

PLACES ONLY SAILS CAN GO

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ABSTRACT

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. We compare the location and energies required for these applications between solar sails, advanced electric propulsion, and conventional rockets. We address the effect on mass fraction to understand solar sail mission cost and capability. Finally, the benefit of potential applications to near term science missions is reported.

Thrust

Solar Pressure dramatically increases as the square of the close distance to the sun. See Figure 1. It is a common mistake to assess mission performance by calculating the distance from the sun at which the solar gravitational inward pull on the spacecraft mass is balanced by the outward push by photon pressure on the sail area. Were this method important, rockets would be of little use at all, plummeting back to

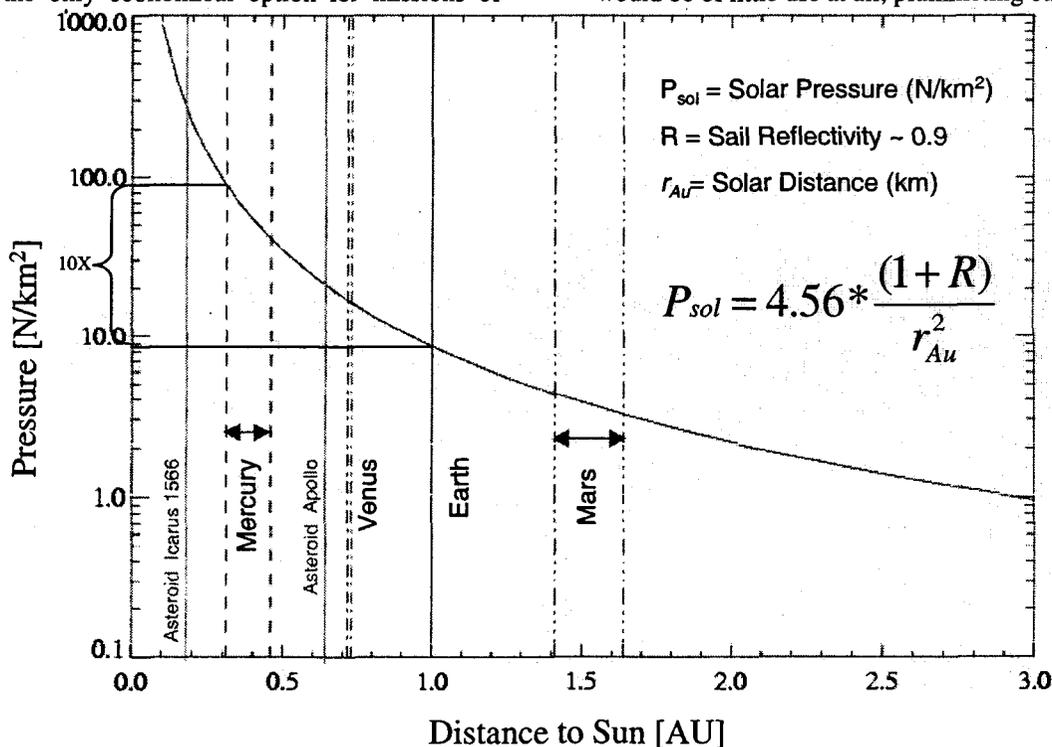


Figure 1. Variation of Solar Pressure with Distance to the Sun

the launch origin as soon as their propellant was consumed and thrust stopped.

Momentum management is the better strategy for mission design including those utilizing propellantless propulsion like sails.¹ A simple, but more facile force balance for heliocentric central force circular orbit motion includes gravity, solar pressure, and centripetal acceleration. The diagrams in Figure 2 illustrate this point for two "tacking" orientations of the sail. In the left hand figure, force on the sail is adding a thrust vector component in the same direction with the centripetal acceleration while the orthogonal component acts to increase the velocity. This maneuver raises orbital altitude. In

the right hand figure, components of the sail thrust are retarding the orbital velocity and acting along the centripetal acceleration. This maneuver decreases orbital altitude. By selection of the thrust magnitude (sail area) and thrust direction (sail orientation), a propulsion system with the full capability to maneuver to desired orbits. For planetocentric operations where the sunlight is not constrained to be from the direction of the central body, then the situations where sail force is additive to the gravitational vector rather the centripetal vector occurs. This provides for more options for thrust vectoring, but the ever-changing relationship between the gravity and solar vectors complicates the optimal mission profile.

