An Overview Of NASA's Solar Sail Propulsion Project

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Abstract

Research conducted by the In-Space Propulsion (ISP) Technologies Projects is at the forefront of NASA's efforts to mature propulsion technologies that will enable or enhance a variety of space science missions. The ISP Program is developing technologies from a Technology Readiness Level (TRL) of 3 through TRL 6. Activities under the different technology areas are selected through the NASA Research Announcement (NRA) process. The ISP Program goal is to mature a suite of reliable advanced propulsion technologies that will promote more cost efficient missions through the reduction of interplanetary mission trip time, increased scientific payload mass fraction, and allowing for longer on-station operations. These propulsion technologies will also enable missions with previously inaccessible orbits (e.g., non-Keplerian, high solar latitudes).

The ISP Program technology suite has been prioritized by an agency wide study[1]. Solar Sail propulsion is one of ISP's three high-priority technology areas. Solar sail propulsion systems will be required to meet the challenge of monitoring and predicting space weather by the Office of Space Science's (OSS) Living with a Star (LWS) program. Near-to-mid-term mission needs include monitoring of solar activity and observations at high solar latitudes. Near-term work funded by the ISP solar sail propulsion project is centered around the quantitative demonstration of scalability of present solar sail subsystem designs and concepts to future mission requirements through ground testing, computer modeling and analytical simulations.

This talk will review the solar sail technology roadmap, current funded technology development work, future funding opportunities, and mission applications.

Introduction

The ever increasing technological demands of civilization (Global Positioning System usage, space based weather observations, satellite telecommunications, etc.) have placed increased importance on space based assets. A high level of service reliability requires the ability to place additional assets in orbits that are not practically accessible via chemical propulsion. The In-Space Propulsion Program mandate is to mature innovative propulsion technologies that will enable or enhance a variety of NASA space science missions and thereby guarantee their performance and reliability for commercial usage. The Solar Sail Propulsion (SSP) Project is one of ISP's three high priority projects whose objective is the near term verification and development of solar sail system level technology through ground testing and the development of subsystems, operations tools and computational models. NASA's Office of Space Science (OSS) funds research based on the results peer reviewed proposals submitted to Topics in the Research Opportunities in Space Science (ROSS) of NASA Research Announcements (NRA). All ISP solicitations are contained within the ROSS In-Space Propulsion Technologies (ISTP) Topic. OSS also firmly believes that the ROSS solicitations should be guided by input from the technology community and this is best achieved through the periodic convening of a Technology Assessment Group (TAG).

The first ISP Solar Sail TAG was held over two days in January 2002. The TAG participants formed three discussion groups (Structures, Trajectory and Attitude Control, and Materials) to define what ground based testing and tools were needed in order to advance solar sail's Technology Readiness Level (TRL). The groups represented the highest priority solar sail subsystems and or components as well as the technical expertise of the TAG participants. Figure 1 is the Solar Sail technology development roadmap that was synthesized from the respective discussion group worksheets[2] and has been used by the SSP office develop all of the subsequent research solicitations.

