Demonstration of a 20-m Solar Sail System

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The NASA In-Space Propulsion (ISP) program has been sponsoring system design development and hardware demonstration activities of solar sail technology over the past 27 months. Validation of a 10-m system solar sail system is complete, and efforts to demonstrate and evaluate a 20-m system are underway. Descriptions of the evolution of the design, results of functional testing to date, and analytical model predictions for upcoming shape and dynamic testing are reviewed.

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**I. Introduction**

Over the past decades many disparate activities addressing elements of solar sail technology have been pursued. As a result, materials technology, fabrication experience, and applicable analytics have been brought forward to a point where projections for system performance have begun to have real credibility. In 2001 the ISP Program, managed by the Office of Space Science at NASA Headquarters, determined that the time was right to pursue a system demonstration of sail technology that would elevate the Technology Readiness Level of solar sailing sufficiently to allow flight implementation. NASA embarked on a competitive, gated multi-year program, implemented by the ISP Projects Office at Marshall Space Flight Center (MSFC), to pursue the development and ground demonstration of system-level sail technology.

Under a 30-month NASA ISP program, ATK Space Systems (formally ABLE Engineering), in concert with other activities also under the purview of the ISP projects office at MSFC, has been developing scalable analytical tools and design technologies for a solar sail propulsion system. The subject ISP Ground System Demonstrator (GSD) development and validation effort, led by ATK-Goleta, is performed with the assistance of the Systems Technology Group of SRS Technologies in Huntsville (sail assembly provider), the Langley Research Center (LaRC) for sail shape modeling and dynamics testing, Arizona State University (ASU) for attitude control modeling.

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Princeton Satellite Systems (PSS) for sailcraft control software, and the MSFC Space Environmental Effects Laboratory (materials characterization and life evaluation).

In the first phase of the program (6 months) activities were focused on design and analysis refinement of the still-evolving Scalable Square Solar Sail (S4) concept and refinement of plans for hardware development and demonstration in Phases 2 and 3. The Phase 2 effort encompassed design, fabrication, and validation—through a series of component and system tests—of a 10-m ¼-symmetry demonstration system. Validation activities culminated with the demonstration of deployment, and sail shape and system dynamics measurement in vacuum at LaRC. Analytical correlation activities demonstrated that mast and sail subassembly and system behavior were predictable.

In Phase 3 a larger and more complete sail system was designed, fabricated, and demonstrated in an ambient environment. This 20-m S4 system is to be tested in the 100-ft diameter Plum Brook vacuum chamber facility in April and May of 2005. The 20-m design is a complete sailcraft system (4 quadrants, 4 masts, instrument offset boom), including flight-representative structure for the central assembly, additional mechanism for deployment and attitude systems control, tiedown/release hardware, solar panels, and payload adaptor fairing interfaces, to comprise a bus chassis, photon propulsion system, and sailcraft ACS.

In this paper some of the recent design developments important to the completion of functionality for an S4 sailcraft and for the ground demonstration system are discussed. Lessons learned in the development of the 20-m hardware are included. The critical demonstrations needed and the validations achieved with the 10-m system are summarized first. Results of testing to date with the 20-m mast and sail subassemblies, and the integrated system, are discussed next. The environmental testing planned, and shape and dynamics at Plum Brook with accompanying analytical performance predictions, are also reviewed.

II. Demonstration and Validation

The ISP projects office at NASA headquarters has prioritized the maturation of solar sail propulsion technologies in order to enable or enhance a variety of space science missions. Solar sails, especially as a system, present complex engineering challenges. In particular, the difficulty of validating modeling results—through testing in a fully representative environment prior to flight—has thus far discouraged near-term mission planners from utilizing this enabling propulsion technology.

The system demonstration and validation activities discussed herein systematically reduce the risk of flight implementation through a series of demonstrations of increasingly more complex solar sail systems and testing of the highest fidelity possible in the terrestrial environment. In our ongoing (Phase 3) activities, analytical and computer models are being refined and will be correlated based on testing of this latest, highly engineered, sail system. The overall program has been built on a structured evolution of hardware size and complexity. Early in the first hardware development cycle (Phase 2 of the 3 phase program), CP1 sails and a prototype graphite Coilable were assembled and tested. Then to culminate Phase 2 a ¼-symmetry deployable system 10 meters in size was built and tested. In the current phase a 20-m full S4 system has been built and validated with thorough ground testing. Deployments will be performed in the 100-ft-diameter thermal vacuum chamber facility at the NASA Glenn Research Center Plum Brook facility. These activities will elevate the Technology Readiness Level (TRL) sufficiently to where a validation flight is warranted.

Figure 1. ISP Program Milestones: Progressive Growth in Technology Maturation, Size, and Complexity
The rationale for the necessity of a flight validation is based in large part on the unsuitability of the ground environment for deployment verification. The deployment kinematics of a Coilable mast are controlled, predictable, and linear. But given the forces of gravity, a large ultra-thin membrane presents difficult challenges in ensuring a predictable, repeatable deployment that has a reasonable simile to in-flight kinematics. The examination of the deployed system is also hampered in a gravity environment. The induced sail tension is >10X higher than in-flight operational stresses, which drives the design and prevents assessment of true low-stress local topology. For a gossamer mast, the local and global waviness can significantly reduce the strength and stiffness performance. The gravity-free shape of the mast, like that of the sail, is critical to performance and yet may not be achieved on the ground. An effort to definitively investigate the load-managing behavior of a slender sail mast is just now entering the flight design phase, but will not be validated in space until late 2007.

Given realities such as these, the reticence of mission planners to adopt solar sail propulsion is understandable. Yet through the scope of work underway in partnership with NASA, all critical issues in sail systems are being rigorously investigated and addressed. With the completion of these efforts, fully validated, scalable, mission-enabling propulsion system architecture will be ready for flight demonstration. The key analytical validations planned for the 20-m S4 system parallel activities performed on the 10-m quadrant in Phase 2. The sag of 5 and 3-micron sails in a 1-g environment under the 3-point loading condition, at various loads, was measured and a reasonable correlation to the pre-test predictions was obtained. Typical results for the 3-micron sail at the nominal load condition, 2.5 lbs on the tack line, are shown in Figure 2.

