TESTING OF A 10M 4-QUADRANT SOLAR SAIL

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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 interim accomplishments of phase 2 of a 3-phase NASA program to advance the technology readiness level (TRL) of the solar sail system from 3 toward a technology readiness level of 6 in 2005. Under Phase 2 of the program many test articles have been fabricated and tested successfully. Most notably an unprecedented 4-quadrant 10 m solar sail ground test article was fabricated, subjected to launch environment tests, and was successfully deployed under simulated space conditions at NASA Plum Brook's 30m vacuum facility. Phase 2 of the program has seen much development and testing of this design validating 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's 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.

I. Introduction

Under the direction of the NASA In-Space Propulsion Office (ISP), the team of L'Garde, NASA Jet Propulsion Laboratory (JPL), Ball Aerospace, and NASA Langley Research Center (LaRC) has been developing a scalable solar sail configuration to address NASA's future space propulsion needs. The 100 m baseline solar sail concept shown in Fig. 1 was optimized around the 1 astronomical unit (AU) Geostorm mission[6][7] and features a sail net/membrane with a striped sail suspension architecture and inflation-deployed beams consisting of inflatable sub-T_g rigidizable semi-monocoque booms and a spreader system[1][2][9]. Sub-T_g or cold rigidization takes advantage of the increase in modulus of certain materials below their glass transition temperature (T_g). The solar sail has vanes integrated onto the tips of the support beams to provide full 3-axis control of the solar sail[4][5]. This solar sail concept can be scaled and used for a number of NASA missions.

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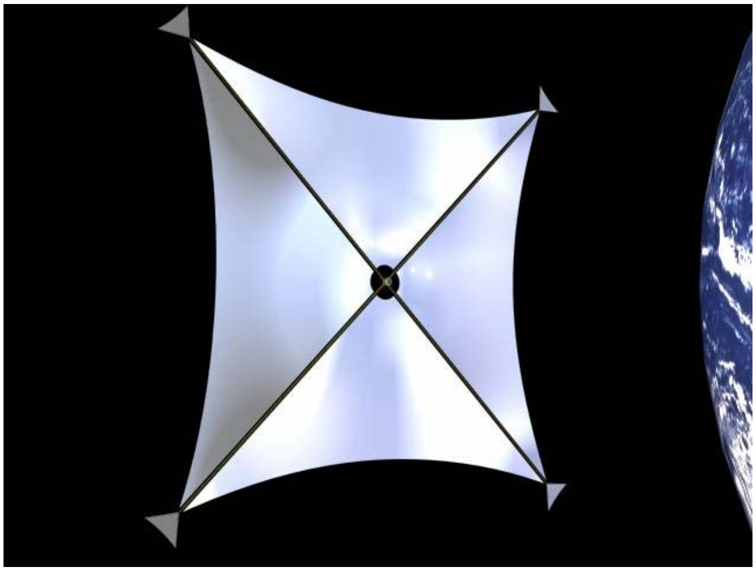


Figure 1. L'Garde's 100m ISP Solar Sail Design

An important aspect of the solar sail program was to generate a test plan to raise the TRL of the solar sail system 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 was fabricated for ground testing at L'Garde and subsequent vacuum deployment and structural testing in NASA's Plum Brook 30 m thermal/vacuum test facility[2]. Currently, a 20 m square test article is being fabricated and will be 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. 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[3][10]. With these techniques, validated predictions of the structural performance of the solar sail configurations at 0 g will be generated.

II. Phase 2, 10 m System Testing

A 4-quadrant 10 m test article was design and fabricated to support the launch environment, system deployment, and thermal vacuum tests. The test article was designed around the 100 m configuration already discussed. The 4-quadrant subscale test article will be the central 10 m of the 100 m configuration. The canister was sized to contain the 100 m sail though only a 10 m square portion of that sail will be stowed for testing.

Ambient Deployment

To complete the launch environment testing an ambient deployment was conducted in L'Garde's high bay. The successful deployment demonstrated that the stowed configuration is compatible with the ascent vent and launch vibration environment simulated during earlier environment tests. The 10 m solar sail after deployment is shown in Figure 2. This important test was a milestone for the technology, and much was learned to improve the deployment in subsequent vacuum deployments. This deployment completed the ambient test sequence and validated the launch environment testing. The 10 m system was re-packaged and sent to NASA's Plum Brook facility for vacuum deployment and structural tests.