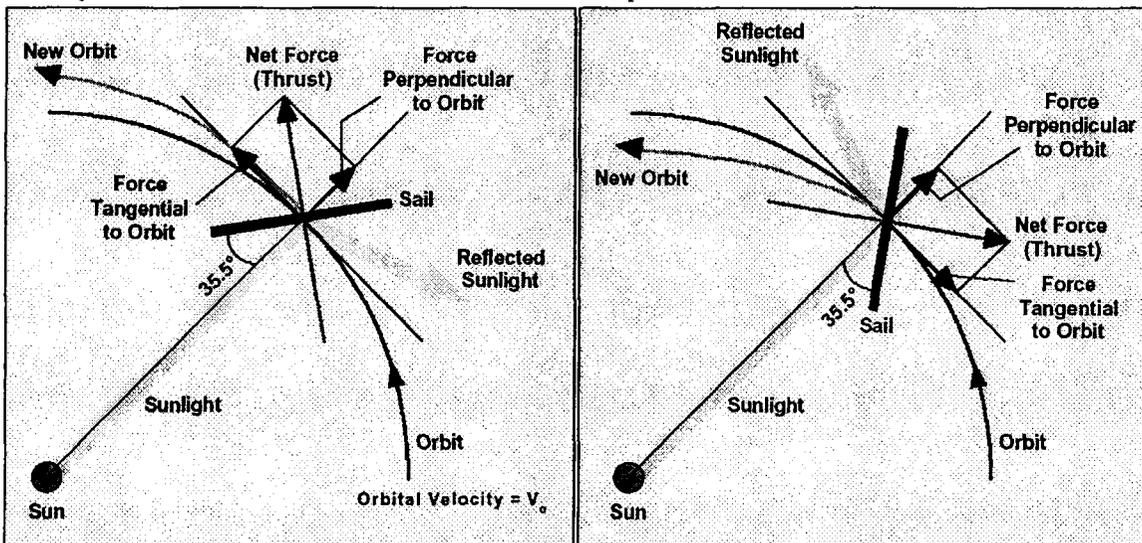


Figure 2. Solar Sail Flight Fundamentals [after McInnes, ref 7]

The consideration of the centripetal term also is evident when the orbital mechanics model is expanded to the restricted three-body problem. For the Earth and Sun (and infinitesimal spacecraft) situation, it seems intuitive that the L1 libration point is the balance between the earth's gravitational pull on one side and the sun's on the other. If this were the case, then what is the explanation for the L2 libration point that is on the side of the earth away from the sun? The more complete model is that the L1 point is the balance point in which the sun gravity plus centripetal acceleration is balanced by the earth's gravity and L2 is where the centripetal acceleration offsets both the earth and the sun's gravity. The L4 and L5 points are in the ecliptic, but displaced off the earth-sun line. They are regions of balance between the

combined centripetal accelerations and gravity fields of the earth and sun.

A solar sail's propellantless nature gives it a unique inherent ability for interaction with the libration points by adding a fourth entity (solar pressure) to the balance equation. Even though the forces involved are small, since they are acting at a near equilibrium position they can actually result in expanding the volume of space in which equilibrium can be obtained. The work of McInnes as expanded by Garbe illustrates this clearly (Figure 3).

A family of curves indicates regions of space where equilibrium positions are possible for solar sails. Instead of just the L1 and L2 points, whole planes of possibilities are enabled. These

are places only solar sails can go. Each equilibrium curve is characteristic of a sail/spacecraft system thrust-to-mass ratio. Sail area and mass are key and are conveniently combined in a metric called areal density. Typical units are grams of sail mass per square meter of sail (g/m^2). Several recent sail projects have selected approximately $24 g/m^2$ as their design goal. The legend in Figure 3 points to a contour (a plain in three dimensional space) extending almost normal to the earth for a very large region of space around the L1 point. Placed very high on this contour, sail supported spacecraft would be in a position looking down

on the polar regions of the planet (earth in this illustration). These mission orbits have been labeled “polesitters”. It should be noted that the locations are not directly above the earth’s pole and are actually a significant distance away from the earth. For polar viewing, a high inclination above the ecliptic (e.g. 40-50 degrees) is needed. There, the sail spacecraft can find equilibrium only if its greater than 200 earth radii out in space. The moon orbits at about 60 earth radii. These orbits are not strictly available to just propellantless systems, but constant thrust for months or years of station keeping could require a large mass of propellant.

