AIAA 2002-1703

Scalable Solar Sail Subsystem Design Considerations

David M. Murphy and Thomas W. Murphey
ABLE Engineering Company, Inc.
Goleta, California

Paul A. Gierow
SRS Technologies, Inc.
Huntsville, Alabama

43rd Structures, Structural Dynamics, and Materials Conference

22-25 April 2002
Denver, Colorado
SCALABLE SOLAR SAIL SUBSYSTEM DESIGN CONSIDERATIONS

David M. Murphy† and Thomas W. Murphey‡
ABLE Engineering Company, Inc., Goleta, CA
Paul A. Gierow§
SRS Technologies, Inc., Huntsville, AL

Abstract

Under recent contract to JPL for the New Millennium Space Technology 7 Program (ST7) AEC-Able Engineering (ABLE) developed a Scalable Solar Sail Subsystem (S⁴). The S⁴ is a minimal mass propulsion subsystem that can be mounted to a general heritage spacecraft to provide continuous low level thrust. The design baseline is a 3-axis-stabilized 4-quadrant square sail with attitude controlled through gimbaling of the spacecraft on an extended boom. The work underway is unique in several aspects. It is the first sail system design effort:

• To incorporate advanced CoilAble longeron technology as the sail masts, providing reliable deployment and structural robustness with minimum weight,
• That proposes a configuration of flat tensioned membrane sails without the incorporation of catenaries, battens, or other structure,
• Which mathematically identifies the significance of structural wrinkles on propulsive effectiveness,
• To incorporate a 5-µm tear-tolerant CP1 membrane with close solar approach capability,
• And incorporate pansospheric camera technology to allow in-space measurement of sail and structure modes, and provide inspiring visual images to ground observers.

The trades performed to arrive at the S⁴ design definition and the resulting configuration and performance versus size are reviewed.

Introduction

Solar sail technology has been identified as enabling for many recent space mission concepts. Non-Keplerian orbits can provide unique perspectives in missions such as the Geostorm Warning Mission. Solar propulsion can also provide a significant cost savings for missions with high delta-V requirements such as the Heliopause Explorer and Solar Polar Imager.

The Geostorm mission seems the best suited for initial usage of solar sail technology as the performance requirements for the sail subsystem are the least stressing of near term applications. The mission plan is to utilize photon pressure to allow a satellite to remain stable at a point closer to the sun than the L₁ point. This would offer a valuable increase over the solar storm warning time provided by the aging NOAA satellite currently in service.

The required sail performance is shown herein to be achievable with reasonable margins and reliability. A demonstration of this technology under NMP funding will ready sail technology for the GeoStorm mission and a series of progressively more challenging missions planned by NASA, NOAA, and the DoD.

Many of the technologies required for solar sailing have yet to be demonstrated successfully in space. Attempts have been made to deploy both spinning (usually circular) and 3-axis stabilized membrane reflectors. The Achilles heel of many membrane system development efforts to date has been the complexity and lack of heritage of the technology configured for deployment. The S⁴ design utilizes a deployer with 100% flight success over more than 50 missions in the past three decades.

ABLE has recently identified a method to optimize this deployable structure, the CoilAble, for the new family of lightly-load applications known as “gossamer” systems. The incorporation of new composite materials into the CoilAble allows the performance goals of
sailcraft to be met with a robust deployment system.

However, the deployment and structural performance of a sail system are only two of the challenges to be met in configuring a successful sail subsystem. The unique technologies of film optical performance, environmental stability, thermal expansion and wrinkle management, system dynamics and control strategies, and many other issues must be addressed with minimum mass solutions.

Much theoretical work has been accomplished in the area of sailcraft orbit dynamics modeling, but that work has generally assumed rigid body motion, due to lack of definition for the sail subsystem design. This sail design effort identifies modes that result from structural system optimization for sail sizes from 20 to 300 m (400 m² to 90,000 m²).

Many attitude control implementations have been proposed by previous studies. This paper shows the design implementation and performance results for the attitude control through center-of-mass offset (versus the center-of-pressure location) by gimbaling of the spacecraft off a short (sail-centered) boom.

The family of sail configuration options for 3-axis stabilized designs are reviewed and contrasted for implementation ease and performance. A 4-quadrant square sail design was selected for detailed design.

The work reported on herein was sponsored by NASA’s New Millennium ST7 program. This work was also reported within the context of a project proposal presented to NASA headquarters in early 2002. The proposal effort was led by JPL and performed with the assistance of Able Engineering (for sail subsystem design), and Swales for attitude control subsystem design. If selected for flight validation follow-on, the sail demonstration would be launched in late 2005.

**S₄ Design Description**

**System Configuration**

General configurations for the sail shape and suspension², such as in Figure 1, were evaluated for their simplicity and performance potential.

