# A Solar Sail Design For A Mission To The Near-Interstellar Medium

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**Abstract.** Mission concepts to several hundred AU are under study at NASA Marshall Space Flight Center (MSFC) and NASA Jet Propulsion Laboratory (JPL). In order to send a scientific probe beyond the heliopause in a reasonable length of time—no more than 15 yr and preferably 10 yr—the ΔV requirements are approximately 70 km/s. The preliminary results of these mission studies indicate that a solar sail can provide a cumulative ΔV of over 70 km/s to send a probe to a distance of 200 AU from the Sun in under 15 years. This is done by using photon pressure on the sail to shape the trajectory in the inner solar system so that a perihelion of 0.25 AU is achieved. This paper presents the results of a design study for a solar sail to achieve the performance requirements identified in an interstellar probe (ISP) mission study to the near-interstellar medium. The baseline solar sail design for this ISP mission assumes an areal density of 1g/m$^2$ (including film and structure), and a diameter of ~410 m with an 11-m-wide central opening. The sail will be used from 0.25 to 5 AU, where it will be jettisoned. The total spacecraft module mass propelled by the sail is ~191 kg. The gores of the sail are folded together and wrapped around a small cylinder. Centripetal force is used for sail deployment. The spacecraft is moved off-center with booms for sail attitude control and thrust vector pointing.

## INTRODUCTION

Solar sails have been studied in the literature for decades as a novel propulsion system for planetary and interstellar missions. Solar sail propulsion could enable missions never considered possible (McInnes, 1999, Leipold, 1996), such as non-Keplerian orbits around the earth or sun, or exciting commercial applications, such as polar communication satellites. NASA's drive to reduce mission costs and accept the risk of incorporating innovative, high payoff technologies into its missions while simultaneously undertaking ever more difficult missions has sparked a greatly renewed interest in solar sails. Solar sails are now included in National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), Department of Defense (DOD), Deutsche Forschungsanstalt fur Luft-und Raumfahrt (DLR), and European Space Agency (ESA) technology development programs and technology roadmaps (Garner, 1999).

A solar sail is a large, flat, lightweight reflective surface deployed in space—essentially a large space mirror—that can propel spacecraft without the use of propellant. Propulsion results from momentum transfer of solar photons reflected off of the sail (photons have no rest mass, but they do have momentum). The concept of solar sailing is not new. Tsiolkovsky (Wright, 1992) proposed in 1924 that large spacecraft could be propelled through space using photon pressure, and in the same year Fridrikh Tsander (Wright, 1992) proposed the lightweight solar sail design that is discussed today-a metallized plastic film.

The technical challenge in solar sails is to fabricate sails using ultra-thin films, deploy these structures in space, and control the sail/spacecraft. For reasonable trip times the sail must be very lightweight-from 20 g/m$^2$ for missions that could be launched in the near-term to 0.1 g/m$^2$ for far-term interstellar missions. Modern sail designs make use of thin films of Mylar or Kapton® coated with about 500 angstroms of aluminum with trusses and booms for support structure. The thinnest commercially-available Kapton® films are 7.6 μm in thickness and have an areal density (defined as the total material mass divided by the material area) of 11 g/m$^2$. A propulsion trade study (Gershman, 1998) identified the benefits and sail performance required to provide significant advantages over other propulsion technologies. The study concluded that sails with areal densities (defined as the total sail mass divided by the sail area) of about 10 g/m$^2$ are appropriate for some "mid-term missions" such as a Mercury Orbiter (Leipold, 1996) or small spacecraft positioned between the sun and the earth. More "far-term" missions such as an Asteroid

Rendezvous/Sample Return require sails with an areal density of 5-6 g/ $m^2$ and films with a thickness of approximately 1-2 μm. More advanced missions require sails with areal densities of under 3 $g/m^2$ for positioning spacecraft in non-Keplerian orbits or 1 $g/m^2$ for fast trip times to 200 AU.

Practical experience with solar sails is very limited. In the 1980's the World Space Foundation fabricated and deployed on the ground a 20-m (400 $m^2$) sail, and fabricated a 30-m (900 $m^2$) sail with an areal density of approximately 65 $g/m^2$ that was stowed in a deployment structure (Garner, 1999). In 1993 Russia deployed a 20-m-dia spinning disk solar reflector based on their Columbus 500 solar sail design with an areal density estimated to be 22 $g/m^2$ from a Progress resupply vehicle to provide sunlight to arctic regions in Russia. The sail, called Znamya 2, consisted of eight pie-shaped panels fabricated from 5μm-thick aluminized PETF film (a Russian version of Mylar) with no supporting structure. Deployment took three minutes; the sail remained attached to the Progress vehicle, which provided attitude control. In February 1999 the 25-m-dia Znamya 2.5 space reflector experiment failed due to a mission operations error and is discussed in more detail in this paper.

The Comet Halley Rendezvous mission studied by JPL in 1977 required a solar sail that had a total surface area of approximately 624,000 $m^2$ (790 m on a side) and weighed over 2,000 kg (Friedman, 1978); this enormous structure came to symbolize solar sail propulsion in the 1970's and 1980's. Despite advantages that could be obtained from using sails, deployment and control of sails of this magnitude in size and mass present a significant technical challenge and inhibit their application to NASA missions.

Recently NASA has encouraged programs to reduce the size and mass of spacecraft used for robotic exploration of the solar system (JPL, 1995). Spacecraft with masses below 100 kg are being studied for performing challenging missions, and microspacecraft technology is being developed that may result in robotic spacecraft with masses of 10 kg or less (Jones, 1991). Solar sail propulsion is synergistic with the new NASA approach to accomplish missions cheaper because the use of solar sails allows the use of smaller, cheaper launch vehicles. Solar sails have been studied in the literature for decades as a novel propulsion system for planetary and interstellar missions. Solar sail propulsion could enable missions never considered possible (McInnes, 1994; McInnes, 1994; McInnes, 1998; McInnes, 1998), such as non-Keplerian orbits around the earth or sun, or exciting commercial applications, such as polar communication satellites.

The basic idea behind solar sailing is simple, but there are difficult engineering problems to solve. The technical challenges in solar sailing are to fabricate sails using ultra-thin films and low-mass booms; package sails in a small volume; deploy these light-weight structures in space; and, understand the dynamics and have the ability to control of the sail/spacecraft. The solutions to these challenges must be demonstrated in space before solar sail propulsion is considered viable for any mission.

The feasibility of solar sail propulsion had been greatly enhanced by two recent developments: the successful deployment of an inflatable antenna from the space shuttle (Freeland, 1996), and reduction in spacecraft mass and sail size. For example, studies indicate that a main belt asteroid rendezvous and sample return mission (Leipold, 1995) can be accomplished within a seven-year trip time using a solar sail with an area of 90,000 $m^2$ (300 m on a side). Alternatively, a Geomagnetic Storm Warning mission (West, 1996) that would maintain a spacecraft at 0.98 astronomical units can be performed using a solar sail with an area of only 4,490 $m^2$ (67 m on a side).

