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Bringing an Effective Solar Sail Design Toward TRL 6

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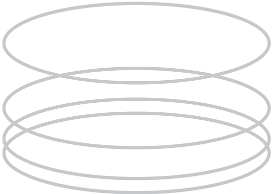

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Abstract

Solar sails reflect photons streaming from the sun and convert some of the energy into thrust. This thrust, though small, is continuous and acts for the life of the mission without the need for propellant (1). Recent advances in sail materials and ultra-low mass 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 NASA, has been developing a solar sail configuration to address NASA's future space propulsion needs. Utilizing inflatably deployed and Sub Tg rigidized boom components, this 10,000 m^2 sailcraft achieves an areal density of 14.1 g/m^2 and a characteristic acceleration of 0.58 mm/s^2. The entire configuration released by the upper stage has a mass of 232.9 kg and requires just 1.7 m^3 of volume in the booster. After deployment, 92.2 kg of non-flight required equipment is jettisoned resulting in a sailcraft mass, including payload and control system, of 140.7 kg.

This document outlines the accomplishments of a Phase 1 effort to advance the technology readiness level (TRL) of the concept from 3 toward a TRL of 6. The Phase 1 effort, the first of three proposed phases, addressed the design of the solar sail, its application to several missions currently under review at NASA, and developed a ground test plan to bring the technology toward a TRL of 6.

Introduction

Early in the program, with the support of NASA, solar sail missions under consideration were researched and a mission set of interest was developed. Relevant mission parameters and environs were identified and defined. These requirements were used to refine a solar sail design meeting and exceeding these requirements. 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 will also be 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 Langley Research Center's (LaRC) 16 m vacuum chamber. Finally, a 20 m square test article will be built and tested at NASA's Plum Brook 30 m thermal/vacuum test facility. This test, which will

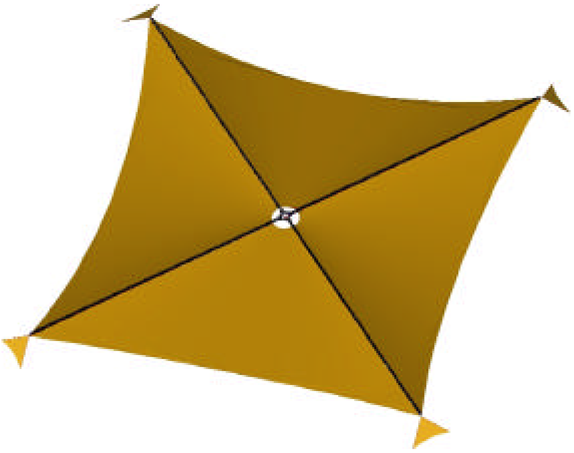

Figure 1. Baseline Solar Sail Design

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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 and vacuum conditions but will still be conducted in 1 g. Many issues related to the 1 g environment 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.