When studies were done by ABLE for JPL in the late 1970’s, a four-point configuration (where non-planarity of the 4 masts allows a planar sail) was favored. This configuration allows a single sail, which is doubly folded when stowed. The deployment can be well controlled by opening the sail in one dimension at a time. However, sail tension loads the masts in bending, which requires more structure (mass) to avoid buckling than a column in pure compression. The same is true for the 5-point option.

A striped architecture, suggested by Mikulas² as a useful assumption to simplify sail stress distribution analysis (catenaries are not needed), was judged to require overly complex sail construction. And the multitude of attachments to the mast would be a detriment to mass minimization. This is true for both the striped architecture and the continuous connection approach. One of our primary desires was to construct a system with the highest potential for complete ground verification. Achieving this objective is greatly aided by separating the actions of the mast and sail deployment.

![Figure 1. General Square Sail Configurations](image)

The proceeding arguments and other lesser concerns left us with the quadrant option and the challenge of catenaries. New analytical techniques³ allowed us to demonstrate that - without catenaries - structural wrinkling would have a negligible effect on propulsive efficiency. So, the design we baselined is a sequentially deployed (masts in parallel, then sails in parallel) quadrant sail without catenaries, as in Figure 2.
Figure 2. Quadrant Layout of S4

Sail Design

The sail quadrant design, developed by SRS Technologies, is a 5-µm thick film construction of CP1 with an aluminized reflective front surface and a black emissive back surface. CP1 is a unique polymer, invented by NASA and commercialized by SRS, with extensive qualification test data and flight heritage. It has favorable structural characteristics and large-scale manufacturability.

CP1 is soluble and can therefore be cast, yielding uniform thickness sheets with isotropic properties. SRS has developed carbon-based additives that can enhance the emissivity. Carbon loading is expected to be of additional benefit by increasing tear strength and modulus, and lowering the sail CTE. However, carbon loading presents numerous difficulties that are still under study. If the material cannot be developed and proven in time to support the first flight opportunity, the fallback will be to use flight-proven (clear) CP1. The emissivity is greatly reduced, but is still sufficient for missions without close solar approach.

Another additive developed by SRS is a de-wrinkling agent. Experiments have shown that by slightly enhancing the creep potential of the base material the packaging (material) wrinkles can be eliminated at low operating stresses.

The soluble nature of CP1 can also be utilized to form adhesiveless seams. Ripstop (overlaid strips of greater thickness) is applied by the same means.

A fold pattern was developed that allows the quadrant to be packaged efficiently alongside the stowed masts. The sail manufacturing methods and fold processes were experimentally explored with a ½-scale demonstrator.

Deployment tests, as shown in Figure 3, were repeatably successful, yet the constraint provided by the floor is obviously non-conservative.

Figure 3. Deployment of ½ Scale Quadrant

Our goal became to configure a deployment scenario that is much more deterministic: All folds must be in a known, or narrowly constrained, position during deployment to avoid entanglement. No significant portion of the sail can be without tension or solar pressure will quickly deform the sail shape. An example of a sequence with high deterministic qualities is discussed in a later section.

Rapid depressurization during the launch ascent can cause premature unfolding or structural overloading. Generally speaking, a two-dimensional fold pattern of a planar sheet leaves a short path for the escape of gases during depressurization. This was demonstrated in tests with a folded sail sample.

Prior to and during deployment the space thermal environment poses challenges to the sail. For example, between folds the thermal extremes can cause entrapped water to freeze and/or a solar oven condition which overheats the sail. Prior to launch, the entire subsystem must be bagged and supplied a continuous nitrogen overpressure to prevent moist air from infiltrating the folds of the packaged sail. A solar oven condition, formed by partially opened folds exposed to the sun, can be prevented with appropriate shading of the packaged portion of the sail.

The temperature of the deployed sail film (normal to the sun) can be derived from a simple heat balance equation.

\[
T (°C) = \left[ \frac{\alpha \cdot \text{Sun}}{(a \cdot \sigma \cdot (\varepsilon_f + \varepsilon_b))} \right]^{1/4} - 273
\] (1)

If the sail is oriented off-sun the temperature will drop only slightly, by the 4\textsuperscript{th} root of the...
cosine. The absorptivity of the sail is minimized as a consequence of optimizing the aluminum reflectivity. The additional frontside coatings considered were not mass effective. The thin aluminum layer will allow a small portion to be transmitted: less than 2%. As the other factors in the analysis are all relatively fixed, the resulting temperature is primarily dependent on the emissivity of the film backside. Results for various emissivities as a function of solar distance in astronomical units (au) are shown in Figure 4.

![Figure 4](image.png)

**Figure 4.** Sail Temperature Allows Closer Solar Approach Than 0.3 au ST7 Goal

Tests of sail samples with various carbon loading fractions demonstrated that a high emissivity – and thus a close solar approach capability – can be achieved. As can be seen in Figure 2, the corner of the sails near the spacecraft would be left unmetalized. The high absorptivity of the carbon-loaded CP1 will prevent 2x solar loading of the spacecraft.

