# SOLAR SAIL HARDWARE DEVELOPMENTS

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**ABSTRACT:** 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 that were never considered possible. This Technology is now included in development programs and technology roadmaps of different Space Agencies like ESA, DLR and NASA.

This paper will focus on a comparison of the technology development of five projects: ESA / DLR, COSMOS 1, ENCOUNTER, NASA JPL and Solar Blade. It will give an overview on the hardware developments for these Gossamer-like structures.

## 1 - INTRODUCTION

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 the momentum transfer of solar photons reflected off of the sail. 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; to deploy these light-weight structures into space; and to understand the dynamics and have the ability to control the sailcraft. The solutions to these challenges must be demonstrated in space before solar sail propulsion is considered viable for any mission. 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 Mylar or Kapton films coated with about 500 angstroms of aluminium with trusses and booms for the support structure. The thinnest commercially-available Kapton films are 7.6 mm in thickness and have an area density (defined as the total material mass divided by the material area) of 11 g/m$^2$.

Practical experience with solar sails is very limited. In 1993 Russia deployed a 20-m dia spinning disk solar reflector based on its Columbus 500 solar sail design. It had an estimated area density of 22 g/m$^2$ and provided sunlight to arctic regions in Russia from a Progress resupply vehicle. The sail, called Znamya 2, consisted of eight pie-shaped panels fabricated from 5 mm-thick aluminised PETF film (a Russian version of Mylar) with no supporting structure. In the US the feasibility of solar sail propulsion has been greatly enhanced by the successful deployment of an inflatable antenna from the space shuttle.

Five solar sail hardware projects are Currently under development:

1. The DLR / ESA In-orbit deployment experiment
2. COSMOS 1 - an in-orbit deployment initiative of "The Planetary Society"
3. ENCOUNTER - a commercial Starship that is to travel beyond our solar system
4. NASA JPL / NOAA Activities
5. Solar Blade - a Carnegie-Mellon University study funded by the US Air Force

This paper focuses on a comparison of the technological development of the five above-mentioned projects. All information is taken directly out of papers available to the public or Internet pages. The indicated Internet references provided considerably more detailed information on the individual projects. One particularly good Internet address is that of Benjamin Diedrich [17]. His report is a summary of a detailed report on hardware developments in the field of Gossamer structures. It focuses on actual developmental work on Solar Sail projects and was inspired by study by Garner et Al [7]. The above-mentioned report also contains a compilation on other ultra-light, deployable structures such as antennae and solar shields. In addition, the development of boom and sail developmental work is described in more detail.

## 2 - SOLAR SAIL CHALLENGE

The hardware of a Solar Sail is faced with tremendous challenges. High residual velocities can only be reached with this propulsion concept if the specific ratio of spacecraft weight and sail size (sail area density) is very small. In most proposed Solar Sail concepts [4], this results in the need for very large sail surfaces, which can easily reach the size of 100,000 $m^2$, see Figure 1. The result is the requirement that the sail must be automatically deployable in orbit.

