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A Summary of Solar Sail Technology Developments and Proposed Demonstration Missions

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ABSTRACT

NASA's drive to reduce mission costs and accept the risk of incorporating innovative, high payoff technologies into it's missions while simultaneously undertaking ever more difficult missions has sparked a greatly renewed interest in solar sails. From virtually no technology or flight mission studies activity three years ago solar sails are now included in NOAA, NASA, DOD, DLR, ESA and ESTEC technology development programs and technology roadmaps. NASA programs include activities at Langley Research Center, Jet Propulsion Laboratory, Marshall Space Flight Center, Goddard Space Flight Center, and the NASA Institute for Advanced Concepts; NOAA has received funding for a proposed solar sail mission; DLR is designing and fabricating a 20-m laboratory model sail, there are four demonstration missions under study at industry, NASA, DOD and Europe, two new text books on solar sailing were recently published and one new test book is planned. This paper summarizes these on-going developments in solar sails.

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 momentum transfer of solar photons reflected off the sail (photons have no rest mass, but they do have momentum). The concept of solar sailing is not new. Tsiolkovsky[1] proposed in 1924 that large spacecraft could be propelled through space using photon pressure, and in the same year Fridrikh Tsander[1] 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 sail mass divided by the sail area) of 11 g/ m^2. A Propulsion Trade Study[2] 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 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 1g/ m^2 for fast trip times to 200 AU[3].

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 ($400m^2$) sail, and fabricated a 30-m ($900m^2$) sail with an areal density of approximately 65 g/m^2 that was stowed in a deployment structure. 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 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[4]; 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[5,6]. 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[7]. 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, 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, dynamics and 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[8], and reduction in spacecraft mass and sail size. For example, studies indicate that a main belt asteroid rendezvous and sample return mission[9] 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[10] 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. This paper summarizes the present solar sail state-of-art, technology developments, mission architecture studies, and flight validation demonstration missions.

1. Programs and Program Plans

1A. National Oceanic and Atmospheric Administration (NOAA)

The FY00 President's Budget Request includes \$4.3M for NOAA to begin funding their portion of the Geostorm mission (discussed in a latter part of this paper). NOAA plans for a continuing series of Geostorm missions, and has requested funds for them as well.

1B. Interstellar and Solar Sail Technology Program at JPL

In March 1999 JPL established the Interstellar and Solar Sail Technology program under the Technology and Applications Program office with funding from NASA's Code SM Advanced Concepts Program office. The program is being managed at JPL by Sarah Gavit. The focus of this activity is to establish an interstellar program for NASA with the goal of launching missions to the local interstellar medium (approximately a few hundred AU) within ten years and to the nearest stars within 40 years. For FY 1999 approximately \$250 K has been allocated for solar sail mission architecture studies, technology roadmapping and planning, and technology development. A strawman solar sail design for a mission to 200 AU in under 15 years was developed under the mission architecture studies. Under technology development funding microwave and laser-levitated carbon fabric and photoablative propulsion experiments are planned to test proof-of-principle high temperature, low mass sail materials. In addition a carbon fabric reflector weighing 0.5 g/m^2 with a reflectivity of ~0.66 is planned. Also planned are modeling of thin film quantum interactions and the design of a rotating solar sail that minimizes the deployment hardware mass that must be carried with the sail after deployment.

1C. Interstellar Propulsion Research Project at MSFC

NASA's Office of Aero-Space Technology recently established within it's Advanced Space Transportation Program an Interstellar Propulsion Research Project at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The project is managing basic research in propulsion technologies that might one day enable travel to another star. Technologies such as matter/antimatter annihilation, fusion, and laser-driven sails are being studied with some fundamental experiments planned over the next few years in each propulsion area. One of the most promising is the use of sails, propelled by laser or microwave photons, to achieve the high velocities essential for making a robotic interstellar voyage within the lifetimes of it's earth-based researchers. Such a sail might be close to 1000 kilometers in diameter and have an areal density of less the 0.1 g/m^2.

Technology precursors to these ambitious beamed energy sail missions to the stars are already being planned. The Interstellar Propulsion Research project, managed by Les Johnson, is working with the JPL's Interstellar Office to support the development of the solar sail for the Interstellar Probe mission. This sail, while only a small fraction of the size required for a true interstellar mission, is nonetheless on the roadmap to the larger sails required and is an excellent first step toward their eventual development.

Fig. 1. A multistage sail, approximately 1000 kilometers in diameter, might be one day propelled by a laser to anther stellar system.

1D. Mission Studies and Advanced Technologies Program at JPL

Code SM's Advanced Technologies and Mission Studies Division has over the last three years supported solar sail studies performed in JPL's Mission Studies and Advanced Technologies program (managed by Robert Gershman). Activities have included technology roadmapping, mission studies, technology development and flight validation studies. In FY 1999 JPL is spending approximately $165 K to advance the state-of-art in solar sail materials and solar sail design, develop low-thrust geocentric trajectory analysis tools, perform controls studies, and conduct an on-going study between DLR and NASA for a low-cost, near-term solar sail demonstration mission study to validate the fundamental principles of solar sailing. In addition JPL will provide the film for 1 quadrant of a 4-quadrant solar sail for DLR's 20-m laboratory model solar sail (described in more detail in a later section of this paper). JPL plans to issue contracts soon to have several types of thin films between 0.5-5 µm thick metallized with vapor-deposited aluminum on one side and chrome on the other side.

1E. Advanced Propulsion Concepts at JPL

JPL's Advanced Propulsion Concepts (APC) program, under $150 K of funding from NASA Code R's Propulsion Research program (managed by John Cole at MSFC) is supporting a diverse range of solar sail activities including mission studies and technology development. These activities include the development of an extensive solar sail mission requirements matrix that will summarize most NASA Theme and advanced potential solar sail missions and their requirements in terms of sail size, expected sail temperatures, sailcraft turn rates, etc. Results from this study will be used in technology roadmapping and in defining solar sail validation missions. Also included under the APC program are the development of high stiffness, low-mass (down to 1 g/m2), high-temperature carbon fabrics at Energy Science Laboratories Inc. (ESLI) in San Diego, Ca, photolyzable substrate materials, microwave levitation experiments with carbon fabrics, and metallization of Dupont PEN films.

