

Solar Sail Roadmap Mission GN&C Challenges

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The NASA In-Space Propulsion program is funding development work for solar sails to enhance future scientific opportunities. Key to this effort are scientific solar sail roadmap missions identified by peer review. The two near-term missions of interest are L1 Diamond and Solar Polar Imager. Additionally, the New Millennium Program is sponsoring the Space Technology 9 (ST9) demonstration mission. Solar sails are one of five technologies competing for the ST9 flight demonstration. Two candidate solar sail missions have been identified for a potential ST9 flight. All the roadmap missions and candidate flight demonstration missions face various GN&C challenges. A variety of efforts are underway to address these challenges. These include control actuator design and testing, low thrust optimization studies, attitude control system design and modeling, control-structure interaction studies, trajectory control design, and solar radiation pressure model development. Here we survey the various efforts underway and identify a few of specific recent interest and focus.

I. Introduction

NASA's In-Space Propulsion (ISP) program is currently completing a comprehensive ground test demo project^{1,2}. The goal of this project is to raise the Technology Readiness Level (TRL) of Solar Sails to 6. The TRL is a NASA standard for flight hardware that is defined in Figure 1. TRL 6 is defined as "System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)."

For solar sails, the standard TRL 6 definition is difficult to test in a ground environment. The one-g environment dominates the structural dynamics that will occur in space. Thus, the ISP Solar Sail Project (SSP) has expended a considerable effort to develop high-fidelity simulations of on-orbit Guidance, Navigation and Control (GN&C)³⁻⁵ for solar sails. Some component-level testing of GN&C actuators is also underway^{5,6}.

Solar sails present unique problems for GN&C. The large, flexible structure has a high inertia-to-mass ratio. Potential structural deformation could affect actuator efficacy. Thrust model errors and uncertainties affect optimal low-thrust trajectory design and execution. If four vanes are used for control, an over-determined problem similar to having too many reaction wheels results⁷. These are a few of the more prominent of the many challenges facing solar sail GN&C.

Roadmap missions for science have been defined by NASA for solar sails⁸. The two missions of nearest-term interest are Heliosstorm and Solar Polar Imager. Heliosstorm is a mission to the L1 libration point in near-Earth orbit, while Solar Polar Imager is a mission to investigate the poles of the Sun. Each of these missions presents unique challenges for solar sail GN&C.

Prior to any science missions, it is highly likely that solar sails will require a demonstration mission in order to build confidence in deployment, controllability, and performance. NASA's New Millennium program sponsors a series of flights known as Space Technology (ST) missions. These missions are intended only to demonstrate new technology and do not require a science justification. The next proposed flight is the ninth in the sequence, or ST9. Currently, solar sails is one of five different technologies competing for the ST9 mission (aerocapture, pinpoint entry landing and descent, large optical structures, and formation flying are the other four).