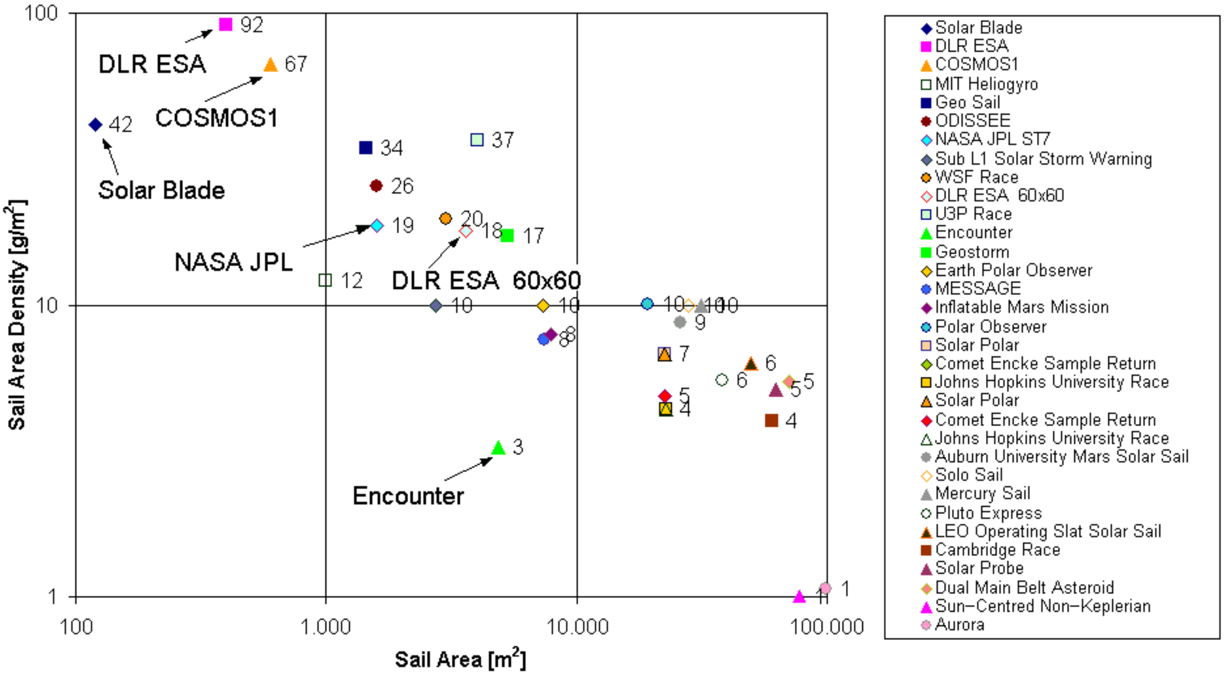


Figure 1: Performance portfolio of proposed Solar Sail missions

A look at the required sail area density of 1 – 10 $g/m^2$ shows that this challenge is hard to meet with the sail material and stiffening structures that are commercially available today. Figure 2 shows the boom area density that can be attained by means of a diagonally-stiffened DLR / ESA Solar Sail concept. In an initial deployment experiment with a boom weight of approx. 14 $g/m^2$, specific densities of approx. 2.5 $g/m^2$ can be reached depending on the sail size and new boom concept. Even for larger sails, further decrease in the boom area density is only possible with other concepts. The weight of the sail has to be added to the boom weight. A 7.5 µm thick Kapton film has a sail area density of approx. 15 $g/m^2$. The most recent Mylar films with a thickness of approx. 1 µm still weigh 2 $g/m^2$. This adds up to a weight of 4.5 $g/ m^2$ for both sail and booms. The weight of the control mechanism and the scientific spacecraft have to be added onto this as well (under the assumption that a necessary deployment module can be separated from the actual sail force after sail deployment). These specifications show how ambitious the goal is to achieve a sail area density of 1 $g/m^2$.

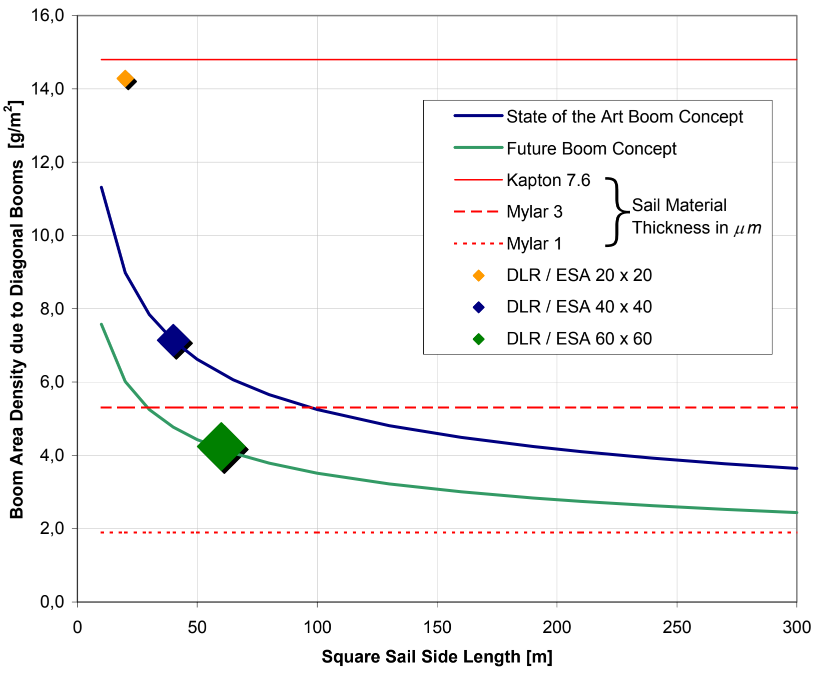


Figure 2: Boom area density due to a rigidizing structure for square sails with diagonal booms, comparison to sail area density of Kapton and Mylar and DLR / ESA in orbit deployment experiments

## 3 - SOLAR SAIL PROJECTS

In this chapter you will find a description of five different Solar Sail projects and in chapter 3.6 a comparison of their main facts.

