L • GARDE INC. CORPORATE PRESENTATION

Development and Gound Testing of a Compactly Stowed Scalable Inflatably Deployed Solar Sail

David Lichodziejewski, Billy Derbes, Rich Reinert,
Dr. Keith Belvin, Dr, Kara Slade, Troy Mann

DEVELOPMENT AND GROUND TESTING OF A COMPACTLY STOWED SCALABLE INFLATABLY DEPLOYED SOLAR SAIL

David Lichodziejewski[‡], Billy Derbès[†]
L'Garde, Inc.

Rich Reinert
Ball Aerospace

Dr. Keith Belvin, Dr. Kara Slade, Troy Mann
NASA Langley Research Center

Abstract

Solar sails reflect photons streaming from the sun and transfer momentum to the sail. The thrust, though small, is continuous and acts for the life of the mission without the need for propellant. Recent advances in materials and ultra-low mass gossamer structures have enabled a host of useful missions utilizing solar sail propulsion. The team of L'Garde, Jet Propulsion Laboratories, Ball Aerospace, and Langley Research Center, under the direction of the NASA In-Space Propulsion office, has been developing a scalable solar sail configuration to address NASA's future space propulsion needs. The baseline design currently in development and testing was optimized around the 1 AU solar sentinel mission. Featuring inflatably deployed sub-T_g rigidized beam components, the 10,000 m^2 sail and support structure weighs only 47.5 kg, including margin, yielding an areal density of 4.8 g/m^2. Striped sail architecture, net/membrane sail design, and L'Garde's conical boom deployment technique allows scalability without high mass penalties. This same structural concept can be scaled to meet and exceed the requirements of a number of other useful NASA missions.

This paper discusses the solar sail design and outlines the interim accomplishments to advance the technology readiness level (TRL) of the subsystem from 3 toward a technology readiness level of 6 in 2005. Under Phase 2 of the program many component test articles have been fabricated and tested successfully. Most notably an unprecedented section of the conically deployed rigidizable sail support beam, the heart of the inflatable rigidizable structure, has been deployed and tested in the NASA Goddard thermal vacuum chamber with good results. The development testing validated the beam packaging and deployment. The fabricated masses and structural test results of our beam components have met predictions and no changes to the mass estimates or design assumptions have been identified adding great credibility to the design. Several quadrants of the Mylar sail have also been fabricated and successfully deployed validating our design, manufacturing, and deployment techniques.

The team of L'Garde, Ball Aerospace, JPL, and LaRC has developed a highly scalable solar sail configuration to meet the in-space propulsive requirements of many of NASA's future missions, while dramatically lowering launch costs. Phase 2 of the program has seen much development and testing of this design validating design assumptions, mass estimates, and predicted mission scalability. Under Phase 3 the program will culminate in a vacuum deployment of a 20 m subscale test article at the NASA Glenn Plum Brook 30 m vacuum test facility to bring the TRL level as close to 6 as possible in 1 g. This focused program will pave the way for a flight experiment of this highly efficient space propulsion technology.

[‡]leo@lgarde.com, [†]billy@derbes.net,

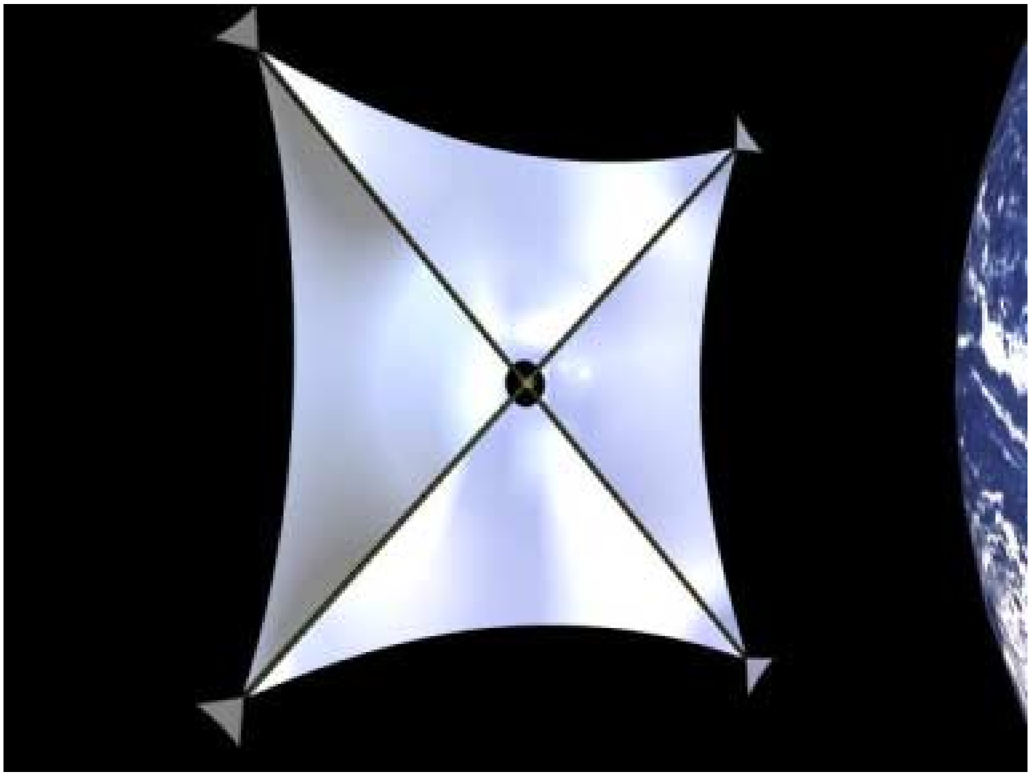


Figure 1. L'Garde's 100m ISP Solar Sail Design

Introduction

Early in the program, with the support of NASA, potential solar sail missions were researched and a mission set of interest was developed. Relevant mission parameters and environs were identified and defined. These requirements were used to develop a solar sail design meeting and exceeding these requirements.(1) This design includes all elements required for power generation, communications, and navigation. An equipment list was generated, components selected, and mass properties developed. To enhance the flight performance of the concept, a carrier concept was developed to jettison all non-essential deployment-related components before the mission.

An important aspect of the Phase 1 effort was to generate a test plan to raise the TRL from 3 toward 6. A list of test articles was developed to validate section properties such as boom modulus, torsional stiffness, and deployability. Sail sections and quadrants have been fabricated for testing and validation. A 10 m subscale system test article will be fabricated for ground testing at L'Garde and will then undergo a vacuum deployment and structural test in NASA's Plum Brook 30 m thermal/vacuum test facility. Ultimately, a 20 m square test article will be built and tested again at NASA's Plum Brook 30 m thermal/vacuum test facility. This test, which will validate the sail system at space thermal and vacuum conditions, will bring the sail system toward TRL 6. Achieving a TRL level of 6 requires testing in a "relevant environment". Our tests will simulate space thermal, vacuum, and acceleration conditions but will still be conducted under an acceleration magnitude of 1 g. Despite offloading many issues related to the 1 g magnitude will remain after testing of this large and gossamer structure. As a result, achieving a full TRL of 6 on the ground will not be possible, however, we will come as close as possible in a ground testing environment.

Design Overview

The baseline design is shown in Figure 1. This 100 m square configuration was optimized around the solar sentinel or sub L1 sun observation mission.(2)(3) This solar sail mission utilizes thrust from the sun to descend below the L1 Lagrange point providing a vantage point closer to the sun yet remaining in the same orbital period as the Earth.(3) This same configuration can be used for a host of other missions with no or minimal modification other than geometric scaling.

