Fabrication and Deployment Testing of 20-Meter Solar Sail Quadrants for a Scaleable Square Solar Sail Ground Test System

Greg Laue[*] and David Case.[†]
SRS Technologies, Huntsville, AL 35806, United States

Jim Moore[‡]
SRS Technologies, Huntsville, AL 35806, United States

In order for solar sail propulsion technologies to be considered as a viable option for a wide range of near term practical missions a predictable, stable, reliable, manufactureable, scaleable, and cost effective system must be developed and tested first on earth and then on orbit. The design and development of a Scaleable Square Solar Sail System (S^4) is well underway at AEC-Able Engineering Co. Inc., and the design and production of the Solar Sails for this system is being carried out by SRS Technologies. In April and May of 2004 a single quadrant 10-meter system was tested at NASA LARC's vacuum chamber and a four quadrant 20-meter system has been designed and built for deployment and testing in the Spring of 2005 at NASA/Glenn Research Center's Plumb Brook Facility. SRS has developed an effective and efficient design for triangular sail quadrants that are supported are three points and provide a flat reflective surface with a high fill factor. This sail design is robust enough for deployments in a one atmosphere, one gravity environment and incorporates several advanced features including adhesiveless seaming of membrane strips, compliant edge borders to allow for film membrane cord strain mismatch without causing wrinkling and low mass (3% of total sail mass) ripstop. This paper will outline the sail design and fabrication process, the lessons learned and the resulting mature production, packaging and deployment processes that have been developed. It will also highlight the scalability of the equipment and processes that were developed to fabricate and package the sails. Based on recent experience, SRS is confidant that flight worthy solar sails in the 40-120-meter size range with areal density in the 4-5g/m^2 (sail minus structure) range can be produced with existing technology. Additional film production research will lead to further reductions in film thickness to less than 1 micron enabling production of sails with areal densities as low as 2.0g/m^2 using the current design resulting in a system areal density of as low as 5.3g/m^2. These areal densities are low enough to allow nearly all of the Solar Sail missions that have been proposed by the scientific community and the fundamental technology required to produce these sails has been demonstrated on the ground test sails that have recently been built. These demonstrations have shown that the technology is mature enough to build sails needed to support critical science missions. Solar Sails will be an enabling technology for NASA's Vision for Space Exploration by allowing communication satellite orbits that can maintain continuous communication with the polar regions of the Moon and Mars and to support solar weather monitoring to provide early warning of solar flares and storms that could threaten the safety of astronauts and other spacecraft.

I. Introduction

Solar sails are one of the high priority technologies being developed by NASA's In-Space Propulsion Technology Program (ISP). In order to develop solar sail technology to the point where it is mature enough to successfully execute a system demonstration flight experiment the ISP program has awarded two competing teams contracts to design, fabricate and test 10-meter and 20-meter system ground demonstrations. One of these teams the

---

[*] Engineer, Aerospace Technologies Directorate, 500 Discovery Drive, Huntsville, AL 35806, and MB.
[†] Engineer, Aerospace Technologies Directorate, 500 Discovery Drive, Huntsville, AL 35806
[‡] Engineer, Aerospace Technologies Directorate, 500 Discovery Drive, Huntsville, AL 35806, and MB.

Scalable Square Solar Sail Team (S^4 Team) consists of ACE-Able (buss, boom and primary ACS mechanical systems), SRS Technologies (Sail Subsystem) ASU (ACS Architecture and Modeling) and Princeton Satellite systems (Flight Software)

The Scaleable Square Solar Sail (S^4) concept was designed such that a single system architecture could be scaled to produce different size sail craft appropriate to a large number of number of missions. The basic architecture was created around a boom optimized for an 80 meter system of which truncated systems of 10 and 20-meters would be ground tested. This approach was devised in order to provide the best correlation between the 10-meter and 20-meter ground test articles required by the ISP program and the predicted size of sails that potential near term flight missions would require. The use of truncated boom structures also enabled the testing of more flight like hardware than would have been possible with a sub scale system. The ultimate goal of the ground program is to increase the TRL level of the system to the highest level possible.

From June of 2003 thru May of 2004 a 10-meter version of a single quadrant or one quadrant S^4 system was designed, produced and tested. This system consisted of two booms, a simulated spacecraft hub, and a triangular sail quadrant and is shown in Fig. 1 and Fig. 2. The 10-meter single quadrant test hardware represented one fourth of a three axis stabilized square solar sail propulsion system. The sail was designed to be suspended by tensioning it between the three attachment points located at the spacecraft hub and the two boom tips. This test series validated the basic design and construction techniques and materials used to build package and deploy this type of structure.

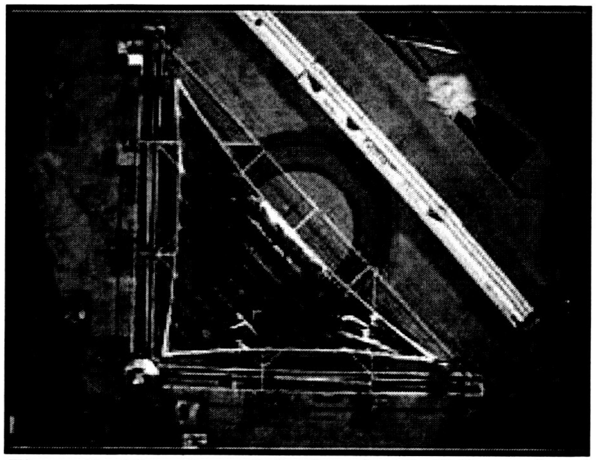

Figure 1. 10-meter sail deployed at LaRC over head view.