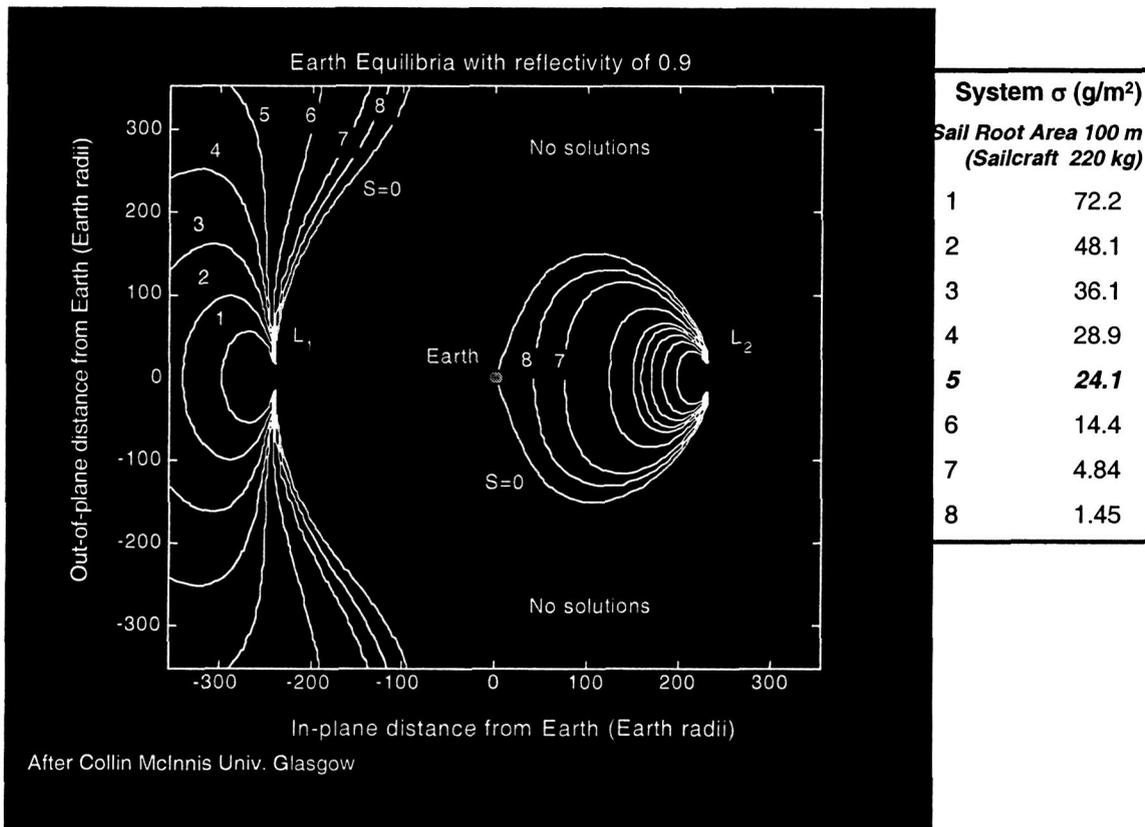


Figure 3. Non-Keplerian orbit contours available to solar sails [ref 6]

Inclination Changes

Missions that have to make an inclination change are known to be challenging for chemical rockets. In the equation below, V is the starting orbital velocity and θ is the plane change angle.² Equation (1) gives the standard relationship for calculating the effect of a velocity change on an orbit.

$$\Delta V = 2V \sin(\theta/2) \quad [1]$$

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 Solar Polar Imager (SPI). See Figure 4. 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 3-D.

corona, and linking of variations in the high latitude heliosphere to surface conditions. The mission profiles calls for travel in the ecliptic then taking up a 0.48 AU heliocentric circular orbit inclined 60 degrees. Mission designers have estimated a sail in the vicinity of 150 meters across will be needed.⁵



Figure 4 The NASA Solar Polar Imager Mission Concept [ref 3]

Long duration missions, high ultimate speed

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.⁵ Figure 5 depicts the comparison between a solar sail and a contemporary electric propulsion system (NSTAR). Chemical rockets are not a viable candidate for these missions.