Support Structure

Earlier solar design work at L'Garde showed that the sail suspension technique has a large impact on system mass and scalability. Several attachment techniques were reviewed (Figure 2) and the stripe architecture was selected as the most efficient.(8) To achieve the striped architecture the sail is attached periodically to the boom. The points for this attachment are readily provided by the innovative conical stowage and deployment technique, which will be described later. The compressive loads in the beam generated by the tension loads in the sail membrane are thus passed into the booms locally at these discrete locations instead of globally at the tips as in the other techniques. Instead of the booms having to withstand these compressive loads over long spans the loads are applied over much shorter distances. Thus the Euler or long column loads are greatly reduced. Further, as the structure is scaled up in size the overall boom length increases, normally requiring a much larger beam cross-section to resist buckling. However, for sails using striped architecture more attachments points can be incorporated mitigating the scaling penalty of Euler buckling. An additional advantage is that the out of plane solar flux bending moments in the beam are distributed, rather than concentrated at the tips.

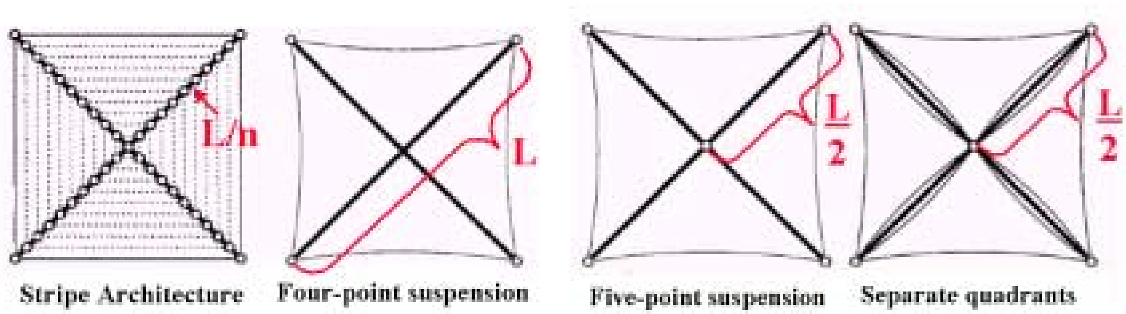


Figure 2. Sail Support Techniques

Beam Design

The beam design is a combination of two elements. The inflatable sub-T_g rigidizable boom, which forms the heart of the support system, and the sun side spreader system which reinforces the boom against the bending moment imparted by the solar flux on the sail membrane, Figure 3. Note that the mass optimized beam is reinforced only against the loads induced by the solar flux sail in the anti-sunward direction. This class of structure is called a Proa structure. Should a reverse loading condition be required an anti-sun side spreader system could be incorporated but would add additional mass.

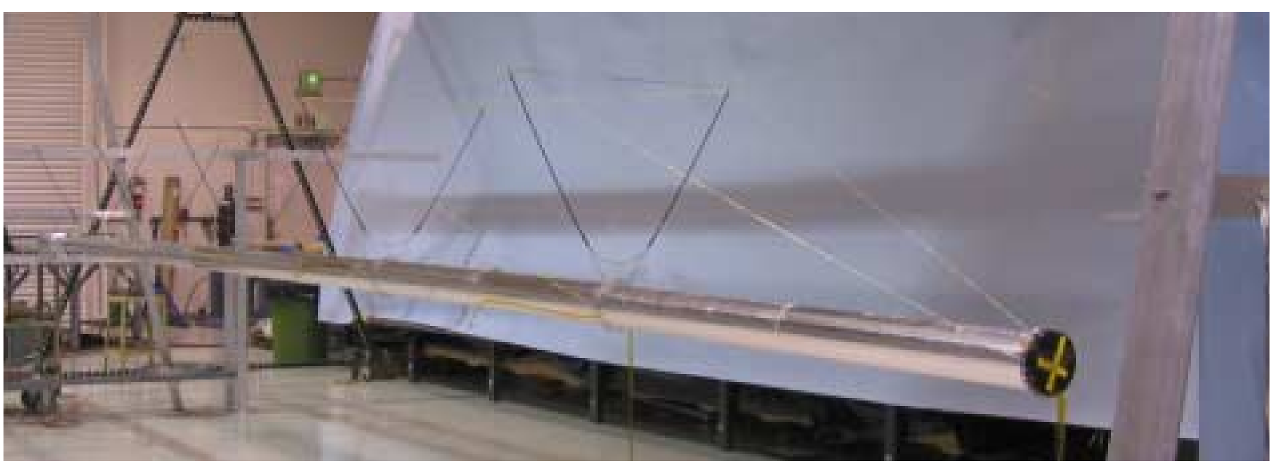


Figure 3. Solar Sail Beam

Semi-Monocoque Boom Design

The booms are designed in a semi-monocoque configuration. High modulus fibers are oriented as shown in a boom built for Team Encounter (Figure 4, left side). The fibers are impregnated with a sub-T_g resin to rigidize the structure after deployment (this is described in the sub-T_g section). Longitudinal uni-directional fibers are oriented to absorb the compressive loads in the booms, while the lateral fibers absorb the inflation loads and stabilize the longitudinal fibers and the cross section. And the external layer doubles as a bladder and shear web. These lateral fibers provide the burst margin required for deployment contingencies.

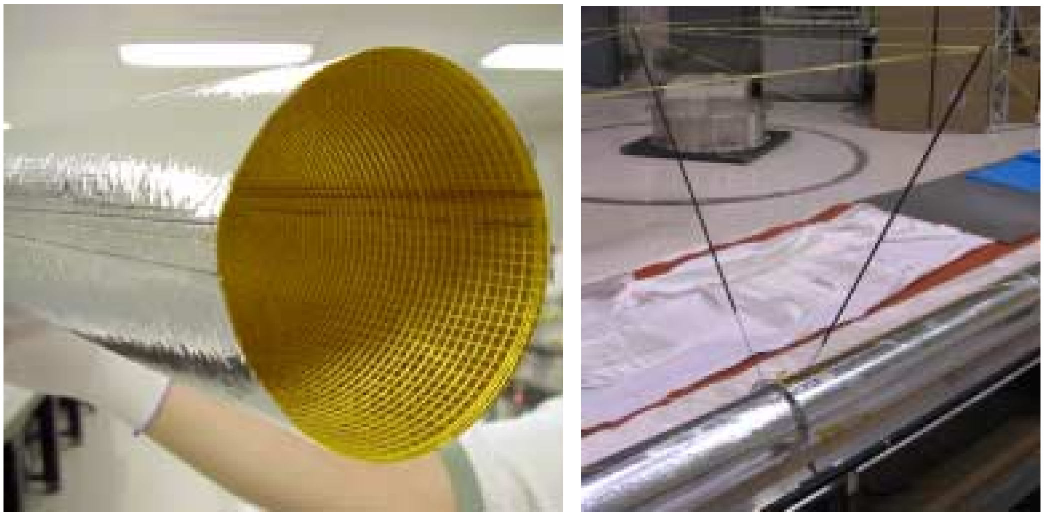


Figure 4. Boom and Spreader Close-up

The thin walled boom absorbs all of the longitudinal compressive loads in the beam structure. Thin walled booms are ideal in compression as they offer the largest sectional moment of inertia for a given amount of material. When utilized in a truss such as the solar sail beam they offer the greatest resistance to Euler or long column buckling, consequently, the bay spacing or distance between spreaders is maximized keeping the mass as low as possible.