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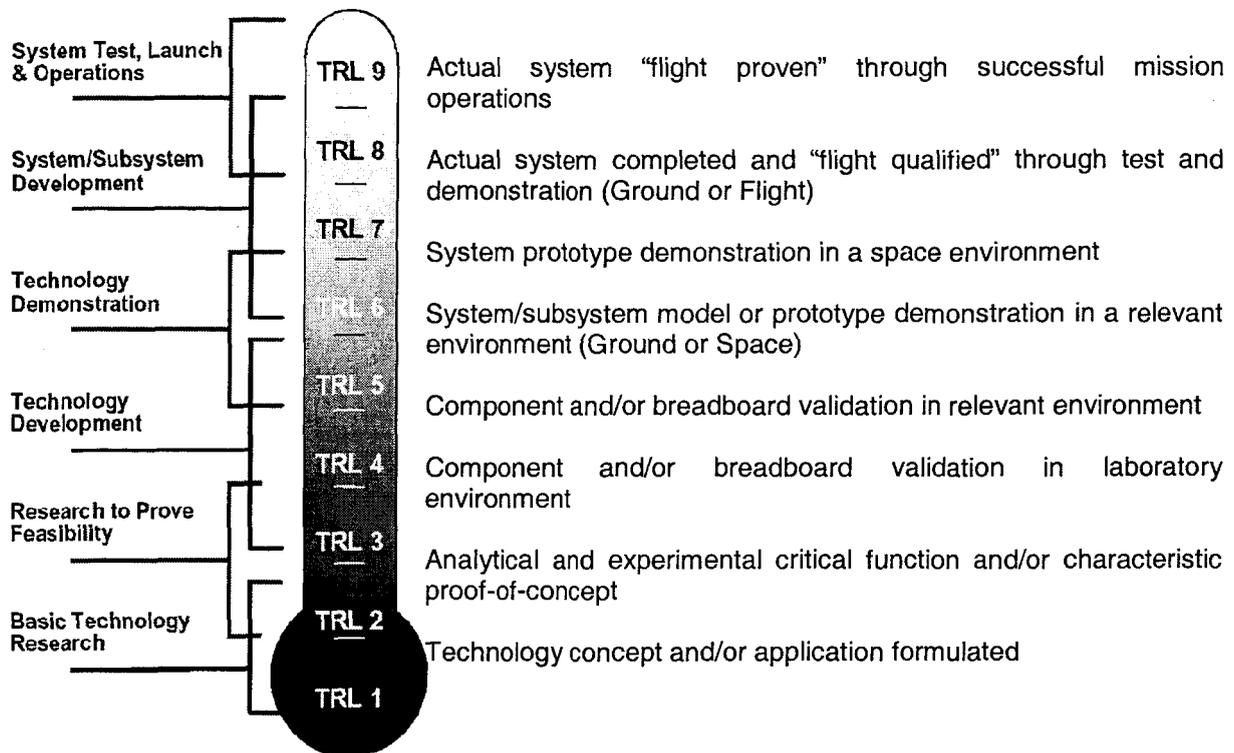


Fig. 1) NASA Technology Readiness Level Definitions

Due to launch constraints, the demonstration mission for solar sails will most likely have to be accomplished in low Earth orbit. Thus, recent studies have focused on two potential different classes of missions for solar sails. One class is derived from Geosynchronous Transfer Orbits, and the other class is Low Earth Orbit (LEO) solar synchronous orbits known as Dawn-to-Dusk Sun-Synchronous. Each of these orbits has its advantages and disadvantages from a GN&C perspective.

II. Science Missions

Currently, the nearest term missions on the official NASA roadmap for solar sails are L1 Diamond and Solar Polar Imager. Additionally, the Heliostorm mission will be added to the roadmap in the near future. The roadmap missions for solar sails have been selected by the Sun-Earth Connections division of NASA Headquarters. Its more accurate to say that science missions have been defined for the Sun-Earth Connections program and that solar sails have been identified as being ideally suited for certain of the missions in the Sun-Earth connections roadmap.

Heliostorm is a mission to a sub-L1 libration point near Earth. Heliostorm is similar to an earlier mission class proposed by NOAA called Geostorm⁹. Heliostorm is also similar in its goals and focus to the L1 Diamond mission. The primary difference between Heliostorm and L1 Diamond is that the L1 Diamond mission involves multiple spacecraft. L1 Diamond also has broader science goals than the Heliostorm mission.

Heliostorm will provide a service currently supplied by the Advanced Composition Explorer (ACE) spacecraft¹⁰. Like ACE, Heliostorm will give early warning of solar flares. The closer the spacecraft is to the sun, the better the warning. A solar sail is expected to approximately double the warning time currently provided by ACE.

Solar sails are uniquely qualified to do the Heliostorm mission for two reasons. The first is that ACE, and for that matter any L1-class mission, will, over time, require a great deal of orbit maintenance (and hence propellant). Solar sails are "propellantless", and thus provide a huge advantage over a standard spacecraft such as ACE. The second advantage is that solar sails, by their very nature, can create an *artificial libration point*¹¹, and hence get

closer to the Sun than a traditional spacecraft. Fig. 2 presents an equilibrium surface around the L1 libration point for the Earth-Sun system and is reproduced from Lawrence and Piggott¹².

