VACUUM DEPLOYMENT AND TESTING OF A 4- QUADRANT SCALABLE INFLATABLE RIGIDIZABLE SOLAR SAIL SYSTEM

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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 3 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 earlier phases 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 a much larger 20 m square test article including subscale vane has been fabricated and tested. A 20 m system ambient deployment has been successfully conducted after enduring Delta-2 launch environment testing. 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 Technology Project (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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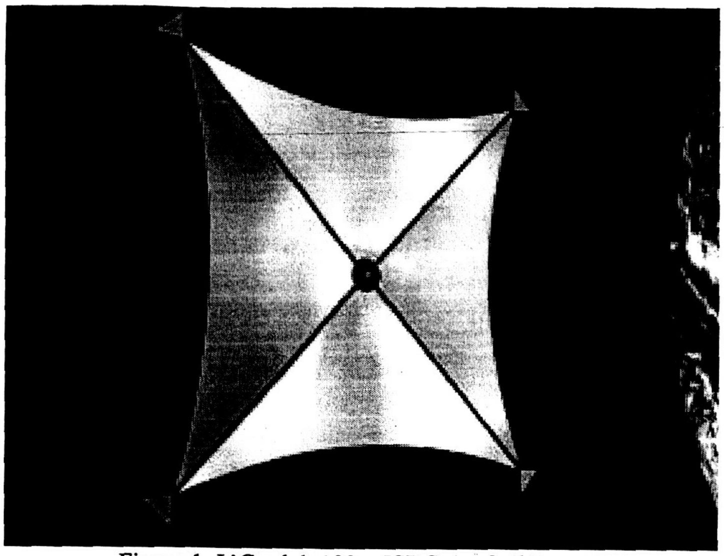


Figure 1. L'Garde's 100m ISP Solar Sail Design

An important aspect of the solar sail program was to generate and execute a test plan to raise the TRL of the solar sail system from 3 toward 6. A list of component 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 vacuum test facility(2). A much larger 20 m square test article including subscale vane has also been fabricated and tested. To date it has successfully endured the Delta 2 ascent vent and vibration testing. A 20 m system ambient deployment has been successfully conducted after enduring the launch environment testing. This testing has paved the way for a comprehensive series of tests planned for the Plum Brook chamber in June 05. These tests, which will validate the sail system including vane control system at space thermal and vacuum conditions, will bring the sail system toward TRL 6. 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 was 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 3, 20 m System Testing

A 4-quadrant 20 m test article was designed and fabricated to support the launch environment, system deployment, and thermal vacuum tests. The test article was designed around the baseline 100 m configuration. The 4-quadrant subscale test article represents the central 20 m of the 100 m configuration. The canister was sized to contain the 100 m sail though only a 20 m square portion of that sail was stowed for testing.

Beams

5 beams were fabricated for the 20m 4-quadrant system, 1 beam is available as a spare in case of test anomalies. The beams are shown during fabrication and alignment in Figure 2, all 5 beams are visible in different stages of fabrication.