Solar Sail Technology Assessment Group Roadmap
In-Space Propulsion Program

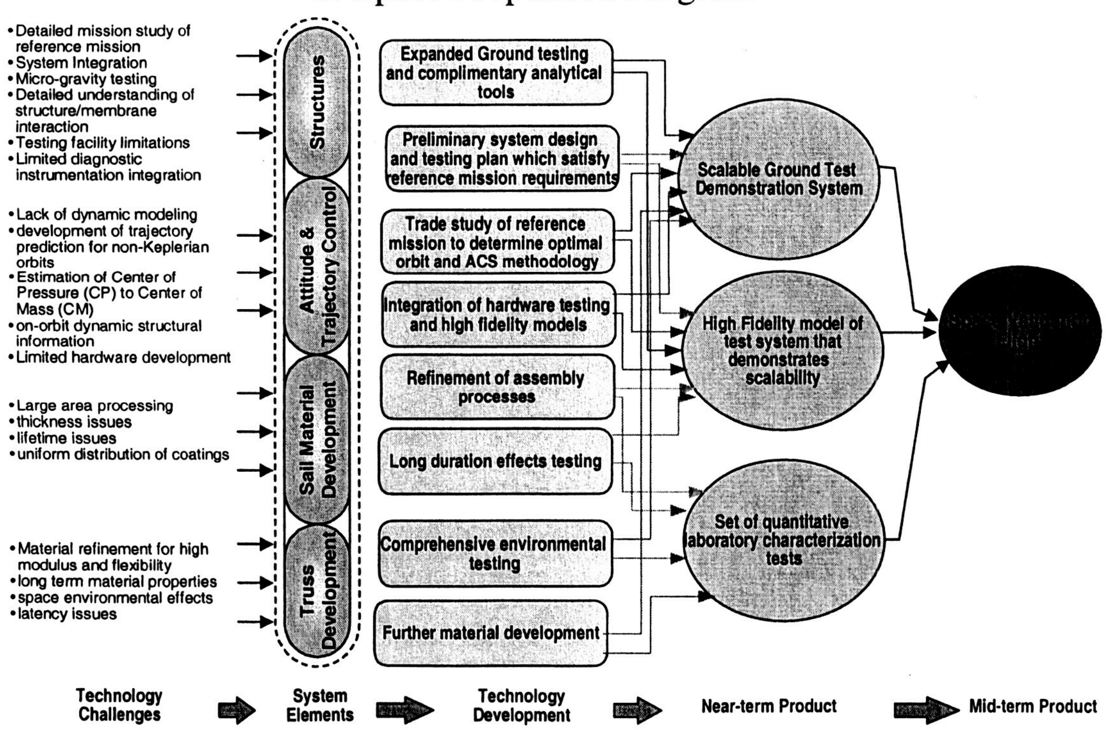

Figure 1: 2002 Solar Sail Technology Assessment Group (TAG) Roadmap

ISTP Cycle 1 Solicitation

System Level Ground Demonstration

The first of two SSP research elements in the ISTP cycle 1 called for a prototype solar sail system for use in ground test that would be used to validate design concepts for sail packaging and deployment, to verify attitude control subsystem function, and to characterize the structural mechanics and dynamics of the deployed sail in a simulated space environment. The solicitation called for 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.. In addition this system was required to meet the characteristics given in Table 1. A sub-L_1 solar monitoring mission concept was also provided as a reference mission for guidance in design and scalability issues.

Dimensions:	20 meters x 20 meters or greater
Sail Subsystem Areal Density	< 20 g/m^2 (with scalability to 12 g/m^2 for 10^4 m^2)
Stowed Volume	< 0.5 m^3 (with scalability to 1.5 m^3 for 10^4 m^2)
ThrustVector Turning Rate about roll axis:	> 1.5°/hr
Effective Sail Reflectance	> 0.75
Anti-sunward Emissivity	> 0.30
Thrust Vector Pointing Range	± 22.5° (centered on the solar vector, thrusting anti-sunward)
Membrane Characteristics	space-durable, tear-resistant material designed for an operational lifetime of at least 1 year in the near-GEO environment.
System Flatness	Effective for Propulsion
ACS	3-axis, minimize propellant usage

Table 1: Cycle 1 System Level Ground Demonstration Required Characteristics

Solar Sail Integrated Software Tools

The second of two SSP research elements in the ISTP cycle 1 called for set of integrated set of 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 GNC subsystem on a future flight mission. In addition, the tools were required to be applicable to a solar sail mission of characteristic given in Table 2 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
- Attitude control system dynamics
- Navigational sensors

Dimensions:	100 meters x 100 meters or greater
Sail Subsystem Mass	120 kg
Spacecraft Mass	80 kg
Total Flight Mass	200 kg
Characteristic Acceleration @ 1 Au	0.35 mm/s^2
Sail Reflectivity	0.85
Mission Class	Sub L_1
Thrust Vector Pointing Range	Cone angle of 40°
Pitch Rates	1.5°/hr.

Table 2: Cycle 1 Integrated Software Tools Required Mission Characteristics

ISTP Cycle 1 Development Work

System Level Ground Demonstration

SSP awarded ground demonstration contracts to two separate companies that had proposed two separate types of technologies in order to achieved the project objective. ABLE Engineering Company's (AEC) proposed work, based on their prior ST 7 work[3], incorporate their rigid coilable boom, a C_P/C_M ACS subsystem and partner SRS' CP1 for a sail membrane. L'GARDE Inc. proposed work, based on the experience they gained on ST 5[4] and as the sail provider for Team Encounter[5], incorporate their inflatable and sub-T_g rigidizable boom, a control vane based ACS and Mylar for the sail membrane. A technical description of work being performed by AEC[6] and L'GARDE[7] is found in the respective teams papers at this conference. The parallel testing and development of these two system level demonstrations that have varied technologies in the three major components removes the risk of this technology development from encountering a single point failure. The system level ground demonstration work has been divided into three phases. A six 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 given in Table 3 and a preliminary test plan for the following two twelve month phases.

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: Cycle 1 Design Reference Mission Characteristics

The 12-month hardware development phase began in June 2003. In this phase both team are building and testing components and subsystems with 10-m quadrants. The most comprehensive of these tests will be when the respective teams deploy their integrated boom and sail subsystem in the LaRC 14-m vacuum facility in the first half of 2004.