### 3.1 DLR / ESA

All information and figures in this chapter are based on the following references: [12], [10], [11], [14] [19].

For the joint technology development of DLR and ESA, a square sail design with diagonal booms to support four triangular sail segments was chosen as the baseline configuration. The sail structure is composed of three major elements: the booms, the sail film segments, and a central deployment module. The four supporting CFRP (Carbon Fibre Reinforced Plastics) booms are unrolled from the central deployment module and the four folded, triangular sail film segments are released from sail containers. The concept is based on the ODISSEE proposal (Orbital Demonstration of an Innovative, Solar Sail driven Expandable structure Experiment) [11]. Once in orbit, the micro-spacecraft and sail module are separated from each other via a 10m collapsible mast which is housed inside the micro spacecraft in its stowed configuration. This structure is referred to here as the central mast, or sailcraft control mast, connecting the spacecraft and the sail structure. The central mast is attached to the sail deployment module via a 2-degree-of-freedom actuator gimbal which allows the rotatation of the control mast and attached micro spacecraft with respect to the sail. This way the center-of- mass (CM) can be offset from the centre-of-pressure (CP), and using light pressure as an external force, a torque can be generated to control the sail attitude. Once the central mast is latched in its final length and system check-outs have been performed, boom deployment is initiated.

The main design driver was a launch option as a “Piggy- Back“ payload on ARIANE-5. This launch vehicle provides the ASAP-5 ring structure which can accommodate up to 8 micro-spacecraft. The volume for each ASAP-5 payload is restricted to 600mm x 600mm x 800mm. In order to provide room for the attachment of a micro-spacecraft to the sail structure, the height of the central part of the deployment module hadto be restricted as well.

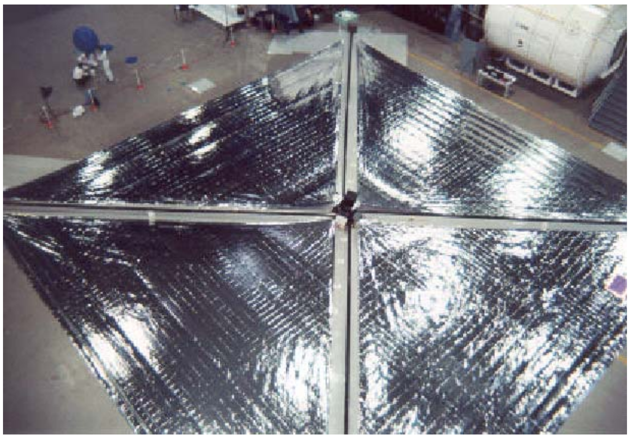


Figure 3: Solar Sail 20m x 20m on ground deployment test, four Sail Segments Fully Deployed

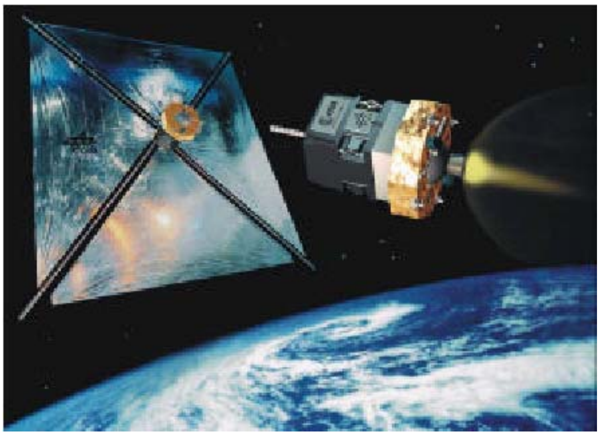


Figure 4: Stowed (right) and deployed (left) configuration of the sailcraft including orbital platform (Artists Impression: BSC, Moscow)

The joint effort between DLR, ESA and the industry has been extremely successful in defining and prototyping an advanced technology concept, in test proofing its feasibility and defining roadmaps for its further development and application. It was shown that deployable ultra-light weight booms and extremely thin sail film materials can be handled and used to manufacture large solar sail structures. In a ground demonstration the functionality of the deployment concept and associated mechanisms was demonstrated in simulated zero-g and ambient environmental conditions. Based on the successful completion of the pre-development project phase, a low-cost flight-validation of solar sail technology in Earth orbit in 2004 is the recommended and proposed next step. The solar sail payload will remain attached to the upper stage of the launch vehicle and will perform an in-orbit deployment test.