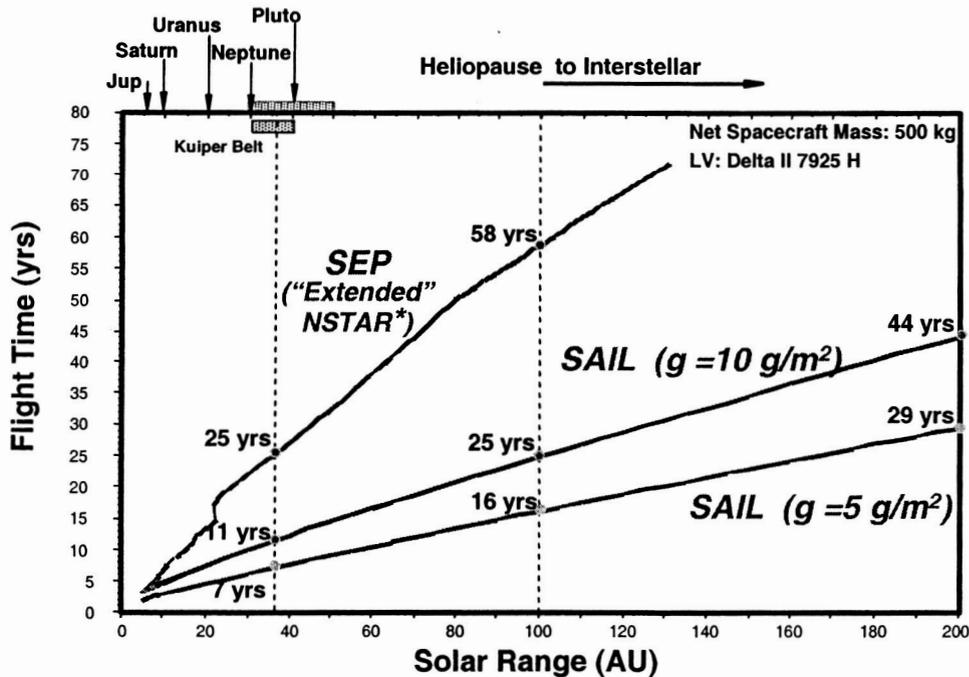


Figure 5. SEP/Solar Sail Performance Comparison

NASA's Sun-Earth Connection Program under the Office of Space Sciences has entered such mission concepts into its official vision. Figure 6 provides a pictorial summary of the Interstellar Probe Mission Concept. It 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 believe at least a 200-meter highly reflective sail will be needed with an areal density of less than 1 g/m^2 - beyond any known technology.

Mass fraction and implications on cost & mission capability

The ratios among payload mass, structural mass, and propellant mass are useful metrics for comparing space transportation options. The propellant fraction has been tied to specific impulse in conventional rocket studies by the familiar relationship.⁴

$$M_0 / M_{bo} = e^{(\Delta V / I_{sp} g_0)} \quad [2]$$

Where M_0 is the initial mass of the fully loaded vehicle and M_{bo} is the mass at burnout when all but the ullage propellant has been utilized. ΔV is the velocity change achieved and g_0 is the gravitational constant. Specific impulse (I_{sp}) is the widely used term that relates to the efficiency at which the propulsion system converts fuel mass to vehicle momentum. For a propellantless propulsion method like solar sails this value has little meaning. Claiming infinite I_{sp} may be good cheerleading but it's not particularly useful in comparing alternatives. Garbe has suggested we consider the sail mass and the velocity achievable per unit time as the specific impulse.⁵ In this case I_{sp} retains its "per unit propulsion mass" relationship, but loses the time integrated nature of the impulse relationship. Nevertheless the following equation is provided for illumination.

$$I'_{SP} = \frac{M_{SC} \Delta V}{g M_{SS_Sys}} \quad [3]$$

M_{SC} is the total mass of the space vehicle including the sail, the bus and the payload. M_{SS_Sys} is the mass of the sail propulsion system only. It does include all the sail system

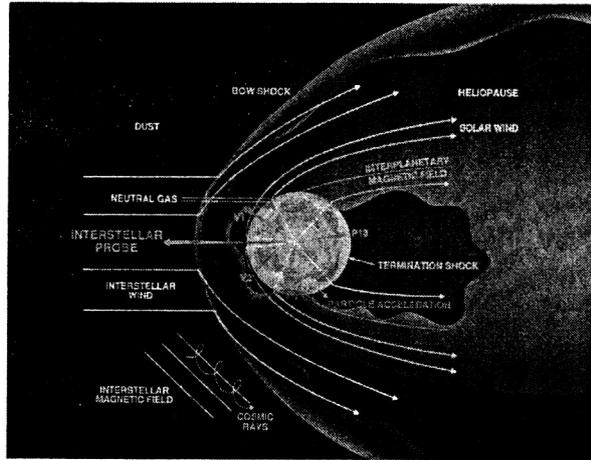


Figure 6. Interstellar Probe Mission Concept [ref 3]

components such as booms, films, coatings, ripstops, riggings, deployment and rigidization mechanisms, sensors, and integral attitude control assemblies.