Spreader system

Low mass rigid rings are mounted periodically along the boom. They serve to stabilize the boom cross-section offering the greatest resistance to Euler buckling. They also provide a hard point for mounting of the spreader bars, (see figure 5, right side). Additionally, they provide an ideal hard point for mounting of the net/membrane attachment points. The spreader system incorporates a number of tension elements running along the boom. The anchor lines running from the spreader tips to the rings provide a shear component transmitting bending loads. The longeron lines running along the spreader tips provide a large moment of inertia to the truss to resist the bending generated by the solar flux. Finally the diagonals crossing over along alternating spreader tips increase the torsional stiffness of the truss while providing longitudinal redundancy in the lines in case one or more lines are severed.

<u>Conical Deployment</u>

Figure 5 shows the conical boom packaging and deployment scheme developed for deployment control of the inflatable rigidizable support booms .(6) The technique uses a unique concentric packaging arrangement about the boom axis and provides a high degree of deployment control (patent pending). To deploy the conical boom, inflation gas is introduced at the base. The resulting deployment is smooth and predictable. Note that the boom is pressure stabilized during deployment and is able to withstand loads during extension.

A deployment sequence of a Team Encounter sail conical boom is shown in Figure 5 on the right. This deployment took place while the boom was floating in a water trough to simulate a 0 g deployment condition in. The deployment proceeded smoothly and in a linear, consistent, and predictable manner.

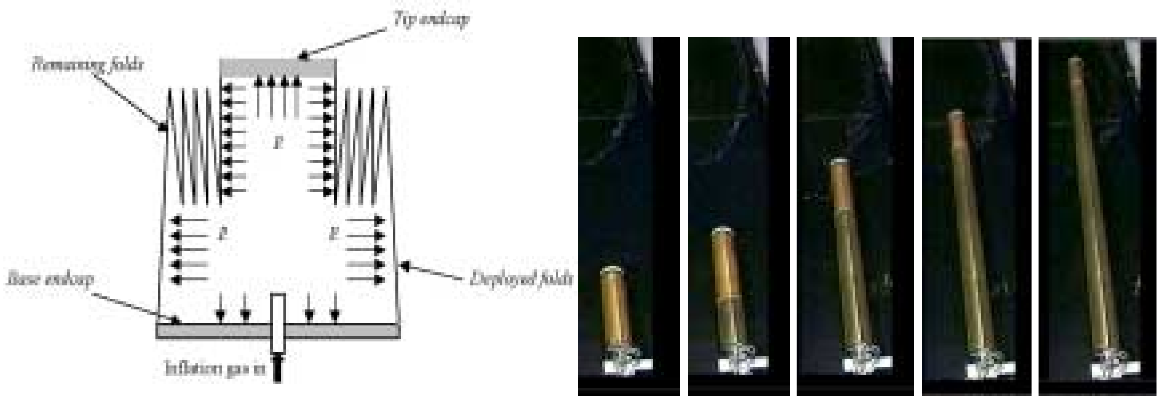


Figure 5. Conical Inflation Schematic and Sequence

<u>Sub-T_g Rigidization</u>

Sub-T_g or cold rigidization takes advantage of the increase in modulus of certain materials below their glass transition temperature (T_g).(6)(7) Sub-T_g structures can be constructed for a variety of missions, from low Earth orbit (LEO) to deep space applications and this technique was selected to form the support structure for the sail.

A solar sail boom undergoing cold rigidization testing for Team Encounter is shown in Figure 6. The boom is housed in a foam test chamber. While not visible through the chamber walls, the position is indicted as shown. The arrows depict the positions and loading orientation of cables used to apply compressive loads to the boom. The cables simulate the static loading of the striped sail architecture after deployment and exposure to the solar flux. This strength is achieved by using the sub-T_g resin at the expected space equilibrium temperatures.

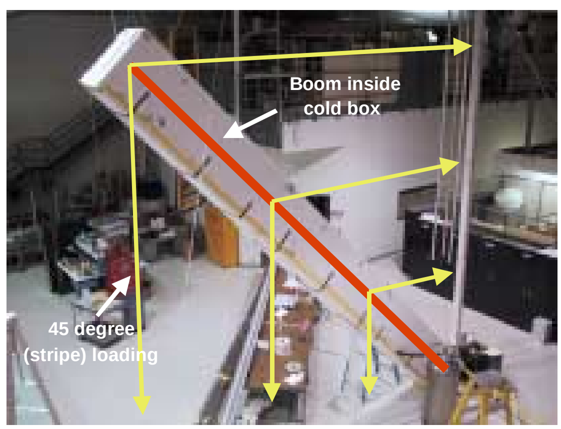


Figure 6. Sub-T_g Solar Sail Boom Test

Sub-T_g rigidizable structures are simple and reliable. They are completely passive and in general require no heaters or vents. However, since their rigidization depends on temperatures below their Tg, a thorough understanding of the thermal environment is required. If the deployed structure must endure large thermal excursions, it will be tailored to have a higher transition temperature and heaters may be required to "soften" the structure for deployment. Multi-layer insulation (MLI) is required to mitigate the effects of on-orbit thermal gradients in any Euler-efficient compressive boom, and also serves to lower overall boom temperature, adding margin to sub-T_g rigidization. Thin heater lines are packaged along with the boom material when stowed, and double as actuator control lines during the mission. The heater wires deploy concurrently with the boom providing a heat source until the deployment sequence is complete. At this point they are turned off and the structure allowed to cool to equilibrium temperatures to rigidize. Note that only a small amount of power is required to maintain the boom temperature during deployment, these heaters are not required to initiate a reaction or maintain high temperatures for long periods as in the case of a thermoset material.

Net/Membrane Sail Design

An important element of the solar sail performance is the predictability and stability of the sail shape during the mission. Many parameters such as solar flux, CTE, asymmetry at attitude, and maneuvering loads can have a large effect on the sail shape during flight. L'Garde's innovative net/membrane sail design eliminates and minimizes many of these effects. The sail is a skeleton-skin structure incorporating chords supporting a Mylar sail. The chords are attached to opposite rings on a quadrant complementing the striped suspension technique. The sail membrane is oversized slightly in the stripe direction to absorb any membrane geometric changes without distorting the net shape. Additionally, the sail is oversized to allow a billow from net element to net element for thermal compliance. In this manner, it is the net, with a low effective CTE to match the surrounding structure that largely defines the on-orbit shape of the sail. A schematic of the net/membrane design is shown on the left in Figure 7, while a section of the 100 m sail is shown on the right.

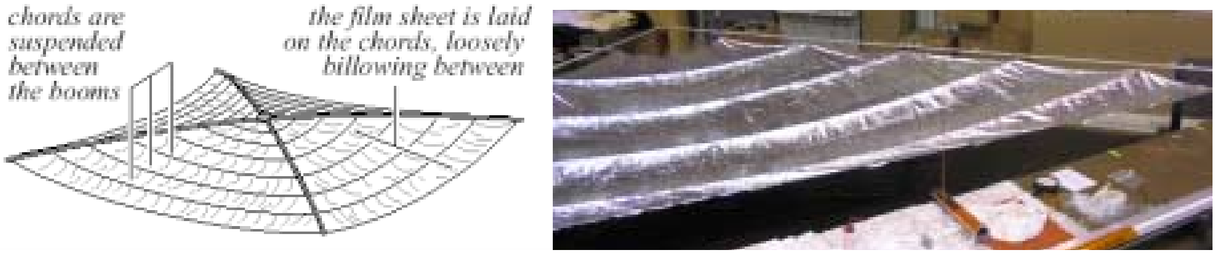


Figure 7. Net/membrane sail

Propulsive reflectivity – Tests at L'Garde under the Encounter program have shown that surface wrinkles in the material have a very small effect on the overall propulsive effect of the sail. Conversely, tensioning the film to stress levels required to remove those wrinkles has a very large impact on the structural mass needed to provide those stresses. To achieve the lowest structural mass practical L'Garde accepts a low film stress in the sail membrane as the lowest mass solution.