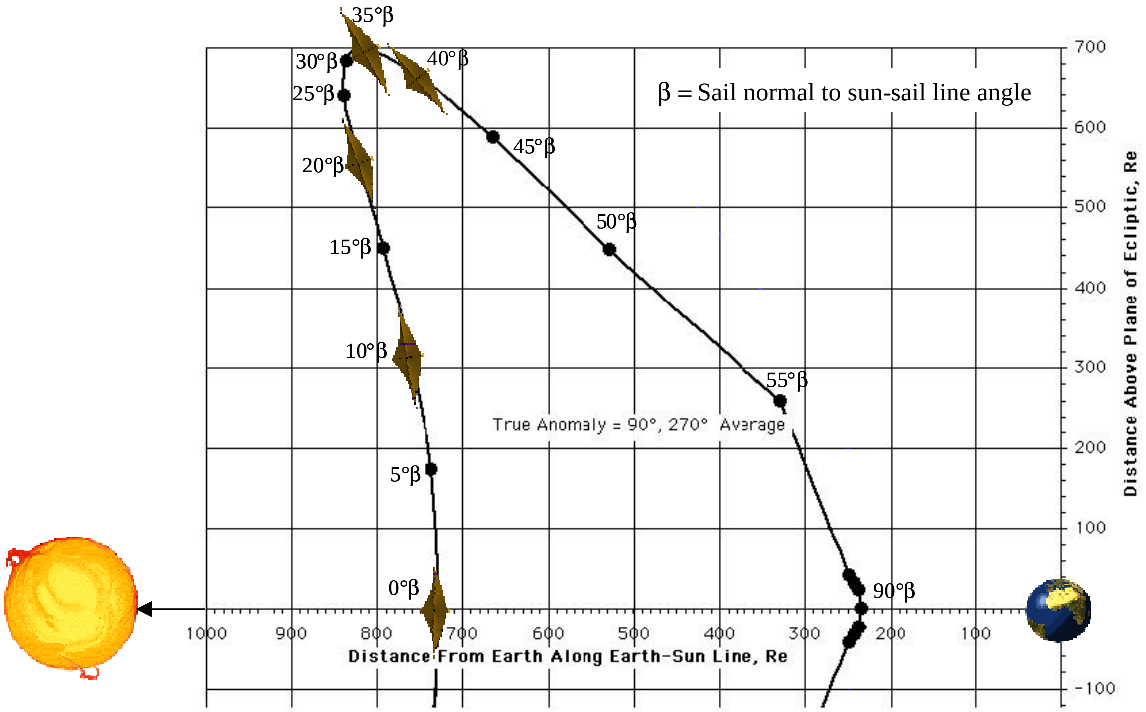
Design Overview

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

Baseline Mission

As future phases of this program will require test articles of a specific configuration, a baseline mission was selected around which to optimize the design. The Solar Sentinel or Geostorm (2) mission was selected as a likely candidate for future missions. This scenario takes advantage of the constant thrust available from the solar sail to place a payload in a solar orbit inside of the L1 point, yet remain in the same period as the Earth's. This position provides an excellent vantage point for solar observation and warning of adverse solar activity. Satellites can station keep at the L1 Lagrange point without the need for additional propulsion, see figure 2. This point is about 230 Earth radii (Re) from the Earth toward the sun along the Earth-sun line. Using the constant thrust from the sail it is possible to descend to a closer orbit to the sun yet remain in the same period as the Earth, and remain on the Earth-sun line. An orbital analysis shows that the baseline sail design can descend an additional 520 Re closer to the sun. This location can provide information of solar activity with a lead-time 3 times greater than current solar observing missions.

Solar sails provide thrust normal to the sail, by changing the angle of the sail normal with respect to the sun-sail line (β), thrust vectors can be developed with components normal to the sun sail line. With a thrust component normal to the plane of the ecliptic, the sailcraft can orbit the sun above the plane of the ecliptic in a non-Keplarian orbit as shown. The line



Includes 50 kg payload and mass margin

Figure 2. Baseline Mission

shown represents a family of solar orbits depending on the β angle of the sail. The baseline design can maintain a position relative to the earth-sun line at a point 700 Re above the plane of the ecliptic, and 800 Re closer to the sun. Additionally, the sailcraft can maintain this distance from the Earth-sun line while orbiting in a halo orbit. Thus several sailcraft can provide multiple simultaneous observation points of the solar wind. By combining the data gathered by these instruments, a 3-D map of incoming solar anomalies can be developed.

Control System

Control vanes resembling one scaled quadrant of the solar sail have been integrated into the structure to provide full 3-axis control. By modulating 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.

Support Structure

During earlier solar design work at L'Garde, it was discovered that the sail suspension technique can have a large impact on system mass and scalability. Several attachment techniques were reviewed (figure 3) and the stripe architecture was selected as the most efficient (5).

