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# RECENT ADVANCES IN SOLAR SAIL PROPULSION SYSTEMS AT NASA

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## ABSTRACT

Supporting NASA's Science Mission Directorate, the In-Space Propulsion Technology Program is developing solar sail propulsion for use in robotic science and exploration of the solar system. Solar sail propulson will provide longer on-station operation, increased scientific payload mass fraction, and access to previously inaccessible orbits for multiple potential science missions. Two different 20-meter solar sail systems were produced and successfully completed functional vacuum testing last year in NASA Glenn's Space Power Facility at Plum Brook Station, Ohio. The sails were designed and developed by ATK Space Systems and L'Garde, respectively. These sail systems consist of a central structure with four deployable booms that support the sails. This sail designs are robust enough for deployments in a one atmosphere, one gravity environment, and are scalable to much larger solar sails—perhaps as much as 150 meters on a side. In addition, computation modeling and analytical simulations have been performed to assess the scalability of the technology to the large sizes (>150 meters) required for first generation solar sails missions. Life and space environmental effects testing of sail and component materials are also nearly complete. This paper will summarize recent technology advancements in solar sails and their successful ambient and vacuum testing.

## INTRODUCTION

The In-Space Propulsion Technology (ISPT) Program is in its fifth year and significant strides have been made in the advancement of key transportation technologies that will enable or enhance future robotic science and deep space exploration missions. At the program's inception, a set of technology investment priorities were established using a NASA-wide prioritization process and, for the most part, these priorities have changed little—thus allowing a consistent framework in which to fund and manage technology development. Technologies in the portfolio include aerocapture, advanced chemical propulsion, solar electric propulsion, and solar sail propulsion.

Solar sails are large, lightweight structures that achieve thrust by reflecting solar photons. Two different 20-meter solar sail systems were developed and successfully completed deployment and functional vacuum testing during 2005 in NASA Glenn's Space Power Facility at Plum Brook Station, Sandusky, Ohio. The sails were designed and developed by ATK Space Systems and L'Garde, respectively. The sail systems consist of a central structure with four deployable booms that support the sails. These sail designs are robust enough for deployments in a one atmosphere, one gravity environment and are scalable to much larger solar sails—perhaps as much as 150 meters on each side.

First-generation sails will vary in size from 100 meters to 200 meters, depending on mission destination, and typically would be three-axis stabilized. They would be compacted and stowed for launch. Once deployed, the sails would be supported by ultralightweight trusses. Solar sails are composed of flat, smooth material covered with a reflective coating and supported by the ultralightweight structures, which are attached to a central hub. Near-term sails likely will use aluminized Mylar or CP–1. Both are materials previously flown in space and are currently under test for long-term exposure to relevant environments for potential solar sail missions. More robust sails might use a meshwork of interlocking carbon fibers.

Solar sail propulsion (SSP) is one of ISPT's three high-priority investment areas, with the objective of near-term verification and development of solar sail system-level technology through ground testing and the development of subsystems, operations tools, and computational models. Table 1 lists the major SSP activities conducted since the project's inception.

| |
|---|
| Scalable Solar Sail System ($S^4$) Ground Demonstration |
| Bringing an Effective Solar Sail Subsystem to TRL 6 Ground Demonstration |
| Solar Sail Spaceflight Simulation Software (S5) |
| Optical Diagnostics System for Solar Sails |
| Advanced Computational Models and Software for Design and Simulation of Solar Sails Including Experimental Validation |
| Development of a Low-Cost, Low-Mass, Low-Volume, and Low-Power Attitude Determination and Control System (L4–ADCS) and High-Fidelity Computational Models of Solar Sail Systems |
| Laboratory Characterization of Candidate Solar Sail Materials |
| Advanced Manufacturing Technologies for Solar Sails using Processes Developed Specifically for Production of Ultrathin Solar Sail Materials for Near-, Mid-, and Far-Term Space Science Missions |
| Structural Analysis and Synthesis Tools for Solar Sails |
| Smart Adaptive Structures Analysis |
| Sail Charging Studies |
| Long-Duration Materials Testing |

**Table 1: Solar Sail Propulsion Tasks.**

## SYSTEM-LEVEL GROUND DEMONSTRATION

Early in the project, In-Space Propulsion funded the development of a prototype solar sail system for ground testing that would be used to validate design concepts for: sail manufacturing, packaging, launch to space and deployment; attitude control subsystem function; and to characterize the structural mechanics and dynamics of the deployed sail in a simulated space environment. A square sail configuration consisting of a reflective sail membrane, a deployable sail support structure, an attitude control subsystem, and all hardware needed to stow the sail for launch were developed. In addition, this system was required to meet the characteristics given in Table 2, columns 1 and 2. A sub-L1 solar monitoring mission concept was also provided as a reference mission for guidance in design and scalability issues, and is summarized in Table 3.