1F. Materials Technology and Advanced Concepts Programs at LaRC

Code S is supporting LaRC's Materials for Inflatables and Materials Technology programs (managed by John Connell[11] and Chris Moore) with approximately $175 K in FY 1999 to develop and characterize advanced thin film materials that have greater resistance to ultraviolet radiation, particle radiation, and atomic oxygen. The mechanical and optical properties of the new materials are being tailored to improve their strength and packageability, and to enhance their thermal control characteristics. These new materials will enable long-duration missions that are not currently possible using existing materials. Several thin-film materials are being characterized to develop a database of properties that can be used by mission designers. This work is focused mainly on materials for the NGST sunshade. The material properties are being measured at the cryogenic temperatures expected for the NGST operational environment. The characterization of thin-films for NGST is relevant for all types of inflatable structures and solar sails. LaRC performed proof-of-principle experiments to laser-perforate thin films for low-mass sails. Under a Director's Discretionary Fund (DDF) LaRC, through a contract with Astral Technology Unlimited Inc., is providing the metallized film for the solar sail segments to be assembled at JPL (discussed in more detail in another part of this paper).

1G. Space Inflatables and Gossamer Spacecraft Program at JPL

The NASA Code S Ultra-Lightweight Structures and Space Observatories (ULSSO) thrust area, managed by Chris Moore at Langley Research Center (LaRC) includes the Space Inflatables program and a new program called the Gossamer Spacecraft program. These two programs, managed by Art Chmielewski at JPL, will support developments in ultra-light-weight spacecraft configurations.

Large ultralight inflatable structures have the promise of revolutionizing 21st century spacecraft. Such a spacecraft would no longer consist of a collection of heavy electronics "boxes" and frames but instead of extremely light weight membranes, fibrous materials, foams and flexible microelectronics components imbedded into polymers. This new "Gossamer" spacecraft will occupy very small stow volume at launch but be capable to assume a large form in space through inflation or self deployment. In particular, one of the most attractive propulsion systems for Gossamer Spacecraft are solar sails. Solar sails are expected to significantly improve low-earth orbit and deep-space missions and enable ambitious missions such as non-Keplerian orbits and interstellar probes. To achieve this promise requires integrated sail systems with areal densities between 0.1-10 g/m^2 and sail areas between 10 m to greater than 1000 m in diameter. Innovative technologies in the areas of sail systems, booms, films and hybrid fiber-film-inflatable structures will be required to make the Gossamer Spacecraft Program a success.

In FY 1999 the Space Inflatables program invested approximately $1M in technologies and studies directly or indirectly supporting solar sails, including development of a 14-m-long inflatable boom at ILC-Dover, a mission study to image distant Jupiter-like planets using a solar sail occulter called Big Occulting Steerable Satellite (BOSS), and the Next Generation Space Telescope Sunshade (NGST).

In FY 2000 between $1-2M is planned to support the solar sail technology development portion of the Gossamer Spacecraft program. However, other elements of the Gossamer Spacecraft and Space Inflatables programs directly supporting the development of solar sails will result in an investment in solar sail technology from LaRC's ULSSO program of up to $4 M. It is expected that up to 60% of this budget will be competitively bid to universities and to industry.

1H. Funded proposals at NAIC

The NASA Institute for Advanced Concepts in Atlanta, Georgia is funding three grants for the development of advanced concepts for solar sails and sail missions. The funded grants are:

1. "Advanced Solar- and Laser-Pushed Lightsail Concepts", Ohio Aerospace Institute
2. "Ultralight Solar Sails for Interstellar Travel", Pioneer Astronautics
3. "The Magnetic Sail", Pioneer Astronautics

1I. SBIR Programs

There are several solar sail-related Phase I and Phase II SBIRs, listed below by managing organization.

I.1. Phase I SBIRs at LaRC:

1. " A Novel Tear Resistant Technology for Thin Film Membrane Applications"
Triton Systems, Inc. NAS1-99045, Proposal # 98-1 19.10-4200A
2. "Ultra Lightweight Solar Sail Material"
Astral Technologies Unlimited, Inc. NAS1-98044, Proposal # 98-1 19.10-0935

I.2. Phase II SBIRs at LaRC:

1. "Fabrication of Large Area Advanced Technology Ultra Thin Films"
SRS Technologies NAS1-99079, Proposal # 97-2 20.10-7000
2. "High Performance TOR-RC Polymer for Space Applications"
Triton Systems, Inc. NAS1-99075, Proposal # 97-2 20.07-4200

I.3. Phase I SBIRs at Ballistic Missile Defense Organization (BMDO):
"Solar Sail Microspacecraft" , Pioneer Astronautics

I.4. Inflatables and Gossamer Spacecraft SBIR Solicitation For FY 2000

Topic 25.02 (Inflatable Structures and Systems) of the ULTRALIGHT STRUCTURES AND SPACE OBSERVATORIES thrust area of NASA's Small Business Innovation Research 1999 Program incorporates inflatables, solar sails and gossamer spacecraft technologies. This SBIR subtopic solicits proposals for sail systems characterized by low packaging volumes while enabling large deployed sizes at very low areal densities, concepts, modeling and demonstration of sail systems including sail configurations, sail assembly, storage, integration to spacecraft, deployment, and control. Included in the solicitation are boom concepts for inflatably deployed booms, composite booms, and other innovative new boom concepts with emphasis on materials and rigidization concepts. Innovative methods to reduce film stress and boom loads, thin film fabrication methods, metallization, ripstop, handling, folding and storage, film characterization, and innovative new film technologies are to be considered for funding.

2. Solar Sail Film Technologies

Thin film, boom, sail design and related materials and structures technologies are being developed under the technology and SBIR programs described above. Below these technologies are summarized by technology category.

2A. Astral Technology Unlimited Inc.

Astral Technology Unlimited Inc. is a small, high technology vacuum metalizing company that specializes in metallization of a variety of films down to below 1 μm thickness[12]. Astral Technology recently completed a NASA SBIR Phase I contract (managed by LaRC) entitled "Ultra Light Weight Solar Sail Material" where polyethylene terephthalate (PET) films 30.5 cm wide and 0.9 micron thickness were metallized with 500 Angstroms chromium to one side and 1,000 Angstroms aluminum to the other side in continuous rolls. The chromium provides a high emissivity on the backside of the sail while the aluminum provides high reflectivity and ultraviolet protection on the sun side. Additionally, laboratory techniques were employed to heat stabilize the material at 150°C which provides for less than 0.2% shrinkage downweb and crossweb. Thermally activated tapes were made that have a yarn reinforcement employed for bonding narrow webs together and for cross web reinforcement and rip stop.