**Mast Design**

The sail masts are an advanced version of the continuous coilable longeron structures ABLE has flown 27 times before in space with 100% success. These robust and reliable continuous longeron structures, which can be coiled and stowed in less than 1% of their deployed length, we term the CoilAble.

This structure can be very mass efficient. Masts (of a similar diameter to the current application), which flew on the IMAGE spacecraft in 2000, were less than 100 g/m. Recently R&D efforts have shown that the mass efficiency of the CoilAble can be radically improved through the selection and proper proportioning of materials as appropriate for the (gossamer) needs of the solar sail application. To form an “advanced” CoilAble, the heritage material for the longerons and battens, S2 fiberglass, are replaced by a modern carbon fiber composite. This is possible because the optimal boom proportions do not exceed the material strain limitations. The modulus is increased by 3.5 times with 20% lower density material.

For the unique load regime of solar sails the coilable is lighter than a tube, and very nearly as light as an ideal iso-grid tube. Once the mass of real-world deployment and rigidization needs is overlaid on the iso-grid, the CoilAble is a clear mass winner.

The complexity and mass of the mast corner fittings have also been vastly improved. The part count per corner has been reduced from more than a dozen to a single molded fitting. The diagonals are laced from fitting to fitting in a helix up the mast.

The CoilAble is self-deployed by the strain energy of the stowed longerons. The tip end is biased to erect first and the transition zone progresses away from the base as the lanyard is payed out.

![Figure 5](image.png)

**Figure 5.** CoilAble Mast Description

The longerons are the primary structure of the mast and determine its key performance characteristics. The diagonals are tensioned by the buckled battens and serve to position the
longerons relative to each other radially and axially. The materials and section properties of these separate elements can be optimized for any particular application:

- Bending stiffness is a function of the longeron section properties, elastic modulus, and distance from the center of the boom.
- Bending strength is a function of the section properties and elastic modulus of a longeron, as well as the length of an individual bay.
- Shear and torsional stiffness are a function of the diagonal section properties, elastic modulus, and angle within the mast bay.
- Shear and torsional strength are developed by the buckling strength of the batten.

For the sailing application the shear and torsional stiffness and strength are of secondary importance. Consequently, their mass may be minimized. Their primary role is to provide sufficient support to the longeron to enforce the local buckling mode to within a single bay. The analysis is that of a simply supported Euler column, modified by any manufacturing tolerances that introduce straightness imperfections.

The overall structure is mass optimized when the global buckling limit is equal to the local buckling limit. The global buckling calculation requires a more involved analysis than the local buckling as detailed in the section on Loadings and Capability.

System Packaging:

The packaged sails and masts are contained in a lightweight construction of graphite facesheets with aluminum honeycomb. The four masts are arranged symmetrically around a central bay that houses the stowed offset boom and 2-axis gimbal. The remaining volume in the same plane is used to store the four sails. The arrangement is depicted in Figure 6, where the structure and packed sails are sectioned to remove the top half to allow better viewing. Inserts on the top deck of the structure allow mounting of launch tieown and release actuators.

In flight, the sail masts would be both deployed and dynamically verified prior to the sails being raised on the halyard lines. Sequential operation simplifies mechanization, increases opportunities for better ground testing fidelity, and improves flight validation activities and reliability.

To minimize mass and increase reliability, the elements needed to secure the masts for launch, to synchronize their deployment, and to spring-tension the sails, are shared. Also, one motor is used to deploy the masts and sails and later to control offset boom rotation for attitude control. Since the four masts are identical and symmetrically arranged, the following discussion of the features of one applies to all.

![Figure 6. CoilAble Mast Description](image)

The stowed mast occupies a cylindrical volume of 23 cm in diameter by 26 cm long (0.9% of the deployed mast volume). The mast longerons are coiled upon one another forming a stack well-supported for launch that is preloaded by tensioning of the lanyard. The lanyard is fixed to the tip plate and runs through the center of the mast to a reel that is mounted around the rotary axis gimbal at the center of the stowage structure. The lanyards from each of the masts share this reel. The reel is grounded to the structure by dual shear pins that prevent the tiedown loads from being reacted through the gimbal gearbox.

The last meter of the lanyard (near the tip plate) is constructed of a high load capacity Elgiloy® steel tape of sufficient length to allow several wraps to be wound onto the reel. The balance of the 30-m lanyard is also Elgiloy®, but of a reduced cross section that provides high margin over boom and sail deployment loads with a mass of only 3 g/m. The lanyard is constructed of two tapes laser-welded together in a nearly continuous pattern for redundancy against imperfections or handling damage to this gossamer line.