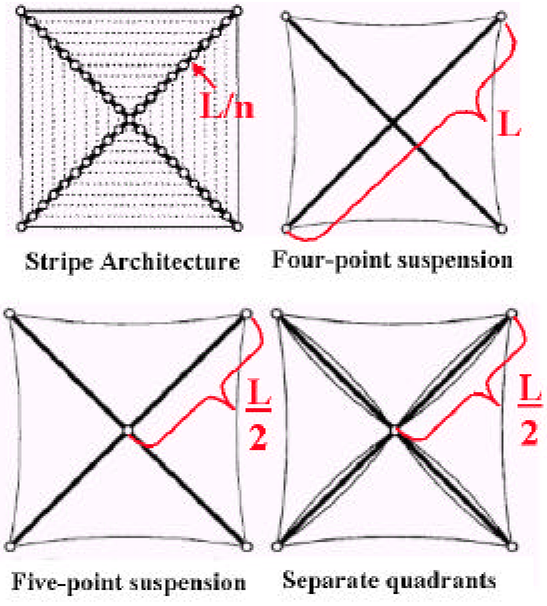


Figure 3. Sail Attachment Techniques

Stripe architecture is highly scalable. For larger sails/booms additional attachment point along the booms can be added to keep the load length L to a minimum. The other methods require large increases in L, which require significant increases to the strength and mass of the booms to defeat the Euler buckling.

Spreader System

The booms are not sized to withstand the bending generated by the solar flux alone. A tensioned truss or spreader system is used to increase the moment of inertia of the boom to absorb the bending, see figure 4. The spreader system consists of lightweight rigid spreader bars mounted to rigid rings integrated into the boom

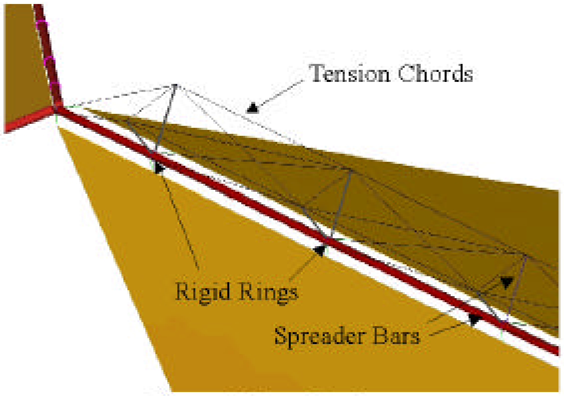


Figure 4. Spreader System

Iso-Grid Boom Design

The booms are designed in an iso-grid configuration. High modulus fibers are oriented as shown in a boom built for Team Encounter (figures 5,6). The fibers are impregnated with a Sub Tg resin to rigidize the structure after deployment (this is described in the Sub Tg 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. These lateral fibers provide the burst margin required for deployment contingencies.

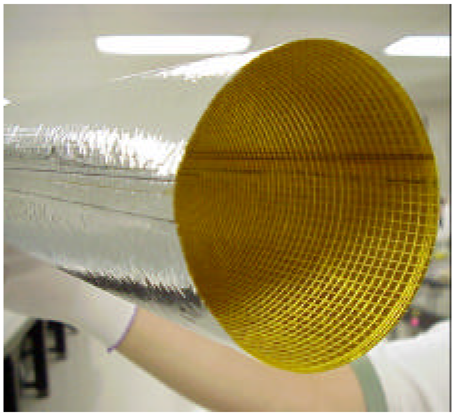


Figure 5. Boom Design

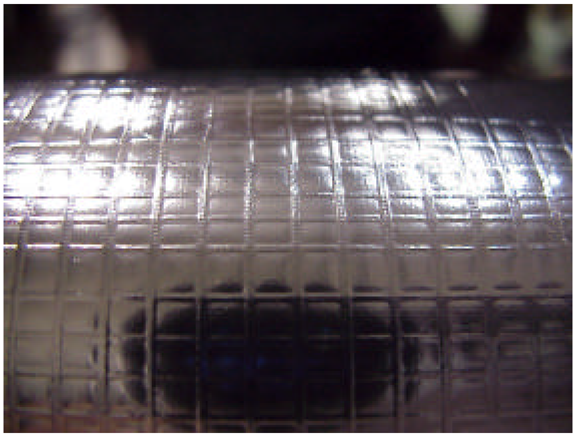


Figure 6. Boom Material Close-up

Conical Deployment

Figure 7 shows the conical boom packaging and deployment scheme developed for deployment control of the inflatable rigidizable support booms (3). 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. As the tube is under pressure during deployment, it is able to withstand loads during deployment.