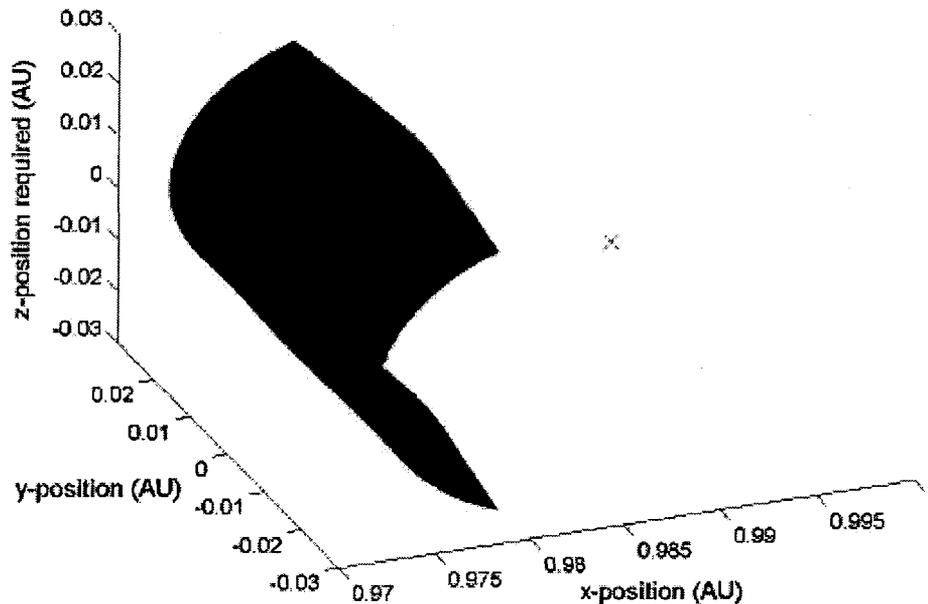


Fig. 2) Sample Sub-L1 Equilibrium Surface¹²

The equilibrium surface in Fig. 2 represents artificial libration points for a given solar sail. The artificial libration points are determined by the acceleration the sailcraft is capable of generating from reflected sunlight. In brief, since light and gravity both obey an inverse-square law, the light pressure on the sailcraft can be considered to "cancel gravity" and allow the L1 point to move closer to the Sun. In Fig. 2, the L1 point is represented by the X at approximately 0.99 AU.

For the case when the sailcraft is directly on the Earth-Sun line, the L1 point simply moves forward and the sail attitude is normal to the incoming light. As the sailcraft is moved away from the Earth-Sun line, the direction of the thrust vector needed to maintain equilibrium must change in direction and magnitude. Hence, the attitude of the sailcraft is different for every point on the manifold. A more detailed description and derivation of sub-L1 equilibrium surfaces for solar sails appears in both McInnes¹¹ and Lawrence¹².

A key issue with the "L1 class" of solar sail missions (including Heliostorm and the L1 Diamond) is that the equilibrium surface in Fig. 2 is quite sensitive to changes in the characteristic acceleration of the sail. Since the characteristic acceleration of a typical near-term sailcraft is small and the distances in Fig. 2 relatively large, the equilibrium surface is quite sensitive to small changes in sailcraft acceleration. Roughly, changes on the order of 1-2 % in the acceleration of the sailcraft can change the location of the equilibrium surface by 10,000s of kilometers.

The fact that the equilibrium surface is rather delicate is well-understood by the solar sail community. It is not considered a problem for controllability per se, as the requirements for the location of a Heliostorm-type mission are not all that stringent. In fact, to avoid solar interference with communications, the sailcraft will have to be at least 5 degrees away from the Earth-Sun line. The only other requirement is to get the sailcraft as close to the Sun as possible. Thus, the requirements for a Heliostorm-type mission literally leave a lot of room for maneuver.

That is not to say, however, that L1-class solar sail missions do not provide challenges. One big challenge is to ensure that, even with the relatively lax requirements to avoid the Sun-Earth line by 5 degrees and move as close to the Sun as possible, the sailcraft still cannot be allowed to "run away" should it lose trajectory control due to the right combination of perturbations. Chen goes into a good deal of detail concerning this problem⁹.

Furthermore, looking again at Fig. 2, we can see there is an enormous area of the equilibrium surface that represents small changes in the sailcraft attitude that correspond to the equilibrium points. Therefore, we must also worry about small changes in attitude causing a lack of equilibrium. Lawrence¹² provides an excellent starting point to try and solve these problems, but work remains to definitively solve the problem of controllability of sailcraft in L1-class missions over long periods of time. The solution of the L1-class controllability problem is well beyond the scope of this paper, however we can see how sensitive mission success is to the level of acceleration produced by the sail. Thus, it is in our interest to be able to accurately predict what the thrust level of a sailcraft will be premission.