Dynamic behavior of the mast and the system were measured by LaRC. The mode shapes and pre-test frequency estimates agreed well with test findings, for predictions made by both ATK (sail results shown in Figure 3) and LaRC. Analysts at LaRC pursued post-test correlation activities of both mast and system behavior and were successful in reducing the frequency errors to less than 1% and 5%, respectively.
III. 20-m System Description

The current S^4 design integrates gossamer Coilable mast and sail membrane technology, solar arrays, launch tiedown and release mechanisms, and attitude control actuators, efficiently packaged within structure shared by other bus components and mission payloads to form a generic scalable sailcraft possessing reliable deployment, structural robustness and determinate sail shape with—most critically—minimized overall mass and volume. The 20-m system is referred to as a sailcraft because it comprises many elements of a spacecraft, but designed uniquely to meets the mass efficiencies required of a photon-propelled gossamer system: multifunctional structures and mechanisms for launch interfaces, bus component and payload platform integration, solar arrays, ACS, and of course, propulsion. In contrast, the 10-m S^4 ground system, tested in the last phase of the program, consisted of only the three major subassemblies: Sail Assembly, Mast Assembly (qty. 2), and Central Assembly. The masts and sails were high fidelity, but the central assembly was a simple aluminum structure which served to house the stowed masts and sail, and mechanism necessary for their deployment. The 10-m system served to develop and confirm mast and sail design, fabrication, and analysis techniques, without the cost and risk of building replicates of more subassemblies than needed. Many lessons learned were carried forward to the 20-m system, allowing fuller concentration on the new elements needed to complete the full sailcraft system. All aspects of the 20-m system are constructed from flight appropriate designs and materials. Views of the 20-m S^4 ground system demonstrator sailcraft system are shown below.

![Deploying](image1)
![Stowed](image2)
![Deployed](image3)
![Mast Tip](image4)

*Figure 4. 20-m S^4 System with Details of Hardware from Functional Testing*

The sizing of the 20-m system was formulated from several criteria. The tip-to-tip size was set at 20-m, as this is the largest system that will fit within the Plum Brook testing facility. The mast is structurally optimized for an 80-m sail system, to improve the accuracy of scaling for larger likely science missions. Useful flight solar sail systems start perhaps as small as 40-m, but significant roadmap missions require 80 to 160-m systems. If we were to build an optimized system for a 20-m solar sail, the tiny dimensions of many critical parts would require wholly different analysis and construction techniques than for later flight systems. To obtain the highest value from the ground demonstrators we chose to size the masts and sails for an 80-m system. So, the masts of the 20-m GSD can be thought of as truncated in length by 75%. The sails are geometrically scaled down by 4x. The cord size, ripstop, and overlaid features are not scaled, but the outline is—to preserve the appropriate scallop ratio, and fill factors for the border and main sail. The central structure is sized for a 40-m system. Consequently, the masts only occupy ½ the volume available. To design a flight validation system near 40-m in size, very little resizing of components will
be required. Overall, these choices of scale reap the highest value from the ISP GSD program, and demonstrate more confidently the scalability to roadmap mission systems.

Two carbon composite 80-m sail masts (diameter of 40 cm, linear mass of 70 g/m) were tested at truncated lengths of 7-m for the 10-m Quadrant system. The same mast design was built for the 20-m system, in 4 lengths of 14.2 m each. New elements were added to the batten assemblies, which guide the ballast masses that can transit from tip to tip on each mast axis, providing ACS authority in pitch and yaw. Roll control (axis normal to the sail) is controlled thru modulation of the collective pitch of the sail quadrants by changing the angle of the spreader bars at the mast tips. Other elements at the mast tip include a stepper motor and controller, a common halyard reel and constant-force springs for the halyards, and various sensors. Three large-diameter thin-section bearings support the halyard reel and spreader bar. The motor first drives the reel to hoist the sails on their halyard lines. When the sails reach their deployed position (controlled by step count and backed by load monitoring), the motor is reversed, which actuates a mechanism to lock the reel together with the spreader bar. The sail tension is maintained constant throughout temperature variations and spreader bar rotations by constant-force springs. The motor then drives the spreader bar, to angles between +/- 45°, as required to null sailcraft roll. The ballast masses and spreader bar mechanisms together provide 3-axis propellant-less attitude control, but only once they are extended. To provide control prior to deployment, and to improve the long term reliability and overall robustness of the ACS, the utility of a secondary mode of control has been explored. The dominant demand on the ACS of a sailcraft is to null the inevitable pressure asymmetries which will be evident immediately after deployment. Once the collective pitch and ballast positions have been driven to where the orientation is nominally stable, a propellant system could again be used for the slow maneuvers and minor attitude corrections that are required for the mission. Limiting the number of cycles required by the mechanical systems over the life of the mission provides for higher system reliability. Maneuvering actually involves at least two-orders-of-magnitude less total momentum change per day than the steady-state requirement to maintain balance. Trimming and maneuvering are disparate ACS requirements best met with separate solutions. The mass of propellant needed for typical missions (with a trimmed sailcraft) is small, given that thrusters are positioned where they are most effective—on the end of the largest possible moment arm. A miniaturized thruster system that converts solid inert propellant (Teflon) to a pulsed plasma which is accelerated by magnetic fields to create thrust is a solid state device. Known as μPPTs, they provide a low mass, low cost option for sailcraft control.14 Provisions for mounting on the spreader frame a quad-nozzle μPPT thruster (design under development) has been designed. In the 20-m GSD, the digital controller at the mast tip has also been programmed to simulate commanding the thruster firings. The robustness of the overall sailcraft ACS is substantially augmented by the addition of μPPTs. They can work effectively in concert, where the ballast mass to trims the sailcraft CG in plane and the spreader bar tilt nulls the roll torque. With the sailcraft trimmed in 3-axes, the μPPT system can provide the torques to reach or return from any orientation quickly and robustly. The control system of the trimmed sailcraft would then have the familiarity and simplicity of a traditional spacecraft RCS jet package. A tip-mounted thruster configuration is effective for attitude control when the system is stowed as well, but a heritage ACS option such as momentum wheels would suffice in this case or for a trimmed sailcraft as well. The μPPT solution offers substantially lower mass and lower cost potential, which are both highly desirable in a sailcraft. The combination of running ballast, quadrant tilt, and μPPTs creates a balanced sailcraft ACS that is lighter weight, lower power, lower cost, more robust, lower risk (multiple units at each tip provide inherent redundancies), and more agile (allowing dithering, corkscrew, high-angle and edge-on flight maneuvering). And this system is controllable with traditional algorithms.15

The ACS (spreader bar positioning and μPPT firing) control box at the mast tip also addresses three accelerometers to measure the first mode bending and torsion of the masts, as well as load cells that provide data on the tension in the halyards as the sails deploy, and limit switches that can be used for rezeroing the spreader bar position in the event of a power failure. The masts can be excited dynamically using piezos that are positioned in-line with the longoners at each mast root in the central assembly.