Low sail stress – Sail stress loads are transferred through the sail material to the nearest net element that then transfer the load to the structure. Utilizing this method there are minimal stress concentrations in the sail and attach points. Low stress concentrations in the sail membrane have a host of benefits. Small holes and minor damage are far less likely to propagate and tear. Degradation in the film due to environmental effects such as particle radiation and UV are similarly less likely to result in a failure.

Sun normal shape – Sail shape determination and stability are critical to the performance and controllability of the sail. After all it is the sail shape that determines the thrust magnitude and direction. Additionally, sail billowing influences stability by offsetting the thrust "center of pressure" from the center of mass of the sailcraft. Unknowns in the sail shape translate directly to unknowns in trajectory, controllability, and stability. Deformations in sail shape through on-orbit loads or manufactured shape have only a local effect between net elements leaving the overall global shape of the sail as designed and very predictable.

Asymmetry at attitude – As the orientation of the sail to the sun line is vectored for trajectory control the solar loading on the sail becomes asymmetric. The force effects of locally changing sun orientation on the sail cause asymmetric billow and thermal gradients both effecting overall sail shape. Again, the net/membrane design serves to minimize these effects through a fixed net shape and thermal compliance making the overall sail shape, and hence the overall sailcraft stability and performance, more uniform and predictable.

Scalability – The shape distortions of a large simply supported sail scale directly with size. The unsupported regions between boundary conditions become very large. The net/membrane design however can improve in relation to the sail with larger scale. By keeping the net element geometric spacing constant with increasing aperture the unknown membrane effects diminish.

Sail Material

Mylar has been selected for utilization as the sail membranes.(9) This material, used in the electronics industry, is low cost and readily available. Most importantly it is readily available in very low thicknesses. Since the film is a major source of mass the thinner the material, the lighter the sail. No other materials are readily available in the thicknesses used in the solar sail membrane. An example of a sail fabricated with thin Mylar is shown in Figure 8. This sail was fabricated and tested for the Team Encounter program. The sail was deployed in the orientation to gravity shown demonstrating the feasibility of successful deployment of these films. Deployment in gravity is highly conservative and gives good confidence for deployment in 0 g.

Figure 8. Mylar Sail During Deployment Test

Test and analysis have been conducted to ensure Mylar is compatible with the space environment for the intended mission duration. Special coatings are utilized to maximize heat rejection to space, keeping the Mylar below its melting point in orbits as close as 0.25 AU from the sun. These coatings are concurrently optimized to shield the Mylar from the degrading effects of ultra-violet (UV) radiation. Tests and analysis have been conducted showing that even after exposure to the maximum expected particle radiation doses, the mechanical properties are ample to withstand the expected sail loading conditions. These specialized coatings, coupled with the low stress concentrations afforded by the striped sail architecture, and the low cost and high availability in low thicknesses, make Mylar an excellent choice for use as a solar sail membrane.

Control System

L'Garde has reviewed many control system concepts during our solar sail development programs. The use of control vanes been selected after much research. These vanes, resembling one scaled quadrant of the solar sail, have been integrated onto the tips of our support beams to provide full 3-axis control (Figure 1). By articulating a small amount of reflective area near the boom tips, forces are generated large enough to control the sail orientation. Actuators mounted at the tips of the boom provide the torque required to rotate the vane. The vanes are rotated around the boom axis to vector thrust and when used in combination can provide sailcraft rotations in all 3 rotation axes. The vane booms utilize the same materials, structural concept, and deployment techniques as the main beams and thus enjoys the same deployment reliability and TRL level as the main beam technology. The vane support booms however do not require a spreader system as the supported vane aperture and subsequent solar loads are much lower.

Propellantless – The forces utilized by the control vanes to vector the sail orientation are provided by the sun and no additional expendable propellant is required. The electrical power for vane actuation is provided by a solar array already required for payload power. These actuators are very small and lightweight as the vane angular acceleration rates required to adequately control the sailcraft are very low. The useful life of the sailcraft mission is thus greatly extended and will be limited only by system lifetime effects.

Static Stability – Operationally the vanes are canted away from the sun by 30° providing static stability in two axes. Provided disturbances are not high enough to overcome this stability, and depending on the failure mode of the control system, the sailcraft experiencing ACS outage will oscillate around the initial orientation until damped out by structural effects. This feature offers a powerful and built in sun-synchronous fail-safe mode should anomalies in control system operation be encountered.

Fault Tolerant – Should one of the vanes actuators experience an on-orbit failure full operation of the sail can still be retained using the remaining 3 vanes. The vane opposing the failed vane can be set to counteract the moments generated by the anomalous vane and the remaining two vanes to achieve full control, albeit at reduced rates.

Trim Control – The control vanes were sized to trim out sail optical or mechanical asymmetries. The current vane size was derived from the worst-case scenario of an entire outer stripe of a sail quadrant in a torn condition. This is a highly unlikely scenario as the sail membrane incorporates rip stop fibers. However, the baseline vane size would be enough to counteract these worst case asymmetries and still provide adequate control margins.

System Stowage and Packaging

The Space Segment consists of all items released from the upper stage. This includes the sailcraft, shown on the top left of Figure 9, and the carrier shown toward the bottom. After deployment of the sail, the carrier is jettisoned to free the sailcraft from all non-flight required components and mass. The 50.0 kg payload envelope is visible toward the center of the sailcraft portion, and all of the spacecraft specific elements are shown toward the top of the configuration. The stowed solar arrays and communication antennas are visible toward the top.

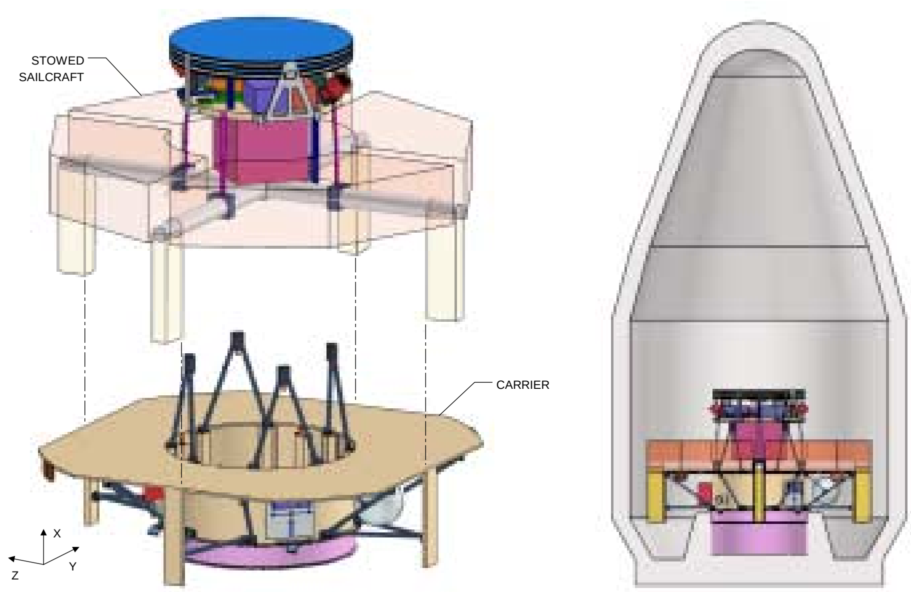
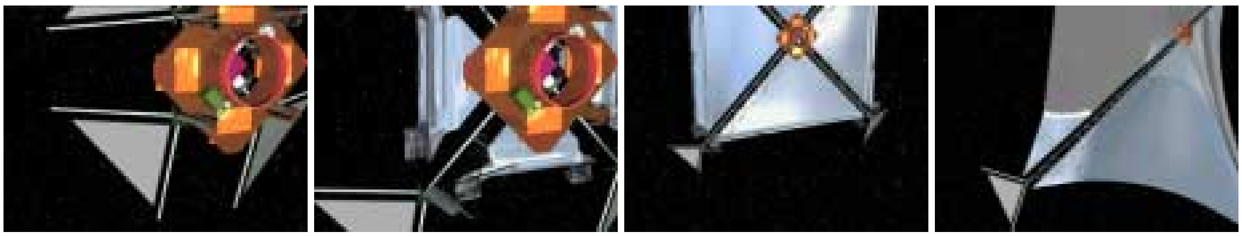