Precursor studies at Kayser-Threde GmbH in the last two years have led to the choice of the Russian launcher VOLNA, a modified SS-18 rocket, which will be launched from a submarine The launch service includes an Orbital Platform which boosts the payload in the correct circular orbit. The payload will have a mass of about 65kg and will be composed of the Sail Deployment Unit

In addition to the proposed space deployment test of a 20m x 20m solar sail structure, the next major steps in solar sail development have been identified. In parallel to the deployment test outlined above, a flight in near-Earth space of a fully manoeuvrable sailcraft is envisioned within „Project 2“ for a potential launch in 2006 or 2007. Here a sailcraft of approximately 50m x 50m or even larger (up to 70m x 70m) would test manoeuvres in Earth orbit in order to demonstrate solar sail controllability and possibly also the technology to accommodate a science payload on a sailcraft. Based on the experience of Project 2, a fully operational solar sail deep space science mission could be launched within “Project 3”.

### 3.2 COSMOS1

The Solar Sail Project of The Planetary Society (By Louis Friedman) with their sponsor, Cosmos Studios. All information from the web side: [18].

The Planetary Society is developing and conducting a privately funded solar sail project with the Cosmos Studios. The spacecraft is being built in Russia by the Babakin Space Center under a contract to the Society. It will also be launched and operated from Russia.

The purpose of the mission is to conduct the first solar sail flight. Solar sailing is recognized as a future planetary flight technology on the pathway to interstellar flight (using laser instead of solar photons). The image products and story of the mission will be publicly available through the marketing of Cosmos Studios and The Planetary Society.

The project was initiated September 15, 2000. A sub-orbital test flight of the inflatable tube sail deployment system was conducted on July 20, 2001. The spacecraft was launched from a submerged Russian submarine in the Barents Sea on a Volna, a converted submarine-launched ICBM now being marketed for commercial use. Unfortunately the spacecraft failed to separate from the third stage of the rocket, and as a result the sails and the re-entry capsule failed to deploy. The capsule continued on its ballistic flight to the Kamchatka peninsula, but has not been recovered so far.

An orbital test flight was scheduled for the winter of 2001-2002, and a second orbital spacecraft is being built for a possible second flight after that. The project has a delay. The approximately 40 kg spacecraft will be injected into a 800 x 1000 km orbit with a motor previously used for de-orbiting of payloads from Earth orbit. The principal data products from the mission will be imaging, although there will be on-board accelerometers to measure the non-gravitational force on the spacecraft. Two imaging systems will be used, one Russian developed, the other being developed in the US. Tracking and telemetry will be Russian responsibilities although US backups are being considered. An S-band and UHF-band telemetry system will be employed.

The basic deployment and structural technology relies on an inflatable tube system to which the sail material will be attached. The 600 square meter sail will be configured in eight roughly triangular blades. The nominal sail material is 5 micron aluminised, reinforced mylar.

Mission success is defined as flying long enough to measurably increase the orbital energy (or period) from sunlight pressure in controlled flight. This could be achieved within a few days of launch; although they hope to fly continuously raising the orbit energy for weeks or even months in orbit.