The central structure is composed of a number of light-weighted carbon-composite/aluminum honeycomb panels, joined with mortise and tenon construction with composite doublers spaced along the mating lines. Four inserts for bolting to the launch vehicle payload adaptor fairing (PAF) are arranged on the anti-sun deck on a 0.42-m-diameter bolt pattern that directs load to the strong inner-structure corners where 3 orthogonal panels intersect. On many spacecraft a Marmon clamp assembly is used to facilitate release. One side of the separation band is left on the spacecraft. To avoid the mass impact on sailcraft performance of separation ring retention, a fixed point system will be specified that provides redundant simultaneous release by bolt fracture, leaving only a portion
of the threaded fastener in the insert. The release assembly envisioned is a heritage SAAB Ericsson Space product, where the fixed points release mechanisms are linked by cabling. The structural plate that interfaces the release assembly to the PAF would be custom-designed to allow mounting to any of a variety of small to medium-sized launch vehicles. The sail system was sized with recognition that a 40-m class solar sail demonstration flight would likely be orbited using a small dedicated-carrier launcher, such as Pegasus, Minotaur or Falcon. The 20-m GSD is sized to contain masts for a 40-m system. A 40-m class S^4 stowed assembly will fit within any of the aforementioned fairings and is also amenable to a Delta II dual-manifest launch option.

The central structure serves to house and support the stowed masts and sails for launch. Integrated into the central assembly are mechanisms for the release of the masts tip plates, sail doors, and ballast bars, plus motion control of the mast lanyards, which are used to both pay out the masts and to position the ballast bars. The deployment sequence begins with the simultaneous release of the mast tip plates. Next, stepper motors allow the lanyards on the Y and Z axes to slowly pay out the masts, driven by the internal strain energy of the uncoiling longerons.

When the masts have traveled about 1.5 meters, the base of the longerons will have straightened completely. This energetic action is used to release cables that hold the sail covers panels stowed. The sail door function during launch is to prevent the drum from rotating and the sail from unspooling. The drum is composed of a thin composite skin wrapped around composite end caps, with a central stiffening bulkhead where the tack line of the sail is connected. The drum rotates on bearings at either end. One end of the drum is fitted with a gear that interfaces with a ratchet mechanism to provide a constant tension on the sail as the halyards pull it from the drum. At the other end the bearing is reacted thru a load cell to provide knowledge of the loading during deployment and the tack line tension when deployed. The drum has a flat side and foam on the inside surface of the door preloads the sail against the drum across the flat. This configuration also allows the volume of the sail hold to be best utilized for volume-efficient stowing of sails. Once a door is released, it springs open initially due to the foam preload. Torsion springs on the hingelines drive the door open past 90°, and the opposing springs catch, slow and center the door in the deployed condition—normal to the sun. The outer surfaces of the door are populated with solar cells that provide power to the bus. The 4 door surfaces, populated with 200 standard multi-junction photovoltaic devices, provide 175 watts from 10 strings of cells producing 30 volts.

As soon as the mast deployment is complete, release of the launch restraints on the ballast bars may be activated. However, they are not functional for attitude control until a mass asymmetry can be arranged relative to the solar pressure vector to produce a canting moment. As the deployment of the masts and sails is quite lengthy, it would be prudent to begin with a non-zero spin rate normal to the sail plane and orthogonal to the sun line. As the masts, and then the sails, extend the spin rate will slow. The edge-on configuration and centrifugal forces will assist in assuring the sails remain in one plane, do not billow, and that destabilizing solar pressure torques are avoided.

Once the masts deploy completely, the halyards—which were stowed alongside the longerons—are spooled up onto the reel at the mast tip and the sails are deployed, as described earlier.

The central structure is designed to function as primary bus structure. A pattern of inserts on the sun-side deck allow palletized bus and payload components to be joined with the central structure that contributes structural rigidity, PAF interfacing, and solar power. Additional payloads are accommodated on the instrument boom. In a validation flight the boom may carry cameras for photogrammetric evaluation of system shape and dynamics. The boom is positioned to deploy anti-sun, where the view of the sails—directed to reflect earthshine or deep space—will allow instructive imaging. An instrument boom may be optionally positioned either or also on the sun side. Booms of up to 20-m each may be packaged within the central structure volume. If less boom length is required, any volume remaining can be allocated to bus components. The instrument boom lanyard shares the same reel in the central structure as the Y-axis masts. The instrument boom deploys at the same rate and the lanyard end comes free as the reel motion continues to deploy the longer masts.

All the structural assemblies, mechanization features, and embedded actuator and sensors that were added to the 20-m design have been validated with extensive functional testing in an ambient environment. These features represent the fulfillment of the technology advancements necessary to complete the S^4 sailcraft system.

**Sail Technology Advancement:** The development of large-scale sail fabrication has required a number of significant technology advances in sail design concepts, material fabrication processes, and assembly methods. Production of high-performance radiation-tolerant sail material is of fundamental importance. Our partner, SRS Technologies, has worked for several years with a NASA-developed polymer, CP1, which is similar to Kapton, but...
unique in that it can be solvent-cured to produce a thin, isotropic film, and thermal-formed and seamed without adhesives. Additionally, this material has been successfully ground-tested under a variety of UV, electron, proton and micrometeoroid qualification tests. SRS has significant experience with large-scale membranes built with flight-applicable construction from this flight-proven sail material. CP1 has been flown on a number of commercial GEO satellites and NASA materials evaluation missions.