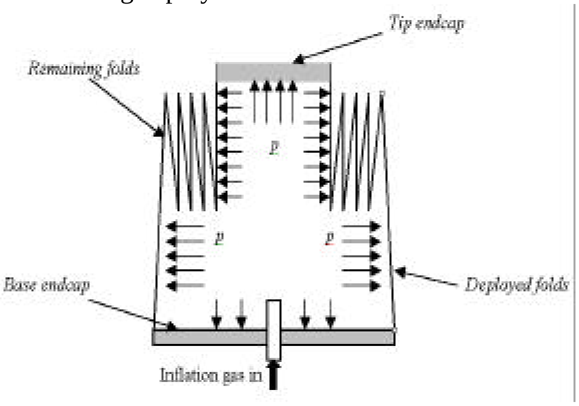


Figure 7. Conical Inflation Schematic

A deployment sequence of a Team Encounter sail conical boom is shown in figure 8. This deployment took place while the boom was floating in a water trough to simulate a 0 g deployment condition in one plane. The deployment proceeded smoothly and in a linear, consistent, and predictable manner.

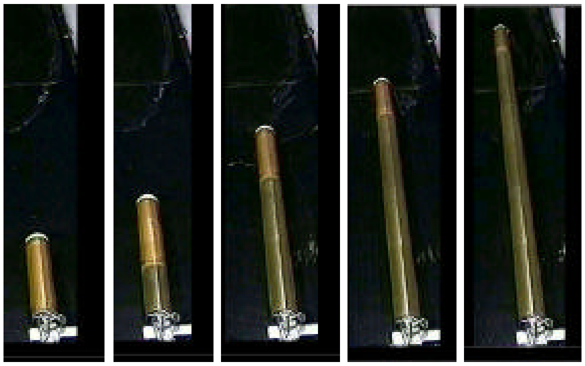


Figure 8. Solar Sail Boom Conical Deployment in Water Trough to Simulate Space Deployment

Sub Tg Rigidization

Sub Tg or cold rigidization takes advantage of the increase in modulus of certain materials below their glass transition temperature (Tg) (3,4). Sub Tg 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 9. 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 Tg resin at the expected space equilibrium temperatures

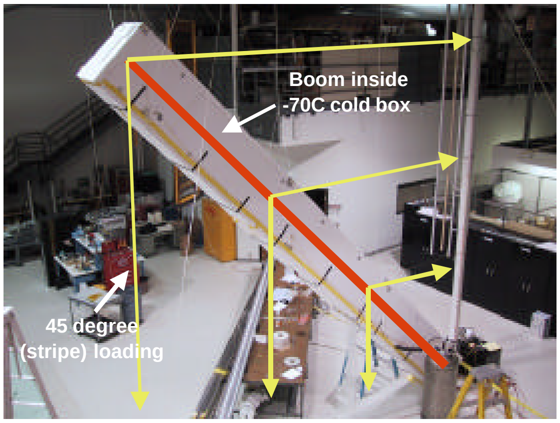


Figure 9. 7m Sub Tg Solar Sail Boom Test

Sub Tg 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 and to retain the initial softening thermal energy during the deployment sequence.

Sail Material

Mylar (6) has been selected for utilization as the sail membranes. This material, used in the electronics industry, is low cost and readily available. An example of a sail fabricated with Mylar is shown in figure 10. 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 thins films. The tension load in the sail due to gravity is roughly 600 times greater than the tension load generated by the solar flux, deployment in gravity is highly conservative and gives good confidence for deployment in 0 g.

Figure 10. 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, make Mylar an excellent choice for use as a solar sail membrane.

Space Segment

The Space Segment consists of all items released from the upper stage. This includes the sailcraft, shown on the top of figure 11, 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.