NASA's Office of Space Science has developed four major themes for space exploration and a portrait of missions that are representative of the key technological challenges and scientific objectives that must be addressed. Two of these themes, Exploration of the Solar System and the Sun-Earth Connection, have identified solar sail propulsion as a technology that will enable or enhance portrait missions.

Progress in developing ultra-thin materials and lightweight carbon-fiber structures has made solar sails a feasible technology for high delta-velocity missions to Mercury, the outer planets and the local interstellar medium. Programs whose goals are to make solar sails a reality are now in place or planned. NASA programs include activities at Langley Research Center (LaRC), Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC), Goddard Space Flight Center (GSFC), and the NASA Institute for Advanced Concepts (NIAC). There are National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DOD) activities as well.

The technical challenge in solar sails is to fabricate sails using ultra-thin films, deploy these structures in space, and control the sail/spacecraft. For reasonable trip times the sail must be very lightweight-from 20 $g/m^2$ for missions that could be launched in the near-term to 0.1 $g/m^2$ for far-term interstellar missions. Modern sail designs make use of thin films of Mylar or Kapton® coated with about 500 angstroms of aluminum with trusses and booms for support structure. The thinnest commercially-available Kapton® films are 7.6 μm in thickness and have an areal density (defined as the total mass divided by the area) of 11 $g/m^2$. A Propulsion Trade Study (5) performed in 1998 identified the benefits and sail performance required to provide significant advantages over other propulsion technologies. The Study concluded that sails with areal densities (defined as the total sail mass divided by the sail area) of about 10 $g/m^2$ are appropriate for some "mid-term missions" such as a Mercury Orbiter or small spacecraft positioned between the sun and the earth. More "far-term" missions such as an Asteroid Rendezvous/Return require sails with an areal density of 5-6 $g/m^2$ and films with a thickness of approximately 1-2 μm. More advanced missions require sails with areal densities of under 3 $g/ m^2$ for positioning spacecraft in non-Keplerian orbits or 1 $g/m^2$ for fast trip times to 200 AU (McInnes, 1999). Ultimately interstellar flyby and rendezvous missions require sails with areal approaching 0.1 $g/m^2$ (Gavit, 1999).

Among the challenging missions potentially enabled by solar sails are missions to the near-interstellar medium and interstellar precursor missions. Concepts for missions to several hundred AU are under study at NASA Marshall Space Flight Center (MSFC) and NASA Jet Propulsion Laboratory (JPL). The $\Delta V$ requirements are approximately 70 km/s to send a scientific probe beyond the heliopause in under 15 yr. The preliminary results of these mission studies indicate that a solar sail can provide a cumulative $\Delta V$ of approximately 70 km/s to send a probe to a distance of 200 AU from the Sun in under 15 years. This is done by using photon pressure on the sail to shape the trajectory in the inner solar system so that a perihelion of 0.25 AU is achieved (Gavit, 1999). Progress in developing ultra-thin materials and lightweight carbon-fiber structures has made solar sails a feasible technology for high delta-velocity missions to Mercury, the outer planets and the local interstellar medium. This paper presents the results of a design study for a solar sail to achieve the performance requirements identified in an ISP mission study (Gavit, 1999) to the near-interstellar medium.

## MISSION DESCRIPTION

In 1999 the Jet Propulsion Laboratory (JPL) conducted a study in support of NASA Strategic Planning activities whose purpose was to develop a baseline architecture and technology list for the proposed "Interstellar Probe (ISP)" mission to the heliosphere and local interstellar medium with a launch date by 2010. This study was led by the JPL Interstellar and Solar Sail Technology Program with support from other NASA and government centers, private industry, and academia as needed. A full mission description is provided in the proceedings of the STAIF 2000 conference (Liewer, 2000). A brief summary of this mission is included to provide background information for sail requirements.

In order to send a scientific probe to the heliopause and beyond in a reasonable length of time—no more than 15 years—the $\Delta V$ requirements are such that advanced propulsion technology is required. To meet that challenge, the study baselined a solar sail propulsion system which uses the pressure of sunlight on a very large, light weight, shaped fabric to "sail" the spacecraft outside of our solar system. The mission baselined includes launching the spacecraft to a C3 = 0 using a Delta II rocket (7425). During launch, the sail is stowed inside of a canister. After the launch event, the 410 m diameter spinning sail is deployed and the deployment device is jettisoned. Solar photon pressure on the sail is then used to decrease the spacecraft velocity, such that the spacecraft swings into the inner solar system and around the sun with a perihelion of 0.25 AU. After accelerating the spacecraft away from the sun, the sail is then jettisoned at approximately 5 AU. This proposed design provides a cumulative $\Delta V$ of >70 km/s, propelling the spacecraft to a distance of 200 AU from the sun in less than 15 years.

The spacecraft, exclusive of the sail and its deployment hardware, can best be described as a "flying antenna". The 2.7 m rigid antenna functions as the main structure of the spacecraft with at least 12 instruments arrayed along its rim and the Ka-band telecommunications subsystem, Reaction Control System (RCS), and Alkali Metal Thermal to Electric Converters (AMTECs) located at the base of the antenna. At launch, this bus is attached to a simple sail control system, which is attached to a large deployment canister and the mechanisms for unfurling the solar sail. Once the solar sail is deployed, the majority of deployment mechanisms are jettisoned to minimize the mass that must be accelerated. While sailing, the movement of the sail is controlled by moving the spacecraft on a rail, which changes the center of mass of the sailcraft with respect to it's center of pressure. In its final configuration, the spacecraft is in a very slow spin with long deployed instrument booms. The spacecraft mass of 190.8 kg includes approximately 30.5 kg for sailcraft control hardware and a solar sail container adapter structure. The estimated accelerated mass (after sail deployment hardware is ejected) is estimated to be approximately 313 kg, which includes approximately 122.6 kg for the sail. A summary of key mission parameters is given in Table 1.

**TABLE 1.** Key Mission Parameters.

| | |
|---|---|
| Launch vehicle | Delta IV or smaller |
| Technology cutoff date | 2007 |
| Launch date | 2010 |
| Arrival at 200 AU | < 15 years |
| Spacecraft mass, kg | 190.8 |
| Solar sail mass, kg | 122.6 |
| Total accelerated mass, kg | ~ 313 |

# SAIL DESIGN

The solar sail design is divided into the following categories:

- Requirements Summary,
- Trajectory Summary,
- Sail Structural Design,
- Gore Assemblies,
- Sail Deployment,
- Mass Summary,
- Sail Control

## Requirements Summary

Sail design details to meet the ISP mission requirements are provided in this section. In order to establish the baseline mission design, an assessment of the key system parameters (distance of closest solar approach, sail radius and areal density, and time of flight) was performed. The distance of closest solar approach drives the spacecraft thermal and mechanical design and the time of flight. The sail size and areal density affects the following: time of flight, packaging and deployment, control and navigation, structural design, and materials and fabrication.