Plum Brook Thermal Vacuum Tests

NASA's Plum Brook 30m Vacuum was selected to conduct the vacuum deployment and thermal vacuum testing. The facility is the largest of its type in the world and the only chamber capable of hosting the 20 m test article planned for Phase 3. This chamber is capable of providing a hard vacuum, however for the 10 m tests, the chamber was set at a rough vacuum of 0.15 torr.

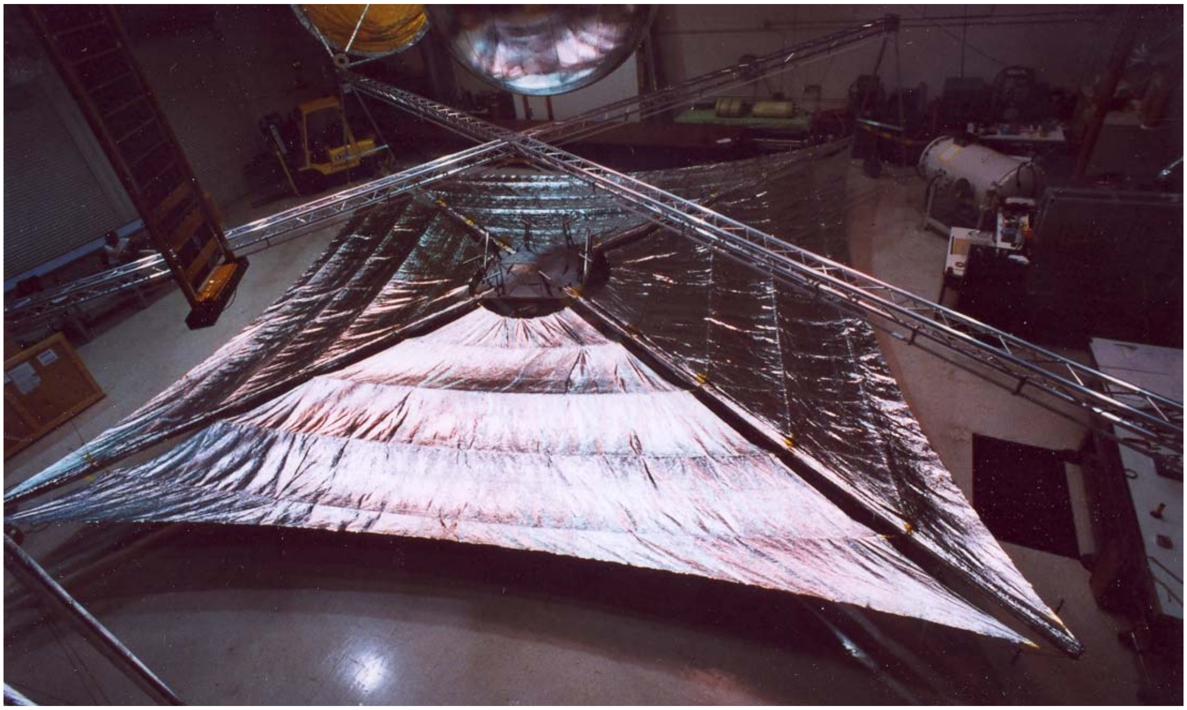
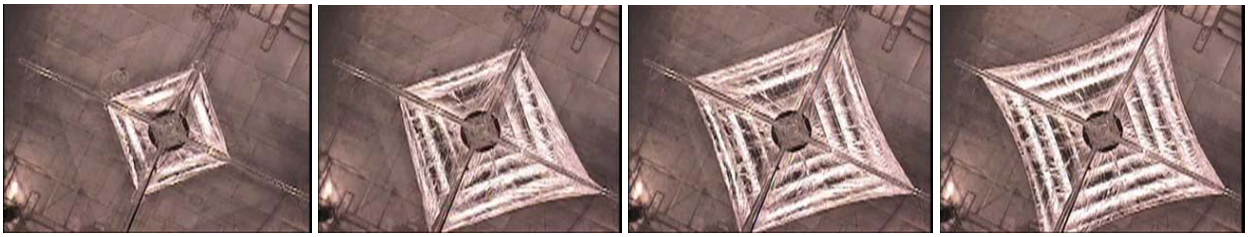


Figure 2.Ambient Deployment of the 10 m System at L'Garde

Vacuum Deployment Test

The successful deployment sequence, shown in Figure 4, was conducted at 0.15 torr over a 35-minute period. All beams and sail quadrants deployed nominally utilizing a computer controlled inflation system. The deployment exhibited some deployment asymmetries due to software issues (b), but the system was able to recover to a proper deployment in rough vacuum (c) (d). This highly successful validation demonstrated the deployment performance and robustness of the solar sail system in a near relevant space environment bringing the solar sail system to near TRL 6. The deploying sail was supported only by the beams and was never in contact with the chamber floor only 1m below. In 1g the load on the sail membrane and deployment forces caused by the sail on the beams is 2 orders of magnitude higher than would be experienced during a space deployment. Additionally, this conservative condition is applied in the same orientation as the acceleration that would be generated by the solar flux demonstrating significant deployment robustness.