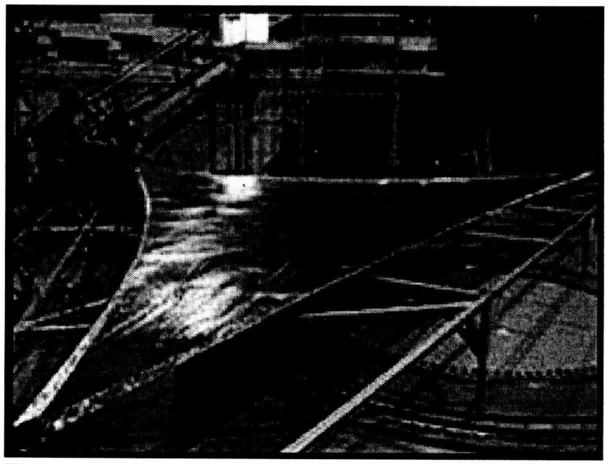

Figure 2. 10-meter sail deployed at LaRC edge on view.

In June of 2004 efforts to design and build a full four quadrant 20-meter sail system for ground testing began. This system consists of four booms, a system buss structure, primary ACS (Attitude Control System) and four triangular sails. The ground demonstration of this system under vacuum will constitute as close to a full flight like system test as can be preformed in a one gravity environment. A top view of the layout for the ground test system is shown in Fig. 3. This paper will outline the sail design and fabrication process, the lessons learned and the resulting mature production, packaging and deployment processes that have been developed. It will also highlight the scalability of the equipment and processes that were developed to fabricate and package the sails. This discussion will include several of the enabling technologies that have been developed to facilitate the production of large 2.5 micron thick solar sails. This paper will also document SRS's preliminary assessment of the deployed quadrants shape and discuss the effects of gravity on sail shape measurements, construction, and testing. Fig. 4 illustrates the nomenclature used to describe the 20-meter Sails and some of the key sail dimensions.

II. Sail Design Development

The basic SRS sail design consists of a cord, a compliant border, and the sail film. The main benefit of the SRS design is that the exterior cord and compliant border allow the sail to be loaded in a biaxial stress state from three points[1]. This provides a flat uniform reflective surface that produces very little scatter and distortion. The simplicity, stability and predictability of this design allows for an easily modeled reflective surface and greatly simplifies the analysis and margin required for designing an attitude control system for a square solar sail flight system.

The Able support system consists of a central structure that houses the storage bays for the deployment booms and the sails[2]. The booms are CoilAble™ carbon fiber structures tipped with a spreader bar mechanism that rotates. When the spreader bar is rotated it changes the angle of the sails creating a pinwheel effect that will allow for roll control of the spacecraft. Pitch and yaw are controlled by ballast bars that can be moved back and forth along the booms creating center of mass center of pressure offsets.

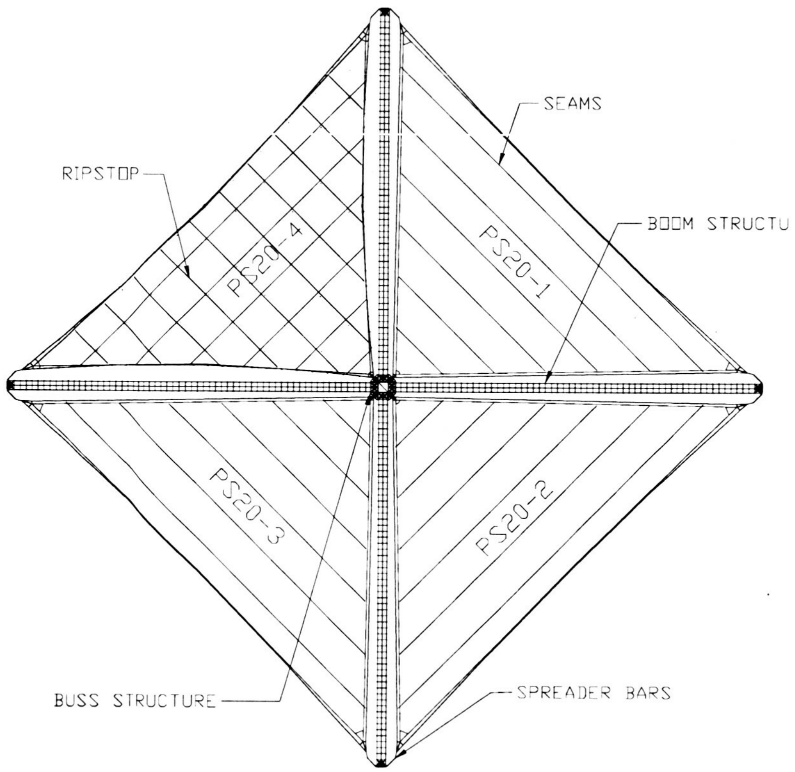

Figure 3. 20-meter ground test sail craft layout.

Geometry of the 20 Meter Pathfinder Sails

No.	X	Y
T	-0.53	-0.53
H1	541.94	6.75
H2	6.75	541.94
S1	4.76	4.76
S2	515.39	14.40
S3	14.40	515.39
R_S	3409.5 in.	
R_L	4494.6 in.	
A_S	117,196 in.^{2}	
G1	0.18	0.18
G2	532.47	8.91
G3	8.91	532.47
A_B	4,747 in.^{2}	
R_{SC}	2,647.5 in.	
R_{LC}	3,378.4 in.	
A_T	122594.6 in.^{2*}	