System Deployment

After release from the launch vehicle, deployment operations would begin with
unfolding of the solar arrays, followed by the extension of the spacecraft offset boom.

Deployment of the masts is initiated by the release of pin pullers on the lanyard reel. The first motion of the reel allows the preload in the mast stacks to be released. The motor is commanded to begin paying out the lanyards. Springs at the inboard end of the longerons bias the mast to uncoil from the base and the transition section progresses out the boom until the tip completely unwinds. The stowed strain energy of the coiled longerons powers the deployment. The gimbal constrains the rate and measures the travel.

Figure 7. Deploy Sequence

The spacecraft attitude control system (ACS) will be disabled during deployment of the masts and sails to eliminate undesired loading as the structure transitions many frequency regimes during deployment. The action of unfolding the masts - at a rate of 2.5 cm/sec. - will occur over a 20-minute period.

Once the mast has fully deployed it is ready to support the raising of the sails. First, the spacecraft inertial system is taken off standby and a series of small inputs of attitude adjustment can be used to achieve 3-axis stabilization and then to excite the masts and investigate/validate the structure modes. The modes will be evaluated using data from strain gages on mast longerons and the images returned by panspheric cameras. This will allow correlation of modeling of the system modes observed after sail deployment.

At the end of mast deployment, the snap action of a longeron tip completing the last few degrees of rotation (to a position normal to the tip plate) will have released the bridle block (see Figure 8) that joins the lanyard to the two halyards that run back down the mast to the quadrant corners of the still stowed sails. In the launch configuration the halyards are wrapped around the longeron so that during mast deployment they unwind and form a slack line from the mast tip to the stowed sail quadrants.

Figure 8. Mast Tip Detail: Lanyard to Halyard

When the mast assessment is complete, the second stage of system deployment, raising the sails, is initiated. The motor is commanded to turn (now in reverse) and the lanyards are reeled in, which pulls the sails up as the halyards run over the pulleys and down the mast. All quadrants would follow this process simultaneously as they share the halyard drive mechanism housed in the stowage structure.

Raising the sails will progress at a slow controlled pace – averaging less than 1 cm/sec - over 60 minutes. The motor revolution count will indicate when the sails are nearly taught. The camera will be used to document the dynamics of the quadrants unfolding and verify the sails are nearly taught. Prior to sail deployment the spin rate of the momentum wheels should be near a maximum to inertially stabilize the spacecraft - with the control mast pointing at the sun - so that the deploying sails will billow under solar pressure in a controlled safe direction.

Tension is applied to all sails by a set of negator style springs located in the central bay. Springs are needed to maintain the desired film stress as the sails cool and contract (33 cm relative to mast) during earth eclipse (expansion is 25 cm at 0.3 au). The negators are fully extended at launch and rotate with the reel (on the gimbal output) during mast and sail deployment. The reel – once decoupled from the negator carrier ring – will rotate around the gimbal body as the negators pull the remaining slack out of the sails. Decoupling is accomplished by actuating a small pin puller.

The “negator” springs will be designed to have a very low spring rate. The sail tension will

---

¶ An animation of the ST7 deployment (produced by M. Hart of the Aerospace Corp) can be seen at http://solarsail.jpl.nasa.gov/tasks/index.html.
vary only slightly over the travel induced by differential thermal growth between the sail and the mast. The overall spring travel allowance provided will be 4 times the expected thermal compliance to allow the motor position to be varied to change the sail tension. (The rotation of the motor needed for attitude control (±180°) is a small fraction of total negator motion.) The effect of sail flatness and frequency can then be explored.

The placement of the negators within the central mechanism allows a (redundant) set of springs to tension all sails equally. More importantly, this configuration and sequence leaves the low compliance of the negators out of the halyard lines during the critical sail blanket deployment phase. The first solar array blanket deployment on the International Space Station failed (EVA intervention was required) because the sticking of folds was not anticipated. The compliance of the negator reels designed to tension the blanket at full deploy, allowed strain energy to develop as the blanket was unfolding. When sections stuck the springs extended fully as the mast continued to deploy. When the springs reached the end of travel stops the mast motion pulled open the stuck fold. The negators would then retract, pulling the blanket back to collide with the base structure. This caused solar cell fractures and eventually led to the negators jamming due to loss of containment.

Similarly for the solar sail application, negator compliance would allow the force required to open a sticky sail fold to be stored as a large amount of energy. The energy that would be returned when the negator retracts; thus, accelerating the blanket. It is clearly desirable to avoid such dynamics and potential failure modes. The proposed mechanism introduces the negator, for final tensioning, after sail unfolding is complete.