Astral has applied for a Phase II of this contract to develop the laboratory techniques to a production mode where thin films 0.9 micron to 3.0 micron (which are available in 300 - 600 mm wide roll) are metalized, seamed together and yarn reinforced to be offered in wide continuous rolls or as full size sails. The production processes developed in this SBIR should be applicable to PET film, polyethylene naphthalate (PEN) or any other new film that might become available in these very thin thicknesses. With these techniques sail film reflectors can be constructed that weigh as little as 2.25 grams/square meter, based on the following assumptions[13]:

	Mass (g/m^2)
Plastic film, 0.9 μm thickness	1.44
Metallization	0.18
Fiber/yarn bundle	0.25
Adhesive	0.34
Tape	0.04
Total	2.25

Presently Astral has a contract with LaRC to metallize 500 square meters of 3 μm PET film in a 600 mm width with 500 Å chromium on one side and 500 Å aluminum on the other side. This material will be used for making solar sail segments at JPL and DLR.

2B. SRS Technologies

CP1 ultra-thin and rip stop films manufactured by SRS Technologies are ideal solar sail membranes with several significant advantages over other membranes such as Kapton film[14]. CP1 is a NASA LaRC developed colorless polyimide with excellent UV resistance and thermal properties. SRS film can be fabricated in large area sheets and rolls with thicknesses down to 1.5 to 2.0 μm. SRS recently shipped to JPL a continuous roll of CP1 film approximately 0.7-m in width and 15-m in length with a film thickness of 1.5 ± 0.5 μm; JPL plans to perform experiments on metallization of these materials in 1999. Under a Phase I SBIR managed at LaRC SRS has developed a 5 μm CP1 film with a unique embedded Kevlar rip stop grid. These Kevlar fibers are actually cast into the film to provide a strong, tear resistant film. In addition to increasing tear resistance, the overall strength, robustness, and handling ability of the film is significantly enhanced over materials such as Kapton. As an example, a force of 10.7N is required to tear a Kevlar rip stop fiber, compared to 2.16N to initiate a Kapton tear and 0.02N to propagate the tear. In order for a tear to propagate past a rip stop fiber in the CP1 film, another 10.7N load must be applied. As a result, catastrophic tears in the CP1 rip stop are contained within the Kevlar grid. An approximately 1.8-m-diameter circle of 5 μm CP1 film with imbedded fiber ripstop was recently purchased by JPL for evaluation. This large section of film is amazingly easy to handle and it's areal density is approximately 6 g/m^2.

Another advantage to the SRS rip stop film is a significant reduction in areal density of 20% as compared to the baseline Kapton. This lower film density results in a significant reduction in sail mass, allowing a cheaper / heavier bus, a smaller sail, or better sail performance. In addition, SRS is currently researching thinner films and rip stops to enable future second generation sails to dramatically increase their performance and reliability.

SRS CP1 films are designed to have superior thermal characteristics as compared with Kapton. Since CP1 is a colorless polyimide with a solar α/ε of 0.1 compared to a value of 0.7 for Kapton, CP1 films operate at much cooler temperatures than Kapton. This enables a wider variety of solar sail missions with much higher solar fluxes than allowed by Kapton. This is especially significant for future missions near Mercury or the Sun. Other material properties such as wrinkling characteristics, contamination susceptibility, and UV resistance are similar to Kapton. SRS CP1 film can also be coated with a variety of reflective coatings such as aluminum, silver, and gold. Aluminized CP1 films have surface reflectivities of up to 90% across the solar spectrum, making them excellently suited for use as solar sail membranes. JPL plans to issue contracts for metallization of 5 μm imbedded fiber film and 1.5 μm CP1 film by July 1999.

SRS was recently selected for a Phase II SBIR managed by LaRC. In Phase II SRS will fabricate imbedded fiber CP1 films down to 1 μm thickness and develop methods to produce continuous rolls of imbedded fiber films.

2C. Triton Systems, Inc.

Triton Systems Inc. [15] has demonstrated advanced materials technologies that will be used in the development of low areal density membranes for solar sail applications. The membranes under development have three technically important characteristics.

- Ultrathin membranes for low weight combined with space durability against atomic oxygen, VUV radiation and electron radiation.
- Integrated "rip stop" mechanism that dramatically increases initiated tear propagation.
- Bulk conductivity of the film membrane that reduces surface resistance for electrical charge buildup dissipation.

Triton processes TOR-LM, CP2 and TOR-RC into continuous 0.3 - 2.0 mil thick films with areal densities as low as 10 g/m^2. Atomic oxygen resistance, VUV stability and radiation resistance have been characterized in ground simulation with corroborating space flight validation for these materials making them good candidates for applications across a wide range of deployment altitudes.

Reinforcement grids from several different types of materials can be integrated into the film as they are cast. These reinforcements then become imbedded into the film structure and significantly increase the force required to tear the membrane. The work to date examined reinforcements with different densities and grid configurations and produced membranes with total thickness in the 1.0 – 1.5 mil range.

Triton has developed a conductive polymer system that provides surface and bulk conductivity through the film membrane. This mechanism is not a coating and does not have brittleness and reliability issues associated with ITO coatings. The surface resistance can be varied from 100 - 10^9 ohm/sq. depending on the concentration of conductive polymer in the films. These conductive films have been cast into thin films and have been reinforced in sheet format. Triton offers products based on its Advanced Polymers made under a series of exclusive patent licenses from NASA. These polymers feature properties that render them uniquely suitable for use in space, in electronics, and in separation membrane applications. Of particular interest for solar sail applications are the UV and particle beam resistant polymeric materials of the TOR, COR and CP classes that have also been reinforced and made electrically conductive (to reduce problems of electrostatic charge buildup). Triton's expertise and accomplishments can be leveraged with current NASA funded efforts to provide ultra thin, rip stop, and conductive materials for solar sails for New Millennium Program applications such as ST-5. An example of such a material is shown below.

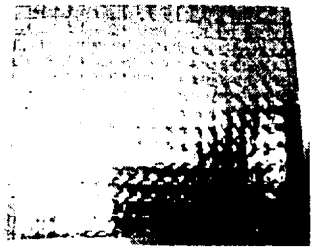

Fig. 2. Electrically Conductive, "Rip-Stop" Reinforced Thin Film Membrane

Also of interest for space applications in LEO, are atomic oxygen (AO) resistant films and threads (10x longer life than current materials) and conductive films.