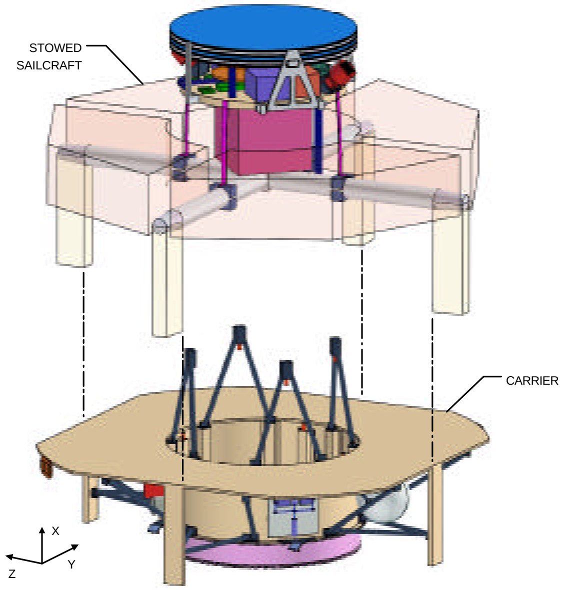


Figure 11. Space Segment (Shown Separated)

The space segment fits well inside of the Delta payload fairing as shown in figure 12. With a sufficient payload interface fixture, it may be possible to fit two space segments on a single launch.

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 pull the vane membranes into their deployed configuration, figure 13, (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 13, (b). An inflation control system carefully monitors the deployment length of each boom and modulates the amount of inflation gas introduced to each boom to ensure the deployment progresses symmetrically, figure 13, (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.

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 14. 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.

The striped sail architecture and excellent mechanical synergism with the conically stowed boom allows scalability without high mass penalties. As shown in figure 14, the baseline design, with minor modification and scaling, is capable of all of the NASA "high-pull" missions shown.

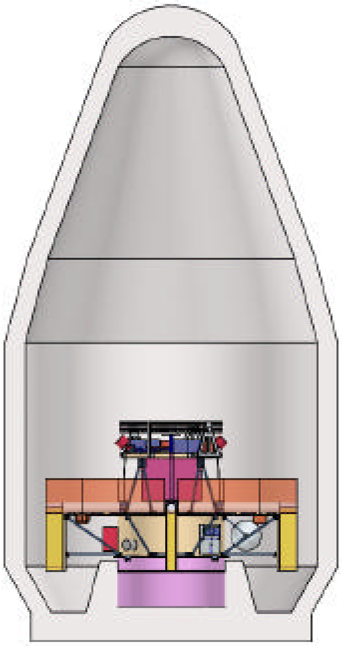
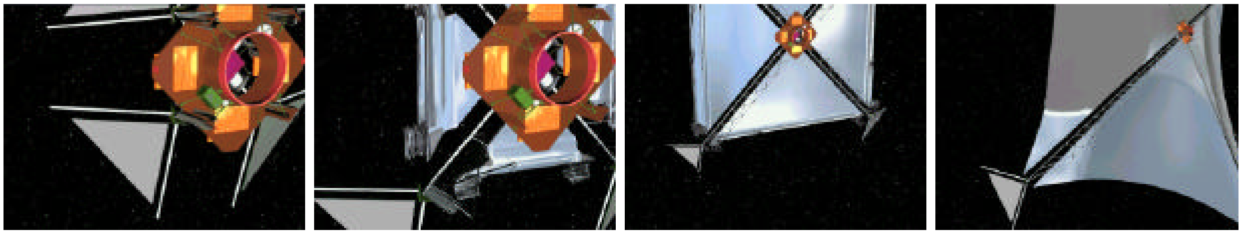


Figure 12. Space Segment in Delta II

Phase 2 and 3 Test Plan

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 is planned that will raise the TRL to ~6. 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 analytic 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



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

Figure 13. Sail Deployment Sequence (Courtesy Thomas Dynamics Modeling)