SSP awarded ground demonstration contracts to two companies that proposed two separate types of technologies in order to achieve the project objective. ABLE Engineering Company (now ATK Space Systems) proposed work based on their prior New Millennium Program (NMP) ST–7 proposal, incorporating their rigid coilable boom, an articulating boom attitude control system (ACS) subsystem and partner SRS' CP1 sail membrane. L'Garde, Inc. proposed work based on the experience they gained on an NMP

| Metric | RFP | ATK | • L'Garde |
|---|---|---|---|
| **Dimensions** | 20 meters x 20 meters or greater | • 20-m system with flightlike central structure<br>• 4 sails scaled from 80 m<br>• Truncated 80 m masts<br>• Central structure scaled from 40 m | • 19.5 m due to Plumbrook<br>• 1 subscale TVCAD vane<br>• Nonflight central structure scaled for 100-m system<br>• Sails and mast truncated 100-m system |
| **Sail Subsystem Areal Density** | <20 g/m² (scalability to 12 g/m² for 104 m2) | • 112 g/m², includes spacecraft bus structure, ACS, power, instrument boom<br>• Scaled to 11.3 g/m² for 100-m design and no payload | • 30 g/m², includes ACS (4 vanes calculated), central structure dropped<br>• Scaled to 14.1 g/m² with 50-kg payload and 41.4-kg bus |
| **Stowed Volume** | <0.5 m³ (scalability to 1.5 m³ for 104 m² ) | • 0.9 m³ scaled to 1.5 m³ for 100-m design | • 2.14 m³ scaled to 1.04 m³ for 100-m design |
| **Thrust Vector Turning Rate About Roll Axis** | >1.5°/hr | • > 35° maneuver in 2 hr | • 63°/hr (0.0175°/sec) |
| **Effective Sail Reflectance** | >0.75 | • 92% over solar spectrum | • 85.9 |
| **AntiSunward Emissivity** | >0.30 | • 0.30 for 3 micron film | • 0.40 |
| **Membrane Characteristics** | Space-durable, tear-resistant, designed for 1 year in the near-GEO environment | • ≈2 micron CP1 with 1000 A of aluminum on front, bare CP1 on back of sail. All materials have space flight heritage. | • 2 micron Mylar with 1,000 A of aluminum on front and 200 A blackened chromium on back |
| **System Flatness** | Effective for propulsion | • 3-point quadrant support with shear compliant border to insure a flat sail, with a proper stress level to obtain local flatness. | • Stripped net loss ≈2% |
| **ACS** | 3-axis, minimize propellant usage | • Sliding trim control mass on truss and tip bars to pinwheel quadrants for roll. Micro PPT backup. | • Totally propellantless using four tip vanes |

Table 2: System-Level Solar Sail Ground Demonstration Reporting Metrics.

| Launch Mass (kg) | Payload Mass (kg) | Payload Power (W) | Total Power (W) | TM Dish (m) | TM Band | TM Rate (Kb/s) | S/C Dia (m) | Launch Vehicle |
|---|---|---|---|---|---|---|---|---|
| 250 | 50 | 100 | 750 | 1.5 | X | 100 | <2.3 | Delta 2425–9.5 |

Table 3: Design Reference Mission.