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

Figure 3. 10 m Solar Sail Vacuum Deployment Sequence

The successfully deployed solar sail, shown in Figure 4, represents a significant milestone for the L'Garde solar sail design and for solar sails in general as this was the first successful vacuum deployment of a full 4-quadrant solar sail system. The sail/net membrane shape is clearly visible. The wrinkles in the radial direction are formed by a small amount of extra material specifically designed to absorb any lateral contractions in the film due to thermal contraction. Lateral deformations are absorbed by the additional material, and the deformation from net element to net element are absorbed by slight change in the billow between net elements. In this way, the net elements and not the sail material dictate the overall shape of the sail effectively decoupling the global sail shape from the membrane material properties.

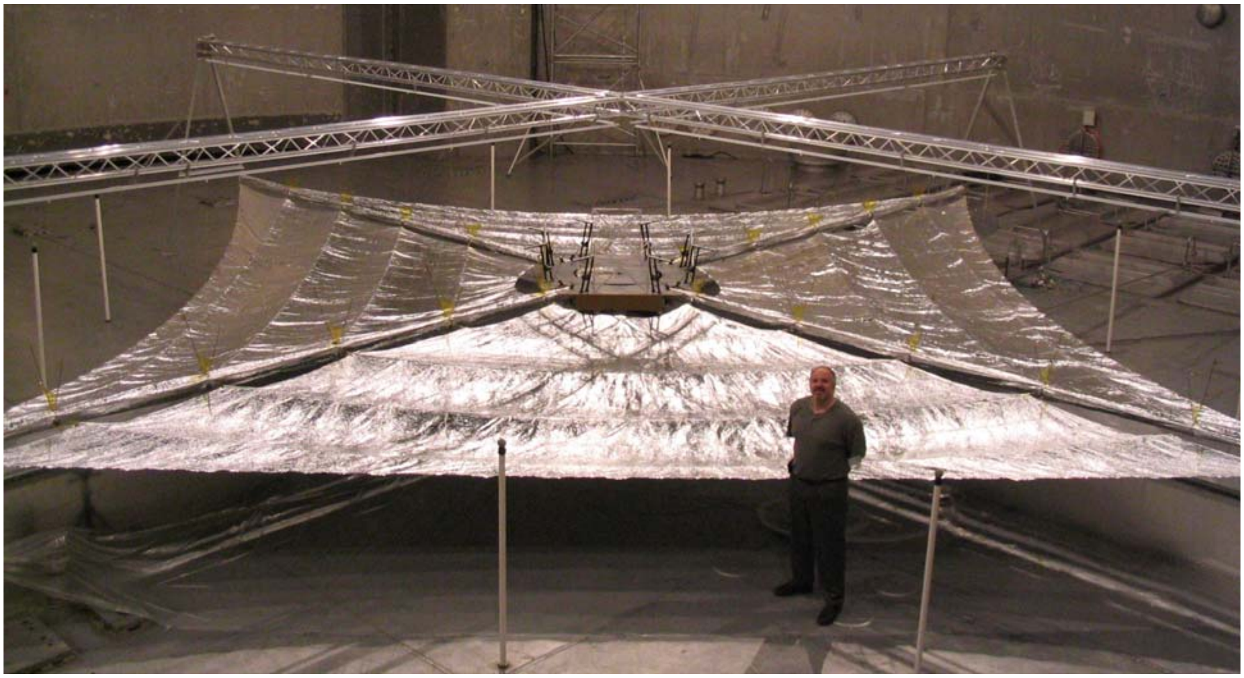


Figure 4. 10 m Solar Sail System After Successful Vacuum Deployment

IV. 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 and permit validation of FEA models simulating the sub-scale solar sail tests. Our highly successful launch environments tests, ambient deployment, and 10 m 4-quadrant thermal vacuum deployment and structural testing have added great credibility to this technology and brought many aspects of this technology to near TRL 6. 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. L'Garde would also like to thank Dr. Gyula Greschik for his continuing assistance in the solar sail design and structural analysis. Many thanks to Robin Brown and the staff at Plum Brook SPF for their support during the test sequence.

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