**Deterministic Deployment**: Deployment of a sail – with its intrinsic flimsiness coupled with the solar pressure – means unconstrained portions of a sail are inherently risky. The potential motions cannot be reliably modeled. Twisting and wrapping of the sail around itself or the masts would surely lead to failure. Although the baseline method of deployment described above is well controlled, a sequence with a higher deterministic quality can be imagined, as shown in Figure 9. All quadrants would follow this process in parallel as they share a halyard drive mechanism housed in the stowage structure. It may be worth the additional mechanism to incorporate this approach as the baseline.

**Mast Loadings and Capability**

The critical failure modes, that effect mast sizing and mass, are global and local buckling. To yield a robust design for this first flight demonstration mission, a minimum factor of safety of three was chosen. The masts for this point design are global buckling limited.

The global buckling load capability of a single mast of length \( L \) can be calculated as a simple pin-pin column as \( P_s = \frac{\pi^2 E I}{L^2} \), or equivalently as a cantilever beam in compression where the load is directed always towards the root. This so-called “follower load” case is non-conservative for a square quadrant sail as the geometry of the sail tensioning means the load is actually directed at a distance of approximately 0.7·\( L \) (assuming the halyard angle bisects the sail corner) behind the center, as indicated in Figure 10. This actually reduces the buckling load by more than 50%.
It is important to recognize the halyard angle \((\alpha)\) varies in flight as the sail changes size due to temperature. While the negators function to maintain approximately the same tension, the variation in halyard angle changes the buckling load margin, and the quadrant frequency as well. The highest frequency corresponds to a slightly higher halyard angle than the bisector angle, as shown in Figure 11.

For this elliptical earth-orbiting application it was chosen to maximize the frequency when the spacecraft was at perigee. This may increase controllability when orientation change is highest and the sail is facing disturbances such as magnetic field interaction. This is when the sail is hottest. Other locations in the orbit correspond to lower halyard angles as shown in Figure 11. Inspection of the quadrant sail geometry, assuming conservatively that all masts would buckle at the same load, reveals that:

\[
\frac{C}{L} = \frac{1}{1 - \tan (\alpha)} \quad (2)
\]

Knowing the location where the load is directed allows a calculation of the correction to the buckling load. Timeshenko\(^4\) provides a transcendental relation that relates \(C/L\) to \(k\):

\[
\tan (kL) = kL \cdot (1 - C/L) \quad (3)
\]

And shows that \(k\) is related to the true buckling load by:

\[
P_{cr} = k^2EI \quad (4)
\]

Therefore, the buckling correction factor is:

\[
P_{cr}/P_s = k^2EI / \pi^2EI/L^2 = (kL/\pi)^2 \quad (5)
\]

One can see in Figure 12 the change in this correction factor - over the range of halyards angles that thermal extremes induce - is very significant.

For a mission that includes close solar approach the variation in buckling margin and sail frequency can be reduced by designing the sail with a larger gap between the masts and sails.

Given the symmetrical arrangement of the masts \(in the plane\) of the deployed sails it is tempting to analyze the statics of mast strength as an column under compression due to sail tension alone (with the proper load direction correction as discussed above) as this is \(by far\) the highest load. For example, the solar pressure exerts a load 2000 times lower on the tip. However, the mast must be analyzed as a beam-column (BC), where the deflection due to such lateral loads is amplified by the compression imparted by sail tension, to obtain true structural margins.

Similarly for the dynamic analyses of the structure the bending stiffness and natural frequency of the mast is reduced due to the compression imparted by sail tension. This “stress softening” effect, which is critical to the correct prediction of the systems lowest mode, is the corollary to the vibration frequency of a beam increasing from a tensile load.

The potential for global curvature is another important consideration in accurate strength margin analysis. The deflection of the boom due to lateral and compression loading (calculated by the BC method) is amplified by initial the free-state curvature of the mast. Curvature can result from manufacturing tolerances and thermal gradients.

Manufacturing tolerances in such a long mast are not insignificant, as they can easily be as large as the BC tip deflection (4 mm) induced by
combining all other loadings. Namely, sail tension, solar pressure, and rotational (orientation) acceleration.

Thermal bending is induced if the sun angle causes one longeron to partially shadow another. The worst case thermal bending is actually very minor for the gossamer graphite CoilAble as the longeron CTE is slight and the small diameter of the longeron (relative to the mast diameter) prevents full shadowing.

Shadowing can be completely avoided by choosing off-sun orientations that do not match the rare combinations that allow any occulting. In contrast to shell structures, the open trusswork of the CoilAble is an important structural asset as the prevention of thermal bowing is critical to the margin obtainable in a BC analysis of strength.

The present design allows a factor of safety of 7.5 over local buckling (of a longeron within a bay). When the mast diameter is increased, the margins over local and global buckling converge for an optimized mast design. Local curvature of the longeron must be considered in the calculation of local buckling load capability for large scale systems. A smaller mast diameter in the present design allowed optimization of the system stowed volume below 1/8 m³ and provided the large local buckling margin.

