preflight deployment and operations tests impossible; therefore, validated system models of solar sails do not exist. Also, continuous ground control attention is impractical. These factors combine to create the need for onboard learning and fine-tuning of autonomous, intelligent solar sail guidance, navigation, and control.

We will implement machine learning and computer vision algorithms to learn appropriate sail control parameters for navigation and control. By combining off-line modeling and on-line learning techniques based on learning flight controllers, we will achieve precise control of the large sail structure. These adaptive controllers will in turn be guided by

autonomous mission planners which combine high-level mission goals, such as desired trajectory, with other factors, such as dynamic solar pressure and spacecraft/Earth geometry, to enable robust operations. Our avionics package will ultimately be capable of completely autonomous flight control.

Three basic maneuvers control the heliogyro. Each of them has a small number of parameters and results in a net force and/or torque being applied to the spacecraft. Using these maneuvers, an intelligent controller will accept desired force and torque values and find the appropriate parameter settings to achieve them. Safety algorithms incorporated into the controller will also learn potentially unforeseen effects on the sails. Because of their flexibility there is the potential for many kinds of uncontrolled oscillations. Memory-based learning algorithms will detect, predict, and avoid control actions which cause them.

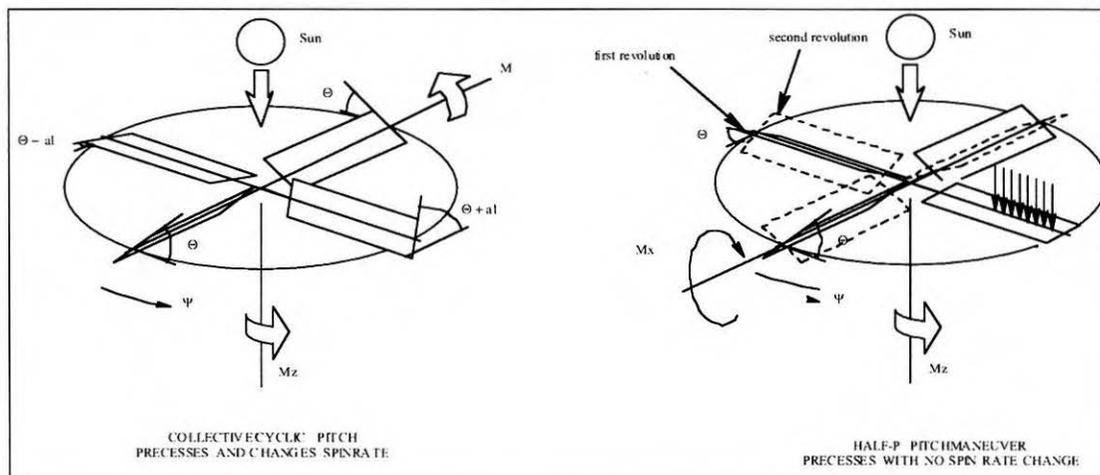
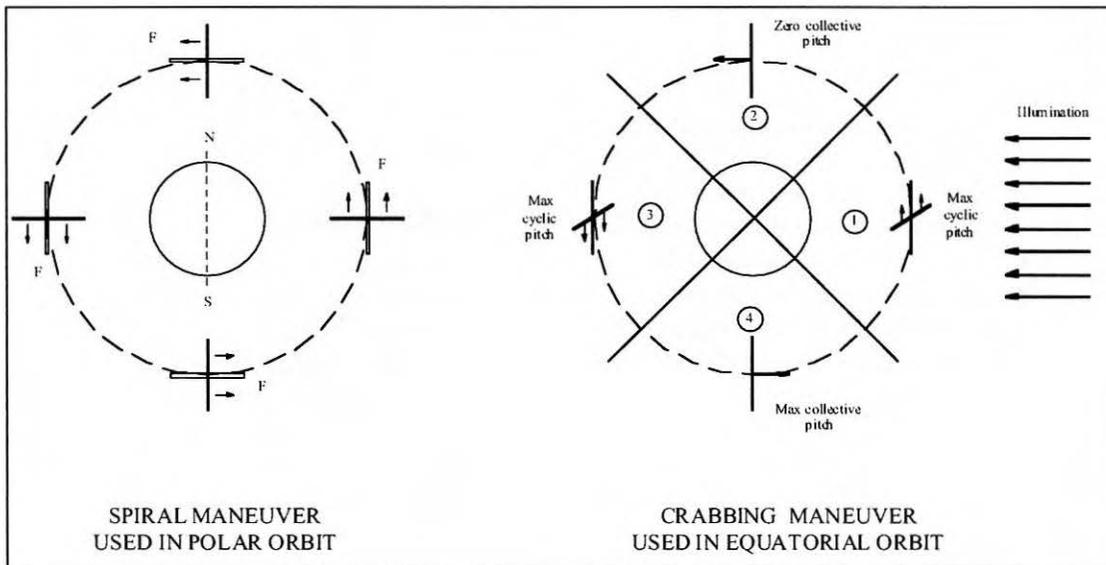
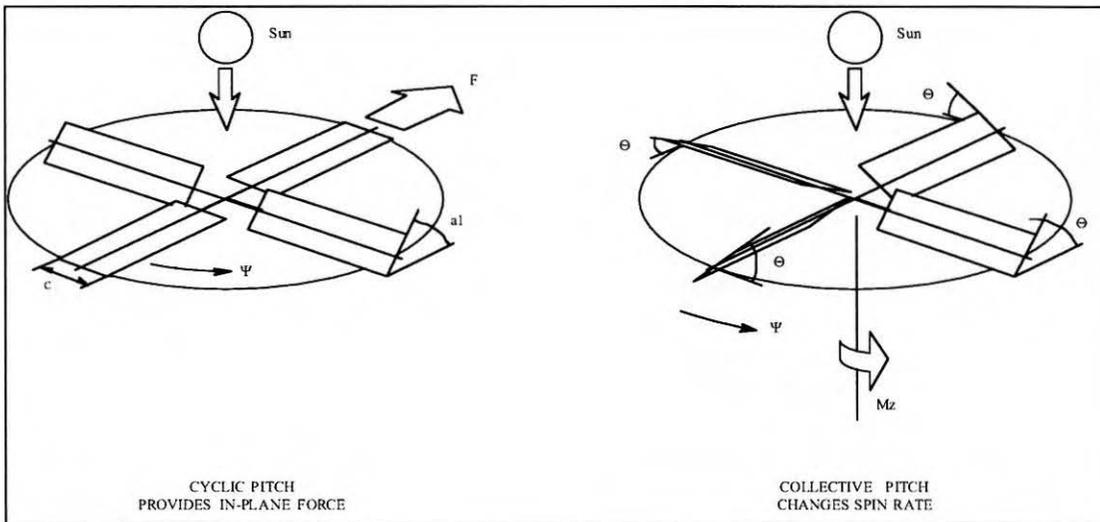