Structural efficiency can be tied to the performance through the characteristic acceleration, a_0 . It relates to the mass of the spacecraft. McInnes chose to include the bus and sail only.⁷ In Garbe's re-interpretation, it is the full launched mass and therefore includes the payload mass. Figure 7 indicates how propellantless sails compare with high I_{sp} solar electric propulsion (SEP) and conventional chemical propulsion for missions of ever increasing length.

The slopes of the curves indicate that sails and SEP are competitive for short missions and that situation improves as the missions get longer. Eventually, the totally propellantless nature of sails overcomes even the highly efficient electric propulsion technology. This simplified analysis ignores two important factors. The first is the size of the payload being moved. The figure is for an extremely modest 100 kg payload. The second factor is the solar flux. This figure also is based on the solar pressure in the vicinity of earth orbit. It is dramatically less in the outer solar system and dramatically higher in the inner solar system. The importance of this latter point is somewhat reduced by considering the option of using a close solar approach to begin a trip to the outer solar system. Matloff's has demonstrated analytically the benefits of the sundiver trajectory.⁸

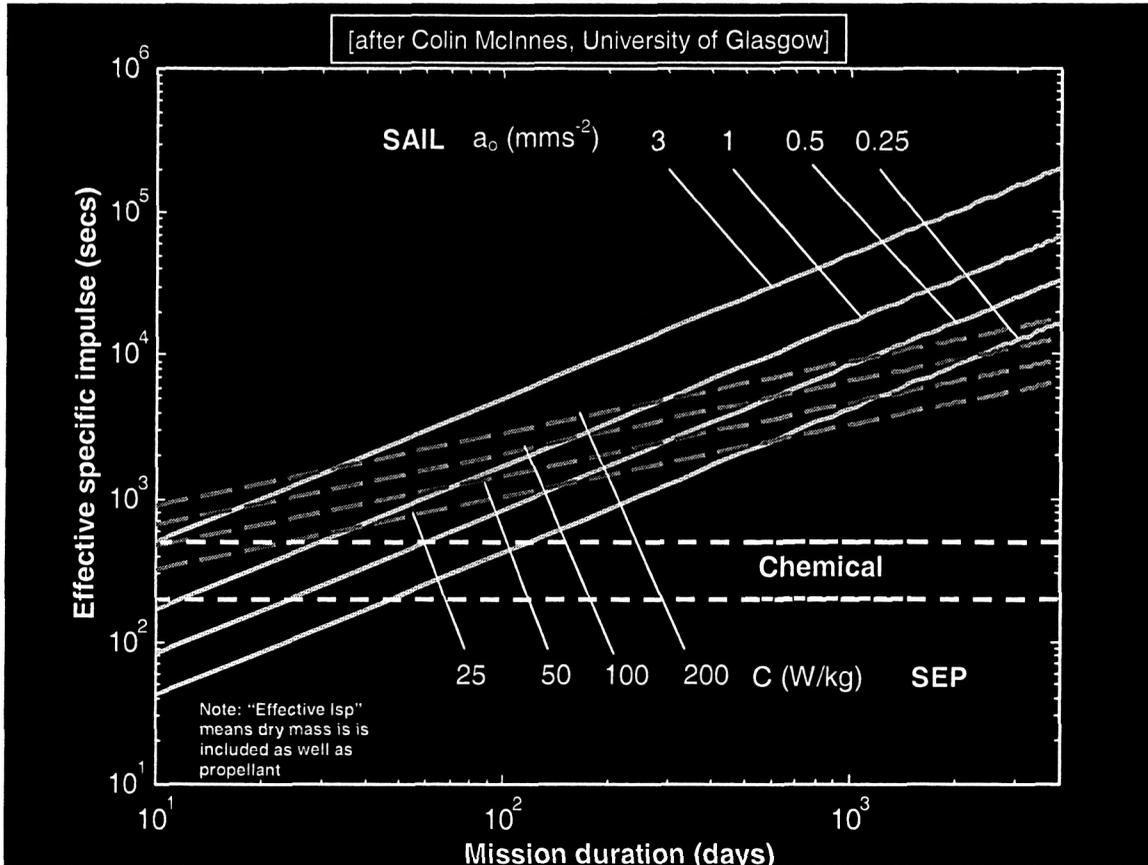


Figure 7. Comparison of efficiency between solar sail, solar electric, and conventional chemical propulsion for missions of increasing duration.