ST–5 proposal and as the sail provider for Team Encounter, incorporating their inflatable and sub-Tg rigidizable boom, a control vane-based ACS and Mylar for the sail membrane. The parallel testing and development of these two system-level demonstrations that have varied technologies in the three major components removed the risk to this technology development if one provider encountered an unrecoverable failure. The system-level ground demonstration work was divided into three phases. A 6-month concept refinement phase was completed in May 2003. During this phase, the two teams provided analysis of their system's performance when scaled to the design reference mission and a preliminary test plan for the following two 12-month phases. The 12-month hardware development phase began in June 2003. In this phase, both teams built and tested components and subsystems, with ATK concentrating on a single 10-meter quadrant and L'Garde developing a 10-meter square sail. The most comprehensive of these tests occurred in the middle of 2004 when the respective teams deployed their integrated subsystem in the Langley Research Center (LaRC) 14-meter vacuum facility (ATK) and the 30-meter vacuum chamber at Glenn Research Center's Plum Brook Space Power Facility (L'Garde). Following a successful second phase, the teams culminated their work in a 12-month system verification phase. In this phase, both teams built and tested fully integrated 20-meter sail systems that included a launch packaging container and operational ACS subsystems. In the middle of 2005, the respective teams tested their system in the Plum Brook Facility under a high vacuum and appropriate thermal environment, as well as subjecting their systems to launch vibration and ascent vent tests. Figures 1 and 2 show the 20-meter deployed systems at the Plum Brook Facility. Table 2, columns 3 and 4, summarizes the final metrics achieved by ATK and L'Garde with their 20-meter systems. Since these sails represent the largest systems that will be tested in a vacuum chamber on the ground, a significant effort was made to collect static and dynamic data on the sails and booms with ≈400 Gb of data collected, primarily raw photogrammetry data. Technical descriptions of work being performed by AEC[1–4] and L'Garde[5–7] on the 20-meter ground system demonstrator (GSD) can be found in the respective team's papers.

## SOLAR SAIL INTEGRATED SOFTWARE TOOLS

ISPT then funded a set of integrated simulation tools to predict the trajectory, maneuvers, and propulsive performance of a solar sail during a representative flight profile. The solicitation encouraged that these tools should be able to be integrated into an optimal guidance, navigation, and control (GNC) subsystem on a future flight mission. In addition, the tools were required to be applicable to a solar sail mission of characteristics given in Table 3 and incorporate the following analytical models:

- Solar radiation pressure acting on the sail as a function of sail orientation and distance from the Sun.
- Disturbance forces acting on the sail such as gravitational torques and thermal deformation of the support structure.
- Orbital mechanics.
- Sail structural dynamics.
- ACS dynamics.
- Navigational sensors.

The Solar Sail Spaceflight Simulation Software (S5) incorporated a 6-month Phase 1 that was completed in September 2003, with Phase 2 completed in July 2004, and Phase 3 completed in February 2006. At the end of Phase 3, of the 173 requirements specified in the S5 Software Requirements Document, 66 were fully implemented and integrated into the S5 system and 50 were partially integrated into the system or fully implemented in a standalone code. See reference 8 for a discussion of the S5 software and recent validation efforts.

## OPTICAL DIAGNOSTIC SYSTEM

The overall objective for this task was the development of an optical diagnostic system (ODS) to TRL 6 for a solar sail. Possible requirements for the ODS included observation of the sail deployment and monitoring of the health and integrity of the sail during and after deployment. After solar sail deployment, the

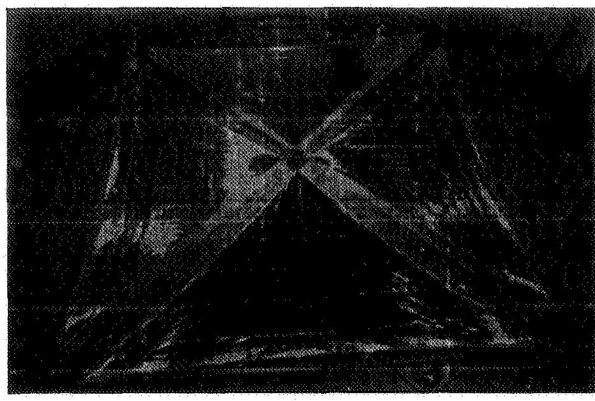

Figure 1: ATK 20-meter GSD.

Figure 2: L'Garde 20-meter GSD.