Trade studies (Gavit, 1999) indicate that the sail loading (defined as the total sail and spacecraft mass to be accelerated by the sail divided by the sail area) required to meet the mission requirements listed above is approximately 2.6 $g/m^2$. This requirement drives the design of the sail, including sail mass, sail areal density and sail diameter. The baseline solar sail design for this ISP mission assumes an areal density of 1 $g/m^2$ (including film and structure), and a diameter of ~410 m with an 11-m-wide central opening. The sail will be used from 0.25 to 5 AU, where it will be jettisoned. The gores of the sail are folded together and wrapped around a small cylinder. Centripetal force is used for sail deployment, and a spin rate of 0.09 rad/s (0.9 rpm) is required for tension in the sail film. The spacecraft is moved off-center on a rail for sail attitude control and thrust vector pointing. A summary of sail requirements is provided in Table 2.

**TABLE 2.** Key Sail Design Parameters.

| | |
|---|---|
| Sail diameter, m | 410 |
| Areal density, $g/m^2$ | 1 |
| Sail loading, $g/m^2$ | 2.6 |
| Perihelion radius, AU | 0.25 |
| Solar sail mass, kg | 122.6 |
| Spacecraft mass, kg | 190.8 |
| Total accelerated mass, kg | 313 |
| $a_c$, $mm/s^2$ | 3.0 |
| Spin rate, rpm | 0.9 |
| Spin axis precession rate, deg/day | 10 |

## Trajectory Summary

A solar sail is used to increase the energy of the heliocentric orbit from a negative value (an elliptic orbit) to a positive value (a hyperbolic escape orbit). For any given delta-V, the energy change is proportional to the velocity at which the delta-V is applied and is maximized when the delta-V is parallel to the velocity vector. Furthermore, the acceleration of a solar sail increases when it gets closer to the Sun. Thus in order to maximize the energy gain for the ISP mission, the sail is first used to reshape the heliocentric orbit to lower perihelion, even at the expense of an initial energy loss, in order to increase both the delta-V which the sail supplies and the velocity at which that delta-V is applied. This increases the effectiveness of the sail so much that the heliocentric energy of the spacecraft can be increased from negative to positive (with an adequate departure velocity) in just one perihelion passage.

This baseline trajectory was optimized using a model of the sail as described below. With this assumption, the flight time is a function of only the characteristic acceleration, $a_c$, and the perihelion radius. A higher $a_c$ or lower radius would shorten the flight time. The study assumed that the sail effectively reflects most of the light incident on it and that the rest of the light is transmitted through the sail without providing any thrust The effective thrust available as a function of the sun incidence angle (angle of the sun relative to the sail normal) was calculated with the following results: 91% at 0°, 90 % at 10°, 89% at 20°, 84% at 30°, 78% at 40°, and 60% at 50°. In this model the maximum incidence angle for which thrust can be achieved is 55°. The spin axis of the sail must be precessed up to 10 degrees per day for this trajectory. Once the solar sail is jettisoned, there is a separation maneuver performed to prevent the sail from obscuring the spacecraft's line of sight to the Earth. This maneuver has an insignificant effect on the trajectory. A plot of the trajectory as a function of time is given in Figure 1, and key angles of the spacecraft relative to the earth and sun are given in Figure 2.

## Sail Structural Design

The solar sail structure includes the solar sail deployment module, the sail including the sail cylinder, and the launch vehicle interface structure. For launch, the spacecraft is mounted atop the control assembly and 1.5 m long x 1.5 m-diameter sail cylinder, which in turn is mounted on top of the sail deployment module housing the sail deployment hardware and booms. The structural load path passes from the 1.2-m launch-vehicle adapter through the sail deployment module, sail cylinder walls, and control assembly, picking up the ring at the base of the 2.7-m antenna (Figure 3).