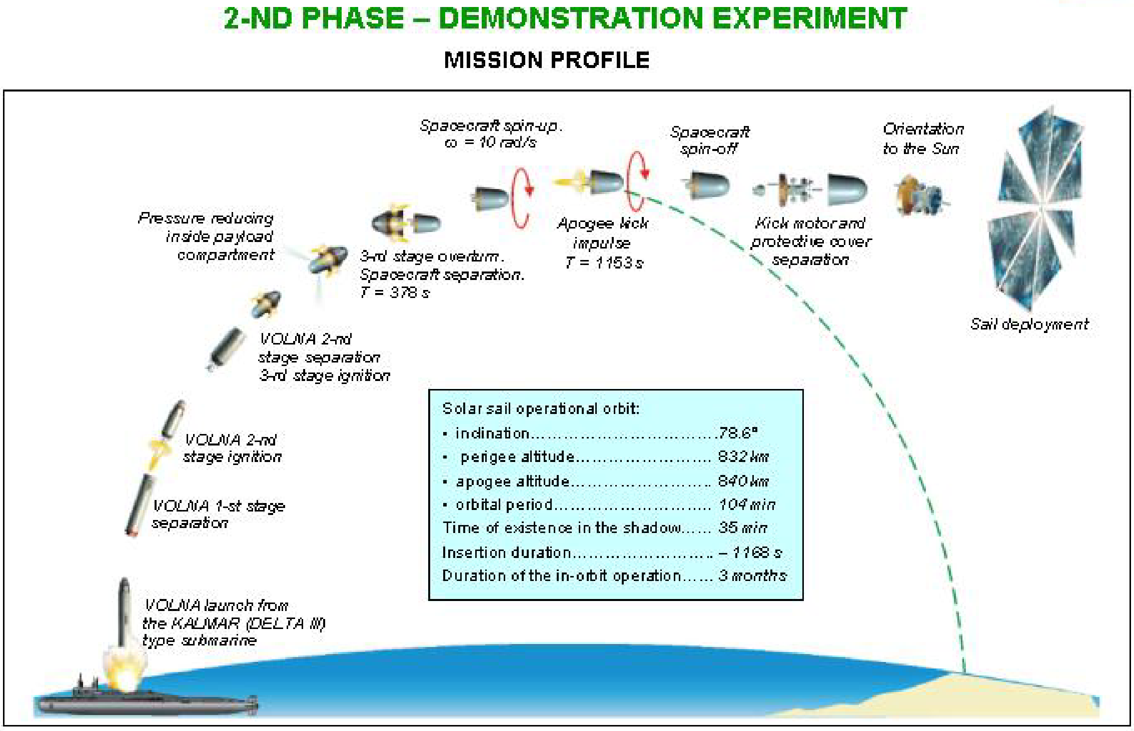


Figure 5: COSMOS12nd Phase  Mission Profile

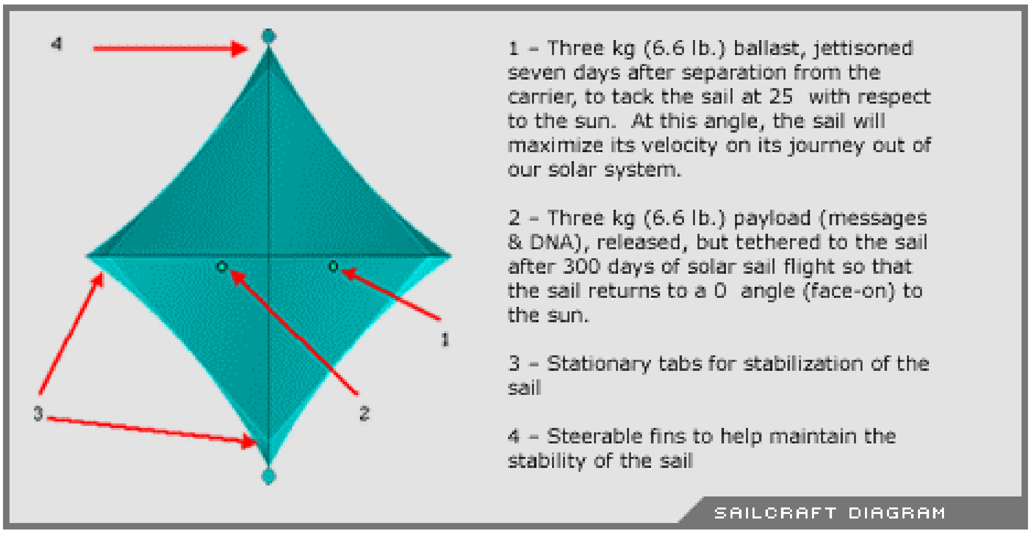
### 3.3 Encounter

All information from the web sides: [16], [22], [24].