One of the goals of the S4 development program has been to produce sails as thin as 2.5 microns, with reflectivity above 90%. The first sails built under the ISP program were 7 microns thick. Over the course of the program, SRS has been successful at producing progressively thinner base material in larger quantities with higher quality, now at film thicknesses of 2 to 3 microns. To coat these ultra-thin films, it was necessary for SRS to design and construct a vacuum-compatible custom web-handling machine. This equipment was installed at a commercial aerospace coating vendor, allowing the production of superior-quality VDA coatings (reflectivity measuring 92-93%) without film damage. This is a significant enhancement for system performance as reflectivity contributes directly to thrust.

The basic S4 sail design consists of three perimeter cords that incorporate scallops, compliant borders, and main sail film with ripstop. Important performance features are imparted by the scalloped edges. The border is trimmed with strong, flexible cords that impart robustness for handling and deployment. Inboard of the cords is a “ruffled” border area that allows thermal and mechanical strain decoupling of the main sail. The cord curvature and shear-tolerant borders work together to insure uniform stress in the sail, which in turn assures a predictably flat shape and border area that allows thermal and mechanical strain decoupling of the main sail. The cord curvature and shear-tolerant borders work together to insure uniform stress in the sail, which in turn assures a predictably flat shape and high propulsive efficiency. The simplicity, stability and predictability of this design allows for easily modeled propulsion and tractable analysis of margins in the design of the attitude control system. When configured with a modest scallop (80% fill factor, relative to the triangle formed by the grommet locations), the border provides these various edge effects without significantly increased boom loads. The fill factors on the 10-m sails (6 were built) were 70-90%. A 20-m sail designed for 3-point support in a 1-g environment would need very large compliant borders, irrespective of scallop depth, to accommodate the shear induced by membrane sag, and thus would not be representative of the fill factor that could be achieved with an 80-m flight sail. The 20-m sail is a geometric scaling of an optimized 80-m design (82.5% fill), thus it possesses undersized borders for a gravity environment. As a result, the 20-meter ground test sails exhibit some wrinkling in the corners under the loading experienced in a horizontal orientation, emanating from where “jumper” straps connect the grommets to the main surface of the sail. The load from the halyard is distributed into both the cords and the jumper straps, where a cone-shaped main-sail doubler patch disperses stress, preventing the sail film from being overloaded in tension. In a zero gravity environment in which the deployed film stress is much lower, the jumper straps carry no load-except for thermal extreme conditions that would occur given an excessive solar off-angle.

Other engineered features of the sails built for the 20-m ground demonstrator system include, but are not limited to, adhesivesless seaming of the main membrane strips with low mass embedded ripstop, and a number of detailed corner and border reinforcing overlays. The thermally-bonded seaming method allows for a lower mass, lower risk sail assembly by eliminating the need for adhesives to hold the sail panels together. This technology advance was extended to included ripstop embedded in the seams and applied orthogonally to form a grid. Ripstop features are essential for assuring survivability in the event an undetected manufacturing or packaging error impedes nominal deployment. Minor imperfections or a tear initiation could easily propagate during deployment to result in a significant propulsive area loss. Ripstop lines are spaced conservatively close together, such that the sailcraft can be controlled by the ACS even in the event of multiple sail tears. The inclusion of ripstop incurs a 3% mass increase on an 80-m sail. The fourth sail in the 20-m system incorporates this latest technology advance, as can be seen in Figure 5.

Reliable deployment is the most critical functionality of a sail system. Much effort has been concentrated on developing and evaluating methods for controlling the sail deployment. In Phase 2 it was determined that the deployment path should be centered between the booms, to avoid any possibility for snagging during deployment. Furthermore; a deterministic, repeatable sequencing for the unfurling was desired. Unrolling off the stowage drum is controlled by a damper mechanism that applies a constant retarding torque. The separation of folds begins when the cross-tied sail is nearly completely off the drum, at a point where the halyard angle develops significant loading in the first tie strip that holds the outboard corners together (refer to Figure 5). For the 10-meter sails the remainder of the sequencers was arranged in a grid pattern over the main sail surface. This approach worked satisfactorily, but was recognized to be mass inefficient—and to create unnecessary tearing risk—for larger thinner sails. For the 20-m sail, the sequencers were moved from the main sail and placed on tabs distributed along the cords. Additionally, the
multi-use anchor and mooring design was replaced with a disposable, but more consistent release approach involving a thin notched ribbon. These strips are tied to the perimeter tabs, so that all loads are reacted into the strong cords. When the strips separate at the reduced cross-section point of the tie, there is no potential for snagging as was identified to exist with the reusable anchor/mooring approach. In ground testing this deployment control method has proven to be reliable and repeatable and has enabled rapid (about 4 man-hours per 20-m sail) and trouble-free deployment and restowage.

Over the past two years, SRS has greatly improved the design and fabrication knowledge base of flight-like sails. Production advancements and deployment verifications of each completed assembly at SRS have shown that the technology readiness is mature enough to build flight demonstration sails. The methods developed to facilitate production of the 20-meter solar sail quadrants are readily scaleable to larger sails. An updated version of the assembly hardware used on the 10-m sails was employed by expanding the table and traveling CNC seaming gantry in one direction only. This approach allows fabrication of any size sail in a workspace that is less than 6 m wide and the length of the desired sail. By seaming orthogonally to the hypotenuse cord, this equipment could produce sails as large as 50 meters in the existing SRS facility.

Figure 5. 20-m Sail Packaging and Sequencing for a Controlled Deployment

Mast Technology Advancement: Like the flight-proven CP1 sail material, the mast technology brings a strong resume to this new application. The Coilable mast builds on ABLE Engineering heritage of 100% reliable deployment in space while incorporating design advances which provide the minimum-mass configurations allowed by the gossamer loading of a sail mission. The sail masts are an advanced version of the continuous coilable longeron structures ATK-ABLE has flown 27 times in space, with 100% success. The Coilable is a very mass-efficient structure: A sail mast as light as 34 g/m, was demonstrated in Phase A of the New Millennium Space Technology 8 (ST8) program. This same mast is proposed for ST9. Performance comparisons between the ISP GSD, ST8, and proposed ST9 mast hardware are shown in the figure below.