Some Potential NASA Mission Applications

In addition to SPI and the interstellar probe mission concepts, NASA is also considering solar sails for missions in unconventional earth orbits, a station in the vicinity of the earth-sun L1 point, and a very close circular solar equatorial orbit.

For example, the Dayside Boundary Constellation solar sail is used to advance the node of precession of an elliptical earth orbit so that the spacecraft revisits the same region of space to sample the interaction of solar wind with the Earth's magnetosphere. The science objectives are to measure the asymmetric, dynamic bow shock and magnetosphere structures. Also the mission will search for the causal relationships between the solar wind, the foreshock, and the magnetosheath. The spacecraft is located in the magneto tail region, enhancing the science return and reducing

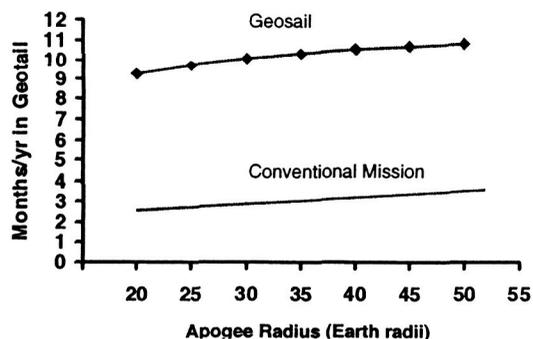


Figure 8. Dwell time increase from solar sail mission risk. Choosing a sail for orbital maneuvers significantly underlying orbital mechanics is similar to investigations documented by McInnes and Alexander at a European conference last year.¹⁰ increases the time the observer Figure 8 illustrates the 3-5X

multiplier on dwell time versus the chemical propulsion alternative.

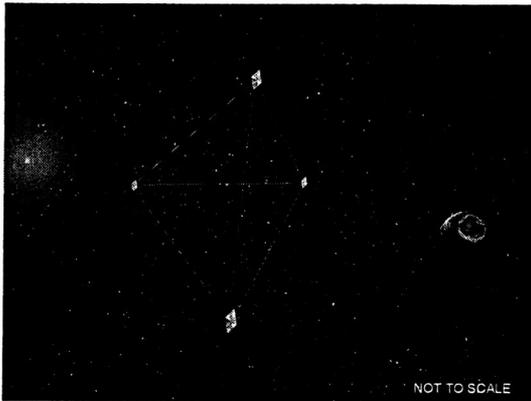


Figure 9. The NASA L1 Diamond Mission Concept [ref 3]

The L1 Diamond mission will use the aforementioned ability to stand off of the Earth-Sun L1 point. It is a constellation of four spacecraft gathering data to validate models of processes in-situ and in-flux through a three dimensional region of sample. See figure 9. 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 convected and 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 suggested to put the spacecraft into a ballistic transfer from Earth to L1 Halo (~90 days). The solar sail would accomplish the transition from L1 to constellation stations. Three spacecraft will be in a triangle formation whose centroid is 280 - 500 Re sunward of Earth on Sun-Earth line. A fourth is located above the ecliptic. Continuous solar viewing for at least three years is needed.

The Particle Acceleration Solar Orbiter (PASO) is a daunting challenge in which a sail will be required to transfer a science instrument payload to a very close solar orbit (0.169 AU). See figure 10. The PASO measurement strategy is to capture high resolution images of high energy

solar flares allowing the detection of composition up to Fe. 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 (Period: 25.4 days). The transition to the final orbit will take three years in which active CME Source regions will be in continuous view. Mission life will then extend to another 4-5 years in the final orbit.



Figure 10. PASO Mission Concept [ref 3]

Technology Challenges

In January of 2002, the results of a panel of experts from industry, academia, and the government was formed to assess the state of the art of solar sail technology and provide guiding inputs for the In-Space Propulsion Program to use in formulating a plan to bring the Technology Readiness Level (TRL) of sails to the TRL 6. This level is defined as a full system validated in a relevant environment. The delineation between it and the next level is use in a space mission. The result of the panel is summarized in Figure 11.