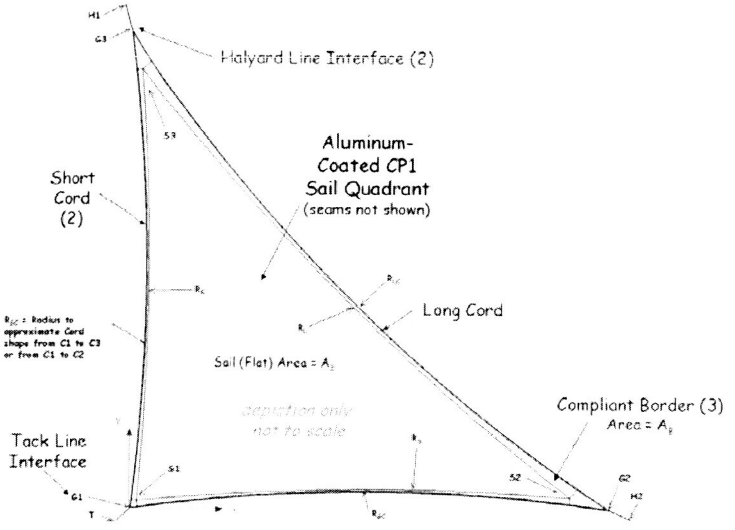

Figure 4. 20-meter ground test sail description.

For the SRS sail design, the edge cord curve is determined by the three point laded halyard load and the desired film stress. The compliant border width is determined by the maximum shear load expected between the cord and sail film. For a flight sail the maximum allowable boom tip load and the minimum film stress required to tension the sail determines the curve of the edge cord and its scallop depth and the predicted thermal extremes drive the compliant border depth requirement. For a flight sail the billow due to solar pressure is very small and will have a minimal effect on sail shape even at very low film stresses of around 1 psi. For a flight sail design the compliant border width requirements are driven by the thermal induced stress caused by the difference in the thermal expansion coefficients for the sail film and the edge cord. In a 1 g environment with a sail deployed in a horizontal orientation the film load caused by gravity is analogous to solar pressure, however, the gravity load ($4.9\text{x}10^{-2}$ Pascal for the 20-meter sail) is four orders of magnitude greater than the solar pressure at 1 AU ($9.12\text{x } 10^{-6}$ Pascal). This poses an interesting challenge for ground testing. The gravity loading has a dramatic effect on film stress during a ground deployment. In order to lift a sail off the deployment surface and suspend it the sail film stress must be increased. The film stress can be increased in two ways:

1) By increasing the cord tension (i.e. increasing the halyard loads). This increases the mechanical strain in the cord and requires a corresponding increase in compliant border width.
2) By increasing the scallop depth allowing for increased film stress without increasing the halyard loads.

Able's mast design has elements that were optimized for an 80-Meter system this was then truncated to 10 and 20-meter for ground tests. This produces a ground test system that is significantly stiffer than an optimized 10 or 20-meter boom would be. The stiffer system allows the use of higher halyard loads producing higher film stress to lift the ground test sails off of the deployment surfaces. For the 10-meter sails the halyard tension was limited by the structural capabilities of the booms. The scallop depth and the compliant border width were chosen based on a desired film stress and the sheer required for that loading. When designing the sail shape for the 20-meter ground test SRS optimized the sail for fill factor based on the max allowable load for an 80-meter flight system. This design was then scaled geometrically to fit the 20-meter ground test system. This design is geometrically correct in terms of the fill factor that could conservatively be achieved with a flight sail. However, a sail designed for the 1 g environment would need a considerably wider compliant boarder region to accommodate the film cord strain mismatch associated with the much higher loads required for ground testing. As a result the 20-meter ground test sails exhibit some small amplitude wrinkling in the corners. A unique design feature called a jumper strap (See Fig. 5) connects sail corner grommets, which attach the sail to the spacecraft, to the main surface of the sail. A cone shaped patch distributes the load from the halyard into enough of the sail to prevent overloading the film in tension. This feature picks up load once the compliant board shear limit is exceeded. In 1g there is a considerable amount of load carried by the jumper straps on the 20-meter sails, in a zero gravity environment the jumper straps would be unloaded. The jumper strap feature was developed to protect flight sail corners during deployment and during off nominal loading conditions that would result from extreme ACS maneuvers (large spreader bar movements) or the extreme thermal excursion that occurs if the vehicle fly's through the Earths or any other celestial bodies shadow. This feature limits the sail corner movement to that which can be withstood by the compliant border. The jumper Straps maintain the structural integrity of the ground test sails under the loading experienced in a horizontal orientation at 1 gravity.

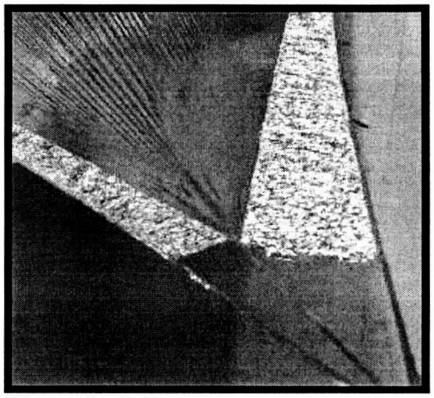

Figure 5. Sail corner.

This produces an issue when measuring the shape at these sails at 1 gravity. The halyard loads and film stress are both an order of magnitude higher than a flight sail would experience and the gravity sag is approximately four orders of magnitude larger. These forces deform the sail and require that flight shape be extrapolated from the ground test measurements. This complicates the issue of shape measurement and limits our ability to verify the dimensional accuracy of the assembled solar sails. The current ACS system is ore than capable of overrunning any minor dimensional variations in sail construction. Further work to develop innovative measuring techniques may allow reduction in ACS ballast bar mass requirements and improve system efficiency and predictability.

One of the innovative methods used to increase the fill factor for the optimized 80-meter sail design (that was scaled to produce the 20-meter sails used for ground testing) was to bias the load to the hypotenuse reducing hypotenuse scallop depth at the expense of short side scallop depth increasing the overall fill factor without changing the biaxial loading or sail mode shapes. SRS was conservative when using this technique for the existing sails and some additional fill factor gains could be made using this technique. A full load bias system level optimization study should be preformed prior to designing a flight sail.