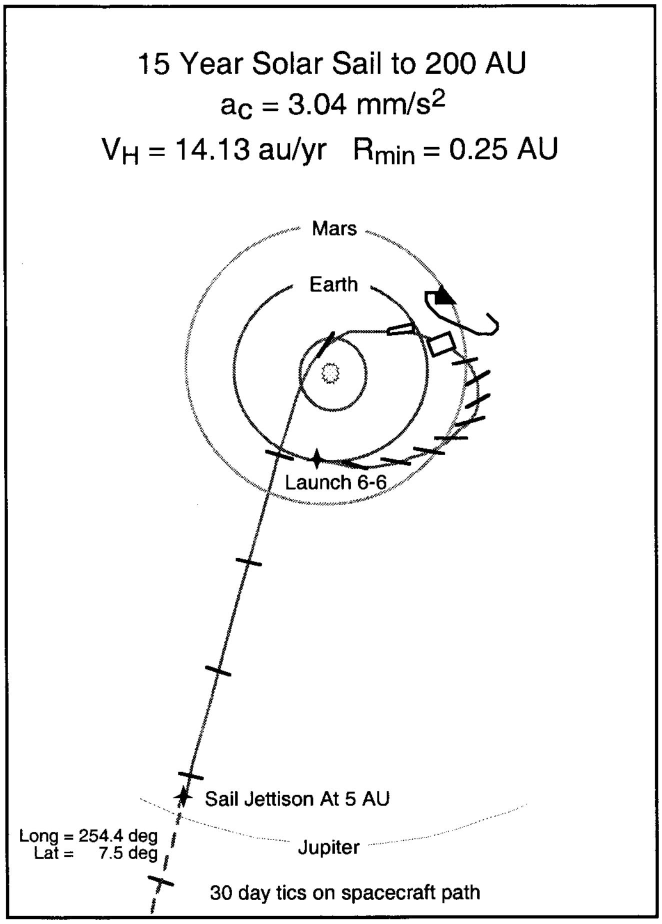


**FIGURE 1.** Baseline spacecraft trajectory.

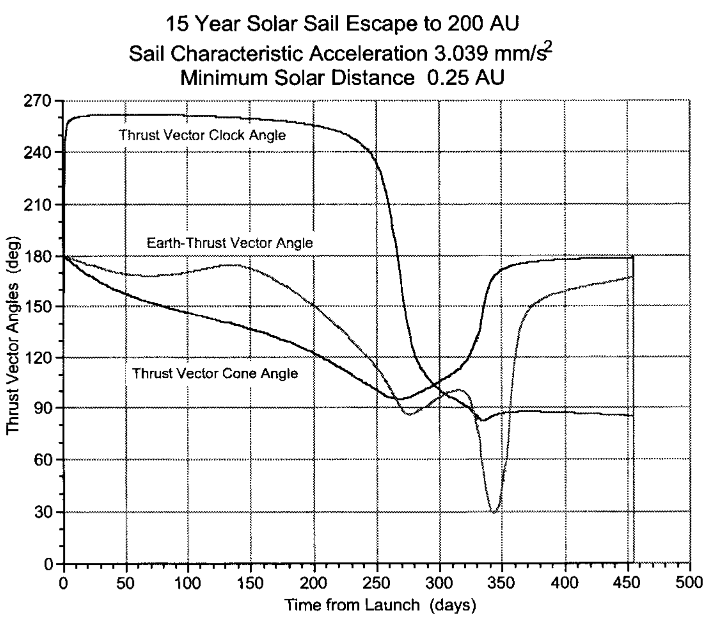


**FIGURE 2.** Thrust vector angles vs. time from launch.

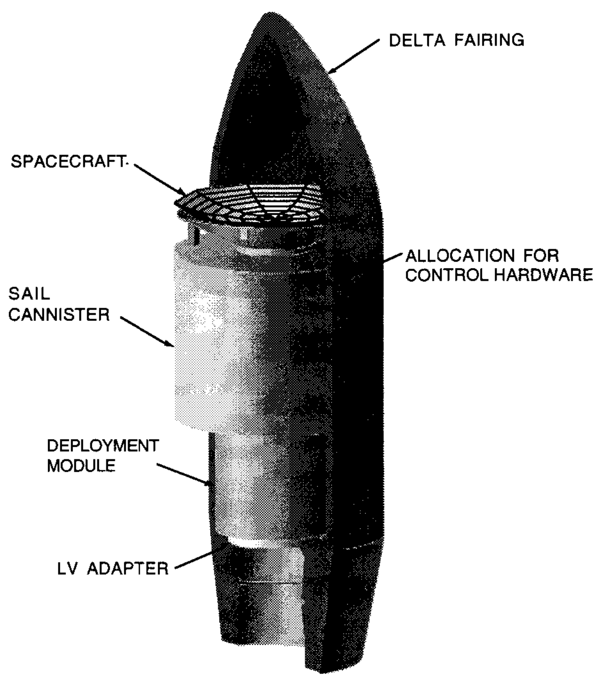


**FIGURE 3.** Sail, deployment module and S/C in Delta IV payload fairing.

Deployment hardware is located in the 1.5m x 1.5m deployment module to minimize the mass that must be accelerated by the deployed sail. Three each 10-m-long orthogonal booms are deployed from the deployment module, and thrusters at the ends of the booms are fired, spinning up the spacecraft and sail cylinder in a controlled fashion. The sail is comprised of 6 pie-shaped triangles which are folded into gores. At launch, the gores are wrapped around a 1.5 m long x 1.5 m diameter sail cylinder with an outer end diameter of approximately 2.2 m to allow for sail packaging. The sail cylinder is surrounded by a bellyband held in place with a marmon clamp. As the spacecraft spins, the bellyband is jettisoned and the sail is released by sequentially releasing restraining devices which allow the gores to slowly unfurl in a controlled manner to prevent snagging and collisions. Tethers holding the center of each gore to the sail cylinder are then played out to form a "wheel rim" which is 410 m in diameter. Each gore segment is then unfurled into a triangle by pulling tethers which connects each sail segment tip to the sail cylinder. After the deployment sequence is completed, the plane of the sail runs along the mid-section of the sail cylinder. After sail deployment, the sail deployment module, including the booms, spin-up assembly , and the launch vehicle interface structure are jettisoned from the spacecraft. Cartoons demonstrating the sail deployment sequence are shown in Figure 4, and the spacecraft with fully-deployed sail is shown in Figure 5.

## Sail Film And Gore Design

Sail design for the ISP mission is complicated by the need for an extremely low areal density and high sail thermal loads due to sail operations within 0.25 AU of the sun. The conventional concept of a solar sail consists of thin sheets of Kapton® or other polyimide, metallized on one side to provide a reflective surface and the other an emissive surface, and seamed together to form the large mirror-like sail . Kapton® provides the mechanical strength needed to carry loads through the sail, including handling, deployment, and photon pressure, and serves as a base to support the thin reflective and emissive metal layers. The reflector, typically aluminum, provides photon pressure which accelerates the sail, and the emissive layer allows for temperature control.

In this study and areal density of 0.5 gm/m$^2$ was allocated for the sail fabric and 0.5 gm/m$^2$ for the rest of the sail structure to achieve a total sail areal density of 1 gm/m$^2$. Polyimide densities are typically about 1.4 gm/cm$^3$, therefore to achieve a film areal density of 0.5 gm/m$^2$ requires a polyimide layer no more than 0.35 μm thick. If allowance is made for seaming, ripstops, and other structures then the polyimide thickness drops to approximately 0.2 μm. In addition, sail operations near 0.25 AU of the sun may result in sail temperatures at wrinkles and folds that exceed the glass transition temperature (~873 K) of polyimides (Wright, 1992). The requirements for the ISP sail mission stimulated investigations into alternatives to conventional sail material designs.

Recently a new material was proposed for use on solar sails (Knowles, 1997). Called a microtruss fabric, it is a porous, thick fabric with discontinuous carbon fibers joined to one another along nodes. Porosity allows light weight, and thickness allows intrinsic stiffness and strength. These fabrics can potentially be used at temperatures exceeding 1800 K or more (Knowles, 1997).

Carbon was selected because it has the following properties:

- High temperature tolerance,
- High emissivity,
- High tensile strength,
- Good radiation tolerance,
- Low Coefficient of Thermal Expansion (CTE),
- Minimal tear initiation capability, and
- Low areal density.

An overview of these parameters for carbon is given in Table 3.