How to measure the thrust once we do launch and deploy a sailcraft is another central area of research and focus for NASA's Solar Sail Program. Essentially there are three ways to estimate thrust. The first method is to simply have an accurate model of the sailcraft and good knowledge of its location and attitude. The second is to attempt to use accelerometers to obtain a direct measurement of sailcraft acceleration. The third is to determine the thrust after the fact using orbit determination techniques. Clearly only the first method could be used in realtime during a mission, although it could be supplemented by the second method and an appropriate navigation filter. Orbit determination could be used over a period of time for a real mission to refine the sail acceleration model.

A demonstration mission for solar sails will have as one of its objectives the measurement of the thrust produced by the sail to as accurate a degree as possible. Quite recently an attempt was made to launch a solar sail by the Planetary Society¹³. NASA had a Space Act Agreement with the Planetary Society to obtain the flight data. Unfortunately the sailcraft, dubbed the Cosmos-1, apparently failed to reach orbit when it was launched on June 21, 2005. The solar sail community had eagerly anticipated flight data from a deployed solar sail, but it was not to be. The Planetary Society is be commended for putting together an attempt that was tantalizingly close to success on a shoe-string budget.

The other major science mission of near-term interest is the Solar Polar Imager (SPI). The mission of the SPI is a scientific investigation of the poles of the Sun. Changing inclination in a heliocentric orbit requires an enormous amount of propellant. The only mission to the solar poles to date, the Ulysses spacecraft, required Jovian gravity-assist flybys to achieve its high inclination¹⁵. One consequence of that approach to achieving high inclination is that Ulysses only approaches the solar poles every five years or so. The concept of the SPI is to achieve more frequent flybys of the solar poles by achieving a high-inclination orbit at 0.5 AU. There is quite a bit of serendipity here; as the solar sail gets closer to the Sun it becomes more efficient and at the same time accomplishes more science.

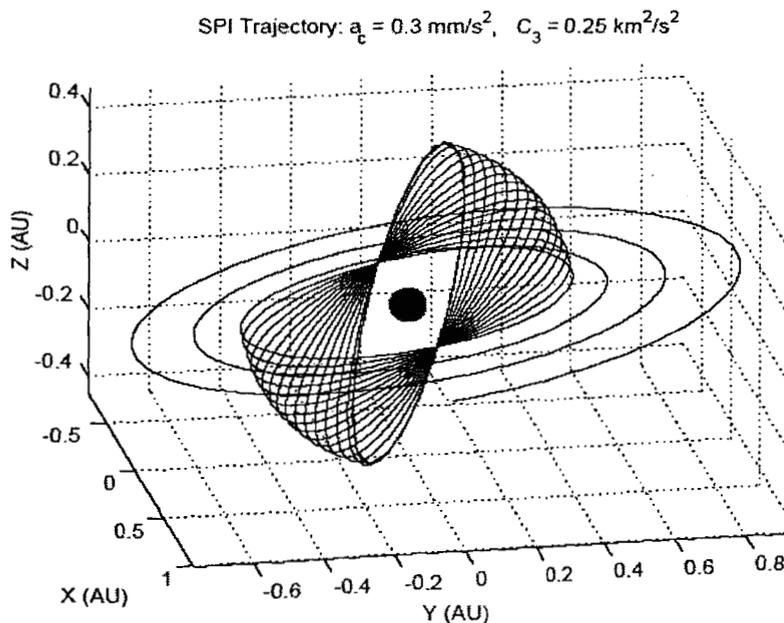


Fig. 3) Solar Polar Imager Trajectory

A preliminary mission design of the Solar Polar Imager trajectory by Carl Sauer of JPL appears in Fig. 3. Note that in Fig. 3, the trajectory "pumps down" (reduces the energy of the orbit) prior to "cranking up" (increasing the inclination. This makes intuitive sense to some extent because more overall thrust is required to change the inclination than the energy. Thus, by reducing the size of the orbit first, the sailcraft gets closer to the Sun and is able to effect the inclination change more efficiently. On the other hand, experts are still uncertain as to whether the inclination change and energy change could be combined into one guidance law and achieve a better result than what appears in Fig. 3.

Furthermore, we note that in Fig. 3, an escape from Earth to a C3 of 0.25 km/s^2 is assumed, which introduces another variable into the trajectory design of the SPI. How much escape velocity is necessary and into what orbit should the sailcraft be initially inserted? Clearly one part of the answer is obvious; the sailcraft should be sent as close to the Sun as possible on the first leg of its journey, so any excess energy over escape from the Earth should be used to lower perihelion. However there remains a tradeoff between the amount of energy over escape that will be available vs. how much time to spend getting to the target orbit.

