

## **In-Space Propulsion**

## **Solar Sail Propulsion**

## **Technology Development**

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# **In-Space Propulsion (ISP) Solar Sail Propulsion (SSP) Technology Development**

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**An overview of the rationale and content for Solar Sail Propulsion (SSP), the on-going project to advance solar technology from technology readiness level 3 to 6 will be provided. A descriptive summary of the major and minor component efforts underway will include identification of the technology providers and a listing of anticipated products. Recent important results from major system ground demonstrators will be provided. Finally, a current status of all activities will be provided along with the most recent roadmap for the SSP technology development program.**

## **I. Background**

Solar sails are a near-term, low-thrust, propellantless propulsion technology suitable for orbital maneuvering, station keeping, and attitude control applications for small payloads. Furthermore, these functions can be highly integrated, reducing mass, cost, and complexity. The solar sail concept is based on momentum exchange with solar flux reflected from a large, deployed thin membrane. Thrust performance increases as the square of the distance to the Sun. In comparison to conventional chemical systems, there are missions where solar sails are vastly more and less economical. The less attractive applications involve large payloads, outer solar system transfers, and short trip times. However, for inclination changes and station keeping at locations requiring constant thrust, the solar sail is the only economical option for missions of more than a few weeks duration. Solar Sails are environmentally friendly and inherently safe technologies. There are no toxic fuels or combustion byproducts, no extreme temperatures or pressures, no high electrical voltages or currents, no heavy masses, or rapidly moving mechanisms. They are simple structures.

Solar sails were identified in a study process performed under the auspices of the In-Space Propulsion (ISP) Technologies Program and funded by NASA's Space Science Mission Directorate. It is the purpose of the ISP program to advance midlevel maturity propulsion technologies to a level needed to be selected and used in NASA robotic science missions. Solar Sail Propulsion (SSP) is the name given to the activity to achieve that goal. The SSP mission statement has three main points:

1. Raise solar sail technology as a primary propulsion system for inner solar system NASA missions to TRL 6.
2. Solar sail propulsion technology shall be scalable to inner solar system NASA missions
3. Attain closest approach to TRL 6 possible on the ground by the end of FY06

## **II. Technology Roadmap for Solar Sails**

NASA's Sun-Earth Connection program has published an evolutionary vision for utilizing solar sails to advance their science goals.<sup>1</sup> Shown in Fig. 1, this mission need roadmap starts with a modest-sized, near-term technology demonstration mission and ends with a very large, very gossamer interstellar probe.

Geostorm, a space weather-related mission, is of less interest now than when the report was written. In the interim, the National Oceanic and Atmospheric Administration has decided to press forward with more conventional propulsion options. The nearest term project pulling the sail technology is the Solar Polar Imager (SPI), followed by the L1 Diamond and the Particle Acceleration Solar Orbiter (PASO). Each of these is addressed below. The new human exploration mission initiative announced by President Bush recently has a component of in-space technology development under the Humans, Robotics, & Technology program. Applications to stationkeeping communications platforms and radiation hazard detection are under consideration.

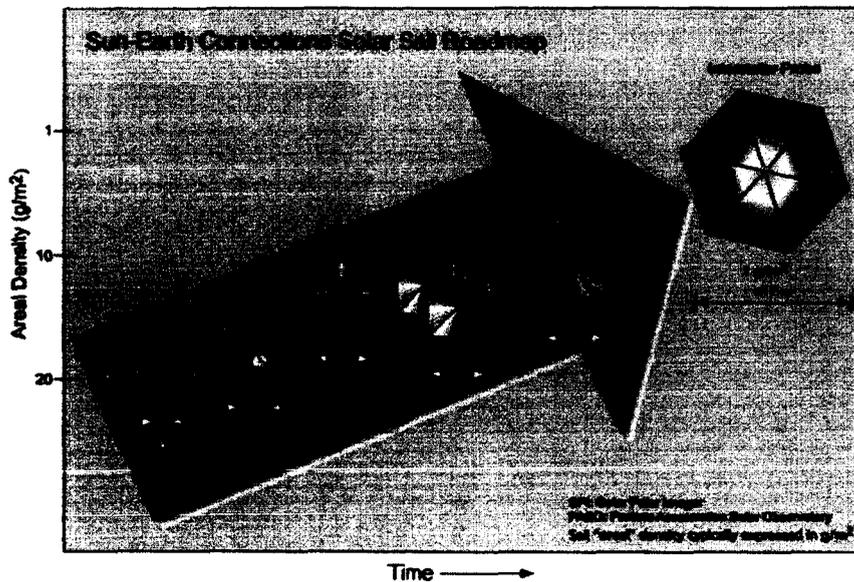


Figure 1: Primary mission pull.