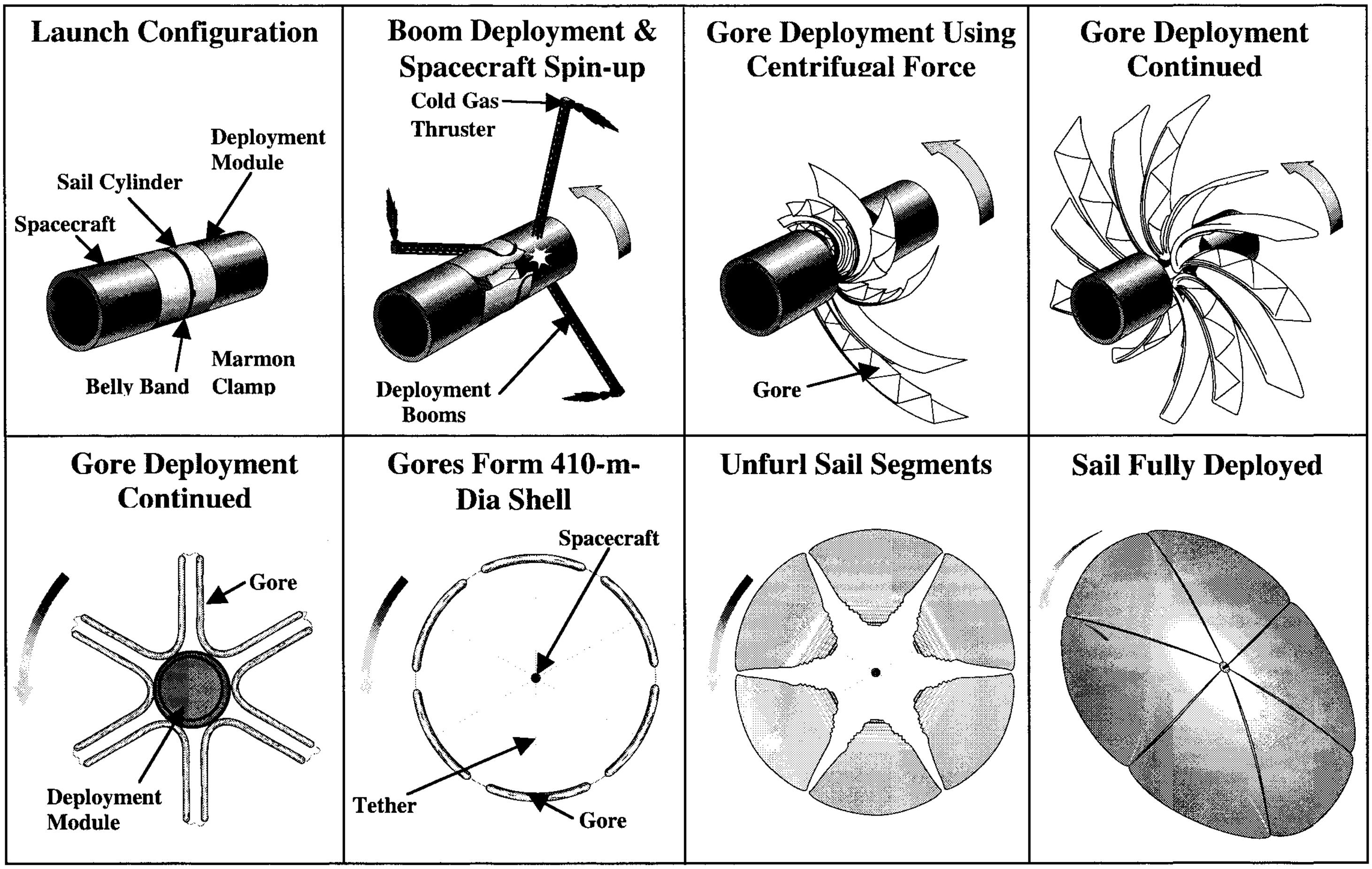


**FIGURE 4.** Sail deployment sequence.

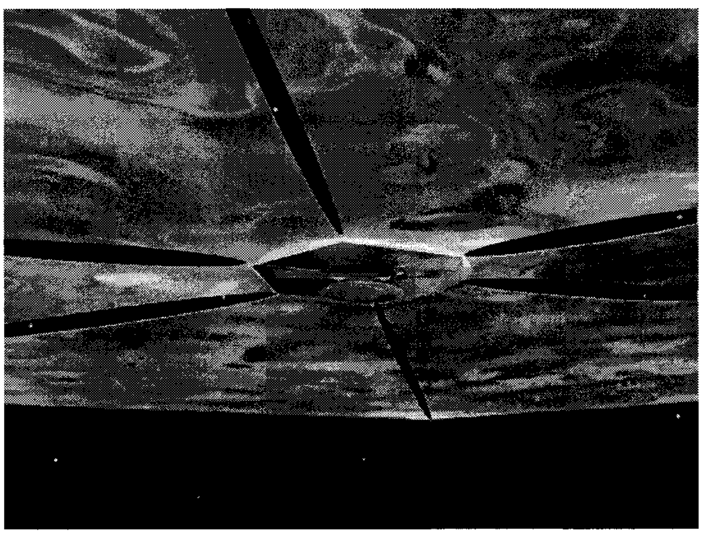

**FIGURE 5.** Spacecraft with fully-deployed solar sail.

**TABLE 3.** Carbon Material Properties.

| **Property** | **Value** |
|---|---|
| Temperature range (degrees K) | 70-2000 |
| Hot spot temperature (degrees K) | 753 |
| Tensile strength at 300 K (MPa) | 2205 |
| Tensile strength at 500 K (MPa) | 2205 |
| Gamma radiation tolerance (Rad) | Excellent |
| UV radiation tolerance (Rad) | Good |
| CTE (per degrees C) | $3 \times 10^{-6}$ |
| Tear initiation at 550 K (Nt/μm) | 3 |
| Emissivity | 0.4-0.9 |

The carbon microtruss fabric consists of 1 μm fibers and 10 μm fibers and is designed to support the aluminum reflective surface and the nanotube emissive surface (Figure 6). Nanotubes made from carbon provide for a high emissivity surface. A tension load of 6925 Pa (≈1 PSI) in the aluminum film is assumed to remove wrinkles. The maximum microtruss span that can be bridged with aluminum film can be calculated using Roark's formula. For a 250 Å thick aluminum film subjected to a load of 6925 Pa, a 563 μm maximum span is achievable. Aluminum was selected as the reflective material because aluminum meets the temperature requirements, there is a substantial technology infrastructure for aluminum deposition and adhesion, aluminum is cost effective, and aluminum is non-toxic. For the purpose of this study, 27 μm gaps formed by the 1 μm fibers were assumed to provide margin, resulting in 74,075 gaps per square meter to support the aluminum film and nanotubes. This margin allows for ground handling of microtruss sail fabric. Samples of carbon mictrotruss fabrics have been fabricated at Energy Science Laboratories Inc. in San Diego, Ca (JPL 1998). A photograph of a microtruss fabric is shown in Figure 7 and a photograph of a microtruss fabric covered with a reflective aluminum layer is shown in Figure 8.

## Sail Segments

Continuous rolls of 1-m-wide microtruss fabric consisting of 1-10 micron fibers, nanotube fibers, and the aluminum reflective film are assembled into sail segments supported by a net of 100 μm carbon ropes (Figure 9). The sail segment width is limited by the manufacturability and handleability of the microtruss fabric. Carbon fiber spun into 100 μm ropes of continuous length ( no breaks) carry tension loads within the sail gores. Tension in the sail film is necessary to provide structural rigidity for handling, deployment, and flight, as well as to remove wrinkles which create hot spots and non-uniformity in the reflective surface. Each 100 μm rope is capable of sustaining a tension load exceeding 23.6 Nt. A continuous net of 100 μm carbon ropes spaced to approximately 14 per square meter are allocated to support the sail. The ropes have small carbon hooks on the side facing the microtruss fabric to affix the fabric to the ropes. A summary of elements which contribute to the thickness and areal density of each sail segment are given in Table 4.