The first evaluation of the completed 14.2-m mast assemblies was a check of stowage and deployment. The masts stowed properly into a 12-cm-high coil, meeting the expected linear compaction factor (0.85%). The mast deployments were performed horizontally. The mast tip was supported by a cable to an overhead trolley that rolled along a taut cable. The mast was rate-limited by an axially-located lanyard and a DC motor. The internal strain energy of the coiled longerons and buckled battens provides an axial push force measured at 7 lbs, as was predicted by closed-form calculations.
Basic functional performance and structural strength and stiffness identification had already been demonstrated on the 10-m quadrant masts, but as these masts were fabricated from a separate pultrusion run, tests of a single mast (on a rigid base) was performed to allow precision model correlation.

Figure 6. Comparison of a Heritage S2 Glass Boom to Gossamer Sail Masts (ST8-L, ISP-R)

Stiffness and strength were evaluated using lateral tip deflections imparted by a simple setup consisting of a pulley and various weights. The deflections were measured using a laser tracking system that followed a corner cube mounted on mast tip ground support equipment (GSE). The compliance of the mast in bending is shown to the left in Figure 7. A linear fit though the data documents a 2.272 in./lb compliance. Deflection is due to both bending and shear compliance. The predicted shear stiffness, based on measurements of the diagonal, and the known diagonal angle is 2,266 lb. The measured (3-point bend) stiffness of the longeron material received in October of 2003, for use on the 10-m quadrant masts, was $EI = 28.72E6$ lb-in$^2$ ($E = 27.3E6$ psi). The predicted compliance of the mast based on these values, with the compliance due to shear added is 2.273 inches/lb. The 20-m masts were built from a later pultrusion run (received in August of 2004). The agreement between the test data and the prediction based on a few measured components, demonstrates the reliable behavior and predictability of the mast design and the pultrusion process.

Figure 7. Mast Stiffness Testing (D = 39.5 cm, L = 14.2-m)

The close agreement between the estimated and measured first mode demonstrates that the Coilable is generally a very predictable, readily-modeled, linear structure. However, longer masts and or substantially lighter designs are susceptible to stiffness, and hence also strength, reduction due to local and global waviness.

Several difficulties were encountered during the build of the 20-m system masts that were not observed on the 10-m system masts. The most disconcerting problem was due to fiber imperfections in the longerons that were not screened out before assembly. These imperfections played a role in at least one of two longeron breaks that occurred during system functional testing in ambient. The graphite material is pushed to a large fraction of the ultimate composite strain capacity when stowed. Stresses are approximately 20% higher in the transition section. The first
break occurred while the +Z mast was being stowed. The cause may have been a surface defect imparted by interferences with the terminal fitting. Unfortunately, the longeron fractures so energetically that post-mortem material evaluation is impossible. The potential for defect introduction by component interferences was overcome with the addition of a tape overwrap. When a second fracture occurred a few days later, in a different location on the +Y mast, the quality of the longerons material and the risk of incomplete screening came into question. All longerons were 100% inspected, this time using a magnifying glass and added light. In all, 132 locations of perceptible non-uniformity were found, but only three were judged to be necessary or prudent to reinforce. The two longeron breaks were repaired with a bonded and over-wrapped glass sleeve splint. The imperfections were found to have been caused by fiber “fuzz balls” present on the raw tows, which got carried along through the resin bath, into the die, and were entrained in the longerons during pultrusion. As there was a risk that more of these small areas of misaligned fiber could be hidden within the longerons in the assembly, a mast performance screening was required. After inspections and repairs were completed, each mast was cycled a minimum of 5 times prior to proceeding with general system functional evaluations. The longeron quality deficiencies were not expected, since the 10-m system masts and the ST8 7-m demo mast suffered no issues with cycling or long term stowage. Consequently the quality controls for the 20-m ground demonstration mast longeron procurement, while consistent with previous material procurements, were proven to be insufficient. The potential for the observed material and pultrusion variables to disrupt quality is a valuable lesson learned though, and better NDI techniques to assure only high quality pultrusion are accepted in a flight build are being developed.

A second issue arising from incomplete inspection criteria also arose unexpectedly in the 20-m ground system mast builds. The batten-to-yoke bonds were not 100% inspected when the batten subassemblies were constructed. Consequently, a small number of bond failures were experienced over the course of tens of deployments. In retrospect, not only should proof testing have been done on all bonded assemblies (even in a ground demonstration program), the bond engagement should be lengthened slightly in future builds to improve the margins sufficiently to overcome manufacturing variances. The recommended change will increase the mast linear mass by only 0.7%.

**Control and Data Acquisition:** The S4 system has a significant number of embedded control systems and sensors, as detailed in Table 1. A control and data acquisition (CDAQ) system was constructed to facilitate testing by providing the operator with a GUI that allows for actuator movement control and sensor feedback display, with concurrent data logging. Providing for an efficient user interface system for extensive systems testing was a primary driver in the configuration chosen. The CDAQ system consists of a master system controller, a COTS motor controller and 4 custom slave motor controllers for 6 motors. The slave motor controllers are implemented in C using an embedded DSP microprocessor with a custom control PCB and a COTS motor driver daughter board. The slave controllers communicate with the rest of the master controller by way of a custom protocol and an EIA-485 interface. The master system controller is implemented in LabVIEW using National Instruments PXI hardware. All controllers are state machines that respond to a defined set of commands. The software architecture is designed in part to emulate commands given by a spacecraft to the master controller, and to allow easy interfacing of various ACS algorithms.