In general, solar sails do not quite behave as other low-thrust spacecraft. In addition to a solar attitude dependence on the amount of thrust available to the sailcraft, there is also the issue of flight time. For a conventional low-thrust technology such as an ion engine, the risk of not hitting the optimal trajectory due to errors in pointing or engine efficiency can be covered by including some margin in the propellant budget. A typical approach (or even usual) is to optimize the propellant mass. Clearly this approach cannot work for a solar sail, and thus only time-of-flight can be optimized. In the case of SPI, this does not matter so much, because if the thrust of the sailcraft does not perform as expected, more flight time can be added to the mission since there is no critical timing involved in merely getting to a high inclination at 0.5 AU as opposed to, say, a Martian rendezvous.

On the other hand, we don't wish to take forever to get there either. Thus, knowledge of the thrust direction and magnitude generated by the solar sail for SPI is still very important. A key question to attempt to answer then, is how accurate must our knowledge of the thrust direction and magnitude of the solar sail be for the SPI mission? It would be very useful if we had some flight data to help us estimate the effect of pointing and acceleration errors on the SPI mission.

The need for flight data to validate that solar sails will be able to execute the science missions is a major goal of the solar sail proposal for a demo flight on ST9. If solar sails are selected for the ST9 mission, it could fulfill quite a few validation objectives and move solar sails from the demo phase to solid reality. The next section discusses the two proposed orbits for an ST9 solar sail mission and discusses the requirements and challenges of the proposed missions.

III. Proposed ST9 Missions

ST9 Requirements

The ST9 mission will be a logical follow-up to NASA's successful ground demonstration program for solar sails. Currently efforts are focused on two classes of mission orbits for solar sails. The first class is Dawn-Dusk Sun-Synchronous (DDSS) and the other class is Geo-synchronous Transfer Orbit (GTO). Both of the proposed missions are thus Earth orbiters.

Ideally, a solar sail should be tested in heliocentric space for a number of reasons. For instance, solar pointing is greatly simplified, since the geometry of the sail to the Sun changes constantly in most Earth orbits. Other reasons are gravity-gradient torques, aerodynamic torques (below 1000 km), and perhaps even magnetic torques are all disturbances that the control system must handle in Earth orbit. Electrical charging of the solar sail in the Earth's radiation belt is another issue. Perhaps the biggest disadvantage is that the true science missions for solar sails do not lie in Low Earth Orbit (LEO), and so we run the risk of validating solar sails as a technology in an environment for which they are not intended.

There are some advantages to conducting the solar sail demonstration mission in Earth orbit. One advantage is that communication with the sailcraft is simplified. Another advantage is that Earth orbiters will perhaps be able to take advantage of GPS coverage.

Nevertheless, we would still prefer to fly the first solar sail demonstration in heliocentric space if possible. The reason we are not currently planning to is simple economics. It is far less expensive to place a sailcraft into Earth orbit than to pay the extra for a heavier rocket that could send it on an escape trajectory from the Earth's gravity well. In fact, economics are the main driver in even considering the GTO class of orbits for solar sails, because often a cheap ride can be purchased as a secondary payload on a spacecraft going to Geosynchronous orbit.

The requirements that must be met by an ST9 solar sail appear in the list below. The performance requirements are based in part on the existing state-of-the-art in solar sails, which is largely derived from the SSP ground demonstration program. The validation requirements below are intended to fully validate solar sail technology and enable science missions to proceed.

Goal 1: Validate processes and design tools for solar sail fabrication

Goal 2: Validate controlled deployment

Goal 3: Validate in-space structural characteristics

Goal 4: Validate solar sail attitude control

Goal 5: Validate solar sail thrust performance

Goal 6: Characterize the sail's electromagnetic interaction with the space environment

Solar Sail Hardware and Performance

The proposed solar sail that will fly on an ST9 mission will be a derivative of the hardware development efforts currently taking place under NASA sponsorship. The SSP is sponsoring two major sail design efforts, one by L'Garde and another by ATK. Each company has designed, built, and tested 20-meter ground demonstration solar sails. Each sail is a four-quadrant square sail, and each is required to also design and test an Attitude Control System (ACS) that does not use propellant.