Further fill factor design optimization was achieved by rotating the sail short side curves in order to relocate the tack line attachment point. This was done in order to take advantage of some of the area lost to the speeder bar tips and moves the tack line attachment into the spacecraft buss structure.

III. Sail Fabrication Process Development

A number of significant technological advances in sail design concepts, material fabrication processes and assembly methods were made during the production of the 10 and 20-meter sails.

A. Film Production and Coating

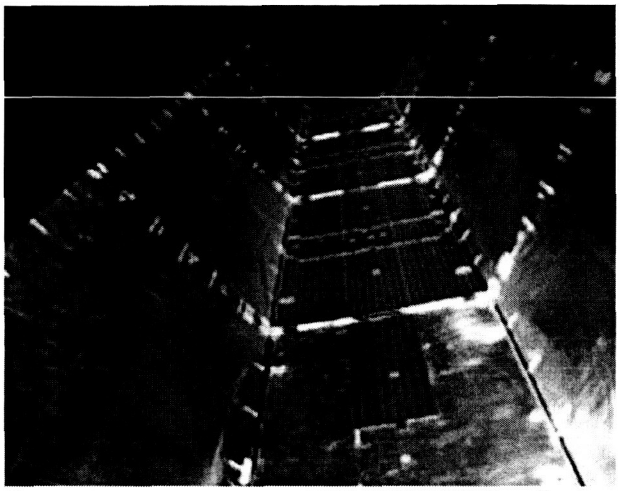

Figure 6. Boeing 702 satellite with SRS reflectors deployed.

CP1 film is a polymer film developed by NASA and produced under exclusive license by SRS Technologies. CP1 has mechanical properties and a density similar to Duponts Mylar^{TM} but has superior thermal properties and has a far superior resistance to radiation exposure. Aluminized CP1 polymer film has been flight qualified and was used for solar reflectors on several Boeing 702 commercial satellites illustrated in Fig. 6. This material (25 micron CP1) has been successfully deployed over 117 times on six separate spacecraft totaling an accumulated area of over 11,500 ft^2 (1,068 m^2) making the reflector system the largest simply supported film structure in orbit today. Prior to the start of the sail program SRS began producing ~60" wide continuous CP1 film using a proprietary continuous roll film production process and had been successful in producing film in the 7 to 5 micron thickness range. One of the goals of the 10-meter development program was to produce sails as thin as 2 to 3 microns. SRS was successful at producing thinner films with the existing process and demonstrated the ability to produce film in the 2 to 7 micron thickness range with less than 10% thickness variation. In order for this film to be used as solar sail material it must be coated with ~900 angstroms of aluminum to provide a reflective surface. This coated film is used as the membrane that makes up the bulk of the SRS solar sails.

A lack of a commercially available coating process that could reliably handle the ultra thin films being produced at SRS led to a collaborative effort between SRS and a coating vendor to develop an acceptable process for coating the solar sail films. A vacuum compatible web handling machine was designed and built by SRS to fit in a supplier's vacuum chamber. By using the combination of an SRS proprietary winding system and the vendors proprietary chamber hardware (shown in Fig. 7) the team has been successful at producing superior quality VDA coatings on SRS CP1 film with out damaging the film. These coatings have consistently had reflectivities measuring between 92 to 93 percent where the best commercially available processes typically produce reflectivity's in the 86-88 percent range. This is a significant enhancement for solar sail applications as reflectivity is directly proportional to sail performance. The development of film production and coating processes that could produce large quantities of high quality aluminum coated CP1 film was a major accomplishment and is one of the enabling technologies that allowed construction of the 2 micron class solar sails.

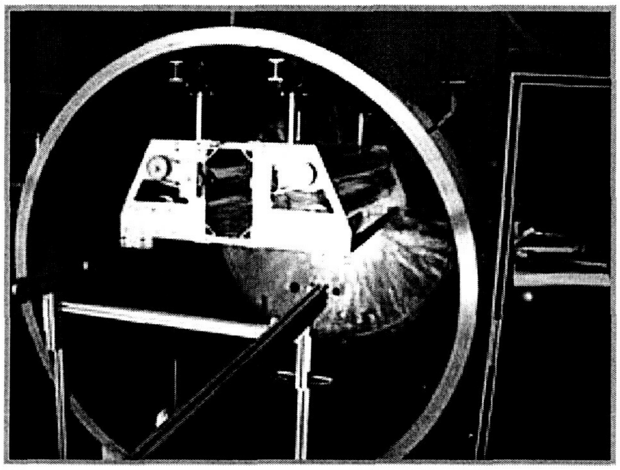

Figure 7. Film coating system.

B. Thermal Compression Seaming Patching and Ripstop Processes

During the 10-meter development effort a thermal bonding method was developed to fuse or seam film sections together. This technique involves no adhesives or foreign materials and produces seams that add no mass to the sail and are as strong as or stronger than the parent material. This seaming process requires uncoated surfaces in the bond region. A method of removing the coating in the location of the seam was devised. Both the coating removal tool and the seaming tool are mounted to a CNC gantry and are used to seam the ~60" wide sail film panels together to build a sail. This process allows for a lower mass, lower risk sail assembly by eliminating the need for adhesives to hold the sail panels together. SRS is continuing to improve this proprietary process and has developed a method of using a similar process to imbed ripstop and to patch damage from handling accidents and material defects. Pictures of some ripstop samples are shown in Fig. 8. SRS is developing a similar adhesiveless process for attaching the edge and corner features to the sail. Using this process it would then be possible to produce completely adhesiveless sails with corresponding improvements in areal density