To make the system failsafe, a master relay switches power to the system. The master relay can only be switched on within the system controller by a user command. If power is lost to a subsystem, if the user commands in software, or if the user hits a large screen button the all control systems will power down. If communication between the master and any slave controllers is

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<tr>
<td>Separation Nut Actuators</td>
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<tr>
<td>Mast Deployment Motor Control</td>
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<tr>
<td>Sail Deployment Motor Control</td>
</tr>
<tr>
<td>Halyard Load, Deploying</td>
</tr>
<tr>
<td>Sail Loading, Deployed</td>
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<tr>
<td>Dynamics (Mast alone &amp; System)</td>
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<tr>
<td>Mast Motion (Static &amp; Dynamic)</td>
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<tr>
<td>Ballast Bar Position</td>
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<td>Ballast Bar Position (cg offset control)</td>
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<tr>
<td>Spreader Position (roll control)</td>
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<tr>
<td>Spreader Bar Home Position</td>
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<tr>
<td>Temperature Monitors</td>
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<td>Electronic Heater &amp; Thermostat</td>
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</tbody>
</table>
lost, that slave controller will independently terminate any motor motion. The master controller uses sensor feedback is used to shut off the motors in the event of an overload, motor stall, or over-travel condition. To enhance safety during testing, remote switches are available to users on the floor to shut off motors and system power.

To make the CDAQ system fault tolerant, the data acquisition is independent of operational status of any subsystem. Operational status of every slave controller is independent from the others. All controllers and the data acquisition run in parallel. Data is acquired at 10 Hz for control feedback, displayed at 3 Hz and logged at a user defined rate up to 10 Hz. Data is stored to a memory buffer, the buffer copied, dumped to disk and cleared when 90 data points have been acquired. Data files on disk are added to until the maximum size for Excel graphing is reached, then a new data file is started.

The CDAQ system is portable, to support testing at ATK (Goleta, CA) and at Plum Brook (Sandusky, OH). The control boards embedded in the system were tested at to assure performance in vacuum and to determine that steady state temperatures of the driver chips would be moderate.

IV. Testing Program

Testing planned for the 20-m S^4 system parallels the activities performed on the 10-m quadrant, only with greater complexity and environmental simulation commensurate with the increased fidelity of the sailcraft system. An overview of test series activities and objectives is given in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Test Activity Intent</th>
<th>Fundamental Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Inspection</td>
<td>Verify/document physical aspects of system are compliant with design intent and documentation.</td>
<td>Documented completion required to proceed into Formal Testing.</td>
</tr>
<tr>
<td>Electrical Inspection</td>
<td>Verify system and GSE are electrically functional IAW design intent/documentation.</td>
<td>Documented completion required to proceed with Functional Testing.</td>
</tr>
<tr>
<td>Baseline Functional</td>
<td>Verify mechanical functional performance in nominal ambient environment.</td>
<td>Performed to establish robustness &amp; readiness (after shipping and set-up) prior to vacuum testing.</td>
</tr>
<tr>
<td>Vacuum Functional</td>
<td>Verify mechanical functional performance in relevant vacuum environment.</td>
<td>Establishes further robustness (thru repetition of deployments) and readiness for highest risk test: T-Vac.</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Measurement of sail global shape to allow model validation and correlation.</td>
<td>Obtain data for model validation to provide confidence in predictions of future scaled system behavior.</td>
</tr>
<tr>
<td>Shape</td>
<td>Identification of mast, and sail system modes to allow model validation and correlation.</td>
<td>Obtain data for validation of dynamical predictions (sail modes are a function of compliance matrix).</td>
</tr>
<tr>
<td>Venting</td>
<td>Validate stowed sail assembly is undamaged by ascent environment (rapid depressurization).</td>
<td>Validate stowed sail is undamaged by rapid depressurization and differential pressures.</td>
</tr>
<tr>
<td>Vibration</td>
<td>Investigate stowed system dynamics, local amplification (resonances), and robustness.</td>
<td>Investigate behavior, evaluate launch survivability, correlate model of stowed structural dynamics.</td>
</tr>
</tbody>
</table>

Ambient Testing: In order to reduce programmatic risks associated with system testing, engineering development unit (EDU) assemblies of the new ACS designs were constructed and tested first. A number of key lessons were learned thru the initial assembly and evaluation of the test bed were incorporated into the 20-m procurements. But given the short initial schedule and the compression of activities due to procurement delays, the build of the 20-m system elements eventually overlapped with completion of the test bed. The subassembly testing was structured generally as shown in Figure 8 below. The particulars of mast testing and sail testing were reviewed earlier. After completion of the mast and sail component testing regimen and their integration into the central assembly, electrical and physical inspections were performed in addition to several system functional (deployment) trials. The 20-m assembly was ready for shipment to Ohio for testing in the Plum Brook Station vacuum chamber.

Mass Properties and Propulsion: The mass estimates of the S^4 assembly are based on component weights and CAD-based projections. The weight of the completed assembly will be measured to validate the existing projected total mass. Given the large number of wires run from the CDAQ system into the central structure, and a desire to ship the system to Plum Brook without disturbing the wiring or disassembling the Central Structure from the central GSE, this measurement will not be obtained until the system returns from vacuum testing. Measurements of components such as the mast and sail assemblies have been performed. A breakdown of the components is depicted in Figure 8.
Figure 8. Mass Breakdown of Mast and Sail Assemblies

The linear mast of the mast (sized in cross section for an 80-m sail) is 70 g/m. The breakdown of the contribution of the various elements of the basic structure is shown. Additional mass is required for the ballast support guides (6.9 g/m), lanyard lines (2.4 g/m), and wiring harness (11.7 g/m). The harness is made up of four wires used to carry digital signals to a processor board at the mast tip, which reads load cells, accelerometers, limit switches, and a commands a stepper motor. The mass breakdowns for the solar sail assemblies represent 3-micron sails, of the design used in the 20-m system. The cord and edge treatments are a lower fraction on a larger sail. The ripstop mass fraction increases as the spacing used on the 20-m sail is the same as would be appropriate for an 80-m system.