#### A. Solar Polar Imager

Missions involving a maneuver to change the inclination of their orbit are known to be challenging for chemical rockets. In equation (1),  $V$  is the starting orbital velocity and  $\theta$  is the plane change angle.<sup>2</sup> Equation (1) gives the standard relationship for calculating the effect of a velocity change on an orbit.

$$\Delta V = 2V \sin \frac{\theta}{2} \quad \text{Eq. 1}$$

This assumes the thrust is directed along the angular momentum vector of the orbit. For chemical systems, the small penalty resulting from the instantaneous change in the direction of the angular momentum vector can generally be ignored. For solar sails, the changing orientation between the angular momentum vector and the solar vector would have to be factored in to the maneuver. The mass penalty for carrying propellant to do these type maneuvers impulsively is high and is one of the strong justifications behind the assessment that solar sails are an enabling technology for the SPI. The science objectives of this mission include measurement of the Sun's polar irradiance and magnetic field, imaging the full effect of coronal mass ejections (CMEs) and evolution on the full three-dimensional corona, and linking of variations in the high-latitude heliosphere to surface conditions. The mission profile calls for travel in the ecliptic, then taking up a 0.48 AU heliocentric circular orbit inclined 60°. Mission designers have estimated a sail ~150 m across will be needed.

A study by Harris<sup>3</sup> established the initial mission concept. Later, studies by Neugebauer<sup>4</sup> and Ayon et al.<sup>5</sup> refined the science objectives and the mission and system design. This current flight system concept was reported in a 1999 study by the Jet Propulsion Laboratory. The SPI mission concept was recently selected (Liewer<sup>6</sup>) for further refinement under the Vision Mission NASA Research Announcement (NRA).

#### B. L1 Diamond

The L1 Diamond mission will make use of a solar sail's unique propellantless thrust nature to hover in space sunward of the Earth-Sun L1 libration point. Conventional spacecraft can be parked in a relatively small region of space that will require only occasional station-keeping thruster firings. The always-on thrust of a sail can be used to park a science experiment in a much larger volume of space. The vantage points available to science are only a function of sail size and lightness and a relatively large range of locations is reachable within the near-term state of the art. L1 Diamond is a constellation of four spacecraft cooperatively and concurrently gathering data to validate models of processes in situ through a three-dimensional sample region of space.

L1 science objectives are to measure the properties of solar wind turbulence (as seen in density, velocity vector, and magnetic field) as a function of separation in space and time, ranging from the dissipation scales of hundreds of kilometers to the outer scale of millions of kilometers. Direct measurements of the possible spatial symmetries of the turbulence is also desired along with measurements of the spatial variation in propagating waves, shocks, and other disturbances in the solar wind. Another objective is the discovery of associations of the turbulence with suprathermal and energetic particles. The Delta IV launch vehicle has been proposed to put the spacecraft into a ballistic transfer from Earth to an Earth-Sun L1 halo orbit that would take approximately ninety days. The solar sail would accomplish the transition from the initial libration point to the various constellation stations. Three spacecraft will be in a triangle formation whose centroid is 280 to 500 Earth radii sunward of Earth on the Sun-Earth line. A fourth spacecraft is located above the ecliptic plane. Continuous solar viewing for at least three years is needed.

#### **C. Particle Acceleration Solar Orbiter**

PASO will drive the next development of the next class of solar sails that will be capable transferring a science instrument payload to a very close solar orbit (0.169 AU). The PASO measurement strategy is to capture high-resolution images of high-energy solar flares, allowing the detection of composition. The mission will also employ a neutron spectrometer and a gamma-ray spectrometer. Solar wind and magnetic field instruments will also be included. The science objectives are to understand particle acceleration mechanisms, distinguish between flare and shock accelerated particles, and study the active region evolution. The mission concept begins with a Delta launch and then transfer from 1 AU to a 0.169 AU circular solar equatorial orbit with a period of 25.4 days. The transition to the final lower solar orbit will take 3 yr during which active CME source regions will be in continuous view. Mission science operations will continue another 4–5 yr in the final orbit.