Figure 14. Operational Maneuvers of the Heliogyro. [4]

As stated earlier, it will not be possible to develop and test the system on a real heliogyro. It isn't possible to adequately simulate low

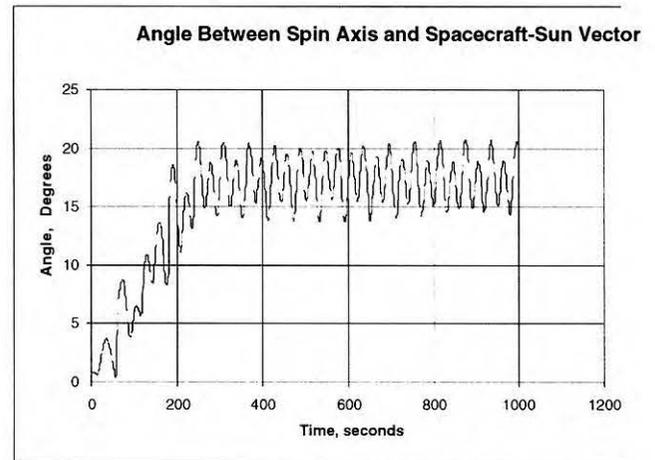
gravity, a vacuum, and solar pressure on a physical device on Earth.

Therefore, the algorithmic research, development, and testing will be done on a computer simulation. Because we are limited in ways to obtain data before flying the heliogyro in space, the simulation will not be accurate. The advantage of learning control is that it is not necessary to have an accurate simulation to test the algorithms. The simulations need only present the learning controller with a problem of similar difficulty.

### Power Strategy

The spacecraft nominally points the solar array directly at the sun. Should the solar array be tilted away from the sun  $45^\circ$ , sufficient to lower power below operational limits (+ 20% cushion), a Lithium-ion battery will power the spacecraft as it corrects its orientation. During eclipse, the spacecraft will power down all but the basic systems to keep the spacecraft functional and the memory contents loaded. Once out of eclipse, the spacecraft will reacquire the sun and realign itself, if necessary, using standard precession maneuvers.

Rotational inertia prevents drift of the spin axis during eclipse. If at any time the spacecraft spin axis is tilted more than  $45^\circ$  from the Sun, however, an emergency reacquisition maneuver rapidly diminishes the tilt. The maneuver consists of rotating blades, two adjacent pairs at a time, in a pattern that quickly changes the angular momentum vector of the spacecraft, as illustrated in Figure 15. The figure was generated from a simulation of an emergency maneuver, with each set of blades rotating once per rotation of the spacecraft, with one pair rotating in the opposite direction than the other.



*Figure 15. Result of a Sun emergency reacquisition maneuver, with adjacent pairs of blades rotating alternately, one pair in the opposite orientation than the other.*

### Operational Requirements

The spacecraft is designed to be nearly autonomous. Commands are sent up on an as-needed basis. Spacecraft data is relayed in a store-forward format, to limit the number of downloads necessary. Typically, data will be relayed 4 times a day during the basic mission, and 1 to 2 times a day during the extended mission.

All operations occur in the Earth-moon system. The duration of eclipse is 35 minutes at 1000 km circular and 70 minutes at GEO circular. Eclipses can be longer for elliptical orbits. During an extended mission, the spacecraft will travel through all the Van Allen belts. Radiation doses will be as high as 100 krads. Nominally, the spin axis along the maximum principal moment of inertia vector points toward the Sun. Therefore, temperature extremes, radiation environment, operational autonomy, data storage, and data throughput are strong drivers of the design.

## Mission Operations Concept

### Mission Scope, Objectives, and Science Requirements

#### Mission Phases

The Solar Blade mission can be divided into four phases:

- Deployment – Spacecraft releases from launch vehicle and detumbles, and acquires the Sun;
- Heliogyro basic operations - Spin-up and spin-down, thrust vectoring, precession of spin vector, and maintaining a sun-pointed spin vector. Duration: up to 1 week.
- Heliogyro primary mission operations - altitude and position changes, inclination changes. Duration: up to 2 weeks.
- Heliogyro extended mission operations - spiraling out beyond the orbital distance of the Moon. Duration: up to 2 years.

During all phases, sensors and on-board computers will determine performance. Ground observations may also aid in determining performance.

#### Mission Modes

Within each phase of the mission, the spacecraft can be in one of three different modes: active mode, standby mode, and safe mode. Active mode represents normal operation of the mission phase as programmed in the flight computer. Standby mode represents a holding pattern, wherein the sail blades pitch to maintain alignment with the sun, a constant spin rate, and a minimized change of trajectory. During this mode, the spacecraft awaits instructions. Safe mode represents a sleeping condition of the spacecraft, where power usage is minimized and all systems are run at a state wherein they can survive for an extended period of time without power input or communication. The

spacecraft enters safe mode automatically during eclipse, when an anomaly occurs, or when commanded from the ground to do so.