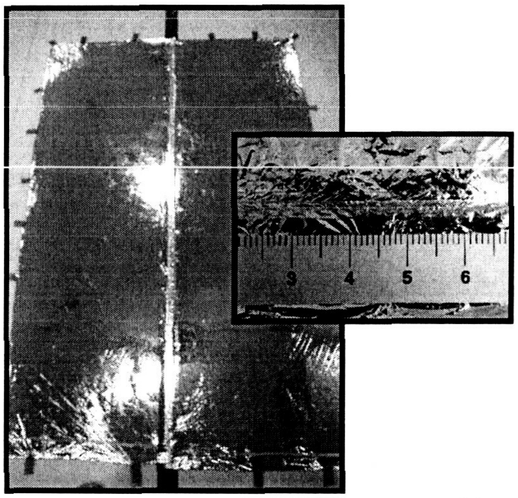

Figure 8. Sample seam and ripstop assembly.

C. Compliant Borders Development

Both the 10-meter and 20-meter sails incorporate a shear compliant border that allows the main bulk of the sail and the edge cord to move independently of each other preventing wrinkling and film buckling throughout the designed operational temperature range. This feature allows the sail to provide a stable and predictable thrust throughout the operational envelope by maintaining a constant biaxial film stress on the sail material. The last two 10-meter sail test articles and all of the 20-meter sails incorporated a corner feature called a jumper strap that allows the corner loads to be redistributed to a larger area of sail material during off design cord loading such as eclipse conditions. This feature shown in Fig. 9 protects the compliant border and allows the sails to survive much larger temperature swings as well as providing addition robustness for sail deployment.

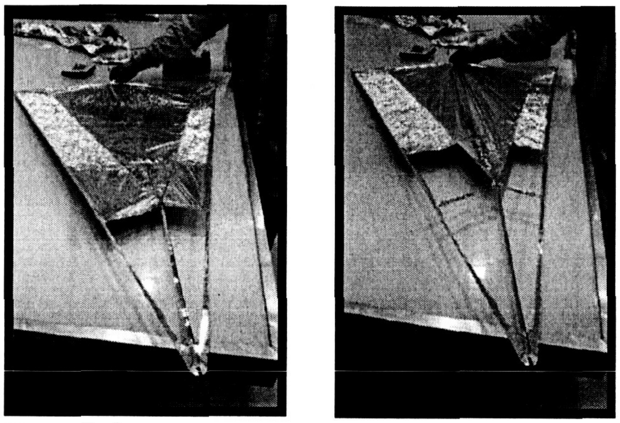

Figure 9. Jumper strap.

D. Fabrication Hardware

After the completion of the 10-meter test program a fabrication process was developed to facilitate production of the 20-meter solar sail quadrants that is readily scaleable to larger sails. One objective was to improve the repeatability and accuracy of the assembly process as needed to produce balanced predictable sail performance. The 10-meter sails that SRS produced in late 2003 and early 2004 were produced on the full sized table shown in Fig. 10 using a CNC gantry system shown in Fig. 11 for seaming. In order to minimize programmatic risk and to further develop the existing manufacturing technology to allow its use on sails of unlimited size it was decided that the 20-meter sails should be produced using an updated version of the existing hardware that was expanded in one direction only. A 20 meter long trapezoidal table was produced and the gantry tracks were extended for the length of the table as shown in Fig. 12. Improvements in the gantry CNC system and its positioning sensors along with additional sail marking and enhanced seaming hardware was developed to demonstrate the ability to accurately produce any size sail in a work space that is less than 20 feet wide and the length of the desired sail. SRS has built all of the 10-meter and 20-meter sails that have been produced to date with the film strips running parallel to the hypotenuse or long side of the triangular sail. If the sail film strips are rotated 90 degrees to run perpendicular to the hypotenuse the table length required to build a sail of a given size would be cut in half. SRS sees no significant issues with this process change and could produce sails as large as 50 meters in the existing facility using this method. Larger facilities would be required for sails over 50 meters. There are several viable options in selecting a reasonable cost facility to produce very large sails including existing hanger and industrial buildings, prefabricated steal structures and inflatable soft sided structures.

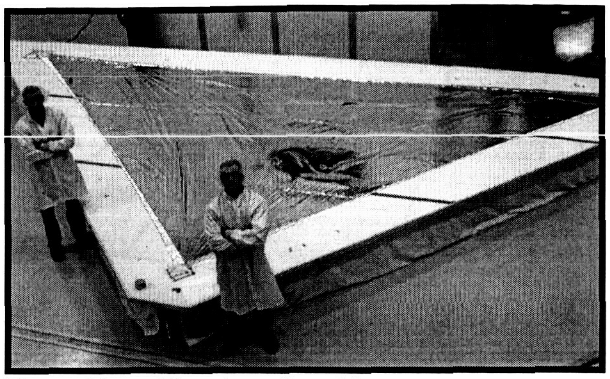

Figure 10. 10-meter sail on 10-meter assembly table.

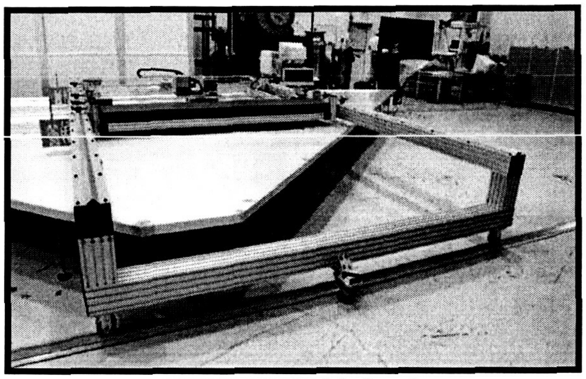

Figure 11. 10-meter assembly hardware.