#### **D. Other Missions for Solar Sails**

Since the thrust of a solar sail is small, it does not suit missions involving massive payloads or short trip times. However, if a very high ultimate velocity is needed, such as fast flyby missions to the outer planets or extra-solar system destinations, solar sails can be the only feasible alternative. Although solar pressure has greatly attenuated at those distances, the long trip time out at constant thrust integrates to a considerable total velocity increase. A study by Price and others showing how the flight times for solar sails to the heliopause is less than half of the most efficient reaction jet rockets.<sup>7</sup> Recent research by Taylor and Matloff suggests that the outer planetary stopover missions for small robotic science packages may also be a possibility utilizing a bimodal sail. The concept is an unconventional, high-altitude pass, low-dynamic-pressure aerobraking maneuver. Gossamer mass properties could enable trajectory shaping with relatively nonstressing (small thermal or pressure shocks) aerobrake maneuvers. Sail and boom loads for a Titan aerocapture might be only a fraction of what the same sail would encounter from solar pressure in Earth orbit.<sup>8</sup>

The Interstellar Probe Mission will measure, in situ, the properties and composition of interstellar plasma and neutrals, low-energy cosmic rays, and interstellar dust. The technology challenges are great. Mission designers initially believed at least a 200-m highly reflective sail will be needed with an areal density of  $<1 \text{ g/m}^2$ —beyond any known technology. However, Matloff showed in a study for the ISP office in the summer of 2004 that outer the interstellar probe mission could be accomplished for modest sized payloads with conventional sail technology with mission duration not excessively more than alternate propulsion technologies.

#### **E. Foundations for the Roadmap**

In January 2002, April 2003, and March 2004, the results of a panel of experts from industry, academia, and the Government convened to assess the state-of-the-art of solar sail technology and provide guiding inputs for the ISP program to use in formulating a plan to bring the maturity of solar sails to technology readiness level (TRL) 6.<sup>9</sup> This level is defined as a full system, validated in a relevant environment. The delineation between it and the next level is that TRL 7 must be in space. The conclusion of the initial Technology Assessment Group (TAG), summarized in Figure 2, was reaffirmed the following two years. In 2004, the TAG indicated that the state of the art had been improved dramatically, was maturing in the proscribed directions, and was addressing the priority needs in a developmental approach. The roadmap was found to be consistent with the recommendations of the technical community. Members of the TAG included US Government, industry, and academia. Export control regulations precluded foreign participation.

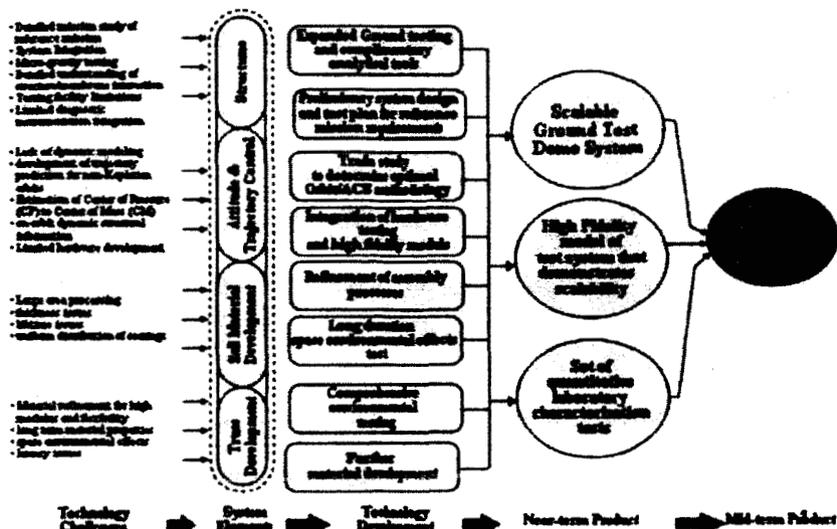


Figure 2. TAG Assessment and Recommendations for Solar Sail Technology Development

### III. Formulation of a Technology Development Program

The Solar Sail Propulsion (SSP) technology area was formed within ISP to accomplish the program objectives for solar sails utilizing the TAG's input. Organizing the topic area began with identifying that four different solar sail types existed. Each has specific characteristics (listed in Fig. 3) that identified a common class of missions and peculiar technology requirements. The first class is indicative of some validation flight concepts and can be said to have some component TRL 7 flight heritage through the Russian Znamiya program and the NASA Inflatable Antenna Experiment. The last mission type is one requiring extremely lightweight systems for which there are no TRL 3 candidates. The other two applications are the focus of the ISP program. In defining a roadmap for those, it logically fit a serial effort to develop first the 1 AU sail, and then extend the technology to the harsher environments at <0.25 AU from the Sun. Budget limitations drove the need to focus technology development on the most near-term classes. A convenient discriminator between the classes is the region of space in which they are intended to support missions.