Figure 9. Space Segment Integration

The space segment fits well inside of the Delta II payload fairing as shown in Figure 9. Using the DPAF, it is possible to fit two space segments on a single Delta II launch. However, the launch mass of the L'Garde solar sail at 232.9 kg greatly underutilizes the launch mass capabilities of the Delta II booster. The conical stowage and deployment technique allow the booms to be packaged in an even smaller footprint than shown by simply shortening the packaged length and stowing the material in a slightly larger boom diameter. In this way much more economical boosters could be utilized for a substantial cost savings to the program.

Deployment

Once the Space Segment has successfully separated from the upper stage deployment can be initiated. Vane deployment is initiated by rotating the vane booms from their stowed position into proper position for deployment. The vane booms are deployed which tension the vane membranes into their deployed configuration, Figure 11, (a). Next, the spreader system, which has been pulled together for stowage, is released in preparation for deployment. The main boom deployment is initiated by introducing inflation pressure into the stowed booms. The booms simultaneously deploy the sails and the spreader system drawing the tension cables into position by deploying the rigid rings in a sequence, Figure 11, (b). An inflation control system carefully monitors the deployed length of each boom and modulates the amount of inflation gas introduced to each boom to ensure the deployment progresses symmetrically, Figure 11, (c). Once equilibrium temperature is achieved and the structure is fully rigidized, the carrier is released. (d). The sailcraft is now in its final configuration and providing thrust.



(a) (b) (c) (d)

Figure 10. Sail Deployment Sequence (Courtesy Thomas Dynamics Modeling)

Phase 2 Testing

To raise the TRL level to 6 a solar sail system must be tested in a "relevant environment." To this end a series of test articles were planned that will raise the TRL to near 6 in 2005. We intend to simulate the vacuum and thermal environs of space during our tests but we are limited to testing terrestrially at 1 g. With a structure as large and gossamer as a solar sail, this 1 g limitation will always be a factor. Suspension techniques will be used to mitigate the effects of 1 g but issues will remain. An important aspect of the effort will be to carefully utilize the test results at 1 g to validate a series of finite element analysis (FEA) models. With these techniques, validated predictions of the structural performance of the solar sail configurations at 0 g will be generated. In this way we will raise the TRL as close to 6 as is possible on the ground, but we will not achieve all requirements for TRL 6, hence the TRL ~6 designation.

The test plan is divided into 3 basic parts. Initially components of solar sail system were tested to validate material and section properties. Next, subsystems of the solar sail system were planned and executed. Finally, full solar sail subsystem tests are planned. Two tests will be conducted in the Plum Brook 30 m vacuum chamber, a 10 m system in 2004 and a 20 m system in 2005.

Component Tests

Booms

Several boom sections were fabricated for structural testing. An example is shown in Figure 11 mounted in L'Garde's thermal structural test fixture on the left, and in LaRC's thermal test fixture on the right. The chamber temperatures were maintained below the boom T_g during the testing. Boom stiffness and buckling data were measured before and after conical packaging and deployment. The stiffness and buckling data from both test matched very well and the results exceeded the analytical predictions validating the design assumptions and safety factors.

Figure 11. Boom Section Test, L'Garde Left, LaRC Right

Longer Boom

A longer boom was fabricated and tested at LaRC's thermal test fixture, the fixture is shown on the left in Figure 12, and a boom close-up is shown on the right. The boom was tested at low temperatures and various loading conditions applied. Boom length deformations were measured using Linear Variable Displacement Transistors (LVDTs). Tests were run in this configuration to measure overall stiffness and buckling.

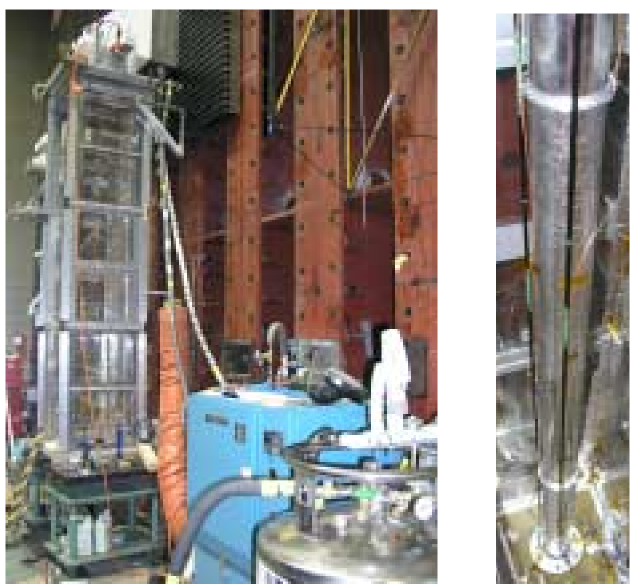


Figure 12. LaRC 3m Boom Cryogenic Test Fixture

Torsion and bending tests were carried out using a dynamic technique. An electromagnetic shaker was utilized to excite various structural dynamic modes in the boom, see Figure 13. The boom frequency response was measured and the parameters of interest discerned. Torsional and bending stiffness were measured and documented. The test results were used to validate and calibrate the concurrent FEA analysis discussed later in the document.