E. Packaging and Storage

Originally, the S^4 Team had devised a sail storage method that involved first folding the sail into 15" strips and then accordion folding this into 5" folds for storage in the sail storage bay. The corners of each fold were to be held in place by small clips called book ends. When this was tried the gossamer nature of the sail proved to be an impediment to making these folds with the precision required to package the sail in this manner. Also the loads required to hold the sail in place were too high to allow deployments without damaging the delicate sail membrane. After the initial attempts to fold and deploy the first 10-meter sail using this method of storage it was clear that a more reliable, easer and more forgiving sail packaging system was needed. The solution that the S^4 Team arrived at was to make the 15" folds and then roll the sail up on a spool for deployment. This was tried on the 10-meter sails and has been carried on to the 20-meter sails with some minor improvements and provides a simple, reliable, and efficient sail storage and deployment system. Sails packaged in this way will easily fit in a triangular storage bay between the boom storage bays required for the CoilAble^{TM} boom systems.

F. Sequencer Evolution

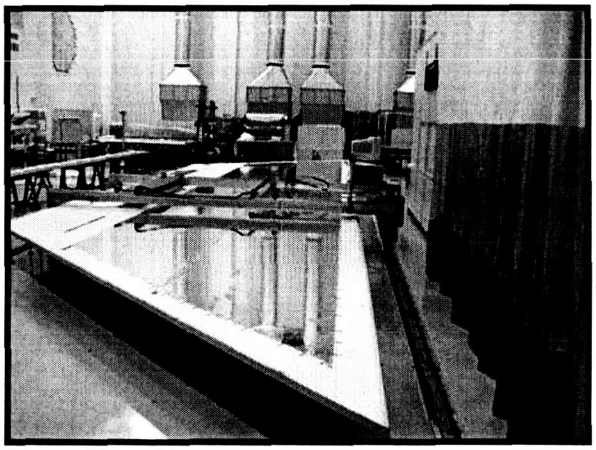

Figure 12. 20-meter assembly system.

With the incorporation of the spool concept for sail storage and deployment the S^4 Team determined that a method was required to provide a systematic controlled sail deployment and unfolding process as the sail came off of the spool. To accomplish this task a series of sequencers were attached to the sail. These sequencers ensure that the sail deployment is controlled, symmetric and deterministic and that the sail remains centered between the booms during deployment. For the 10-meter sails the sequencers were placed in a grid pattern thought the sail surface, as shown in Fig. 13. The sequencers consisted of a series of cords and anchors that could be attached to moorings these would hold the folds together until the deployment loads pulled the anchors out of the moorings and released the fold. This approach worked reasonably well on the 5 micron and 3 micron 10-meter sails. SRS and Able began looking for improvements that could be made to reduce the mass and the risks associated with the sequencers for larger and more delicate 20-meter sails. One of the sequencer design improvements made prior to the start of the first 20-meter sail build was to remove the sequencers from the main sail and place them along the cord, as illustrated in Fig. 14. This had several benefits:

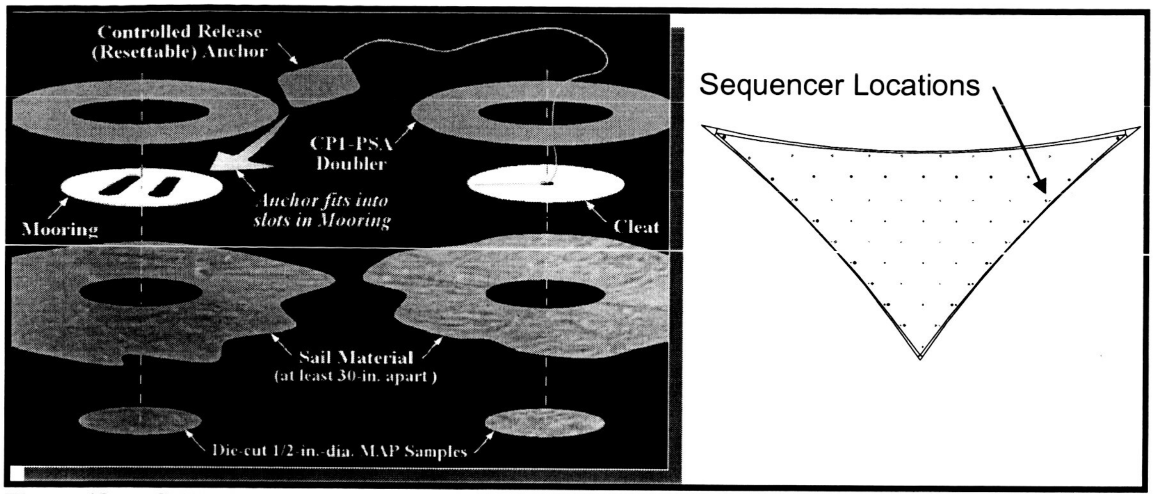

Figure 13. Sequencers on 10-meter sail.

1) It eliminated attaching sequencers to the delicate sail film and allowed them to be attached to the much stronger cord improving the survivability and durability of the sequencers and the sail
2) The number of sequencers required increases proportional to the length of the sail edges with sequencers attached along the edge and proportional to the area with sequencers distributed throughout the main sail body. On larger sails this will provide a significant weight savings.
3) Greatly reduced the time required and risks to the sail during the installation and attachment processes.

Once sail deployments began it became obvious that additional sequencers changes would be needed to facilitate the successful deployment of the thinner sails. Further improvements were developed during initial deployment testing at SRS and are discussed below.