There are a few differences in the designs. The L'Garde design uses inflatable booms, while ATK uses its patented COILABLE boom. Another major difference is that the ATK design uses CP1 for the sail material, while the L'Garde design uses aluminized Mylar. Table 2 gives a summary of the performance expected from the ATK design [ref], while Table 3 does the same for the L'Garde design. The L'Garde numbers are derived from "thrust and moment coefficients" for the L'Garde design that are similar to lift and moment coefficients for aircraft [ref].

The L'Garde and ATK sail designs also use different Attitude Control Systems (ACS). The L'Garde sailcraft uses vanes. Vanes are miniature solar sails mounted at the corners of the sail that serve a purpose similar to ailerons, elevators or rudders on an aircraft. A part of the solar energy impinging on the sail is used to generate control torques and keep the sail pointing in the right direction.

The ATK sail design¹⁴, by contrast, uses masses that translate along the booms to control two of the axes of rotation (which we call pitch and yaw). The roll axis, which is the axis normal to the main body of the sail, is controlled by the use of spreader bars that twist individual quadrants of the sail into slightly different angles, thereby generating a so-called "pinwheel torque".

Both ACS designs have advantages and disadvantages for the orbits proposed for ST9. The main disadvantage of using just vanes is that it becomes very difficult to control the sailcraft while in the Earth's shadow. The vanes do provide non-propulsive ACS. One of the great advantages that solar sails enjoy is the lack of propellant. It would be unfortunate if a sail had to carry propellant for ACS, as it would defeat this advantage.

The thrust performance of the sail design that will fly on the ST9 mission will be critical to the mission's success. Prior to flight, we must ensure two things. One, the sail must be capable of generating enough thrust so that its effect on the orbit can be quantified. Two, we must develop techniques that allow the thrust of the sail to be measured and validated and these techniques must be as accurate as possible. Small errors in thrust accuracy can build up over time.

The SSP has sponsored development of GN&C software associated with both hardware efforts in order to assess potential sail performance. The performance of each sail should be sufficient to meet all mission validation

objectives. However, the proof will come in the actual flight demonstration. The better we are prepared to assess the efficacy of the solar thrust in the demonstration mission, the greater a success the mission will be.

Geo-synchronous Transfer Orbit Mission

As noted above, the primary reason that the GTO mission is even considered has as much to do with economics as it does with engineering. However, the GTO mission does offer some advantages. One advantage is that a sailcraft in a GTO will spend a lot of time near apogee away from the Earth and in full Sun. The time near apogee minimizes environmental torques from the Earth and also high enough to avoid the major radiation belts in LEO. A GTO mission probably comes closest to emulating a heliocentric trajectory of the two missions under consideration.

The GTO mission will, however face some challenging problems. One problem is that the sail will be traveling very rapidly near perigee. If the same orientation relative to the Sun is to be maintained, the sail must be turned with a high rate. Although propellantless ACS is a great idea and a goal of the proposed ST9 mission, it does not provide a great deal of control authority. Another problem with the relatively low perigee of a typical GTO orbit (~500 km) is the large gravity gradient torque that occurs at lower altitudes. Thus, there is a tradeoff that has to be considered: adding mass and cost for an apogee kick motor to raise perigee or accepting the higher gravity gradient and perhaps aero torques at a lower perigee. A final disadvantage is that if the GTO is attained via a secondary payload opportunity, then we have to accept whatever orbit the primary payload is going to. So in the case of a secondary payload, we may have to accept less-than-optimal lighting or other environmental conditions for a solar sail demonstration mission.

The GTO mission offers both advantages and disadvantages. The disadvantages seem to outweigh the advantages, but if a very low-cost secondary launch opportunity presents itself (cost < \$10 million), then it would be difficult to refuse in spite of the disadvantages. In the final analysis, the opportunity would be worth pursuing.

In any event, it would be quite advantageous to get flight data from a GTO mission. There should be sufficient solar pointing opportunities to allow the solar thrust to significantly alter the orbit and thus fulfill a large part of the purpose of the demonstration mission. Also, a GTO mission will sufficiently exercise the ACS of the solar sail and should otherwise be able to fulfill all the ST9 Validation Goals listed above. A preliminary navigation study has been completed for DDSS-type orbits discussing what navigational dispersions might result from a solar thrust. Such a study should be completed for GTO orbits as well.