Fig. 3. Metallized TOR-LM™ Film (silver/inconel)

2D. Orcon Corporation

Orcon Corporation[16] provides lightweight reinforced Mylar® and Kapton® films, and MLI blankets for space and cryogenic applications. Orcon specializes in manufacturing low-mass reinforced film products using a proprietary process to minimize the fiber and adhesive mass required for the reinforcement. Under funding from JPL's Mission Studies and Advanced Technologies program the Orcon Corporation recently demonstrated that Kevlar® reinforcing fibers could be applied to Mylar films down to 2.5 µm in thickness. By applying individual reinforcing fibers at 2.54 cm intervals, the areal density of the reinforced 2.5 µm Mylar reduced to approximately 3 g/m2. Handleability and tear resistance of the material has been significantly improved with application of the Kevlar reinforcement. Scuffing of the reflective non-reinforced side of the film was minimal. The adhesive used to bond the fibers is a proprietary formulation which has been qualified to meet space application requirements, including temperature endurance and minimal outgassing. JPL plans to perform measurements of the reinforced film to determine the reflectivity after processing. Future plans at Orcon include technology programs to further reduce the mass of the adhesive on the reinforcing fibers and processes.

2E. Energy Science Laboratories Inc (ESLI)

The current baseline solar sail concept consists of a metallized polymer film that is tensioned and controlled by a rigid frame or through centrifugal forces. ESLI in San Diego, California[17,18] has developed a novel, thick, porous material called a microtruss fabric, made with high strength carbon fibers and whiskers material with applications ranging from solar sails to light-weight mirrors and antennas. Porosity allows light weight; thickness allows greater stiffness; and fibers allow tailoring of the mechanical and optical properties. ESLI forms lightweight microtruss structures using discontinuous carbon fibers that are joined to one another at "nodes." When the mean free fiber length between nodes is short, the structure acquires compressive strength without need for a potting matrix as used in conventional fiber composites. Carbon fiber microtruss structures have volume density ~50 kg/m3; microtruss sheets having thickness ~1 mm will thus have areal density ~50 g/m2.

ESLI is currently under contract with JPL for a number of sail-related activities. ESLI has developed a series of lightweight carbon-carbon fabrics having areal densities in the range of 1-10 g/m^2 (Fig. 4). Such porous 3D fabrics handle easily, and may be stowed by rolling, after which they elastically unroll. Because of intrinsic stiffness, sail tensioning is not required. They have good microwave reflectance-recently the reflectivity of a 2 g/m^2 carbon fabric was measured to be approximately 90% with 5 cm microwave radiation[19] and outstanding high temperature capability. ESLI also successfully incorporated a metallized polyimide film to a 6 g/m^2 carbon fabric (Fig. 5). Roll-to-roll fabrication of these fabrics is feasible. Such fabrics have been used in preliminary microwave photon thrust experiments at ESLI, and further testing will be conducted at JPL in the near future. ESLI is investigating photolyzable substrates that may be used to assist in sail fabrication and deployment. One polymer studied is PBMA (polybutylmethacrylate) that volatilizes in vacuum under one solar illumination at a rate of several microns per hour (100°C) . Films of such material have been integrated with ESLI carbon fabrics and then volatilized. ESLI is investigating two concepts for beamrider sails: dished sails with angle-dependent reflectance based on lightweight carbon fiber velvets located at the sail perimeter; and chiral sail materials that develop angular momentum from unpolarized solar radiation.

2F. NGST Sunshade Films testing at GSFC

The Next Generation Space Telescope (NGST) requires a sunshade 9 m x 18 m to maintain a temperature surface near the telescope of approximately 60 K. The sunshade will consist of several layers of 25-µm-thick polyimide film. Under NGST program funds GSFC plans to conduct long-term, broad-band UV testing, stressing/manipulation to simulate folding, storing, and deploying, and 10 year, L2 environment exposure[20]. This will be on 25-µm-thick films, coated with VDA on one side, and exposure on uncoated sides. Films planned for testing include Kapton-E, CP-1, CP-2, Upilex-S, and TOR-LM.

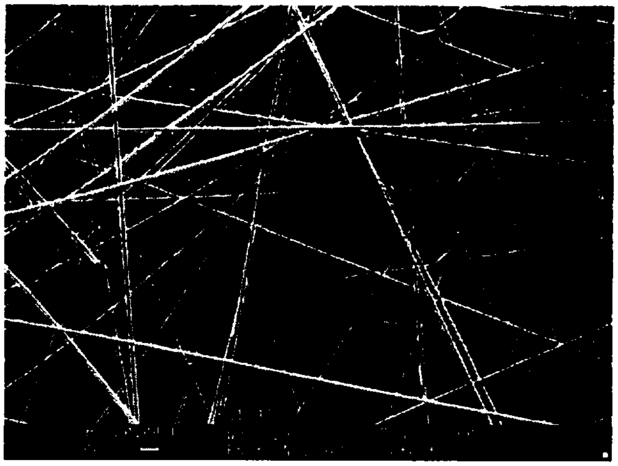

Fig. 4. Carbon microtruss fabric at ESLI.

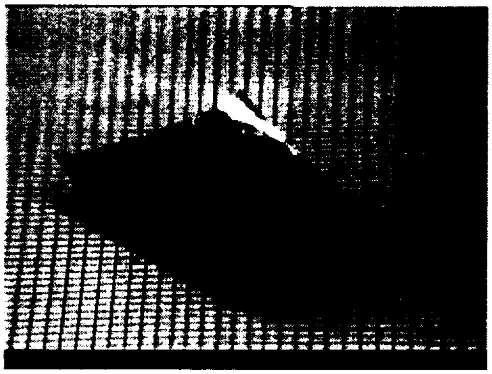

Fig. 5. ESLI Carbon Fabric 6 g/m^2, 2 mm thick, aluminum metallization on fibertruss-stiffened polyimide

2G. Boeing Defense and Space Materials Testing

A ground-based simulated space exposure experiment is being conducted at the Boeing Radiation Effects Laboratory for NASA LaRC[21]. The environments of interest are the conditions present at 0.98 AU for spacecraft including the Geostrom Warning mission and at L2 for the Next Generation Space Telescope (NGST) mission. The materials of interest are candidates for possible use as the solar sail on Geostrom and the sunshade for NGST. The materials will be exposed to a simulated 5 year mission which will include low energy protons and electrons and UV radiation.