A significant mast loading can arise during the sail deployment if the folds have any tendency to stick together. This can be caused by blocking forces, electrostatic charging, or yield stresses induced by packaging with particulate contaminants. An exploratory series of tests were performed to ascertain the pull force of compressed sail folds. Tests were run in vacuum and in air, for CP1 to CP1 (back to back) and metal to metal and CP1 to metal over a range of peel angles. Blocking was not evident. The carbon loading was effective in preventing any measurable forces associated with static charge. When scaled to the proposed fold dimensions the “peel” load for all configurations (with carbon-loading) was generally less than 1 g. It is expected that the addition of slip stitching to provide a deterministic deployment will induce larger loads than fold parting.

S4 Structure and Sail Vibration Modes

The tensioned quadrant and stress-softened mast frequencies both are important in the determination of the systems modes. Results of prestressed dynamic FEA for the system closely matched simple estimations. The vibration modes analysis is complicated by the need to include any wrinkled area.

The support of the quadrant by 3-point tensioning causes compressive second principal stresses in the sail membrane. These compressive stresses cause negative eigenvalues and result in chatter modes in a dynamic analysis. The required methodology is to perform a structural wrinkle region analysis first.

This analysis corrects the stress distribution to account for wrinkles and eliminates compressive stresses and negative eigenvalues.

The system’s first mode (0.036 Hz) is shown in Figure 13. The next ten modes are all below 0.06 Hz. The modes are driven by the sail tension. A minimum stress of 1.5 psi was chosen to assure folds would be opened and packaging wrinkles would be stretched sufficiently, as discussed in the next section.

Figure 13. Lowest System Frequency

This model is for a free-free system that includes a 140 kg spacecraft on a 2-m offset boom. The cantilever frequency of the tip-weighted boom on the orientation gimbal is >10X the system frequency, even assuming the gossamer sail mast design is used for the offset boom. It is the “root” flexibility (the crossed sail masts) that dominates the first mode of the boom.

Sail Flatness and the Effect on Propulsion

An allowance for moderate wrinkles is supported by an analysis of the effect on propulsion. Errors in sail flatness will reduce propulsion as a portion of the momentum transferred by photons reflected at angles others than the mean do not add fully to the desired thrust vector. Wrinkles can be attributed to packaging, structural, and thermal effects.

Material wrinkles are due to creases induced by folding of the sail. The sail can be compressed to a significant fraction of the volume the material would occupy as a solid.
The “solid fraction” for the current sail construction based on the allocated volume is 18%. This means that folds in the 5-micron (near-term thickness) sail will be separated by 23-microns on average. Although the fold pattern generally prevents stacking of folds and hard creases are not intentionally input during folding, the folds are strained past yield. The sail material has a low modulus and can be stretched to a point which reduces the area affected by the residual strain energy of a hard crease to less than 1% of the distance between folds. The non-flat area on the sail assuming all folds are hard creases is only 4%.

Structural wrinkling arises from the non-uniform stress distribution that exists in the quadrant. The incorporation of catenaries has been baselined in many previous sailcraft designs6-8 to provide a uniform equal bi-axial stress field. It has been assumed that wrinkles would significantly degrade the thrust performance of a sail and therefore it is prudent to design to prevent them1.

But the methods proposed to avoid structural wrinkles (e.g. catenaries, strip designs,...) add significant weight and manufacturability penalties to sail designs. So, a trade-off exists between eliminating wrinkles and maintaining a reasonably light and simple system design. In the analysis of the quadrant sail, we have been able to demonstrate that while structural wrinkles do arise, the effect on thrust is negligible.

The region prone to structural wrinkles lies outside a circle inscribed within the quadrant, as shown in the photograph of the highly stressed membrane shown in Figure 14.

Figure 14. Structural Wrinkles in a Highly Stressed Sail Quadrant (scale model)

Analytical tools employed in the past have not provided information as to the number of wrinkles or the amplitude of wrinkles. Lacking this information, it has been assumed that knowledge of the local inclination of a wrinkle (needed to determine how photons reflect) is similarly unknown. But FEA codes used to determine the wrinkled region can in fact reveal useful wrinkle surface inclination information, namely through the aspect ratio parameter of wrinkle amplitude to wavelength. With this information, integration over the wrinkled surface can be performed to find the effective thrust.3

The thrust produced by photon reflection can be resolved into two components: A force along the sun line and another tangential to it. The effect of wrinkles on the radial thrust component can be seen in Figure 15. Interestingly, the radial thrust will increase (neglecting the projected area loss) as the angle of incidence increases.

Figure 15. Effective radial thrust averaged over a wrinkle for various angles of incidence

The effect of wrinkles on the tangential thrust is independent of angle of incidence. The reduction grows to 30% at a/l = 0.2.