Dawn-Dusk Sun-Synchronous Mission

A sun-synchronous orbit is one in which the orbit plane maintains the same orientation relative to the Sun throughout the year. The Dusk-Dawn Sun-Synchronous mission is typical of the general class of sun-synchronous orbits. In order to match the apparent movement of the Sun with respect to Earth, we must choose an orbit that has a nodal regression rate of about a degree per day. The nodal regression rate is a measure of how far the plane rotates with respect to inertial space, and "regression" implies that it rotates counter-clockwise when viewed from above the ecliptic pole. The regression rate cancels with the apparent solar motion in a day, and thus "freezes" the orientation of the solar sail with respect to the Sun.

In order to achieve the proper regression rate for a sun-synchronous orbit, we must trade altitude vs. inclination, which are the two things that most affect the planar rotation rate. With the right combination of altitude and inclination, an orbit that just matches the apparent movement of the Sun relative to Earth can be selected. Typically, a high inclination is required for a sun-synchronous orbit. The current target orbit we are working with for the ST9 mission has an inclination of about 97 degrees and an altitude of approximately 1000 km. This combination creates the "Sun-Synchronous" part of the DDSS mission.

The other factor to consider is that we would prefer that the orbit be in daylight all the time, or in "full Sun". Going through the Earth's shadow would obviously be a big disadvantage for a solar sail that depended on non-propulsive ACS. We can achieve a full-Sun condition by selecting the right launch time. The orientation of the orbit plane is controlled initially by the local time at the launch site. The initial orbit plane is a function of local latitude. So if we wish the solar sail to be in full-Sun condition, with the orbit plane normal to the Earth-Sun line, the sailcraft should be launched at sunrise or sunset, hence the term "Dawn-Dusk". So, by launching into a high

inclination orbit with the right altitude and at the right time of day, we achieve the DDSS mission: an orbit that is normal to the Earth-Sun line and one that maintains essentially the same planar orientation with respect to the Sun over time.

One thing we should note about sun-synchronous orbits in general and the DDSS in particular is that the orbit plane geometry is not completely invariant with respect to the Sun. While it is possible to closely match the apparent movement of the Sun caused by the Earth's rotation about the Sun, the Sun also has a slower apparent movement from in a celestial North-South sense that is caused by the Earth's tilt on its axis, which we can call a seasonal movement. This apparent motion of the Sun means that the plane of the orbit will change in a relative sense over the course of a year. However, the maximum deviation of the plane due to this effect is limited to the Earth's obliquity of 23.5 degrees.

Another point to make is that rarely is it possible to hit the perfect sun-synchronous orbit exactly. Due to uncertainties in rocket motor performance and launch vehicle performance, a sun-synchronous orbit will often have a small amount of drift. Over long periods of time, this could add up to a large deviation from an ideal full-Sun DDSS. However, the mission life of the ST9 is expected to be less than 6 months, so this effect should be fairly minor.

The DDSS orbit has many advantages. First, it allows a full-Sun condition to exist. This is probably its greatest advantage. If the sail is going to use a non-propulsive ACS, then a full-Sun condition compares very favorably to an orbit that must go through a shadow period. A full-Sun condition also allows the sail to be used for the entire period of time on-orbit. Second, the geometry of the DDSS orbit changes very little as the sailcraft moves around the orbit, so less steering of the sail is required. This is good not only because less maneuvering is required but also because it makes the effect of the sail on the orbit much easier to predict, control, and detect. Third, the DDSS has a constant altitude, which means that the gravity gradient torque will be essentially constant and so easier to predict and control. If the altitude is above 1000 km (currently this is considered the acceptable minimum for a DDSS orbit), then aerodynamic torques are not an issue. Overall, the DDSS orbit possesses many advantages over GTO or other Earth orbits.

However, the DDSS does have some disadvantages. While it is an advantage to have an approximately constant gravity gradient torque, unfortunately it is always there, in contrast to the GTO where it is negligible for a good portion of the orbit. Another disadvantage is that the magnetic torque will be larger and also will vary, since essentially north-south motion of the sailcraft in a DDSS orbit causes it to encounter a wide variety of magnetic field directions. Another disadvantage is the proximity to the Earth's albedo, which can reflect a significant proportion of the Sun's light and create a large source of noise for the evaluation of the solar thrust. This last disadvantage is also possessed to some extent by the GTO, but is only an issue near perigee. If perigee occurs in shadow, then it is not an issue at all.