The candidate films are all 12.5 µm thick with vapor deposited aluminum of 600-1000 angstroms thick on one side. The samples consist of several commercially available polyimides: Upilex-S, Kapton HN and Kapton E and several experimental polymers: CP-1, CP-2, TOR-LMBP and TOR-RC. Periodic measurements of solar absorptance in-situ under vacuum will be made through out the exposure. Pre and post normal emittance and thin film tensile properties at room temperature will be also made.

2H. Italian Film Developments

Ultra-light "metal sail" films are required for fast trip times to 200 AU. Italy is developing films that photolyze in space[22]. Experimental devices to test three different methods of plastic removal were setup. A method has emerged particularly useful in orbit and shall be tested as soon as an experimental solar-sail mission in LEO is available for testing the film concept.

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3. Proposed Flight Demonstration Missions

The greatest impediment to the application of solar sails for space missions is the lack of any complete flight experience. Below are discussed flight demonstration missions under study or development and a summary of both Russian Znamya flights. The missions under study are ST5, DLR/JPL demonstration mission concept, a concept under development at Carnegie-Mellon.

3A. ST5

The New Millennium Program (NMP) is a NASA program managed by the Jet Propulsion Laboratory (JPL) to identify, develop and flight validate key advanced technologies and capabilities needed to enable 21st century NASA Space and Earth science missions[23]. The Program focuses on technology validation in a systems approach to retire risk for the first use of technology in a science mission. NASA's vision for its space and Earth science programs in the 21st century comprises frequent, affordable missions using many small, low-cost, highly autonomous spacecraft to explore our planet, solar system and the universe. Accomplishing this vision will require new technologies and new ways to partner with industry, universities, and other government agencies. NMP is interested in those breakthrough technologies which will enable high-priority space and Earth science missions in the 21st century at significantly reduced life-cycle cost. NMP is seeking those technologies that are at TRL 3 or 4 and have a realistic plan to reach level 7 in time to support a flight in 2002 - 2003.

The NMP has formed Project Formulation Teams for its proposed Space Technology 5 (ST5) mission. Teams will develop project concept proposals to support one of the following three project concept areas which have been approved by NASA Headquarters to enter into the formal project concept definition phase:

1. Solar Sails
2. Constellation of small satellites
3. Disturbance reduction systems

The present plan calls for NASA to select one of these mission proposals being developed by the ST5 Teams by August 10, 1999[24]. Should ST5 select solar sails for validation, the Phase B would begin by Fall 1999 and launch in late 2003. The total project costs for ST5 are capped at $28M. Project costs include all elements of the project, including the technology development and validation, project implementation and operations, technology infusion, and science. If solar sails are selected for ST5 the state-of-art in solar sailing will be greatly enhanced.

The ST5 solar sail mission studies, managed by John West at JPL, include two sail options, both of which, if successful, will validate all the fundamental principles of solar sailing. The two options are the Minimum Sail Project Concept and the Sub-L 1 Project Concept. They are both derived from the concept shown in Fig. 6; they differ in the size of the sail and the performance goals[25]. The description below comes from Reference 23.

The concept for the solar sail propulsion system is shown in Fig. 7. It consists of a square sail supported by crossed ribs. The sail is deployed from a stowage canister that is mounted on top of the spacecraft bus and can be jettisoned. Five subsystems make up the solar sail propulsion system:

- Long, deployable sail struts
- Sail membranes
- Sail stowage canisters and deployment subsystems
- Spacecraft buses and bus components
- Engineering diagnostic and scientific instrumentation.

The sail propulsion system is spin-stabilized at a spin rate of 0.3-0.45 degrees/second in the sail-attached configuration and is either spin-stabilized or three-axis stabilized after the sail is jettisoned. The spacecraft bus includes a conventional monopropellant hydrazine propulsion subsystem to perform attitude control prior to sail deployment, during operations with the sail attached, and after sail jettison should the project operations scenario require that the sail be jettisoned. Requirements for flight validation are different for two project concept options described below. All flight validation occurs with the sail attached to the spacecraft bus.

Minimum Sail Project Concept

The sail in the Minimum Sail Project Concept is square with a dimension of approximately 40 m on a side. The performance goal is a characteristic acceleration of ~ 0.17 mm/s2. The solar sail propulsion system provides the delta-V for 45 days of orbit pumping from Medium Earth Orbit (MEO) at (approximately 1000-1500 km altitude) to an unspecified higher orbit. Flight validation will be performed for:

- Sail deployment
- Functionality and performance of the sail including the effects of the sail on otherspacecraft instruments and systems
- Functionality and performance of the sail as a propulsion device
- Sail jettison

Sub-L 1 Sail Project Concept

The sail in the Sub-L1 Sail Project Concept is square with a dimension of approximately 70 m on a side. The performance goal is a characteristic acceleration of ~ 0.3 mm/s2. The solar sail propulsion system provides the delta-V for 12 months for transit from the Earth's L 1 point to a sub-L 1 operational point of approximately 0.98 AU and for maintaining the heliocentric operational point. Flight validation will be performed for:

- Sail deployment
- Functionality and performance of the sail including the effects of the sail on other spacecraft instruments and systems
- Functionality and performance of the sail as a propulsion device
- Sail functionality for extended in-space stationkeeping
- Delivering data from a sub-L1 location

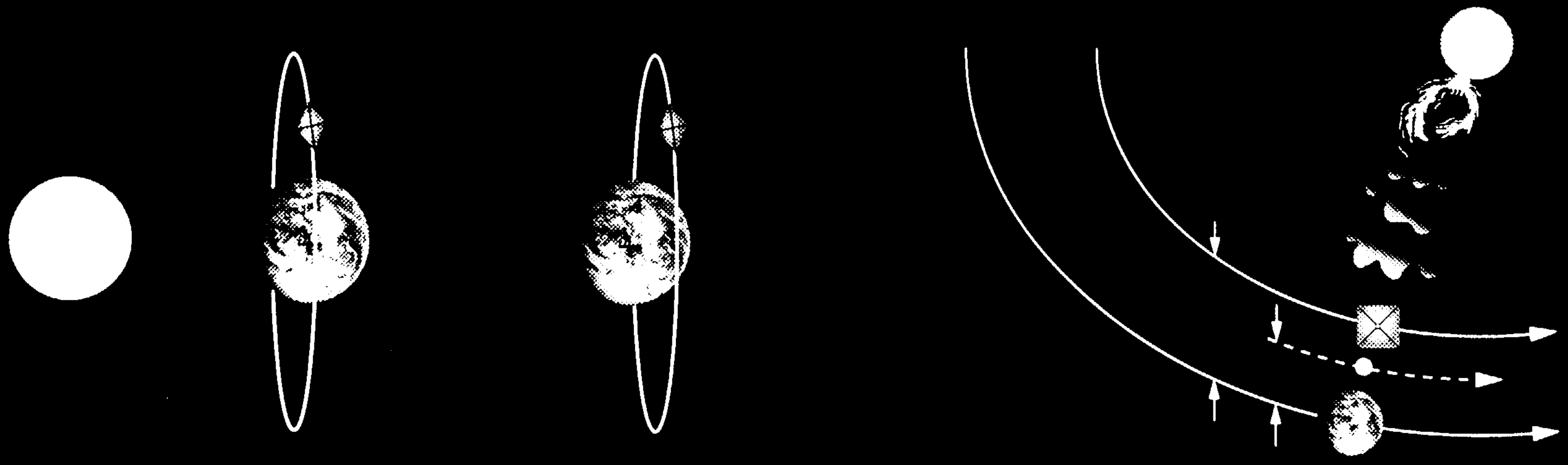
3B. DLR/NASA-JPL Demonstration Mission Concept Study