While mass summations are the fundamental determinant of sailcraft propulsive performance, thrust is also a function of global and local shape and sail material reflectivity. 3-micron sail material specularity at in-space stress levels has been measured using a laser to access the effective diffuseness of a crinkled (due to repeated packaging and deployment) film. A conservative knockdown for crinkling, $k_c$, to the 92% specular reflectivity, $r_s$, measured on virgin films, was found to be < 2% at 1 psi. The effective propulsion factor, $F_p$, for normal illumination of an imperfect sail film is then,

$$F_p = 1 + r_s = 1 + r_s k_c$$  \hspace{1cm} (1)$$

Thus the characteristic (1 au) acceleration can be formulated as,

$$a_c = F / m_T = P_{Sun} F_p / m_T = P_{Sun} (1 + r_s k_c) / m_T$$  \hspace{1cm} (2)$$

Additional corrections are needed for treatment of the sail border (and other significant areas where light falls), thermal emission, global billow, and ACS surface orientations. It has been shown how the total propulsion can be computed with a customized interface to finite element program. These effects and other environmental disturbances are also treated rigorously in the solar sail control toolbox built by Princeton Satellite Systems, which includes functions for multi-body dynamic modeling, attitude control systems design, thrust vector control management, orbit analysis, solar sail mission analysis, thermal analysis and power subsystem analysis as well.

Environmental Testing: The 20-m system design was configured to maximize the size of the ground validation hardware relative to the largest available vacuum chamber, the 100-ft-diameter Plum Brook Station facility at NASA Glenn Research Center in Sandusky, Ohio. System testing in vacuum is necessary because both the deploying and deployed dynamics of a sail could otherwise be greatly affected by the surrounding air mass. As an illustration, the air within 2 mm of either side of the sail surface alone is equal in mass to a 3-micron sail film. In order to validate deployment characteristics as well as sail shape and system dynamics, a series of tests were planned utilizing the Plum Brook chamber. The priorities for testing are first to validate deployment in vacuum at thermal extremes, second to validate models for system dynamics, and third to measure deployed shape of the sail billowed under gravity loading.

The ATK/LaRC/GRC test team has planned an extensive series of tests to capture the data needed to support these priorities, as well as to meet goals for developing test methods applicable to larger scale testing and to in-flight investigation. The testing at Plum Brook is scheduled to take place over a period of four weeks. Preparations for testing have been ongoing for several months. Hazard analysis documentation and review, chamber cleaning, integrated vacuum systems verification of high vacuum pump down rates and stability, and cold plate installation have been completed. Prior to S4 system testing, there are two weeks dedicated to test hardware installation by ATK and LaRC. The setup of the S4 assembly, supporting GSE, and CDAQ by ATK occurs in the second week, following the installation and checkout of dynamics and shape measurement instruments and supporting GSE and wiring by LaRC.

Formal testing in the first week begins with a system deployment in ambient pressure. This test primarily is intended to confirm the setup of GSE and the integrity of the test hardware after shipment. It also allows a practice
run at the vacuum deployments that follow, and provides the only opportunity for close viewing of the full system deployment by other interested parties. Functional testing includes ACS demonstrations or spreader bar and ballast mass rate and range of motion. Shape testing, scheduled to immediately follow, is performed on the deployed system to measure the gravity-induced sail sag, with spreader bar position as a variable. Five photogrammetry cameras are used to image 44 targets on each sail and 3 targets on each mast tip, to identify tip droop and spreader bar angle. A laser ranger is also employed (which can confirm the photogrammetry results) as it is built into the vibrometer, which has been installed overhead for dynamics testing. The purpose of the test is to gather shape data useful in the correlation of finite element system models of stress distribution and shape. While the sagged shape has some analogy to solar-pressure induced billow, the stresses and deflections are more than three orders of magnitude larger. The shape correlations are part of modeling activities for the prediction of system dynamics. If these models can be verified and post-test correlation improved, as occurred in 10-m quadrant testing, then projections of scaled larger systems can be performed with greater confidence. The system shape correlation helps confirm load distribution and shape-induced stiffening that are important to accurate modal predictions.

Dynamic testing is the focus of the second week of testing. This testing is performed on the deployed system in both ambient and vacuum conditions. Mast testing is performed in ambient pressure, to avoid the necessity of breaking vacuum to decouple the sails, and then pumping the chamber down again. Mast excitation options include the on-board piezos in-line with the longerons at the mast root (baseline) and standard mechanical exciters mounted on GSE. The motions of the mast tips will be monitored with on board accelerometers (baseline) and by a laser vibrometer to identify the first mast bending and torsion mode frequencies.

System testing is performed at a pressure of approximately 1 torr. LaRC personnel will execute the testing using a series of preplanned routines that drive excitations such as burst random and limited sine sweeps. Variables such as frequency range, resolution, amplitude, phasing, number of inputs active, and spacing of the magnets to the sail are all software controlled. The motions of each target on a sail are repeatedly measured by the vibrometer, the results are averaged and recoded, and custom software drives a 2-axis mirror system to position the laser to acquire the next target. This sequential process is expected to require a few minutes per target and there are 44 targets per sail, so the time to iterate and execute and large number of tests can quickly accumulate. Consequently, a detailed plan of attack is being formulated for a significant number of potential test-analysis correlation (TAC) targets. The test goals are to obtain sufficient data to permit correlation with mathematical models of 3-6 fundamental modes. Preliminary results of frequency response curves, and coherence plots, from scans of a subset of sail targets will be used to adjust input and output variables and to narrow the TAC selection set before time-consuming full target set scans are collected. The first 3-6 sail-dominated system modes, at various spreader bar angles, will be pursued.

In the third week the system will be deployed again, this time in a high vacuum (< 1E-3 torr) condition. Two of the threes deployments planned (but not shape or dynamics measurement) will occur in high vacuum conditions to approximate the relevant environment. The third deployment will include an even more critical aspect of the relevant environment, a thermal gradient. A pre-deploy gradient of 40°C will be imposed by positioning a liquid nitrogen cold plate beneath the stowed system. This condition conservatively assumes a deploy position with the instrument boom oriented towards the sun, rather than the preferred orientation of sail edge on and slowly rotating as described earlier. The successful completion of the ATK functional test series and the Plum Brook relevant environment deployments will rigorously demonstrate the repeatability and reliability of the 20-meter S4 system.

The test hardware and GSE will then be disassembled and shipped back to ATK-Goleta for other tests needed to fulfill TRL level 6 requirements. First a stowed sail will be exposed to a rapid depressurization test to validate the sail assembly is undamaged by the ascent environment. Secondly, the systems will be vibration tested to investigate stowed system dynamics, local amplification (resonances), and overall robustness. The intent of this test is to obtain sufficient data for launch environment modal analysis correlation. Visual inspections and pre/post exposure deployments will be performed for each environmental test.