**Team Encounter** is a group of dedicated and experienced scientists, engineers, entrepreneurs and space visionaries who are building and will launch a solar sail-powered spacecraft that will transport a three-kilogram payload out of the solar system. The payload will include messages, drawings, photographs, and DNA signatures submitted by up to 4.5 million participants.

The spacecraft consists of a rocket-powered "carrier" (Carrier - design, construction and integration provided by AeroAstro, Inc.) that will boost the spacecraft out of Earth orbit, and a "sailcraft" (Sailcraft design and construction provided by L'Garde, Inc.) that will use a giant solar sail to carry the payload out of our solar system. The Encounter spacecraft (the combined carrier and sailcraft) will be one of up to eight micro-satellites launched onboard a single Ariane 5 rocket. These micro-satellites will be placed in the "Ariane Structure for Auxiliary Payloads (ASAP)" ring, which is placed atop the Ariane 5 rocket.

Constructed of material one seventy-sixth the thickness of a human hair, the Team Encounter solar sail will be approximately 76 m by 76 m (249 ft. by 249 ft.) with a mass, including payload, of only 19 kg (about 42 pounds). This ratio of a large size sail to low mass will give the spacecraft high performance acceleration for this technology. The sail design represents a major advance in space propulsion, enabling missions to the outer solar system that are virtually impossible with existing rocket technology.



1 - Three kg (6.6 lb.) ballast, jettisoned seven days after separation from the carrier, to tack the sail at 25 with respect to the sun. At this angle, the sail will maximize its velocity on its journey out of our solar system.

2 - Three kg (6.6 lb.) payload (messages & DNA), released, but tethered to the sail after 300 days of solar sail flight so that the sail returns to a 0 angle (face-on) to the sun.

3 - Stationary tabs for stabilization of the sail

4 - Steerable fins to help maintain the stability of the sail

Figure 6: Encounter sailcraft diagram

Shortly after leaving Earth orbit, the spacecraft will unfurl its sail from a heated container (60 cm x 60 cm x 15 cm) by porting gas from the carrier's Attitude Control System into inflatable booms that form the sail's masts. Once deployed, the booms will stiffen in the cold environment of space, and provide a rigid structure to support the sail and effectively capture solar light pressure. A sunshield will cover the booms to insulate them from solar heating.

- The aluminised Mylar sail, with an effective surface area of 4,900 square meters (52,900 square feet), and its payload of messages and biological signatures of Team Encounter participants will have a combined weight of only 19 kilograms (42 pounds).

- The carrier will properly orient the sailcraft relative to the sun, after which tabs on the edge of the solar sail will be used to fine tune the sailcraft's motion. A star camera and sensor onboard will monitor the solar sail's orientation and adjust the fins as needed. Solar panels near the center of the sail will provide electricity to power the sensor and move the tabs.

As part of this pioneering endeavor, Team Encounter successfully tested a segment of solar sail material identical to that which will actually fly in space. The test was performed January 15, 2002 in Tustin, California by engineers at L'Garde, Inc., which is constructing the solar sail for Team Encounter. The purpose of the test was to determine if the ultra thin, lightweight solar sail can be deployed, or "unfolded" without ripping. The triangular-shaped sail segment used in the test measured approximately 7 meters by 7 meters by 10 meters (23 feet by 23 feet by 33 feet). The sail segment used in the test was made of metallized mylar. One side of the mylar is covered with a thin layer of aluminium. The other side, which will face away from the sun, is covered with a thin layer of chromium.

Team Encounter conducted a successful development test of a sample boom segment February 14 and 15, 2002 in Tustin, California. The boom segment was approximately 7.6 m (25 ft.) long.

## 3.4 NASA JPL / NOA activities

Information from [6].

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. There are important applications for solar sails beyond the science missions that NASA has planned. The National Oceanic and Atmospheric Administration (NOAA) needs this technology to create a new class of space and earth weather monitoring stations that can provide greater coverage of the earth and provide more advanced warning of the solar storms that sometimes plague communications and electrical power grids. There are also a number of military missions in earth orbit that can be enabled by low cost sailcraft [21].