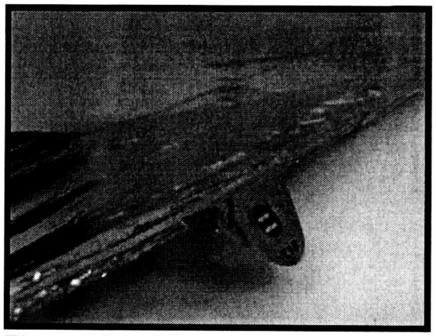

Figure 14. 20-meter sequencers located on cords.

IV. Sail Tensioning and Deployment Testing

Following the 10-meter testing the S^4 team decided that SRS should conduct deployment testing prior to delivering sails to Able for system integration and testing. This decision allowed SRS to build hardware to simulate a deployment including two pylons that represented the Able boom tips as well as a simulated sail storage bay and perform deployment tests much earlier in the program than if testing had to wait until the actual 20-meter hardware was completed and checked out. Testing early provided an opportunity to correct issues that were observed and work on and check out packaging ground support equipment and procedures. During the initial SRS deployment tests several significant issues were identified. By identifying these issues early in the program while the first sails were still at SRS and the 3rd and 4th sails had not been completed time was available to solve these problems in a quick and efficient manner. Two issues were discovered during these tests. :

1) That adhesive from patches and the corner feature attachment process caused parts of the sail to stick to each other and sometimes caused sail damage.
2) The sequencer anchors were causing sail damage after they released as they were drug across the sail surface.

The adhesive issues were resolved by the addition of several inspection steps throughout the assembly and packaging process and the addition of some repair processes developed to eliminate "sticky spots" on the sail once they were identified. The first attempt to eliminate the sequencer issue was to try changing the thickness and the shape of the anchors. The shape change resulted in a reduction in the number of occurrences but did not eliminate the sequencer induced defect problems. The thicker sequencers produced release loads well above those desired and in fact caused some minor cord and compliant border damage to one of the sails. With the current sequencer design posing a substantial risk to sail deployment, an alternate sequencer designs was sought. A concept was developed that replaced the multi use anchor and mooring design with a break away ribbon. The break away ribbons would have to be replaced after each deployment but this was considered a small inconvenience especially as a flight sail would never be redeployed in space and a few hours additional prep time between ground tests was viewed as a small price to pay for a successful deployment. The design that was first tested was attached to the old sequencer tabs with a adhesive patch on both ends and contained a single hole punched in the middle of the ribbon for a break point. Several ribbon sizes and hole sizes were tested to produce ribbon failure loads in the desired sequencer release load range. These sequencers were attached to the PS20-1 sail prior to its successful deployment on January 19, 2005.

This test was repeated successfully on January 21st with PS20-1 and again on January 25th with PS20-2. A picture of the PS20-2 following its successful deployment is included as Fig. 15; PS20-1 and PS20-3 are visible in the background of this picture. A series of pictures illustrating the deployment process has been included as Fig. 16. Since these deployments an alternate ribbon sequencer attachment process that involves tying the ribbons to a mount and eliminates the PSA has been developed and installed on PS20-3. In addition to the tie on attachment method a redundant ribbon defect was added to each ribbon to reduce the variation in release loads. The resulting sequencer design has shown nearly an order of magnitude decrease in the release load variation during component testing and has eliminated sequencers as a source of sail damage during deployment. The new design features will be tested with at least two full deployments in mid March. Once the design changes have been verified by deployment testing the remaining sails will be retrofitted to the new design prior to ambient and vacuum deployment testing at NASA's Plumb Brook facility in April and May of 2005

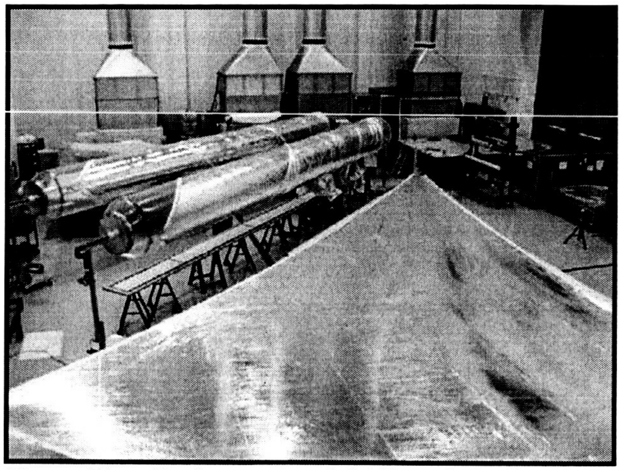

Figure 15. Deployment and folding of the first 3 20-meter sails. From left rear to right front sails 3, 1 and 2 are shown.