V. Predictive Analytics

FEA modeling of the S4 system was pursued cooperatively at ATK and NASA LaRC, employing ANSYS and NASTRAN respectively, to generate pre-test predictions of the behavior characteristics to be tested at Plum Brook. Experience gained in the development and test-analysis correlation of 10-m sail models was applied, but the greater size and complexity of the 20-m system still posed numerous challenges. The basic intent was to predict sail shape and dynamics under 1-g loading. The sail sag is analogous to the billow that would be produced under the pressure
of sunlight, although the deformations are much greater. The 20-m sail would billow less than 0.3 mm in space, but the forces of gravity can cause a 50-cm sag. It is necessary to model the sag as the doubly-curved surface shape both stiffens the overall sail and produces wrinkling. This stress stiffening and load path variations affect the dynamic modes.

Convergence on the gravity-induced shape was a challenging analytical exercise. Treatment of various constraint and load step application was determination of incremental applications that lead to successful convergence requiring spreader bar positioning. The shape of the sail in 1-g is significantly affected by the travel +/- 45 degrees from the plane of the masts. The bars can change the angles of the spreader bars. The bars can travel +/- 45 degrees from the plane of the masts. Assuming some collective pitch of the sails will be required to balance asymmetry about the X-axis (roll) on-orbit, the sail was designed around a 22.5 spreader bar setting.

Obtaining convergence of the sail shape under 1 g was pursued first, but with the sail horizontal by shortening the bar length, then the true position of the spreader bar was incrementally introduced. In subsequent load steps the results for spreader bar angles from 0° to 45° were obtained. The minimum deflection, 0.6 m, is for the nominal case (22.5). The deflection magnitude grows slightly when the spreader is rotated further because the load vector of the halyards is shifted toward the hypotenuse. The point of maximum deflection shifts towards 0. The tip pulleys are coming closer together and consequently the halyard load vectors are shifting load to the short side cords. Refer to Figure 9, where the nominal shape under gravity can be compared to extreme spreader bar positions and to the zero-g shape.

Figure 9. Comparison of Sail Deflection Predictions

The length of the halyard is designed such that at the extreme spreader bar angles the load vectors are still well within the cord lines, maintaining an evenly stressed sail and hence a flat propulsive shape and near-constant first mode frequency. Axial compliance in the cords, and design features such as shear compliance in the sail border, and constant halyards loading (grounded to constant force springs) aid in producing this desirable behavior.

The modes of interest in a flight system are dominated by the sail compliance. For the 20-m ground system the truncated masts are even stiffer, relative to the sail. However, tip GSE mass—required to compensate for gravity effects—results in the lowest system modes, 0.5 to 0.8 Hz, being associated with mast bending and torsion. These artificial modes will not be targeted in test. The system modes that have the highest mass participation from the first 3-6 modes of the sail, referred to as sail modes, are the targets for test-analysis correlation. These modes, which are
between 0.8 and 2.5 Hz, are impacted very slightly by mast compliance. The hub structure was verified to have negligible influence on shape and dynamics using detailed modeling in NASTRAN.

Evaluation of the sail modes is complicated by incomplete information about the load sharing between the cords. The sail is designed with scallop depth and border area ratios appropriate for an 80-sail. In other words, the sail is a simple geometric scaling of an optimized 80-m fight design. Consequently, the width of the compliant border in insufficient to support the shear induced by gravity loading. There is a thin strap located between the converging ends of the cords, which connects into doublers at the sail corners. This strap is designed to protect the border from being overstressed during deployment and 3-point support in 1-g. Once deployed on-orbit these straps would be slack. But, given the large deformations induced by gravity, the straps share the halyard load necessary to produce manageable sag. As this strap supports a portion of the load more directly to the center of the sail, the sag is reduced approximately 30%, and the first mode is raised 25%. The strap loading has the effect of shifting the point of maximum amplitude in the static and first three mode shapes towards the perimeter. Yet, as can be seen in Figure 11, the fundamental mode shapes are still clearly evident.

The static shape and dynamic behavior of each sail will be characterized by measurements made at 44 points distributed over the surface, at the locations indicated on the sails in Figure 11. These points, each a 1-in. retro-reflective target, will be imaged by photogrammetry and a laser ranger to measure shape, and a laser vibrometer for dynamics. The masts will be measured by photogrammetry as well. Targets on the tips spreaders will be used to confirm spreader bar angle, as the position strongly affects shape in 1 g. The fundamental modes will be measured by the laser vibrometer, with input by a standard mechanical shaker. Dynamic excitation options that utilize embedded actuators and sensors (piezos and accelerometers) that would enable on-orbit system identification will be
employed. Traditional methods will also be used in test to validate the performance of the embedded systems, and to ensure the highest quality data for correlation activities.

![Figure 12. Effect of Strap Loading on Sail Frequencies](image)

VI. Ongoing Activities

Testing at Plum Brook begins in late April. As significant test data is gathered, model correlation activities will commence. The rich data sets being pursued will provide ample opportunity for detailed correlation activities, our highest priority after functional demonstrations in the relevant environments. Given correlated (and scalable) models to predict membrane shape 1 g, analyses of dynamics can be made with greater confidence. The ability to confidently predict the general shape and approximate frequencies of the first few system modes is essential for robust control system design for flight.

The on-going demonstrations and validations of $S^4$ system technology elevate the TRL in all areas critical to support a low-risk flight validation mission in earth orbit.

VII. Summary

ISP program activities have systematically reduced the risk of flight implementation with substantial technology development, through a series of demonstrations of increasingly more complex solar sail systems, and by testing of the highest fidelity possible in the terrestrial environment. The functionality and performance of 10-m Quadrant has been validated by test and modeling has been correlated and applied to a 20-m ground system demonstrator of sailcraft technology. Ambient validations of the functionality of this system have been completed and a detailed series of environmental testing and performance measurements are underway. These activities will have, by June of 2005, elevated the TRL of solar sailing technology to the point where a flight program is the next logical step to advance solar sailing to operational readiness.

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