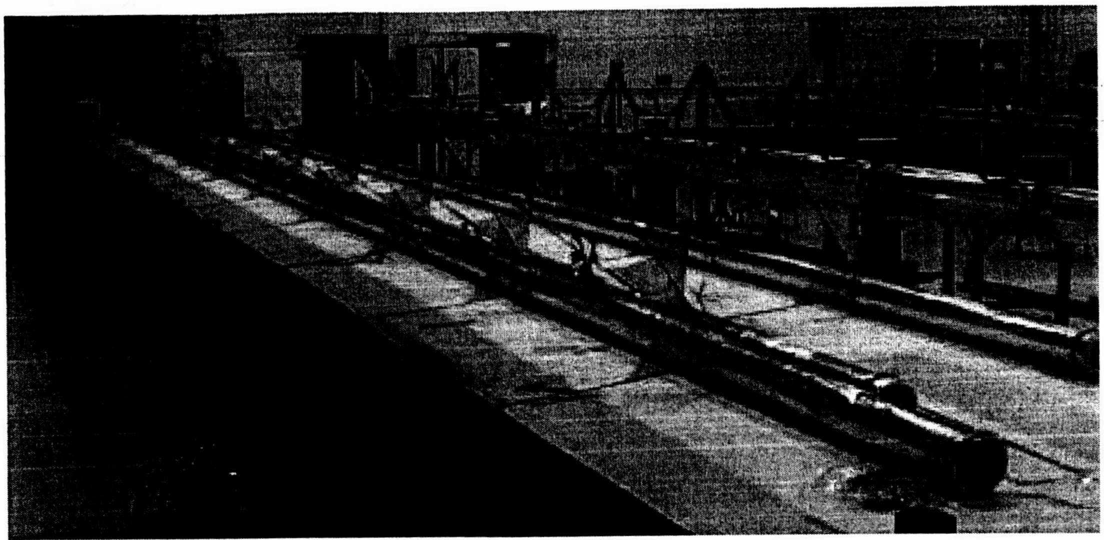


Figure 2. 14m Beams During Construction

Quadrants

Four flight-like 20m quadrants were fabricated for testing, Figure 3. These quadrants, fabricated from easily acquired and metalized 2 μ Mylar, incorporate all features required for flight. Rip stop fibers, demonstrated to halt the propagation of rips across the membrane, were bonded to the sail in a 1 m grid pattern. Grounding straps were incorporated to provide a conductive path between the front and back surfaces. Also included were the net elements[(2)] that define the sail shape and provide the attachment points to the beams. The wrinkles in the radial direction are formed by a small amount of extra material specifically designed to absorb any lateral deformations in the film due to thermal effects. Lateral deformations are absorbed by the additional material, and the deformation from net element to net element is absorbed by slight changes 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.

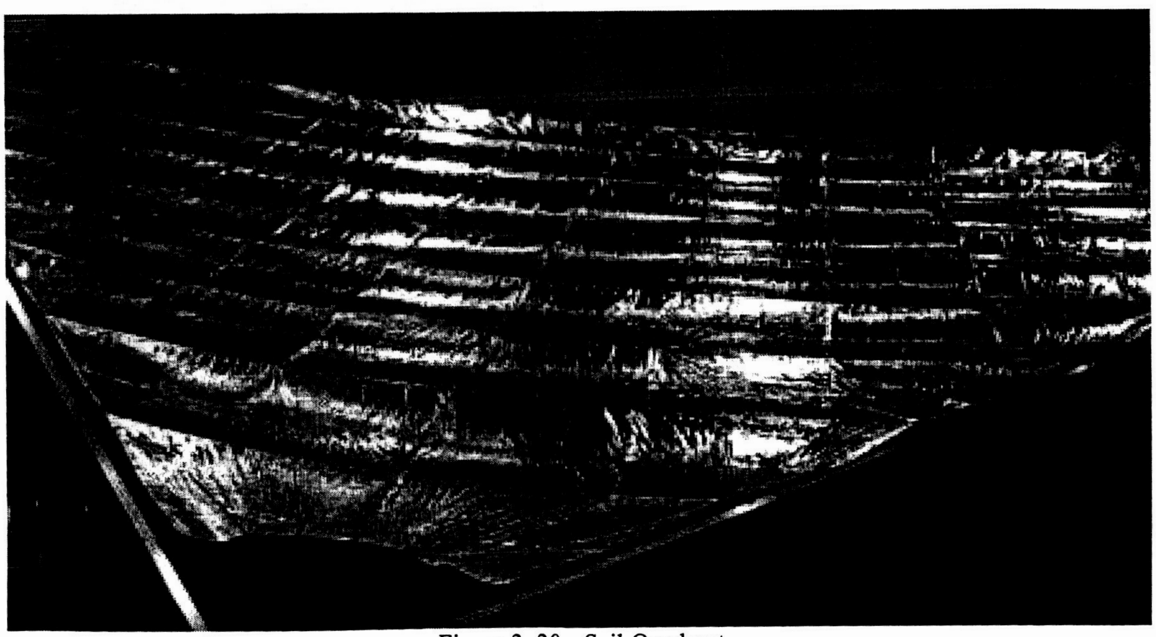
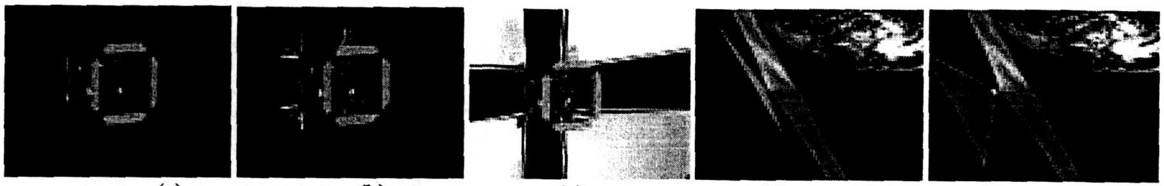