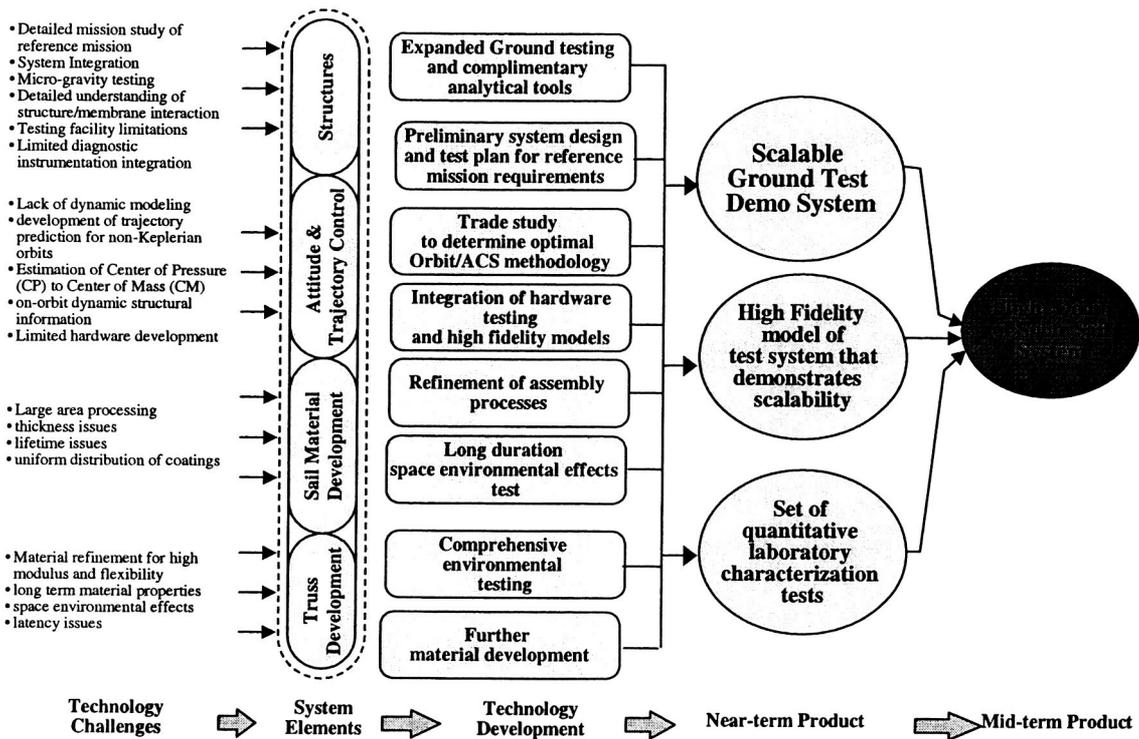
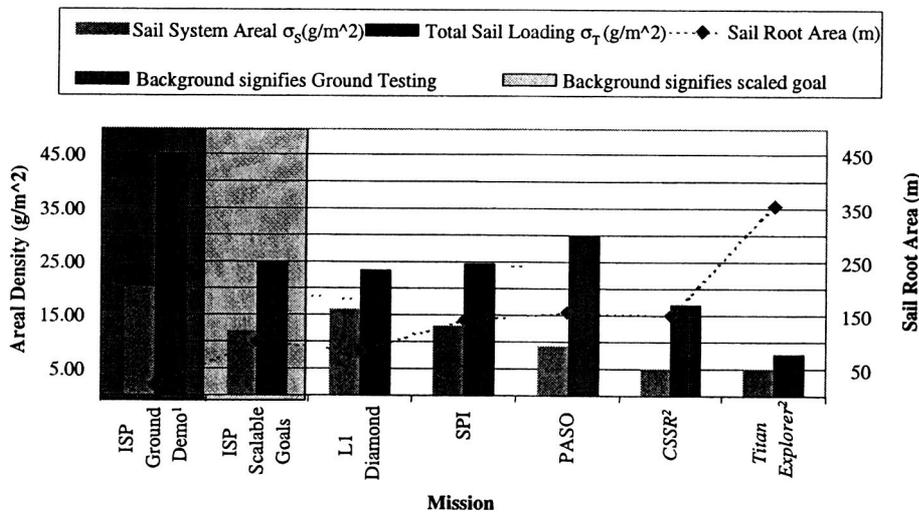


Figure 11. Solar Sail Technology Assessment Group Roadmap In-Space Propulsion Program [ref 9]

In addition to the workshop results, an assessment of mission pull was utilized to drive down to the next more detailed level of requirements definition. Looking across the board at the mission concepts, Figure 12 was derived from a survey of the two key sail design parameters, areal density and root area. The

former indicates the level of material science and fabrication knowledge needed. The latter indicates the design expertise needed as the nature of the structural solution evolves sharply at transition through plateaus around 15meters, 70 meters, and 150 meters.