A joint NASA/JPL - DLR solar sail concept study has been ongoing since 1997. The goal of the study is to identify solar sail demonstration mission options that can be performed at low cost. Studies completed to date resulted in the conceptualization of a low-cost validation mission of a fully operational solar sail micro-spacecraft in Earth orbit[26,27]. Such a validation flight above the influence of the Earth's upper atmosphere could demonstrate the basic principles of sail fabrication, packaging, storage, deployment and control. The concept calls for a 40-m square sail to be packaged on an ARIANE 5 micro-ASAP (ARIANE Structure for Auxiliary Payloads) for launch into a GTO, or placed on a Shuttle HitchHiker Pallet with a kick stage for injection into a circular orbit of at least 1500 km altitude.

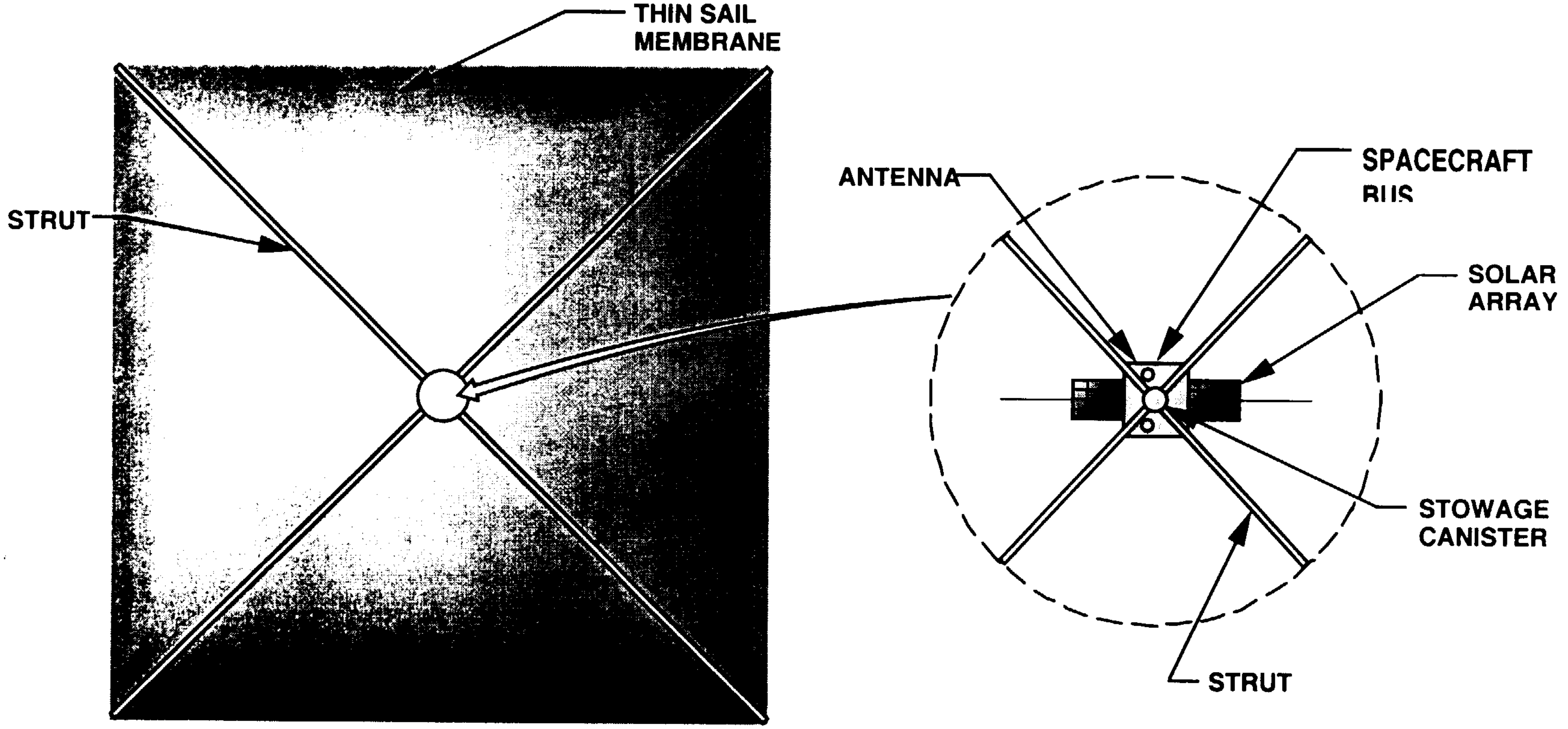
Currently, on a co-funding basis between DLR and ESA, a 20m x 20m breadboard model is being designed and fabricated [28]. It is intended to demonstrate the feasibility of a fully deployable light-weight solar sail structure via a ground demonstration in a 1g environment under ambient environmental conditions by the end of 1999. Participation of NASA/JPL by assembling an advanced sail material segment with a film mass including rip stop of under 6 g/m^2 for individual sail segments of the breadboard model is currently under discussion. The design of the breadboard model is oriented towards a potential low-cost technology validation flight in Earth orbit. "Piggy-back" launch volumes place extreme volume constraints on the design of the solar sail hardware, and requires high density packaging of the booms and sail segments.

The baseline design for the breadboard model employs carbon fiber (CFRP) booms to be deployed mechanically from a central deployment module housing the rolled-up booms and folded sail segments. The ESA-DLR design for the central deployment mechanism will allow simultaneous deployment of four booms to support a square sail. Fig. 8 shows the sailcraft baseline concept in a partially deployed configuration.