| Mission Class     | Timeline  | SOA   | Technology Challenges   | NASA Mission Application  |
|-------------------|-----------|---|---|---|
| GEOSTO Short Life | Past/Now  | Encounter(?), Cosmos, ST-7, Znamiya, Inflatable Antenna Exp | AO, radiation belts effects, high GG torques  | None  |
| 1 Au              | Near Term | ISP Ground Demo, ST-5 Constellation                         | Validation in a space environment, infusion into mission applications                         | L1 Diamond Solar Polar Imager (SPI)   |
| <0.25 Au          | Mid-Term  | Mission analysis, Future ISP work                           | Materials environments, Thrust vector range, Lightweight system, 100m system scale size       | Particle Accretion Solar Observatory (PASO)<br>Titan Explorer<br>Saturn Ring Observer                         |
| Extra Solar       | Far-Term  | Mission concept analysis, Gossamer, Encounter(?)            | Ultra-lightweight system integrated system architecture<br>Sub to kilometer system scale size | Interstellar Probe (ISP)<br>Geospace System Response Imager (GSR I)<br>Outer Heliosphere Radio Imager (OHR I) |



Figure 3: Sail technology classes

An investment strategy was derived utilizing the guideline that at least 75% of the program investment would go to competitively selected efforts. The budget given by NASA drove the procurement of the 1 AU sail in three annual NRA cycles. The next inner solar system sail class would then follow in three additional cycles. Figure 4 illustrates the SSP roadmap.

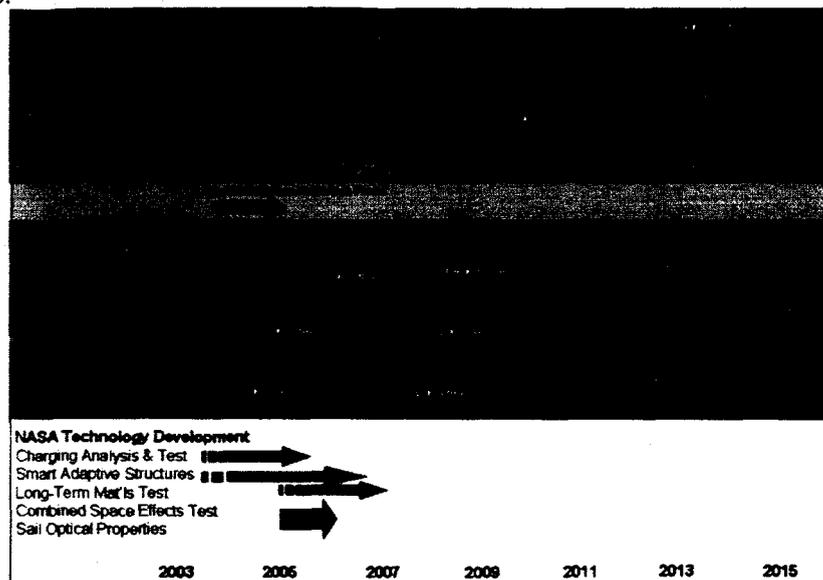


Figure 4: SSP roadmap.

#### IV. TRL 6 Definition

As the SSP program has continued to mature at a rapid pace over the as two years, our ability to understand the further development needs have come more into focus. Recognizing that past technology effort have failed to retire enough risk to enable science mission managers to apply those technologies, the ISP program has chosen the SSP project to serve as a pathfinder for defining what must be done to make a successful claim to TRL 6 maturity.

#### V. Future Plans

In response to the recommendations of the 2004 Solar Sail TAG, a solicitation is currently planned for the ROSS NRA to procure some extremely low thrust measurements using a solar simulation facility. Also, analyses for predicting the variation with system size of solar sail characteristics such as mass, stress distribution, and propulsive efficiency will be sought from industry to complement those being developed in-house by the ISP project. Directed tasks were proposed by Marshall Space Flight Center and Glenn Research Center for (1) long duration, normal dosage tests of solar sail materials in a simulated space environment (2) cyclic loading of sail material while exposed to space environmental effects combined with characterization of large sail and edge support technology using simulated solar Energy, cold walls and hard vacuum, and (3) compilation of solar sail optical property data. The directed tasks are contingent on the availability of funds, but were included in the budget request sent forward by the agency for FY05.

In the farther term, ISP is finalizing an agreement to partner with the New Millennium Program to provide a solar sail system space validation demonstration on the ST9 mission planned for launch in 2009. Consistent with the TAG recommendations, ISP plans to invest in the design, build and demonstration a 40 meter square sail on the ground to bridge the current ground development program with the Solar Sail Flight Validation (SSFV) mission.

## VI. Summary

The objective of the SSP technology area investment is to develop solar sail technology to the level of validating a system in a relevant environment. High value science missions have been identified that require solar sails. Experts have met and defined the development needs and products, and a time-phased program has been laid out to prepare NASA to go places only sails can go.

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## VII. References

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