From virtually no technology or flight mission studies activities three years ago solar sails are now included in NOAA, NASA, DOD technology development programs and technology roadmaps [13]. NASA programs include activities at Goddard Space Flight Center, Jet Propulsion Laboratory, Langley Research Center, and Marshall Space Flight Center; NOAA was funded in FY 2000 to study a joint NASA/DOD/NOAA solar sail mission; and there are sail demonstration missions under study at NASA, NOAA/DOD. Technology developments include thin film and boom developments, carbon fabric development, beamed propulsion feasibility experiments, and subscale model sail deployment tests. NOAA has signed a purchase agreement (March 2002) with Team Encounter. The one year contract entitles NOAA to certain test data of the Encounter Solar Sail [3].

The In-Space Propulsion (ISP) technology program at NASA has been working in partnership with the New Millennium Program (NMP) to potentially provide the Solar Sail Subsystem to a flight validation mission, if selected for the Space Technology 7 (ST7) mission. If approved, the tentative launch date for this mission is planned for December, 2005. For ST7 Solar Sail was again (ST5) not selected [1].

JPL’s Solar Sails together with ILC Dover [20]: Solar sails are a form of satellite propulsion technology that utilizes inflatable rigidizable booms and membrane structures to deploy and support large flat thin film surfaces that are accelerated by impact with the solar wind. ILC Dover has been participating in solar sail design and manufacturing efforts since the 1970s. ILC has recently been involved in several solar sail programs for system concept development, ultra-lightweight rigidizable boom design and manufacture, solar sail material development and testing, and prototype fabrication.

Large sail quadrant Program Details: ILC designed sail quadrant with ripstops ($0.5m^2$). JPL planed to providing sail to DLR for integration in DLR / ESA Solar Sail. 3 micron thick polyester film produced by Astral, Film coated with aluminium on one side chromium on the other. Finished assembly: 13m x 13m x 18m, $6g/m^2$. Novel assembly techniques developed to counter edge curl.

Figure 7: ILC Dover sail test, 3 micron

NASA's Marshall Space Flight Center announced that they are now developing solar sail technology for an upcoming mission likely to launch in 2010. Designed to be over 400 meters across, the sun-powered sail will push the spacecraft to a hurtling 93 kilometres/second, and send it to the outer reaches of the solar system over the course of its 15-year mission [15].

### 3.5 Solar Blade

Carnegie-Mellon University (CMU) is conducting a study under funding from the US Air Force to develop and fly a Solar Blade Nano-Satellite [5]. All information from the web side: [2], [23].

Carnegie Mellon University will employ nanosat technology to dramatically reduce spacecraft payload mass (5 kg), which shrinks the size of the sail and overall spacecraft mass. This reduction of size and weight makes a heliogyro type sail design eminently more practical and flyable than previous solar sail spacecraft.

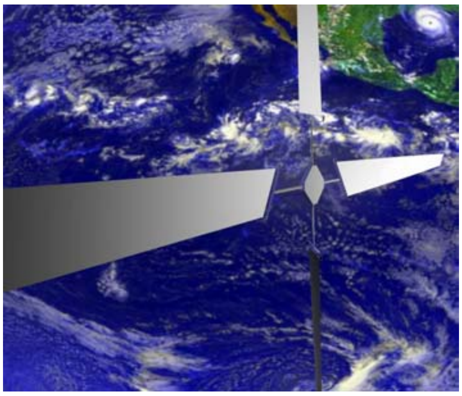


Figure 8: Solar Blade Solar Sail

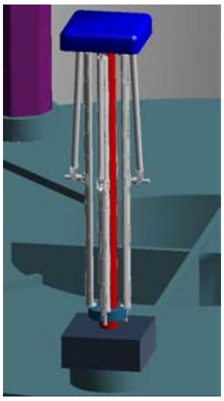


Figure 9: Solar balde deployment mechanism

The Solar Blade Heliogyro Nanosatellite has the appearance of a Dutch windmill and employs sail control akin to a helicopter. Four solar reflecting blades, each 30 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 5 kilograms, and, when stowed, is a package approximately the size of a golf bag. Total launch mass, including stowage carriage, is 35 kilograms. Among the secondary launches to higher orbits, an Ariane microsat slot is favorable for a number of reasons: first, flight slots are available for the 2001-2002 time frame; second, the space on an Ariane is more than adequate; and third, cost and integration issues are kept to a minimum,

The stowage vehicle that attaches to the solar sail during stowage is equipped with a cold gas thruster system, batteries, a communication system, and a camera for viewing the deployed solar sail. The sail blades stow as rolls and attach to a central core structure through thin-walled aluminium struts. The struts and blade rolls fold up and register on holes on a sliding ring. Moments after separation from the launch vehicle, the ring slides, releasing the blade roll supports. hen, the sail and stowage vehicle spin up to 60 rpm. A release device keeps the stowage vehicle and the core together until then, after which they separate and the blades slowly unroll.