### Mission Description

#### Launch

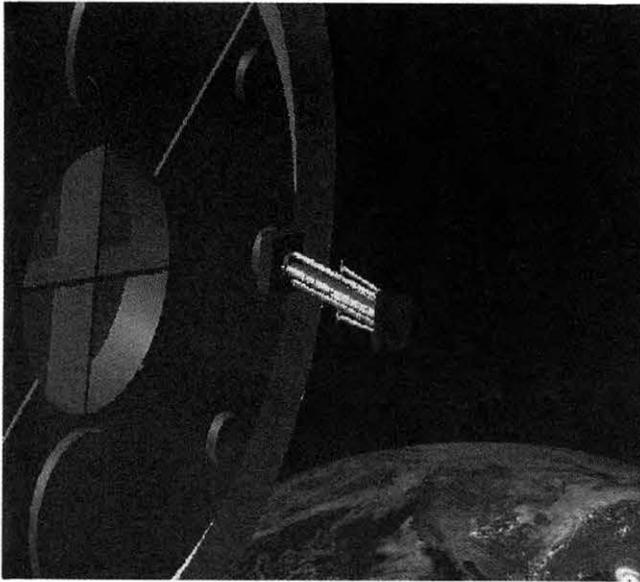
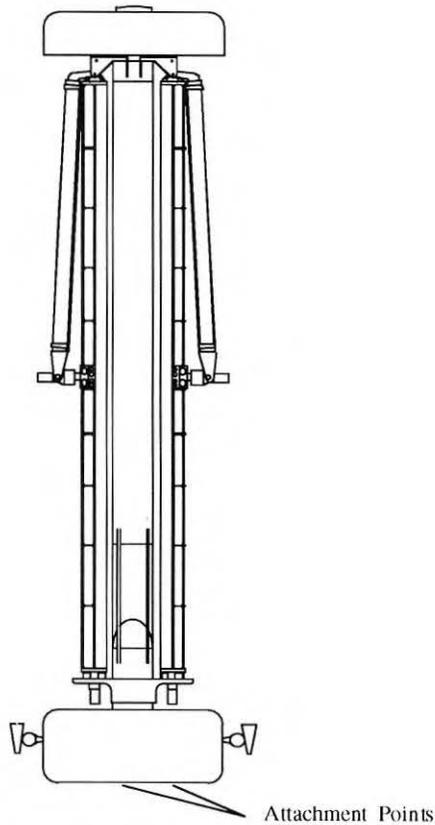
The spacecraft is injected into a GTO orbit of 580 x 35,786 km and ~ 0° inclination, aboard an Ariane V ASAP. The Ariane V launches from an Arianespace facility in French Guiana. After release of the primary spacecraft, Solar Blade separates from the ASAP.

#### Deployment

Deployment of Solar Blade occurs in five steps:

1. Separation from the launch vehicle and detumble maneuver;
2. Release of the blade roll holders from the stowage vehicle, and spin-up to 5 rpm;
3. Precession-nutation maneuver to acquire and lock-on to the Sun; Spin up to 60 rpm;
4. Unfurling of the blades and deployment picture-taking from panospheric camera; and
5. Separation of the core from the stowage vehicle.

Before step 1, the Solar Blade and stowage vehicle look like the package shown in Figure 16, with stowage attachment points as indicated. An interface plate permanently bolts to the base of the launch vehicle, and contains the release hardware for step 1.



Solar blade is released from the launch vehicle in the stowed configuration in a tumble (1). A breakwire release signal activates the initial Detumble and Sun Acquisition system. After the struts and blade roll holders deploy, the spacecraft fires the spinup thrusters to ensure the spacecraft is nutating with its desired spin axis and is spinning at an approximate 5 rpm spin-axis component of spin (2). A simple bang-bang controller with output from a rate gyro chip removes the spacecraft nutation with the precession thrusters. The spacecraft's momentum vector is then precessed towards the Sun using a simple Sun crossing diode sensor. When the spacecraft's spin axis is within  $5^\circ$  of the Sun, the Sun acquisition logic is shut off with a command from a sun presence diode. The spacecraft is then spun up to 60 rpm with the spin up thrusters (3). At step 4, deployment motors, situated as shown below, control the feed rate of the blades. The feed rate is balanced to maintain a positive trailing edge stress and symmetry among the four blades, while feeding the blades out expeditiously. To boost angular momentum, the blade rolls collectively pitch at the stage of deployment when the spin rate starts to drop below the nominal operating rate of 1 rpm. After the blades are deployed, the stowage vehicle separates from the Solar Blade and slowly falls back to Earth (5).