Following a successful second phase the teams will culminate their work in a twelve month system verification phase. In this phase both teams will build and test fully integrated 20-m sail systems that will be comprised of its launch packaging container, and an operational ACS subsystem. In the first half 2005, the respective teams will test their system in the 30-m thermal vacuum system at Glenn Research Center's Plumbrook Space Power Facility.

Applicability to OSS Missions

The Sun Earth Connection (SEC) division of OSS has identified solar sail propulsion as an enabling technology[8] because it is the only propulsion system that can deliver several SEC mission payloads to their desired destinations. Figure 2 shows a roadmap of these missions and the Solar sail performance characteristics required. The axis on the left is the solar sail system areal density which is shown decreasing as the axis moves towards the top of the plot while the bottom axis is time. The first two missions shown on this chart (Flight Validation and Geostorm) are missions that would provide the space validation and confidence that would enable the last four roadmap missions (Solar Polar Imager, L1-Diamond, Particle Acceleration Solar Observatory, and Interstellar Probe). The first two of these missions are Mid-term mission and their mission requirements have strongly influenced the formulation and implementation of the previous described SSP work.

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 began building a technological foundation that can be readily used by future programs (e.g., New Millennium Program) in their pursuit of providing space validation of this technology.

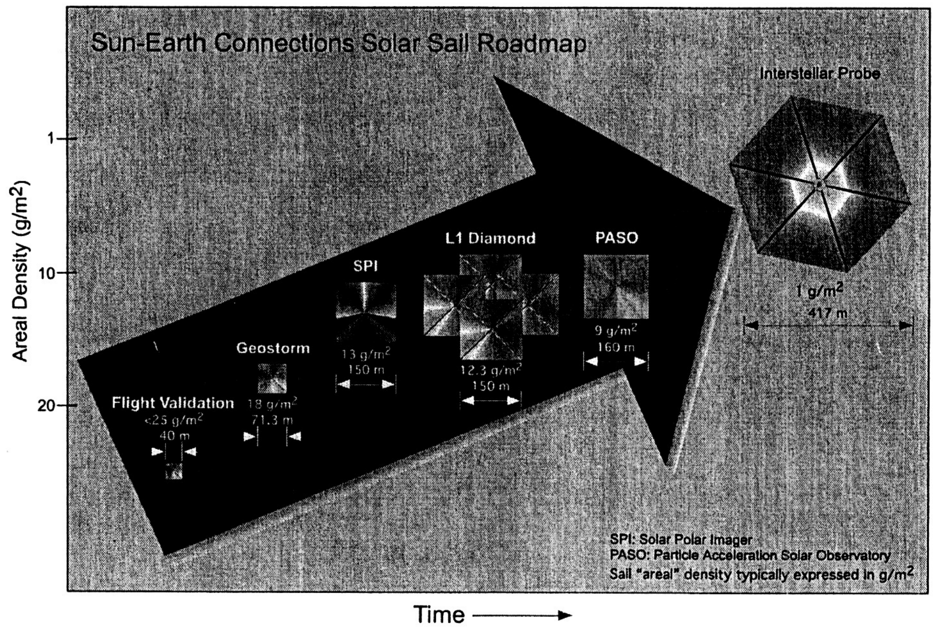

Figure 2: 2003 Sun Earth Connection Solar Sail Mission Roadmap

References:

[1] Integrated I-Space Transportation Plan, NASA, 2000.

[2] G. Garbe, 2002 Solar Sail Technical Assessment Group Report, NASA, 2002.

[3] D. Murphy et al., "Scaleable Solar Sail Subsystem Considerations", 43rd AIAA, Structures, Structural Dynamics, and Materials Conference, AIAA2002-1703.

[4] West, J. L. and B. Derbes, "Solar Sail Vehicle Design for the Geostorm Warning Mission", Structures, Structural Dynamics, and Materials Conference, AIAA2000-5326.

[5] B. Derbes et al., "Team Encounter Solar Sails", 39th AIAA Joint Propulsion Conference, AIAA2003-4797.

[6] D. Murphy et al., "Progress and Plans for a System Level Demonstration of a Scaleable Square Solar Sail", 39th AIAA Joint Propulsion Conference, AIAA2003-4794.

[7] D. Lichodziejewski et al., "Bringing an Effective Solar Sail Design to TRL 6", 39th AIAA Joint Propulsion Conference, AIAA2003-4659.

[8] Sun Earth Connections Roadmap 2003 – 2008, September 2002.