## Gore Assemblies

This study has baselined a 410 m diameter circular sail with an 11 m diameter opening at the center. It includes six pie-shaped gores which are ≈ 205 m long and are separated at a maximum distance of 7 m midway along the spokes. The separation distance between gores is driven by the desired sail fill fraction of ~ 90%, which is defined as the total actual physical area of the sail gores divided by the area subtended by the sail. The gores consist of approximately 199 ea, 1-m wide continuous rolls of microtruss fabric sail segments atop a net of 100 μm carbon ropes, and connected via hooks in the ropes. However, where folds are required, segment to segment connections are made using fibrous tape (Knowles, 1999). This planar array of tape consists of a ladder-like net of carbon fibers that connect to the 100 μm ropes or the microtruss fabric via a network of many interlocking, curled carbon fibers akin to Velcro®. The tape will be low density, extremely lightweight, and deformable in shear. This design has the advantage that it has built in ripstops, and can be folded without damage since folds are made along the carbon lines or the planar tape. The microtruss fabric connects to the 100 μm carbon net and fibrous tape as shown in Figure 10.

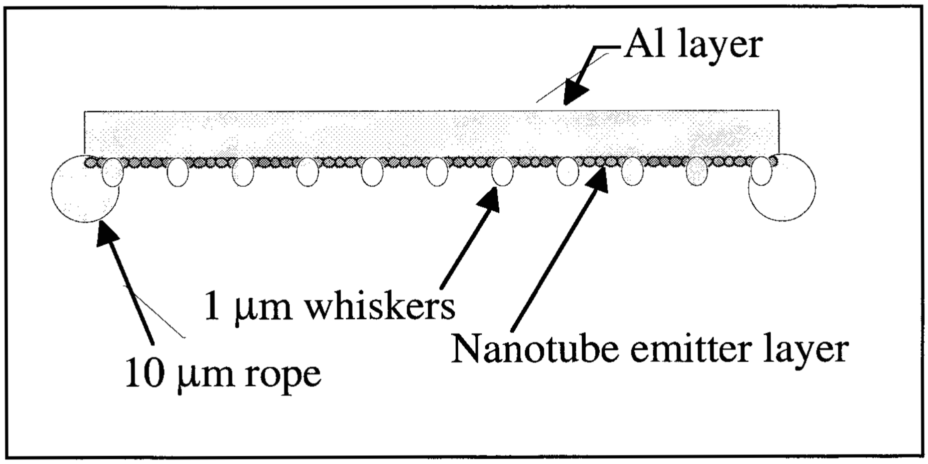


**FIGURE 6.** Schematic diagram of carbon fabric for the ISP sail.

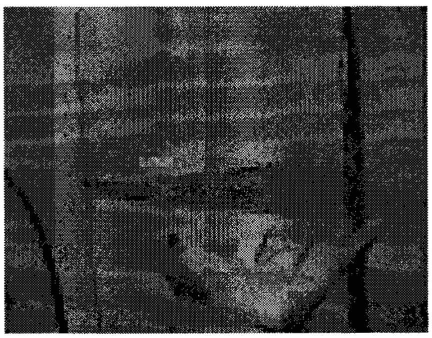

**FIGURE 7.** ESLI microtruss fabric, 1 gm/m$^2$.

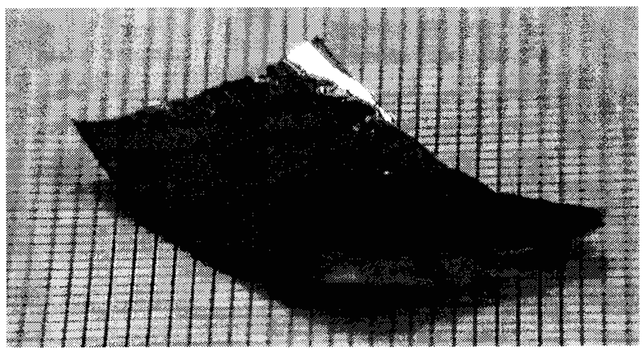

**FIGURE 8.** Microtruss fabric with aluminum layer.

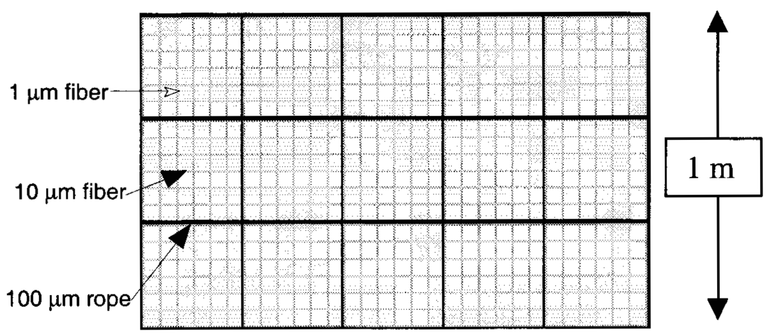


**FIGURE 9**. Top view of a continuous segment of sail material.

**TABLE 4.** Sail Segment Thickness and Areal Density.

| Element | Thickness | Areal Density ($g/m^2$) |
|---|---|---|
| Carbon Nano-Tube Layer | 100 Å | 0.003 |
| Aluminum Layer | 250 Å | .07 |
| Carbon Whisker Net | 1 μm | 0.1 |
| 10 μm carbon rope | 10 μm | 0.1 |
| 100 μm carbon rope | 100 μm | 0.1 |
| Contingency | NA | 0.187 |
| TOTAL | 20 μm | 0.5 |

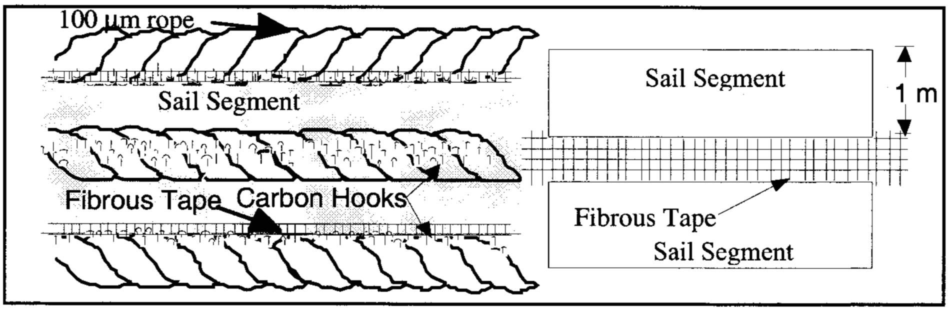


**FIGURE 10.** Gore seaming design. The left side shows how sail segments attach to the100 μm ropes with velcro-like fibers; the right side shows folds between adjoining sail segments are made on the fibrous tape.