### 3.6 Comparison of Solar Sail Concepts

Non off the mentioned Solar Sail concepts have launched jet. The proposed launch date of the Solar Blade Concept was 2001 and the proposed launch date of COSMOS1 was winter 2001/ 2002. The DLR/ESA, COSMOS1, Solar Blade and NASA JPL ST7 Solar Sails are in orbit deployment experiments to show the technological feasibility. Only the Encounter Solar Sail will act as a real Solar Sail to fly away from earth.

| **Data** | **DLR / ESA** | **DLR / ESA 60x60** | **COSMOS1** | **Encounter** | **Solar Blade** | **NASA JPL ST7** |
|---|---|---|---|---|---|---|
| Solar Sail Concept | Quad | Quad | Disk | Quad | Blade | Quad |
| Sail dimension [m] | 20 | 60 | 30 | 76 | 30 x 1 | 40 |
| Sail size [$m^2$] | 400 | 3.600 | 600 | 4.900 | 120 | 1.600 |
| Boom length [m] | 14,1 | 42,4 | 240,0 | 53,7 |  | 28,3 |
| Required boom stiffness S=2 [$Nm^2$] | 1.621 | 14.590 |  |  |  | 6.485 |
| Stiffness / Mass | 286,6 | 716,4 |  |  |  | 573,2 |
| Specific boom mass [g/m] | 100,0 | 120,0 |  |  |  | 100,0 |
| **Total boom mass [kg]** | **5,7** | **20,4** |  |  |  | **11,3** |
| Sail material | Kapton | Mylar | Mylar | Mylar | Kapton | Mylar |
| Film thickness [µm] | 7,50 | 3,00 | 5,00 | 1,00 | 8,00 | 1,00 |
| Specific film mass [$g/m^2$] | 10,80 | 4,20 | 7,00 | 1,40 | 11,52 | 1,40 |
| Film mass [kg] | 4,32 | 15,12 | 4,20 | 6,86 | 1,38 | 2,24 |
| Coating Al + Cr) [kg] | 0,15 | 1,36 | 0,23 | 1,85 | 0,05 | 0,60 |
| Bonding (10%) +etc.** [kg] | 1,43 | 2,51 | 0,42 | 0,69 | 0,14 | 0,22 |
| **Total sail mass [kg]** | **5,9** | **19,0** | **4,8** | **9,4** | **1,6** | **3,1** |
| Specific Sail mass [g/m2] | 14,8 | 5,3 | 8,1 | 1,9 | 13,1 | 1,9 |
| **Deployment module mass [kg]** | **25,0** | **25,0** |  |  |  | **15,6** |
| **Sail & Structural Mass [kg]** | **36,6** | **64,4** | **40,0** | **16,0** | **5,0** | **30,0** |
| **Sail structure area density [$g/m^2$]** | **91,4** | **17,9** | **66,7** | **3,3** | **41,7** | **18,8** |
| **Payload / Adapter mass [kg]** | **35,0** | **27,8** | **0,0** | **3,0** | **30,0** | **110,0** |
| **Launch mass [kg]** | **71,6** | **92,2** | **40,0** | **19,0** | **35,0** | **140,0** |
| Acceleration [$mm/s^2$] | 0,05 | 0,35 | 0,14 | 2,32 | 0,03 | 0,10 |
| Launcher | *Volna* SS-N-18 submarine |  | *Volna* SS-N-18 submarine | Ariane 5 ASAP | Delta II | Ariane 5 ASAP |
| Launch Date | 2004 | 2006 | 2002 | early 2004 | 2002 | Dez. 2005 |
| Funding | DLR / ESA | - | Planetary Ssocie<br>Cosmos Studios<br>A & E Network | Club Members<br>NOAA | USAF<br>CMU | NASA NMP<br>JPL |
| Volume | 4.8 MEURO | 10 MEURO |  | 20 M$ |  |  |

Table 1: Comparison of Solar Sail Concepts

## 4 - ACKNOWLEDGEMENTS

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