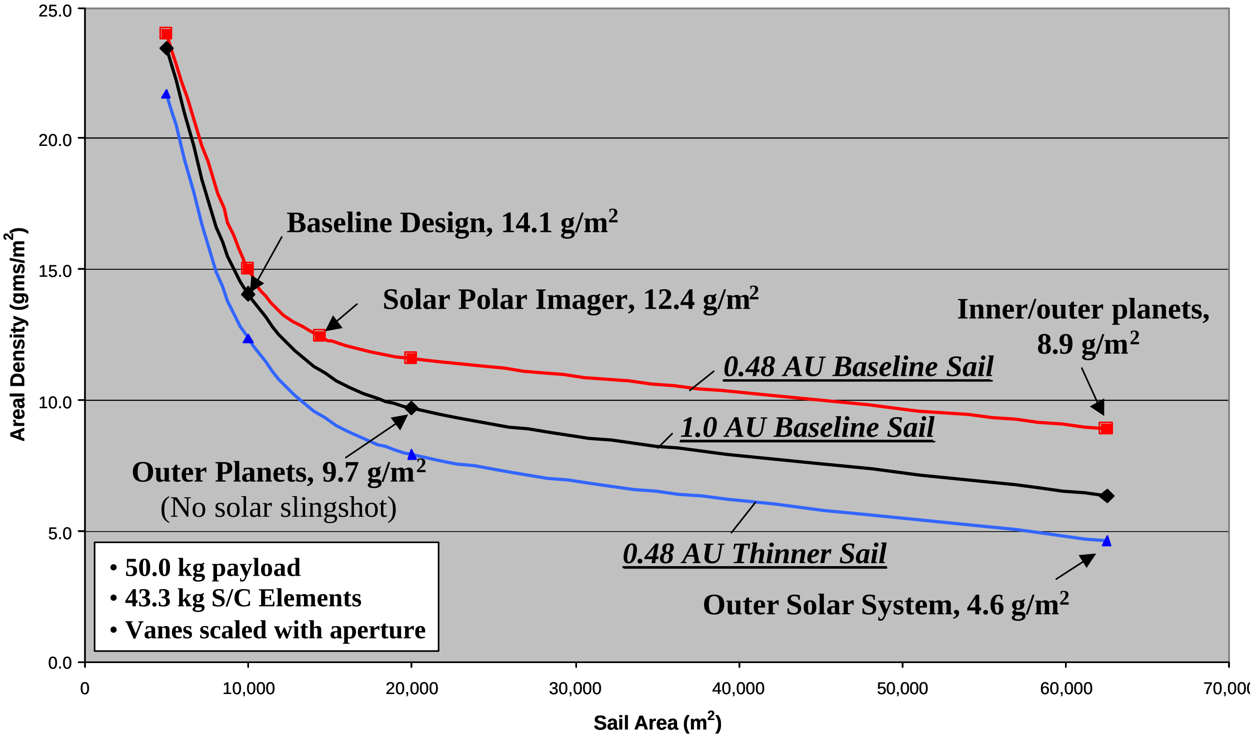


Figure 14, System Scalability

achieve all requirements for TRL 6, hence the TRL ~6 designation.

Component Tests

Initially material and component test will be conducted. The sail and Sub Tg laminate will be subjected to UV and particle radiation to validate and expand on tests already conducted. Component tests of sail and boom sections will be used to validate the mechanical characteristics. This data will be used to validate the structural models.

Subsystem Tests

A 10m sail quadrant will be deployment tested in ambient conditions as will a full-scale vane quadrant. Additionally a boom with spreader system will be deployed both in ambient and vacuum condition in LaRC's 16 m vacuum chamber. Finally a sail quadrant with two full booms and spreaders will be deployed and tested in the LaRC chamber, as will the full-scale vane and representative actuator. Structural data will be obtained, as will photogrammetry and laser vibrometry. All data will be used to validate structural assumption and the structural FEA models.

10m Test Article

The component and subsystem tests will lead to a 10m sector test of a full solar sail configuration. As scaling of the various materials of the concept is not feasible, a 10 m on a side sector of the full-scale configuration will be fabricated and tested. While the LaRC chamber is not equipped with cryogenic capabilities, 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.

20m Test Article (Phase 3)

In a planned follow-on contract, a larger 20 m 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.

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 utilizing inflatably deployed and sub Tg rigidized booms. Striped sail architecture, coupled with L'Garde's conical boom deployment technique allows scalability without high mass penalties. A comprehensive test plan was developed 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 Greg Garbe 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 assistance in the solar sail design and structural analysis. Thanks also to TDM for the deployment animations. Part of this research was carried out at the Jet Propulsion Laboratories, California Institute of Technology, under a contract with NASA.

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