Notes: 1) ISP Ground Demo σ_T assumes non-sail system mass of 10 kg
 2) Solar Sail Propulsion is being studied to determine its viability to SSE Missions

Figure 12. Survey of sail technology metrics for key SEC missions

Future plans

NASA plans a vigorous program to bring solar sails to prepare solar sail technology for validation and flight implementation in the missions shown. After review of the technology and the mission set, it became apparent that four classes of solar sail technology were under consideration. These are

- Short Duration / LEO
- 1 AU
- <0.25 AU
- Outer planet/extra-solar

The first class is indicative of some validation flight concepts and can be said to have some TRL 7 flight heritage through the Russian Znamiya program and the NASA Inflatable Antenna Experiment (IAE). 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 less than 0.25 AU from the sun.

In Figure 12, the roadmap developed by the In-Space propulsion program is presented. The objective of the program 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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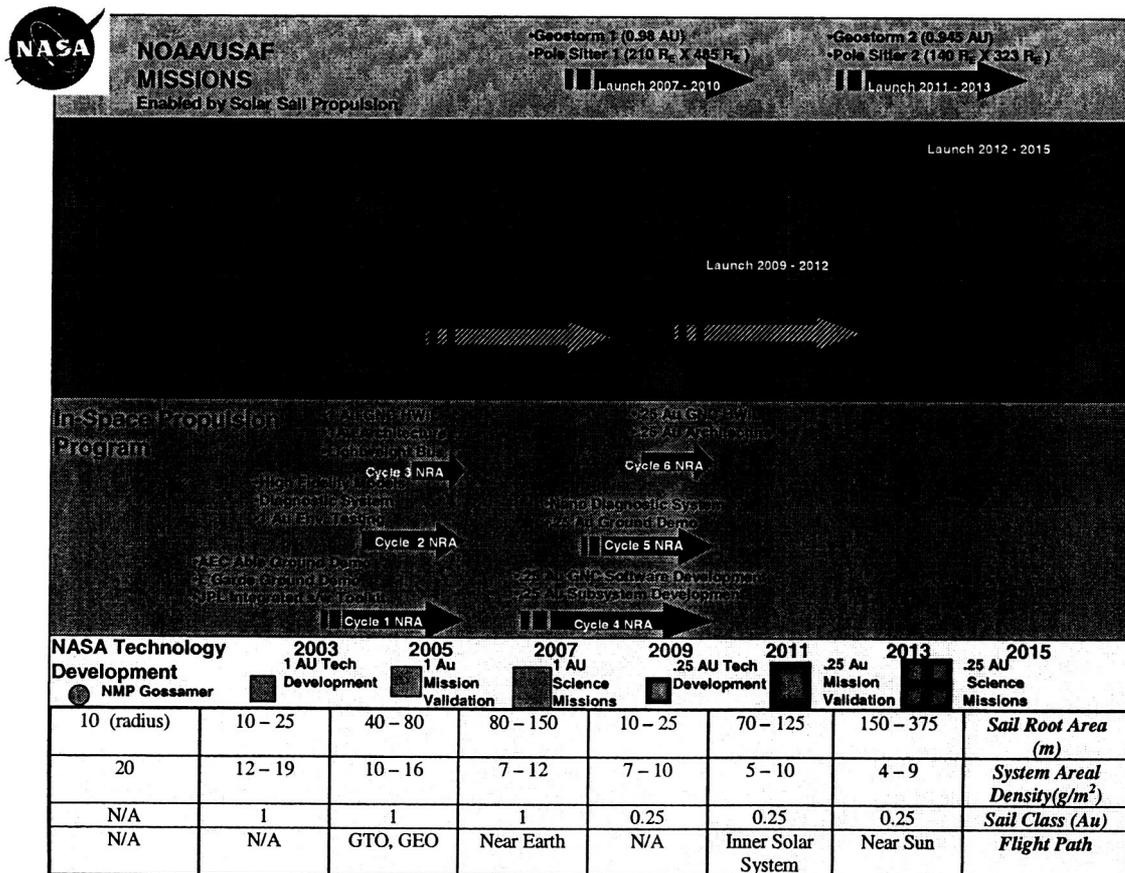


Figure 12. Solar Sail Technology Development Roadmap

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