Figure16. Attachment to Launch Vehicle

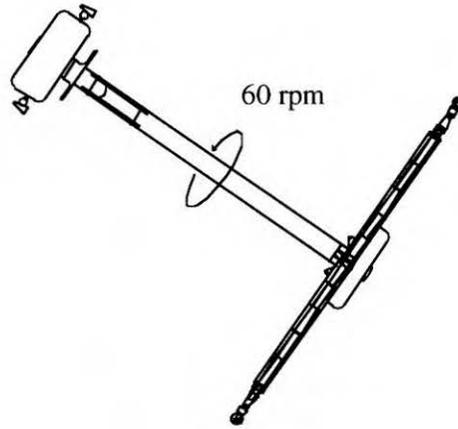
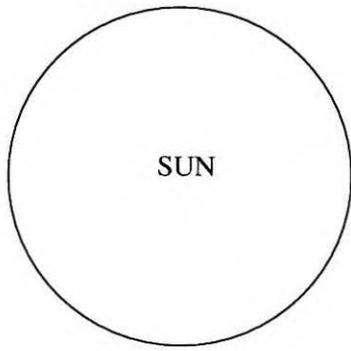


Figure 17. Blade Roll Holder Release, detumble, and Sun acquisition (steps 1-3).

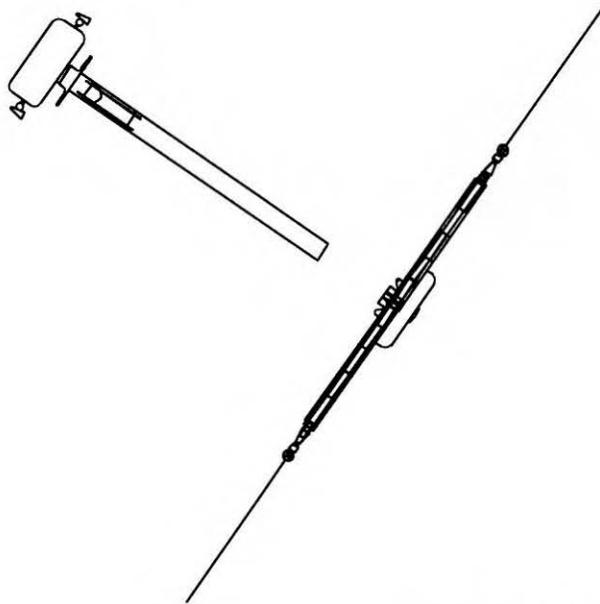


Figure 18. Stowage Vehicle Release.

### Communications Strategy

During Deployment and Basic Operations phases, the Solar Blade will communicate with a ground station system that is capable of a relatively high data feed rate. This two-way communications link will take care of initial communications with the spacecraft before deployment, such as health checks of Solar Blade and the stowage vehicle, deployment commands, imaging and memory storage of deployment, and relay of deployment images down to Earth.

Once the Solar Blade and stowage vehicle have separated, the Solar Blade will communicate with the ground exclusively. The basic, mission, and extended mission phases will be preprogrammed on the spacecraft, with each waiting for a prompt from the ground to begin. Software changes can be uplinked to Solar Blade. The downlink information will consist of data representing the performance of the spacecraft, the settings the spacecraft is using (learned through artificial intelligence coded in the flight software), its location and attitude, and occasional images of the Earth and Moon. Information will be relayed to the POCC at Carnegie Mellon for storage and analysis.

The spacecraft is designed to be nearly autonomous. Commands are sent up on an as-needed basis. Spacecraft data is relayed in a store-forward format, to limit the number of downloads necessary. Typically, data will be relayed 4 times a day during the basic mission, and 1 to 2 times a day during the extended mission.

### Conclusion

Successful completion of the Solar Blade mission is enabling to the use of solar sails in real science and exploration missions. The required development work will also contribute to the knowledge base of solar sail design. The proof of viability of the heliogyro will provide researchers and explorers an effective tool to dwell at sub-

L1 Lagrange points, hover above a planetary pole, and travel to the distant reaches of the solar system, where conventionally propelled spacecraft cannot reach.

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