For packaging, deployment and control it is desirable to have a sail with the minimum sail diameter. The fill fraction can be increased by reducing the gap between gore edges, introducing rounded gore edges on the outer periphery (rounded gore edges will subtend more area than flat gore edges) and by adding mass to the perimeter of the gores to introduce radial tension into gores with rounded edges. The disadvantage of this design is the need for additional mass for these weights. A design study to optimize the trade between the amount of perimeter mass vs. fill fraction was not performed. For purposes of this study a fill fraction of 90% was assumed.

To reduce the gap between gores the radial tension must be increased (to "flatten" the edge from a rounder, Znamya-like gore) with masses located at the tip of each gore, or by increasing the spin rate. An optimization between the tip mass and spin rate was not performed, however a maximum spin rate under 1 round per minute (RPM) was assumed, for control reasons. This then drives the amount of tip mass required to flatten the edges of the gore. Each gore has 2 tip masses, located at each outer tip, for a total of 12 tip masses for the sail.

To obtain the maximum reflection capabilities the radial and tangential stresses in the sail should be equal and constant along the radius of the sail. Tip masses coupled with perimeter weights distributed along the outer perimeter of the sail gores are required to assure a minimum film stress of 6925 Pa (1 PSI). Perimeter weights, called "rim masses", are located along the perimeter of the curved outer edges of the gores. Since the tensioning characteristics of the microtruss fabric are unknown, we assume here that they are identical to an equivalent 0.33 μm Kapton® film which meets the film areal density requirement. It is assumed, based on the structure of the carbon microtruss fabric, that the actual stress required in this fabric will be less compared to Kapton® because the carbon fabric has stiffness intrinsically built into the fabric. The gores are connected to the sail cylinder using three ea, 1000 μm carbon tethers which run between the gores and the sail cylinder at the other end. Because there are sections of fabric that require additional strength (e.g.to provide reinforcement near the 11-m hole and yoke plates), 6 kg of additional mass has been allocated to the sail for additional material support such as ropes and plates. Diagrams of a section of a gore segment at the periphery and near the center are shown in Figure 11 and Figure 12 respectively.

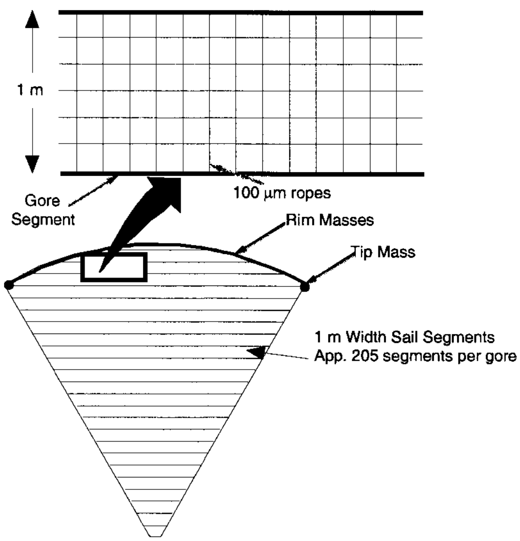


FIGURE 11. Blow-up of a sail segment.

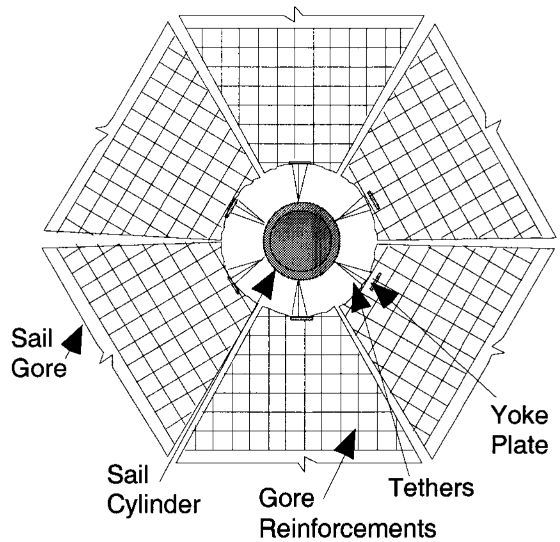


FIGURE 12. Blow-up of center section of the sail.

## Sail Deployment

Prior to deployment, the sail is wrapped around the sail cylinder. The sail cylinder includes the following elements: central structure (1.5 m diameter X 1.5 m long, reinforced Al honeycomb); miscellaneous sail cylinder structures such as gore locks, rollers and tethers; undeployed sail with yoke plates, restraining plates, bolts and pyro devices; bellyband and marmon clamp to contain the sail prior to deployment.

To minimize the mass required to be accelerated by the sail, most of the sail deployment hardware is packaged in the Deployment Module which is ejected after deployment is complete. The Deployment Module includes the following elements: reaction control system (RCS) thrusters; three deployable booms (to provide the RCS thrusters a moment arm); pyrotechnic devices (for releasing gore restraining straps, cutting deployment tethers, and separating the deployment module from the sail canister); pulleys and motors (to deploy the gores); batteries (for electrical power to deploy the sail); and on-board computer (to control the sail deployment).

In their launch configuration, the gores are connected to each other at each tip, along their edges at various locations, and to the sail cylinder with 1000 μm tethers. The gores are Z-folded into pleats 1 m in width, which are then sandwiched between the yoke plates and restraining plates (Figure 13). The Z-folded gores are then folded in half (Figure 14) and wrapped around the sail cylinder. Each gore is then held to the cylinder with straps crossing every 10 meters or so, and the entire sail assembly is held down using a bellyband (Figure 15).