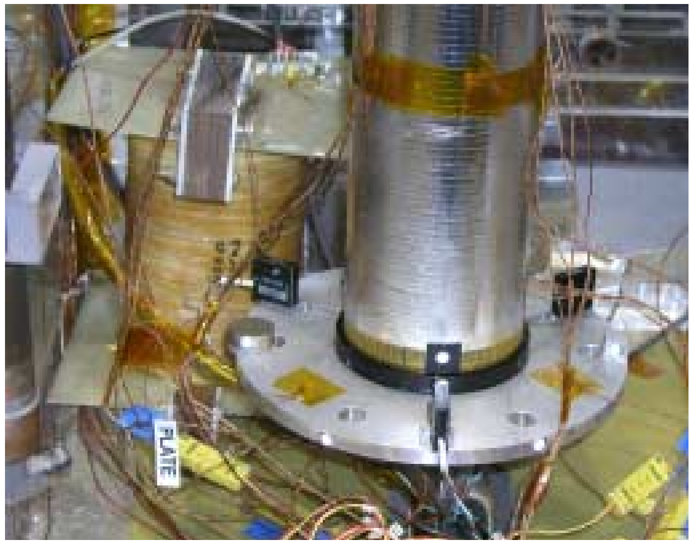
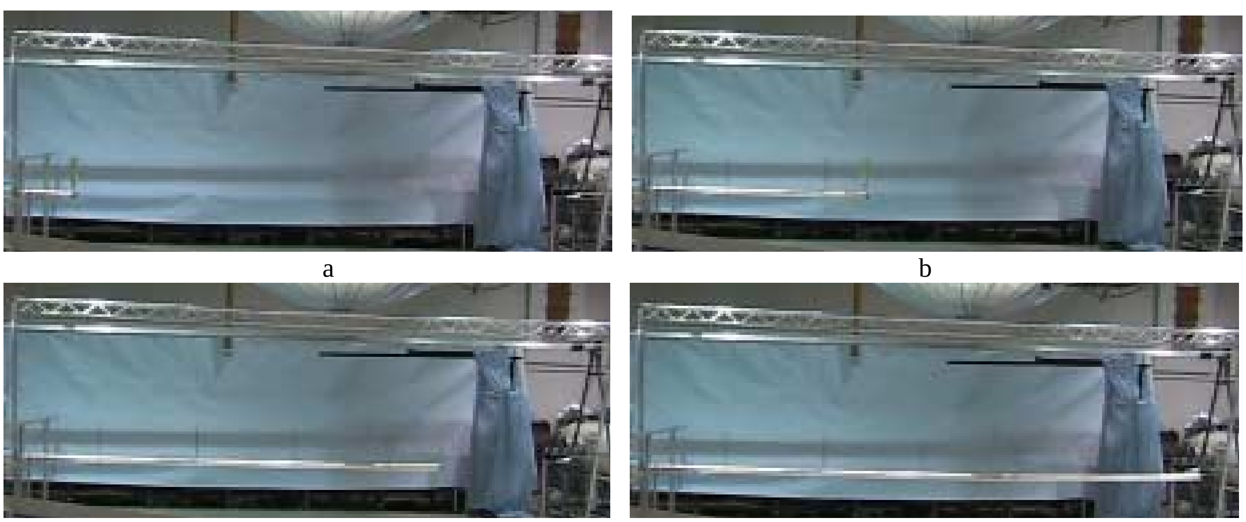


Figure 13. Dynamics Test Setup

Subsystem Tests

Beam Ambient Deployment Test

An ambient deployment on a section of solar sail beam was conducted in L'Garde's high bay. This was a very important test as it was the first time we deployed a conically stowed boom with spreader system attached. A sequence depicting the successful deployment is shown in Figure 14. The deployment was smooth and predictable, and with the exception of one line snag that required manual intervention, very successful. The source of this snag has since been eliminated. In order to simulate a 0 g environment the beam was supported at the ring locations by a truss system and sliding cars allowing the system to deploy.



a b

c d

Figure 14. Ambient Deployment Sequence

Beam Thermal Vacuum Deployment Tests

The stowed beam was installed in Goddard's Thermal Vacuum Chamber in Virginia. For the deployment and subsequent beam testing we utilized a rough vacuum of 0.1 Torr and the temperatures in the chamber held at the operational temperatures of the sub-T_g beam material inside the insulation layer. The structure was instrumented with an array of thermocouples, pressure gauges, photogrammetry targets, and cameras. Once the chamber pressure and temperature were achieved the first stage of the deployment was to activate the integrated heaters to bring the material temperature above its T_g. This was the first test of the integrated heater system, which performed as designed. The deployment sequence took about 30 minutes. The beam is shown stowed on the left side of Figure 15, note that the spreader bars are already separated, when fully stowed the tips of the bars are brought together to further reduce the stowed volume and footprint. The boom after deployment is shown on the right side of Figure 15.

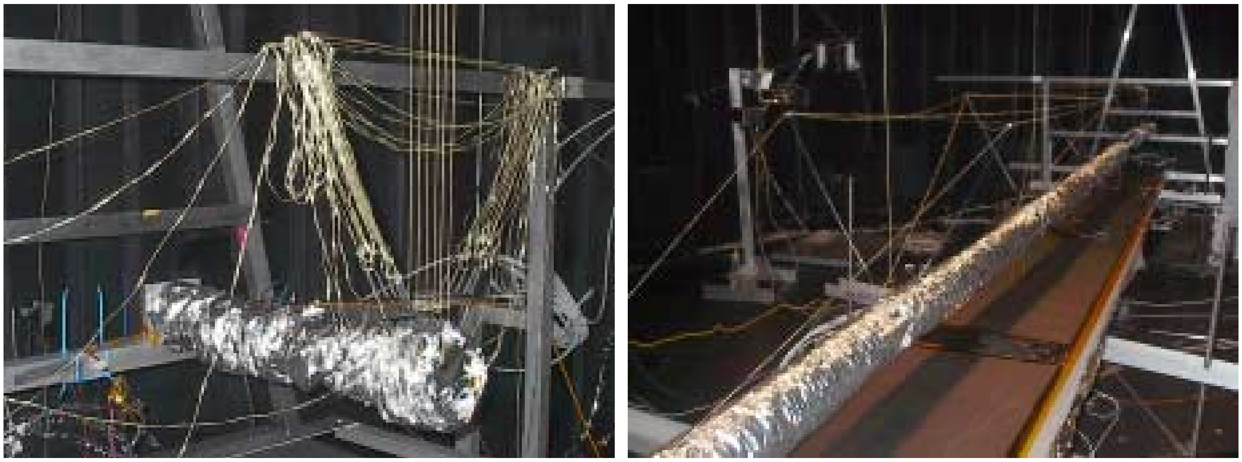


Figure 15. Beam Thermal Vacuum Deployment, Pre and Post-Deployment

Many aspects of the design were validated by this successful deployment. The heater system, which had heretofore never been tested in a thermal chamber functioned perfectly and remained functional and maintained the boom temperature above its T_g through the deployment. An innovative internal inflatable mandrel used for deployment control also functioned nominally.

Combined Loading/Bending Test

A key goal of the Goddard thermal vacuum test was to demonstrate that our structure can withstand the loads imparted by the sails at a 1 AU solar flux condition with a significant safety factor. To this end a loading setup was devised that provides this condition, and further, simulates the loads seen at the base of a 100 m sail at operational loads, the highest loaded beam section of the configuration. To simulate this condition on the beam it was necessary to augment the loads on the structure to simulate the bending, compression, and shear imparted to the root section by the outboard sections of beam and sail. A diagram of this loading condition is shown in Figure 16.

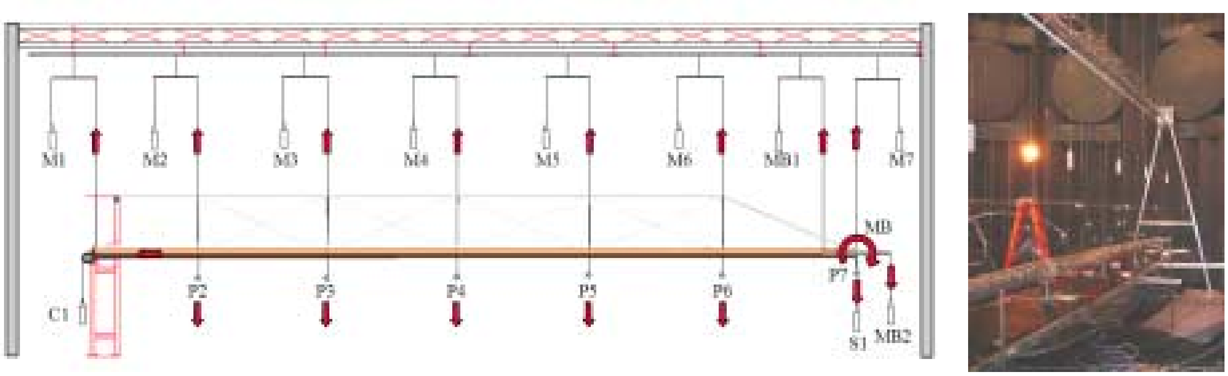


Figure 16. Combined Loading Diagram and Chamber Test Setup

To impart this proper loading condition into the beam a novel apparatus was devised, first to offload the structure to simulate 0 g, and then to impart the operational 1 AU solar flux condition loads. This was accomplished first by “floating” the structure on balance beams to simulate the 0 g condition, and then by carefully applying loads by modifying the off loading masses, and imparting moments through moment bars. An overall view of this setup is shown in Figure 16. Additionally, Our LaRC teammates responsible for the test instrumentation provided a stepper motor and gauge setup that allowed us to impart a varying shear load to the boom during testing.