NMP



FLIGHT SYSTEM CONFIGURATION*



SAIL

SPACECRAFT BUS (TOP VIEW)

* COMMON TO BOTH PROJECT OPTIONS

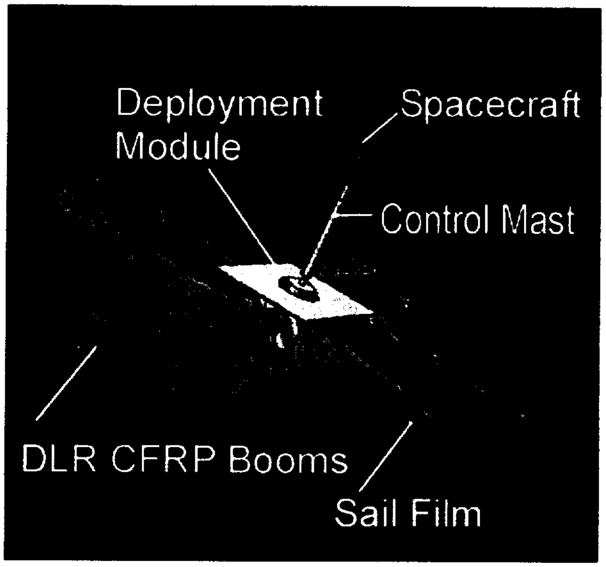


Fig. 8. Sailcraft Baseline Concept - Partially Deployed

The CFRP booms combine high stiffness with high strength, low density, and can be stored in a small volume. The booms consist of two laminated sheets which are bonded at the edges to form a tubular shape. They can be pressed flat around a central hub for storage. To deploy the booms, the hub is rotated to uncoil the booms from the hub. Once free of the deployment structure, the booms resume their original tubular shape with high buckling strength. Several prototypes of the CFRP booms have already been manufactured at DLR (see Fig. 9). The booms have a unit weight of about 100g/m. and provide a bending stiffness of 5100N-m^2 to 5500N-m^2. The booms are also structurally sized to carry high bending moments up to 65Nm (critical bending moment).

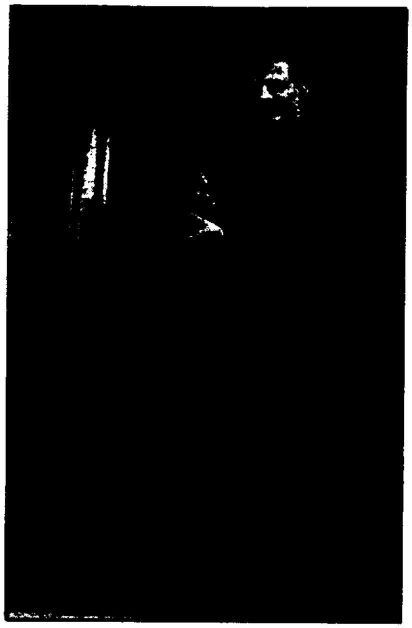


Fig. 9. Prototypes of DLR's CFRP Light-Weight Booms

The breadboard model will be equipped with sail segments using 7.5_m Kapton as well as 4.0_m PEN (Polyethylen-naphthalate) film for individual, triangular sail segments. The film will be coated with 50 to 100nm Aluminum on the front side to provide high reflectivity. A Chromium coating on the back side to provide high emissivity is currently under investigation. The sail segments are folded in two directions ('accordion' folding, also referred to as 'frog-leg' folding due to the unfolding behavior), so that storage volume is minimized. In order to test the deployment behavior of sail segments, DLR has recently built a 8m x 8m solar sail mock-up which is shown in Fig. 10. The upper triangular sail segment was folded and stored in the original size sail container planned for the orbital test flight, and was deployed successfully in several ground tests involving sail deployment ropes and motors to unfurl and tighten the sail.

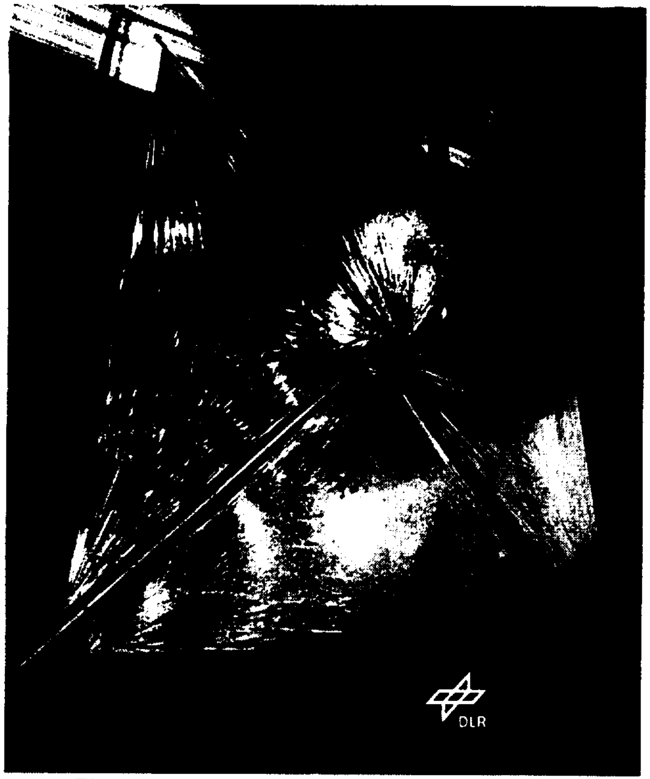


Fig. 10. 8m x 8m DLR Solar Sail Mock-Up

3C. Carnegie-Mellon University Study

Carnegie-Mellon University (CMU) is conducting a study under funding from the Air Force to develop and fly a Solar Blade Nanosatellite[29]. The Solar Blade Nanosatellite concept consists of a 4-blade heliogyro[30] solar sail approximately 10-m in diameter. The spacecraft is stowable in a package approximately the size of a fire extinguisher and weighs under 5 kg. A Pegasus or Roron launch vehicle will raise the sailcraft to an initial circular orbit of 1000 km altitude, the Solar Blade spacecraft will unfold itself and then fully deploy the 8-µm-thick Kapton solar blades. The satellite's flight dynamics will be controlled through the rotation of these solar blades relative to the sun's rays. The satellite will demonstrate attitude precession, spin rate management and orbital maneuvers. The spacecraft will be capable of communicating to Earth enabling orbit determination via standard radar ranging and basic attitude estimation relative to the sun line. CMU hopes to launch their sailcraft into orbit by the summer of 2001.