For the nominal sail tensioning (1.5 psi in the sail center), the predicted wrinkle aspect ratio is less than 0.0005. So, while a reflected image would be distorted if viewed from far away, the effect on thrust is negligible.

The calculations of aspect ratio also allay a previous concern that wrinkles would allow multiple reflections and thus “hot spots” on the sail. For operation at a 40° angle of incidence (beyond projected mission needs), it can be shown3 that the wrinkle aspect would have to be 40x larger than predicted to result in a (specular) light ray reflecting to strike the sail a second time.

Work remains to be done in the quantitative assessment of packaging wrinkling. If the packaging volume allotment enforces hard creases, these together with the strains due to secondary folding (especially in corners) could change the effective constitutive properties of the sail appreciably. Without their inclusion in the modeling, a structural wrinkling analysis might be unconservative. Further development
of analytical techniques and/or a dependable de-wrinkling agent would be important contributions to further efforts.

**Mass Performance**

The mass of the S\(^4\) system was calculated from the summation of the over 70 unique parts designed for the application and estimates for conceptual components. The mass breakdown by subsystem can be seen in Figures 16 and 17.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail Assy</td>
<td>12.96</td>
</tr>
<tr>
<td>Mast Assy</td>
<td>5.76</td>
</tr>
<tr>
<td>Stowage Structure</td>
<td>3.65</td>
</tr>
<tr>
<td>Mechanism, Central</td>
<td>1.62</td>
</tr>
<tr>
<td>Control Mast</td>
<td>1.50</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24.1</strong></td>
</tr>
</tbody>
</table>

*Figure 16. ST7 S\(^4\) Mass Summary*

![Graph showing mass distribution of S\(^4\)](image)

*Figure 17. Mass Distribution of S\(^4\)*

**Validation Mission**

**Objectives**

The primary objectives of the ST7 solar sail technology flight experiment is to validate the Solar Sail as a controllable propulsive device capable of enabling several key missions in NASA's Space Science Enterprise Strategic Plan. Using the sun's constant supply of photons, a solar sail can economically achieve the high delta-V needed to support missions such as the Heliosail Explorer, a precursor mission to Interstellar Probe. Solar sails are uniquely capable of providing the continuous thrust needed to adjust an orbit out of the plane of the ecliptic, thereby enabling Solar Polar Imager, a heliocentric polar orbiter. Other missions in the Living With a Star Initiative will require non-Keplerian orbits that can be only achieved with a solar sail. Geostorm and similar sentinel-type missions that provide continuous solar monitoring and alerting are only practical with solar sail technology. The New Millennium Program Solar Sail technology validation experiment will advance solar sails from concept to a space-proven propulsive subsystem to support these important missions.

Of key importance to the realization of solar sails is the capability to perform a predictable and controllable deployment of the gossamer sail film and supporting structure in the space environment. This requires development and validation of an ultra-lightweight, stiff, deployable strut that can be stowed compactly: A graphite CoilAble. The thin sail membrane must also be packaged compactly - in a manner that yields controlled deployment - and must possess sufficient strength margin for the deployment and tensioning loads.

Successful completion of a thorough ground test qualification including the primary challenge – deployment – is highly likely given the low risk elements selected for incorporation in the S\(^4\) system and the sequential deterministic plan for deployment.

Once deployed, the orientation of the thrust vector to the desired direction will be accomplished with the offset boom (center of pressure to center of mass offset). Roll control will be accomplished in a propellant-minimal manner using momentum wheels and cold gas thrusters for wheel desaturation.

Once deployed and in controlled flight, orbital predictions and measurements will be made to confirm the performance of the solar sail as a propulsive device.

Solar sail system technology needs flight validation due to the risk involved in deployment issues. Even with a deterministic deployment, risk exists in that this would be one of the largest space structure ever deployed (5x greater area than a ISS solar array wing). Zero-g deployment behavior and sail shape can never be fully validated by a deployment on Earth. Flight is required to certify numerous aspects of the system performance such as:

- Deployed planarity of the 4-mast structure
- Deployment dynamics of the sails
- Deployed shape of the sail quadrants (packaging and structural wrinkling)
Modal behavior of the deployed sail and mast structure system

In addition, the flight dynamics and control of the integrated sail system can only be verified by on-orbit demonstration. Near-earth perturbations such as magnetic field interaction, gravity gradient torques and atmospheric drag will be uniquely challenging. Future missions all require robust control of the sail thrust vector and the ability to predict and confirm the resultant flight path. Only a free-flying sailcraft can provide the platform to demonstrate those capabilities. The flight validation, as proposed for ST7, will provide the demonstration of combined orbital maneuvering and attitude control functions of the solar sail.