The combined loading test was conducted with the chamber at 0.1 Torr, and at the operational temperature of the structure. At this point the internal pressure in the structure was vented, and loads were absorbed strictly by the sub-T_g rigidized beam material. The shear load was increased until the loads matched those of the center section of a 100 m sail operating at 1AU. The structure successfully demonstrated the ability to withstand those loads at operation conditions without buckling. Further, to validate the safety factor, the shear was increased until a 2x 1 AU solar flux equivalent stress condition was created at the beam base. Again the structure demonstrated that it can withstand the loads imparted by a 2x 1 AU solar flux condition without buckling. The test demonstrated a safety factor of greater than 2.0 at operational loadings in a relevant environment including a credible technique for offloading gravity.

Beam Torsion Test

An important structural parameter, particularly in light of the tip vanes mounted at the ends of the beams is the torsional stiffness of the beam. The ability of the beams to withstand torsion will dictate the accelerations that can be applied to the vanes for effective stability and control, though remember these rates are very small. This setup utilized the stepper motor and strain gauge to apply a load to a moment bar mounted to the end of the beam. By using a series of balance beams the applied load was divided in two, one side was applied in the upward direction, while the other was applied in the downward direction. In this way a pure torsion was introduced to the beam without causing any bending or translation. The test was conducted in vacuum at an operational equilibrium temperature to assure proper structural rigidization and material stiffness. The results of this testing matched predictions and validated the FEA analysis.

Dynamics Testing

Dynamics testing of the beam was conducted to research the natural frequencies of the beam and to prepare and exercise techniques for more rigorous tests scheduled for later in the year. The dynamics test setup, assembled and operated by LaRC personnel, is shown in Figure 17. The beam tip was excited by the large electromagnet shown. A control system was able to vary the electromagnet frequencies driving the beam dynamics. The setup was designed to excite modes in the longitudinal direction only, however, cross-coupling between modes allowed this same setup to work for lateral dynamics also. Again the data collected was used to validate the FEA analysis.

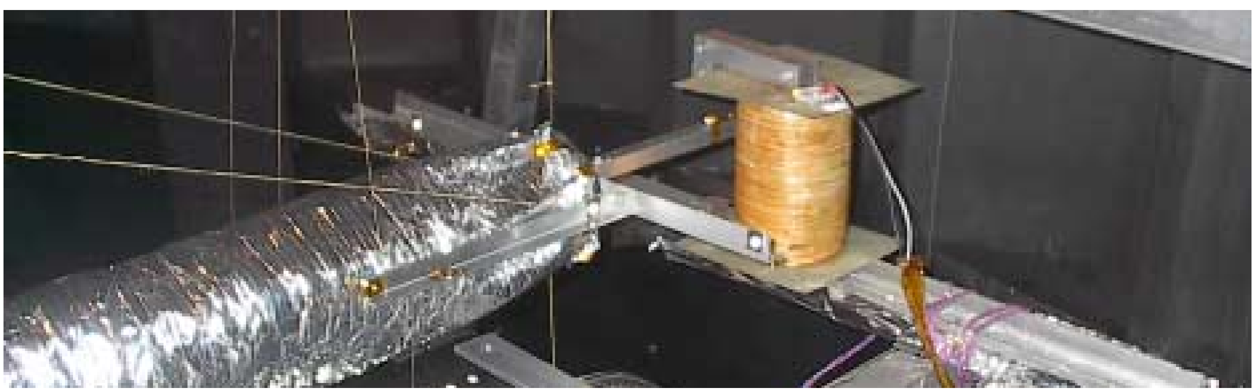


Figure 17. Dynamics Test Setup

Sail Deployment Tests

Several sail quadrant deployment tests have been conducted. Initially a 2/3 scale Mylar quadrant test was conducted in order to validate the membrane packaging and deployment concept. More recently a thinner Mylar sail fully representative of a section of the 100 m flight article has been fabricated and successfully deployed. The initial billow acceleration of the sail material away from the beam plane under 1 g is much larger then the billow acceleration imparted by the solar flux, but importantly, it is in the same direction. L'Garde has taken the approach to fully constrain the sail such that it can deploy under its own weight in 1 g. It is intuitive under these circumstances that a 0 g deployment is similarly very well constrained. A membrane management system was developed to constrain membrane dynamics during deployment. A sail quadrant deployment sequence is shown in Figure 18. Tracks were mounted along the sides to simulate the boundary conditions imposed by simultaneously deploying the solar sail beams. The tracks were mounted 1 m above the high bay floor. During deployment, even under 1 g conditions, none of the sail membrane came in contact with the floor and was fully controlled. Even under a much higher acceleration magnitude that it will ever see in space the sail deployment was smooth, predictable, and deployed without ripping.

Figure 18. 10 m Sail Quadrant Deployment

Upcoming Tests

10 m Test Article
The component and subsystem tests will lead to a 10 m sector test of a full solar sail configuration. As scaling of the various materials of the concept is not feasible, a 10 m square sector of the full-scale configuration will be fabricated and tested. While at the Plum Brook 30 m vacuum cold plates will be used locally to rigidize the boom components and allow structural testing. Again, photogrammetry and laser vibrometry will be conducted and all data will be used to validate structural assumption and FEA models. A successful conclusion of this test will bring the solar sail system technology to a TRL of 5 or greater.

20 m Test Article (Phase 3)
In a planned follow-on contract, a larger 20 m square sector of the solar sail configuration will be thermal vacuum tested in NASA's Plum Brook 30 m chamber. This ambitious test will bring all of this work and analysis together. A successful conclusion will see the solar sail system TRL level raised as close to 6 as is possible under ground test conditions paving the way for a flight experiment.

Structural Analysis

A major objective of the ISP L'Garde Solar Sail effort is to validate through testing our analytical methods in order to generate credible predictions of much larger gossamer structures. Our near term goal will be to predict the structural responses of a 10 m and 20 m configuration due to be tested later in the program, and ultimately to generate credible predictions for a 100 m flight article. For programmatic risk reduction a two-prong analytic approach was undertaken. Two separate teams are developing models using different tools. L'Garde is using a combination of NASTRAN and FAIM, while LaRC is utilizing ABAQUS, Figure 19. So far both teams have successfully completed and exercised the beam models and full 10m configurations including sail quadrants are well underway.