3D. Interworld Transport Commercial Solar Sailing Project

Interworld Transport[31] is currently engaged in the construction and flight testing of hardware meant to demonstrate deployment techniques of a solar sail structure in space. Interworld Transport entered a partnership with JP Aerospace (JPA) in 1995 to fly sail test equipment on test flights of inexpensive sounding rockets (about $5,000 US) capable of delivering one half kilogram to an altitude of one hundred kilometers. As long as deployment tests can be performed fairly rapidly, a suborbital flight is sufficient for early testing.

An experimental solar sail package with a wrapping approach to stow carbon fiber straps around a composite core within another containment cylinder flew on the 5/23/99 JPA sounding rocket test flight. The goal of the test to determine if the structure would survive the acceleration (~30 g) and vibration loads delivered by the launcher. Examination of the returned payload after flight demonstrated it to be slightly overbuilt. The next flight version will use a lighter boom modeled on the DLR German sail group with additional inflation pieces in the core. It will also include enough equipment to actually deploy the sail structure and deliver data via radio on the amateur radio bands. The next flight is planned for the summer of 1999.

3E. Flight Mission Proposal to Italian Space Agency

On 8th February 1999, a national workshop[32] organized by the Italian Society for Aeronautics and Astronautics was held in Rome on solar sailing development in Italy. The space scientific community strongly recommended an experimental mission to the national space authorities where all major conceptual and technological issues related to solar sailing should be tested". As a consequence, the following firms

a. Telespazio SpA (Rome)
b. Contraves Spazio (Rome)
c. ENEA (Rome)
d. Politecnico di Torino (Turin)

made a proposal to the Italian Space Agency (ASI) for the first experimental solar sail mission. Actually, the whole envisaged mission consists of a full mission and one sub-mission. 250 kEuros or US k$ 270 was requested for a Phase-A study of the sub-mission. The feasibility study, should last 10 months. Evaluation by ASI is in progress.

3F. Pioneer Astronautics Solar Sail Demonstration Concept

Pioneer Astronautic's Solar Sail Microspacecraft (SSM) is a low-cost concept for implementing solar sail propulsion on a practical spacecraft with present-day technology. The concept is being supported under an SBIR funded by BMDO. In the SSM, a simple micro-spacecraft derived vehicle is employed which could cheaply investigate multiple targets and simultaneously demonstrate the utility of small solar sails. The SSM reduces technology risk by using off-the-shelf aluminized mylar. A very small core vehicle with short range communication systems drastically reduces the size of the sails, allowing the spacecraft to be launched as a hitchhiker payload. Because the spacecraft is small, the sail is small, allowing it to be self-deployed using either a rolled spring-steel or inflatable self-deploying boom system. Because of its maneuverability, the SSM could visit multiple targets, engaging in photographic inspection of friendly or adversarial satellites. A SSM could be used to disable or destroy other satellites by parking itself in a position where it blocked the target spacecraft's solar arrays. It could also be used to interfere with the operation of an opponent's remote sensing vehicle by using its sails to block the view. This proposed study shall examine the design and construction of a low-cost, near-term SSM vehicle for immediate use in near Earth space.

3G. Russian Space Reflector Deployment Tests

On February 4, 1993 the Russian Space Regatta Consortium (SRC), under the leadership of Vladimir Syromiatnikov, deployed a 20-m-diameter rotating solar reflector called Znamya 2 which design was based on the Russian Columbus 500 solar sail[33]. Znamya 2 was the first in a series of planned space tests of large deployable solar reflectors to illuminate regions of the Earth at high lattitudes during winter months. The reflector consisted of 8 each, 10-m-diameter petals fabricated from 5-μm-thick PETF, a type of Russian PET (Mylar) film. The reflector and it's deployment structure were attached to a Progress resupply vehicle which disengaged from the MIR space station. Crew on board MIR were able to view and record the Znamya 2 deployment. The Progress resupply vehicle provided all necessary attitude control and maneuvering. Deployment was achieved by rotation of the structure; centrifugal force deployed each of the 8 individual 10-m-diameter petals. Rotation rates varied during the deployment process; the rotation rate of the fully-deployed Znamya was 1.8 rad/s. The deployment test was a complete success.

Znamya 2.5 was a continuation of SRC's space reflector experiments that hopefully will lead to the deployment of 200-m-diameter reflectors. The reflector was 25-m-diameter and was constructed of materials and design similar to Znamya 2. The main goals of the Znamya 2.5 experiment were: to verify the principal improvements of the film structure, to run "Novey Svet" illumination experiment, and to operate the new manual attitude control mode to further test operational stability of the system and the film structure[34]. Deployment of Znamya 2.5 was attempted on February 4, 1999. Unfortunately, due to a mission operations and software error, no command was sent to the Progress spacecraft to retract the Progress docking antenna[35]. As the sail unfurled it collided with and wrapped around the docking antenna, entangling the sail petals around the antenna and each other. The antenna was retracted and an attempt was made to redeploy the reflector, however the reflector had been damaged by the antenna[34].

3. Navigation Developments

DLR is active in mission analysis and software development for low-thrust trajectory analysis and attitude control for solar sail spacecraft. Geocentric as well as heliocentric solar sail low-thrust transfers have been analyzed. The analysis includes orbiter missions to Mercury (including a sun-synchronous orbiter), Venus, Mars and Jupiter, rendezvous as well as sample return missions visiting small bodies (main belt asteroids and short-period comets), missions to the Sun, as well as fly-by missions to the outer planets, and, finally, fast trajectories to the heliopause and beyond[36-40].

Interworld Transport is also developing tools to model simple sails in the inner solar system. Called the SailAway simulator v1.0, this software will be capable of representing a simple sail in solar orbit with a realistic radiation force orbit propagator. Later versions will include planetary interactions and an approximated atmospheric drag model.

The University of Illinois at Urbana-Champaign, Department of Aeronautical and Astronautical Engineering, is developing low thrust trajectory tools for solar sails with funding from JPL's Mission Studies and Advanced Technologies program[41]. They have derived and successfully implemented a sail angle control law that yields escape trajectories. Modified equinoctial orbital elements are used to describe the trajectory because they provide a convenient transition from elliptic to hyperbolic orbits. Also, the numerical integration of the thrusted orbit is performed on 5 slowly-varying elements and one fast element (the true longitude).

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