Launch Accommodation

The ST7 Sail experiment has identified several low cost launch opportunities. The baseline utilizes the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). ESPA is a developmental product designed to carry up to six small satellites of up to 180 kg each, along with a 6,800-kg primary payload into space on the next generation of US launch vehicles - the EELV. It is designed to provide transportation for secondary payloads as a ride-along on the primary payload adaptor ring. As shown in Figure 18, the standard volume box is exceeded somewhat by the ST7 spacecraft, but the proposed volume is expected to be within negotiable limits as it does not rise above the primary payload separation plane.

![Figure 18. ST7 Launch Package on the ESPA Carrier Ring](image)

Trajectory Plan

The targeted ESPA flight opportunity will launch into a Super Synchronous Transfer Orbit (SSTO). After separation in SSTO, the perigee will be raised to a minimum of 2000 km. A high circular (e.g. geostationary) orbit is preferable, as the sail would not be subjected to gravity gradient and aerodynamic torques. Such influences complicate the control and measurement of solar thrusting. The SSTO orbit will provide the benefits of a high orbit without the cost of a launch to geosynchronous orbit as the spacecraft will spend >80% of the time above 30,000 km.

Scalability Demonstration

It is critical that the flight validation results be applicable to larger sails with lighter films for the more stressing missions to come. The $S^4$ is fully scalable without need for design reconfiguration. Modeling of performance for sail sizes from 20 to 300 meters square have been performed.

For the data presented below, two key assumptions were made which emphasis a nominal film stress to straighten out packaging wrinkles and a constant structure margin of safety.

The first is that the quadrant center tensile stress is kept constant (at 1.5 psi). This causes the halyard tension to increase linearly with sail size. It would also increase proportional to a film thickness change. In Figure 19 the first mode of the quadrant is shown versus sail size. This constraint allows a frequency falloff, as a minimum controllable frequency has not been established. Note that this frequency relation is independent of film thickness (for equal stress).

![Figure 19. First Mode vs Sail Size (m)](image)
maintained at 3.0. Clearly, as the halyard tension and sail size increase, so must the mast diameter increase to maintain structural margin. The mast diameter versus sail size is shown in figure 20, along with the mast slenderness ratio. It is not until the higher sail sizes are challenged that the slenderness ratio will exceed our flight experience. The L/D ratio of the (three identical) booms on the LACE flight was 192.

![Figure 20. Mast Size vs Sail Size](image)

In the next graph is shown the generic sailcraft parameter “system loading”, which is the mass of the sail subsystem and spacecraft divided by the reflective sail area. If combined with the effective reflectivity and the solar flux, the acceleration provided can then be calculated. As bus architecture and payload requirements vary drastically by mission, curves for various spacecraft masses (in kg) are given. The performance of the S4 is fairly constant above 60 meters. Larger sail sizes are only useful for offsetting more massive spacecraft, not for added propulsion. Increased thrust for a mission is dependant on the spacecraft mass reduction.

![Figure 21. System Loading (g/m²) vs Sail Size](image)

The current performance is already sufficient to meet the most likely first mission, a sentinel position at sub-L1. As can be seen in Figure 22, the increase in warning time provided by a 5-um sail S4 propulsion system of 100-m size is 150% (assuming a 100 kg spacecraft). If the thinner CP1 sail (targeted at 2 µm) can be demonstrated to be low risk, then the same warning time increase can be achieved with an 80-m sail.

![Figure 22. Sub-L1 Sentinel Performance vs Sail Size and Sail Thickness](image)

The appropriate size of the sail depends on the desired warning time increase and the spacecraft mass. If the mission could be performed with a 50 kg spacecraft and only a doubling in warning time was desired, the near-term (5 µm) system size would be only 50-m.

**Summary**

Solar sails provide thrust without mass expenditure. The continual acceleration of this technology makes cost-effective non-Keplerian paths and unique sentinel perspectives such as a sub-L1 solar storm observer. Able has designed and analytically investigated a promising system level design for a robust scalable solar propulsion subsystem. The technologies selected for the mast, sails and the system arrangement combine to provide a viable solution to near-term missions. As has been shown, the scalability of the S4 system allows for more stressing future missions as well. Reduction in sail thickness and advances in payload miniaturization are expected to increase the number of exciting missions best performed with solar sails in the coming years.

The S4 technology, as developed under New Millennium Space Technology 7 Phase A funding, presents a credible low-risk path for component ground development and validation followed by flight demonstration. The In-Space Propulsion (ISP) technology program at NASA
has been working in partnership with the New Millennium Program (NMP) towards providing a Solar Sail Subsystem for a flight validation. If selected for the ST7 mission, the tentative launch date is in late 2005. It is to be expected that NASA will take this opportunity, or another soon, to bring forward this valuable technology as it can greatly benefit future space missions and will likely greatly arouse the imagination of the public.

**Acknowledgements**

Thanks to Bob Crawford, Bill Layman, and Martin Mikulas for helpful discussions and technical input.

**References**