ODS would be available to provide shape and vibration measurements adequate to infer the stress state of the solar sail by aid of computational structural models which could then feed real time into a closed-loop spacecraft guidance and control system. The initial 6-month base period included concept development preceded by definition of the goals, priorities, and requirements for the ODS.[9] It was determined that continuous real-time integration with the guidance system was not necessary due to the quasi-steady-state nature of solar sail operations. In addition, studies by Zeiders[10] and Ewing,[11] showed the relative insensitivity of the thrust vector magnitude and direction to sail billow. The conceptual design process identified a number of significant challenges to on-orbit photogrammetry including significant weight, power, and data requirements for instruments and support structures for camera clusters, achieving sufficient image contrast, integrating targets into the sail membrane, and considerable software development needs. The concept development activities were conducted in parallel with the development of the ground test capability for the solar sail demonstrator hardware. A developmental test of a L'Garde inflatable boom in a thermal vacuum chamber at Goddard Space Flight Center, as well as tests on smaller sail quadrants,[12] provided an opportunity to familiarize researchers with cameras, analytical tools, and test operations. Building on this experience and adding capabilities for dynamic excitation and laser vibrometry, imaging, and a "truth" instrument, the ATK 10-meter demonstrator testing was performed in the 16-meter vacuum chamber at LaRC. These activities formed the foundation for the test methods and instrumentation employed in the final 20-meter demonstrations tests. An exceptional team of photogrammetry experts from LaRC, working in conjunction with the contractor test teams, were successful in acquiring both static and dynamic deflection data in a number of various thermal and vacuum conditions and system configurations despite tremendous difficulties that arose. For example, condensate "rain" fell on the test article as the huge Plum Brook chamber was pumped down, causing boom tip positions to change so much that complex, remotely operated, adjustable instrument platforms had to be devised. A tremendous volume of data was required to provide high-resolution measurements over 400 square meters of area and data collection was made difficult by the clean aluminum walls and floor of the chamber, which provide little natural contrast to the aluminized sails. Finally, the cost of operations in such a large chamber is not inconsiderable. The teams were constantly under the gun to debug problems, acquire data, and assess data quality quickly with limited hands on the equipment and only a few pump-downs allowed. The difficulty of photogrammetry was not insurmountable, but it did indicate the challenges identified in the conceptual design phase were real. Combined with a better understanding of the lack of a need for on-orbit photogrammetry, the further development of a flight system was not pursued.

## ADVANCED COMPUTATIONAL METHODS

To address the concern that conventional finite element models might be inadequate to evaluate solar sails, a phased approach to address the structural design issue was pursued. The first relied on the prime contractors to apply standard practices using the existing state of the art. As part of the ground system demonstrations, finite element anlayses (FEAs) were created by LaRC, ATK, and L'Garde of the 10-meter systems using both COTS and custom software. These models didn't always converge and were computationally intensive, but no more so than is experienced in typical spacecraft design. The purpose of this task was to create methods/algorithms/techniques that improved the conventional FEA of the membranes, booms, and other subsystems. Several methods were identified, but the option phases to complete and validate them were not funded due to the success of the prime contractors in modeling the 20-meter systems with conventional techniques, thus lowering the priority of this task below the level of the available funding.

## STRUCTURAL ANALYSIS AND SYNTHESIS TOOLS

This task also addresses the structural analysis issue by developing from the ground up new and unconventional modeling techniques. Techniques considered included direct transfer function modeling (DTFM) and parameter variation processing (PVP). The overall objectives for this task were completion of DTFM modeling/analysis methods for long booms, completion of capability to evaluate effects of imperfections, completion of PVP method for analyzing wrinkled membranes, and completion of test/analysis correlation by using existing test data. As in the above task, this effort was terminated prior to completion due to success using conventional modeling methods with the 20-meter systems and a lack of funding.

## LIGHTWEIGHT ATTITUDE CONTROL SYSTEM

The objectives of this 2-year project were: (1) to design, integrate, and test a sail attitude control system (SACS) employing a two-axis gimbaled control boom and (2) to develop a high-fidelity, multiflexible body model of ATK's solar sail for the purpose of validating a thrust vector control (TVC) concept employing a two-axis gimbaled control boom. One of the major findings from this study was that the two-axis gimbaled control boom was not a mass efficient method of controlling a solar sail.[13] A more efficient method was derived based on an offset mass moved along the booms by a clotheslinelike apparatus to control pitch and yaw and rotating stabilizer bars at the sail tips to pinwheel the sail quadrants for roll control. This finding led to a major redesign of the ATK 20-meter hardware to accommodate the new TVC concept. An attitude determination and control block diagram was derived to present the application/integration of the inertial stellar compass with a range of ACS options from cp/cm offset to pulsed plasma microthrusters.[14]