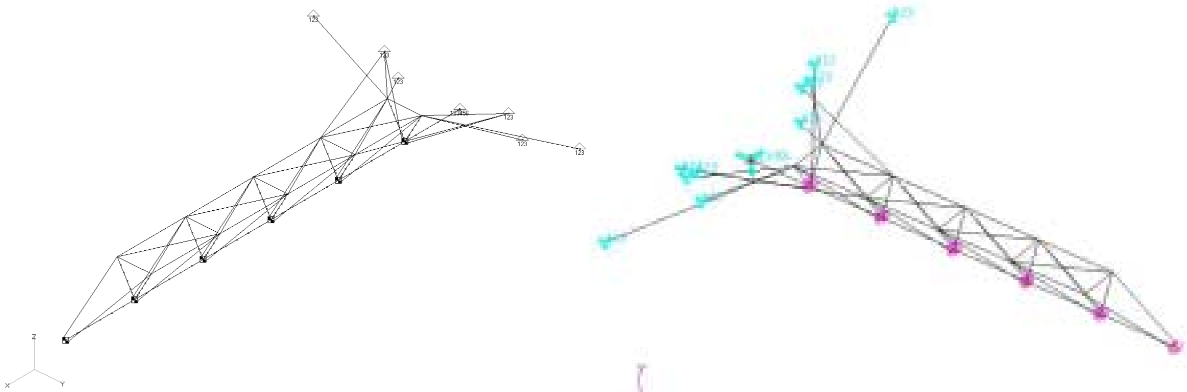


Figure 19. L'Garde NASTRAN and LaRC ABAQUS FEA Models

Scalability

Many missions require large sails in order to carry more payload or to achieve higher specific accelerations. A scaling analysis was undertaken using L'Garde analysis tools and the results shown in Figure 20. The X-axis depicts the size of the sails in square meters, while the Y-axis shows the areal density of the sailcraft. All configurations shown on the chart assume a 50.0 kg payload, and 43.3 kg of spacecraft elements for power generation, communications, and guidance and control. In reality these requirements will likely change with the given mission scenarios, however, in the interests of this scaling analysis, these parameters were fixed.

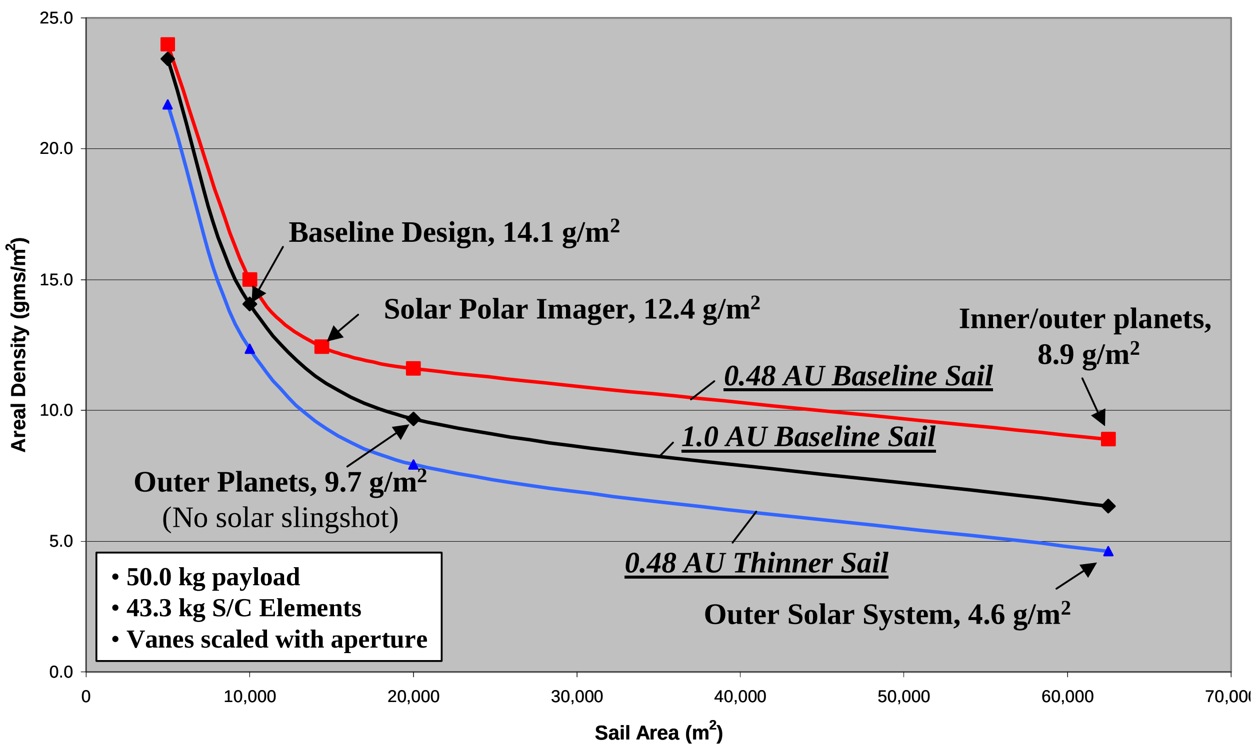


Figure 20. Mission Scalability

The striped sail architecture and excellent mechanical synergism with the conically stowed boom allows scalability without high mass penalties. As shown in Figure 20, the baseline design, with minor modification and scaling, is capable of all of the NASA "high-pull" missions shown.

Summary

The team of L'Garde, Ball Aerospace, JPL, and LaRC has developed a highly scaleable solar sail configuration to meet and exceed the requirements of many of NASA's future missions. This configuration was enabled by inflatably deployed and sub-T_g rigidized booms. Striped sail architecture, net/membrane sail design, and L'Garde's conical boom deployment technique allows scalability without high mass penalties. A comprehensive test plan was developed and is underway to raise the TRL level of this technology toward 6 by 2005. This focused program will pave the way for a flight experiment of this highly efficient space propulsion technology.

Acknowledgments

Much appreciation is extended to Roy Young and Sandy Montgomery of NASA Marshal Space Flight Center, for their vision, advocacy, and technical expertise in development of the solar sail. Many thanks to Team Encounter for access to their design and hardware, their work forms the foundation for much of the solar sail design shown. The team would like to acknowledge the support of Jeff Bladt of Ball Aerospace, and Dr. Guru Singh for their control system expertise. L'Garde would also like to thank Dr. Gyula Greschik for his continuing assistance in the solar sail design and structural analysis. Structural FEA analysis courtesy of Yuki Michii of L'Garde, and David Sleight of LaRC. Part of this research was carried out by John West at the Jet Propulsion Laboratories, California Institute of Technology, under a contract with NASA. Thanks also to TDM for the deployment animations.

References

1) D. Lichodziejewski, B. Derbès, J. West, R. Reinert, K. Belvin, R. Pappa "Bringing an Effective Solar Sail Design Toward TRL 6". AIAA 2003-4659, JPC Huntsville, July. 2003.

2) J. West, "The Geostorm Warning Mission: Enhanced Opportunity Based on New Technology", AAS 2004-102, Feb 8-12 2004 Maui 14th AAS/AIAA Space Flight Mechanics Conference.

3) G. Garbe, E. Montgomery, "An Overview of NASA's Solar Sail Propulsion Project", AIAA 2003-5274, JPC Huntsville, July, 2003

4) McInnes, C.R., Solar Sailing Technology, Dynamics and Mission Applications, Springer-Praxis, London, UK, 1st Ed.

5) West, John, and Derbès, Billy, "Solar Sail Vehicle System Design for the Geostorm Warning Mission". AIAA-2000-5326, September 21, 2000.

6) D. Lichodziejewski, R. Cravey, G. Hopkins, "Inflatably Deployed Membrane Waveguide Array Antenna for Space" AIAA 2003-1649, 4th Gossamer Spacecraft Forum, April 7-10, 2003, Norfolk, VA

7) K. Guidanean, D. Lichodziejewski, "An Inflatable Rigidizable Truss Structure Based on New Sub-T_g Polyurethane Composites", AIAA-2002-1593, 3rd Gossamer Spacecraft Forum, Apr. 25, 2002, Denver, CO

8) Greschik, G. and Mikulas, M.M., "Design Study of a Square Solar Sail Architecture", Center for Aerospace Structures, University of Colorado, Boulder, CO.

9) DuPont, Inc., "Mylar Product Information," no. 222367D, December 1997