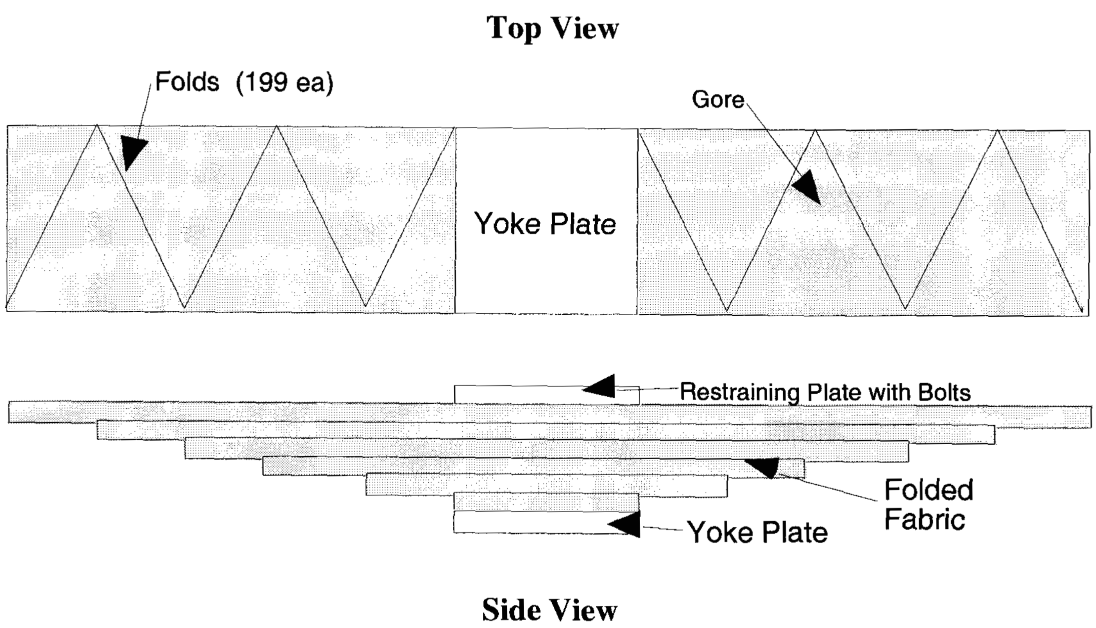


**FIGURE 13.** Diagram of folded gores.

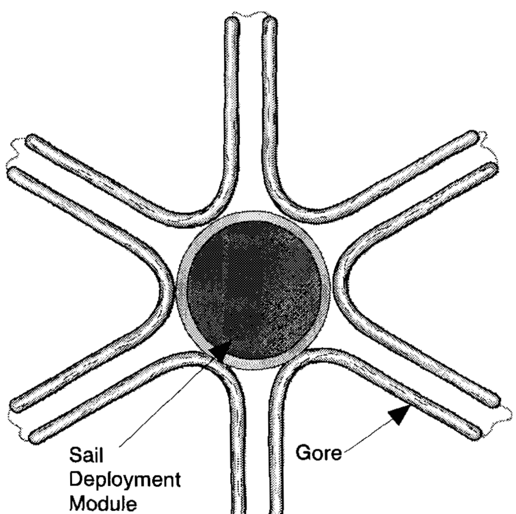


**FIGURE 14.** Each gore is folded in half before being wrapped around the sail cylinder.

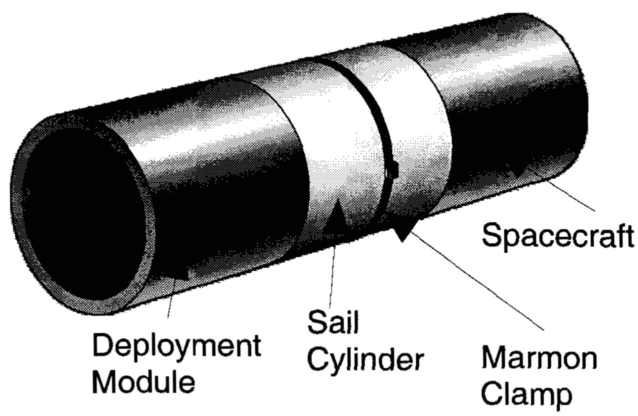


**FIGURE 15.** Sail cylinder, deployment module, and spacecraft

The sail deployment sequence is shown in Figure 4. A discussion of this sequence is discussed below.

- The deployment module spins up the sail cylinder to an appropriate speed.
- The marmon clamp is cut and the bellyband securing the sail film is jettisoned.
- Pyros in the deployment structure are fired and motors begin retracting the gore restraining straps. The straps run over the sail film and wind up on rollers inside the deployment structure. Each gore unfurls in a "V" shape, restrained at the centers by tethers connected to yoke plates at the center of each gore. Sandwiching plates on the other side of the gore fabric form a "gore sandwich" with the fabric between the yoke plates and sandwiching plates. The tips of the gores are connected to adjoining gores with short tethers.
- Tether locks in the sail cylinder are opened along with actuation of motors in the deployment structure that release the straps securing the gores to the sail cylinder.
- Each gore is played out such that the 6 gores form a circle 1 m wide and 410 m in diameter. In this way the gores are deployed out of the sail cylinder in a controlled manner with less risk of gores shredding or entangling adjoining gores. The deployment module adjusts the spin rate to approximately 0.45 RPM.
- Pyros on the restraining plates fire, cutting bolts that release the restraining plates. Motors in the deployment module reverse to pull on the tethers between the yoke plates and the sail cylinder, pulling the gores inward.
- After unfolding the gores, tether locks in the sail cylinder lock, and pyros in the deployment structure fire, cutting the tethers between the deployment structure and sail cylinder. At the conclusion of this sequence, the spin rate is 0.9 RPM.
- Pyros fire which separate the deployment module from the sail cylinder. The sail is fully deployed.

## Mass Summary

The mass of the sail (including all sail hardware carried by the sailcraft after the sail is deployed except for control) is ~ 122.6 kg for a total areal density of 1 $g/m^2$. A mass breakdown of the sail components is given in Table 5. Control hardware is included in the spacecraft mass allocation.

**TABLE 5.** Sail System Mass Summary.

| System | Element | Mass (kg) |
|---|---|---|
| Sail | Sail fabric mass | 61.4 |
| | Cylinder, brackets, braces, rollers | 15 |
| | Seaming tapes, gore reinforcements | 12 |
| | Rim and tip masses | 13 |
| | Yoke plates, tether locks | 9 |
| | Gore deployment tethers | 0.2 |
| | Miscellaneous structures | 12 |
| | TOTAL | 122.6 |
| Deployment Structure | LV structure | 30 |
| | 10-m booms, 3 ea | 30 |
| | Discarded sail structure | 109 |
| | Launch release mechanisms | 15 |
| | RCS to spin up sail | 36 |
| | Deployment Structure SubTotal | 220 |
| | Contingency (30%) | 66 |
| | Deployment Structure Total | 286 |
| **Sail System Total** | | **408.6** |

## Sail Control

The spacecraft module and sun shade are centered in the 11-m-diameter central aperture of the sail. Attitude control and thrust vector pointing of the sail is provided by moving the spacecraft mass relative to the system center-of-pressure. This is accomplished by moving the spacecraft on a 2.7 m rail to precess the sailcrafts's spin rate by 10 degrees per day. The spacecraft can move up and down the rail, and the rail, on bearings that decouple the sail cylinder spin and spacecraft spin rates, can rotate to any position required for full sailcraft control.

## ACKNOWLEDGEMENTS

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