## CHARACTERIZATION OF CANDIDATE SOLAR SAIL MATERIALS

The purpose of this task was to conduct laboratory characterization of several candidate solar sail materials. The space radiation and micrometeoroid environments for 1.0 (Heliostorm) and 0.5 (SPI) astronomical units missions were defined and candidate materials were tested against these radiation and meteoroid environments. Through a series of learning tests, the sample holddown designs was optimized and a flexure test developed. Several samples of the SRS and L'Garde membrane materials were tested by subjecting them to gigarad levels of radiation—in simulations of long-duration solar wind mission types.[15] While some of the samples showed significant levels of degradation in mechanical strength, solar sail loading is so low that very little strength is needed.

## ADVANCED MANUFACTURING TECHNOLOGIES FOR SOLAR SAILS

The purpose of this task was to investigate and develop an integrated approach to ultrathin film solar sail manufacturing. The focus was on improving coating processes and technologies; developing sail seaming technologies for large monolithic sails; providing an integrated approach to membrane coating, acceptance, assembly and integration; and integrating future improvements (such as electrospun nanofibers for ripstop enhancement without added mass and the addition of carbon black nanotubes to the sail backside to increase emissivity)[16] into the process. The final results of this 2-year effort are the development of a scroll coating system, the development of coating capabilities of <2.5 microns, and the development of a membrane seaming system able to form monolithic sails with coatings at least as thin as 2.5 microns.

## SMART ADAPTIVE STRUCTURES

In order to mature the technology readiness level (TRL) of solar sail propulsion, advancements must be made in the pointing and dynamical control of these large space structures. This task's objective was to develop and verify structural analytical models, develop structural scaling laws, and develop adaptive control laws for solar sails to be verified on a >30-meter vertically supported boom. In the summer of 2006, a closed loop boom controller will be demonstrated.

## CHARGING IN SPACE ENVIRONMENT

Due to two extreme characteristics of future solar sail missions, the large surface area of the sail and the long-duration of potential missions, typical spacecraft charging issues will be exacerbated. The purpose of this task was to characterize charged particle environments for analyzing solar sail charging in the solar wind and at geostationary orbit and to model surface and internal electric fields and potentials for solar sails using existing spacecraft charging models. Solar sail materials were tested in simulated charging environments to determine permeability and charge retention properties. The task was completed March 1, 2006. A significant finding was that there will be very little charging of the sail surfaces, ≈10 volts as a worst case in sunlight. The study found that problems arise if the sail material backing is nonconductive or electrically decoupled from the front surface. In that case, the shadowed back surface can reach potentials of –30 to –40 volts relative to the space plasma in the solar wind—on the order of arcing onset potentials. The solution is to make sure the sail material is conductive front to back and end to end if the sail is to be in geosynchronous orbit or in the auroral zone and be very careful with electrically isolated objects in the shadow of the sail.[17]

## LONG-TERM SPACE ENVIRONMENTAL EFFECTS

Critical to the development of solar sails is an investigation of space environmental effects on these large thin film materials and the edge support technologies. This task was related to the "Characterization SS Material" task above. The above task used accelerated dose levels over a shorter period of time to simulate the total dose of radiation received by a material for many years. The purpose of this task was to provide critical thermal, optical, mechanical, and surface data on large sails taking into account edge stresses and edge support technologies that can only be characterized using large size sails but not at accelerated levels. These resulting test data could be used to validate the accelerated dose test methodology regarding the durability of candidate sail material (embrittlement, optical, mechanical, surface, and thermal properties). This task was recommended by the 2004 Technology Assessment Group.

## FUTURE DIRECTIONS

The SSP project approach of providing near-term verification of solar sails through the development of system-level technology using ground testing and the development of subsystems, operations tools, and computational models has begun building a technological foundation that can be readily used by future programs. Solar sail propulsion is under consideration for a flight validation mission as part of NASA's New Millennium Program; selection will be made in late 2006 or early 2007.

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