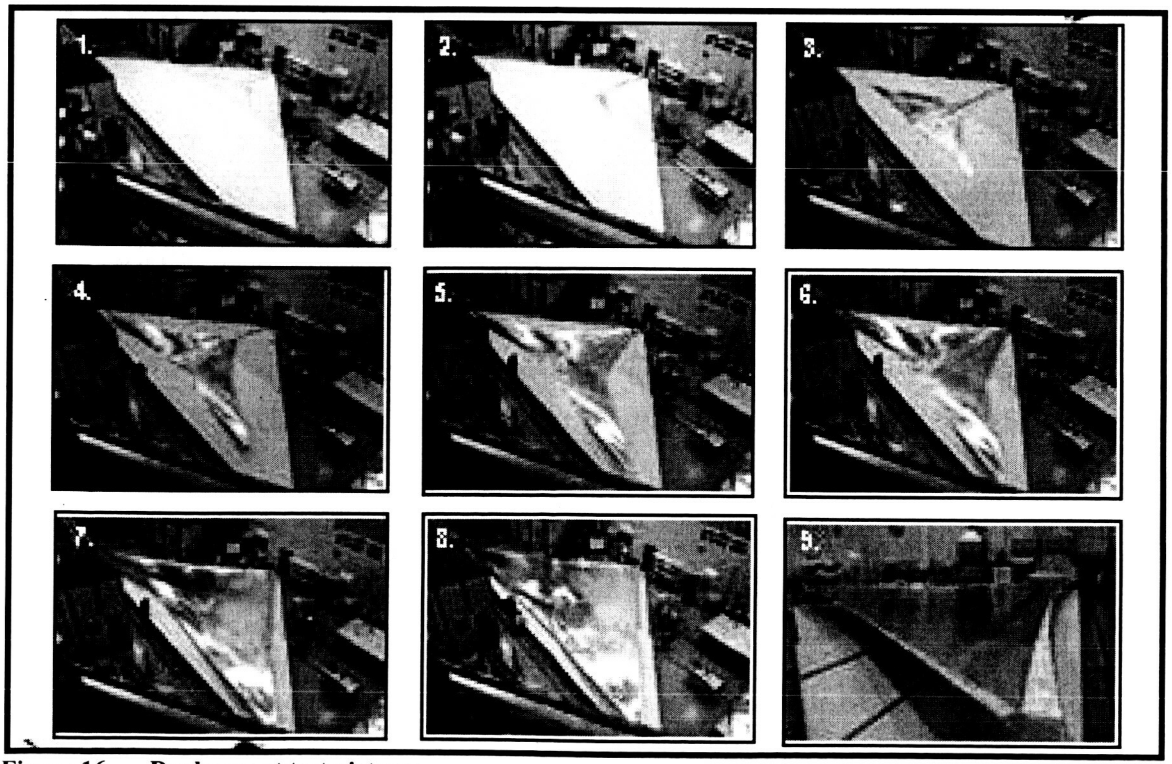

Figure 16. Deployment test pictures.

V. Ripstop Technology Development

Ripstop features are desirable for the solar sail membrane structure to provide survivability and limit the impact of an undetected manufacturing or packaging defect or micro meteoroid puncture and limit the extent to which one of these defects could propagate during deployment. Rripstop will add robustness to the system and allow a damaged sail to perform reasonably well. The spacing of the ripstop should be chosen such that the worst case of losing the outer most section on two adjacent sails could be overcome by the ACS system. SRS has experimented with several concepts since work began on solar sails that could accomplish this task. A viable adhesiveless ripstop option that could be added to a sail with less than a 3% mass increase and could be accomplished in time for the fourth and final 20-meter sail build was identified in December of 2004 and demonstrated on the coupon level in January of 2005. Prior to implementation of this feature on the fourth 20-meter sail a full up assembly test was conducted on the 3-meter assembly shown in Fig. 17. This was done to validate the planned assembly method and determine the optimal order for the assembly operations. During sample testing the adhesiveless ripstop provided around two orders of magnitude increase in the loads required to cause tear propagation in a trouser tear test. The ripstop application process and the resulting ripstop features are relatively new and would require further testing and evaluation prior to flight. This testing should include solar environment, thermal and life testing. The initial ripstop testing and functional evolutions are very encouraging and this ripstop provides significant increase in sail robustness at a minimum weight penalty.

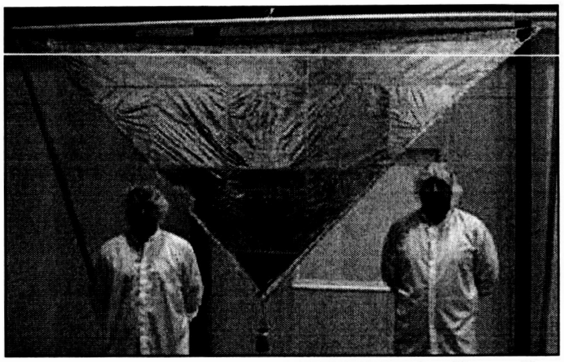

Figure 17. 3-Meter ripstop demonstration sail.

VI. Conclusion

Over the past two years, with funding from NASA's ISP program, SRS has developed the design and production technologies required for the production of large flight worthy, high TRL solar sails. The development activities and testing required to conduct the 10-meter and 20-meter deployment tests has greatly improved the design and fabrication knowledge base to the point where the design and construction of large flight like sails with high confidence is possible. Where additional materials testing and analysis would be required prior to building a flight system the remaining technical concerns with a flight test system could be answered early on as part of the design and development efforts for a flight system. The S4 solar sail team has identified the work that is needed and is poised to began work on the design of a flight sized system. The enormous potential and mission enabling capabilities of a solar sail propulsion system and the maturity of the technology that has resulted from the NASA ISP investment in this technology make it a prime candidate for near term flight demonstration and use. Solar Sail propulsion makes the use of non-Keplerian, high inclination and retrograde orbits as well as the use of artificial LaGrange points practical for long duration missions. The availability of a propulsion system that is low mass and low cost and can maintain these orbits indefinably enables a wide array of observational and communications missions. With the tremendous capabilities of solar sails and the relatively mature state of the technology the next logical step is a flight validation mission.

Appendix

An appendix, if needed, should appear before the acknowledgements.

Acknowledgments

The work described in this paper was funded in whole or in part by the In-Space Propulsion Technology Program, which is managed by NASA's Science Mission Directorate in Washington, D.C., and implemented by the In-Space Propulsion Technology Office at Marshall Space Flight Center in Huntsville, Ala. The program objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing cost, mass or travel times

References

1 Mikulas, Martin, "Solar Membrane Panel Concentrator Boundary Shape and Stress Analysis," unpublished, April 1997

2. Murphy, D. M., Murphey, T. W., and Gierow P. A. "Scalable Solar-Sail Subsystem Design Concept," *Journal of Spacecraft and Rockets*, Vol. 40, No. 4, 2003, pp. 539, 547.