Overall, the DDSS orbit seems to be better suited to an ST9 mission than the GTO. However, both orbits will allow validation goals to be achieved, and if economics dictate a GTO, it will be acceptable. Both missions will need to continue evaluating the expected thrust levels and effects on the respective orbits so that researchers will be able to readily identify the effect of the solar sail on the orbit.

We should point out that there is a considerable risk involved in an overdependence on ST9 for a solar sail validation flight. The risk is caused by the level of competition from four other technology areas, as well as the fact that to date only two ST missions of the eight awarded so far have actually flown (although ST8 appears to have a good chance of launching.). Certainly one way to mitigate this risk is to pursue other flight opportunities, and this is occurring to the extent that such opportunities are available.

Another way to compensate in the event that another technology is chosen would be to try and fly sail subsystems as secondary payloads on some other vehicle. For instance, we could only a quadrant of the 40-meter per side sail proposed for ST9 on a spent upper stage as a potential de-orbiting technology. A third way to at least begin validating solar sail models is to simply use existing spacecraft that experience relatively high solar torques or solar disturbance forces that appreciably affect the orbit.

A previous paper by the author identified the Chandra mission as a nice candidate for modeling solar torques. To briefly review, Chandra is in an elliptic orbit with a high apogee (144,000 km). When it is above roughly 40,000 km, the gravity gradient torque is negligible and the solar torque dominates. Furthermore, the solar torque on Chandra is closely monitored and modeled, because it affects operations. The model of the solar torques are used when to predict the need for momentum-dumping from the Chandra reaction wheels and if the prediction is too conservative, momentum dumps can be scheduled too often and take time away from scientific observations. So Chandra makes a good candidate to test solar torque models because it is in a favorable orbit for that purpose, it has long periods of time where on-board disturbances are limited for science reasons, and it has a very mature solar radiation model and data on solar torques that is available to researchers. However, the effect of solar radiation on the Chandra orbit is considered a fairly small contributor compared to the effect of the Sun and Moon.

A good candidate for modeling the effects of solar radiation pressure on an orbit is Echo-2 mission. This mission was launched in 1964 and consisted of a 41-meter diameter balloon made of aluminized Mylar, and had a mass of 256 kg. The Echo-2 mission orbit was a 1013 km by 1357 km orbit with an inclination of 81.5 degrees. So, not only was a large reflective surface launched into orbit, but it was at a high inclination and an altitude somewhat similar to that of the proposed DDSS. Yet another attractive feature of the Echo-2 is that, being a sphere, it has no attitude dependence. In many ways it provides an ideal test candidate for validating solar sail technology with existing spacecraft like Chandra, or, in the case of Echo-2, an older mission. Evaluation of the Echo-2 mission is a near term goal of the SSP and should lead to the refinement of analytical techniques and solar sail models for evaluating solar thrust, as well as provide some risk mitigation if solar sails are not awarded the ST9 mission.

V. Conclusions

There are many GN&C challenges facing solar sail technology for the proposed ST9 mission. However, there are also many opportunities. Science missions also face many GN&C challenges. The DDSS orbit seems the better choice for an ST9 validation mission, but the GTO is acceptable if economics dictate that we use it. Work needs to continue to further evaluate the stability of the trajectory control system for the L1 class of science missions. More work also remains to be accomplished for the Solar Polar Imager trajectory guidance. Furthermore, other types of potential science missions for solar sails can and should be explored. The ability to fly a spacecraft without the need for propulsion is simply too valuable a concept to not try and expand the envelope of acceptable missions.

Regardless of what mission is selected for ST9 or what the first science mission for solar sails will be, more research needs to be focused on the ability to correctly predict, model and detect solar thrust on orbit. This ability will help meet the validation goals of the ST9 mission, and also greatly mitigate risk for science missions like Heliostorm. ST9 will provide an excellent opportunity to validate the models and techniques of measuring solar thrust, should solar sails win the competition. If not, we should seek other launches. In the meantime, research will continue into the ideal test case of the Echo-2 mission, which bears many similarities to the proposed ST9 solar sail. And if solar sails are not selected for ST9, Echo-2 data analysis could provide valuable insight into modeling and measuring solar thrust.

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