Figure 3. 20m Sail Quadrant

Subscale Vane

A subscale vane was designed and fabricated to demonstrate stowage, deployment, and actuation of the vane component subsystem. The vane design includes all component required for stowage in the canister, rotation of the vane into the plane of the sail for deployment, and finally to provide the cant angle to provide passive stability during operation. The vane deployment sequence is shown in Figure 4. The vanes are stowed in the corners of the canister adjacent to the stowed sail quadrants (a). At initiation of the deployment sequence they are rotated into the plane of the sail for deployment (b). All four vanes are deployed simultaneously using the same deployment techniques and control as the main beams and quadrants (c). After the main sail quadrants and beams are deployed the vane cant angle is actuated (d), (e). The 30-degree vane cant angle provides static stability in two axes to stabilize the sailcraft in case of control system anomalies [4].



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

Figure 4. Vane Deployment Sequence

The completed subscale vane and deployment and actuation mechanism are shown in Figure 5. The beam/vane assembly is shown on the left and a close-up of the vane deployment/actuation mechanism is shown on the right. This mechanism provides all of the launch restraint/release systems required for the vane deployment.

Figure 5. Vane Assembly and Mechanism

Beam/Vane Test

To demonstrate functionality of the 14m beam with integrated vane assembly and gravity offloading, a beam/vane test was conducted. A stowed beam and vane assembly were deployed from the canister to their fully deployed configuration. The test was completed successfully resulting in the configuration shown in Figure 6. The figure on the left shows the stowed beam and vane with the gravity offloading masses.

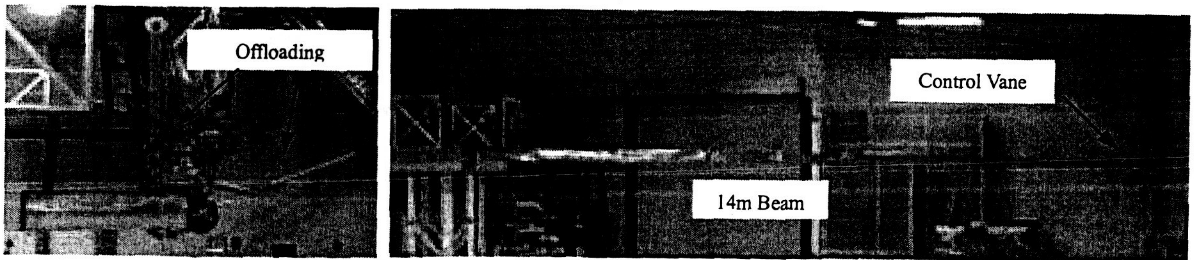


Figure 6. Beam/Vane Deployment Test (Stowed and Deployed)

Canister
A flight-like canister, sized for a 10,000 m^2 sail, was designed and fabricated. The canister contains all components necessary for the stowage and deployment of the solar sail system including heater wires and instrumentation. While the design is flight-like, for economy and efficiency it was fabricated from honeycomb aluminum central structure instead of the lighter composite honeycomb envisioned for a flight article. The stowed canister is shown on the left side of Figure 7, all components of the 20 m system are stowed inside. The canister with doors partially open is shown on the right side of Figure 7. The stowed sails are visible as are the beams in the cruciform arrangement toward the top, a vane boom is also visible at the top left. Note the large blocks of vacuum compatible foam attached to the doors. These blocks simulate the stowed volume of the outer 90m^2 of sail area not modeled during this testing.


Figure 7. Stowed Canister (Doors Closed and Open)

The canister incorporates 4 doors that restrain the sail quadrants against the launch loads. The canister includes the carrier plate, which separates from the sail after deployment. The actual automatic separation hardware is not included, however manual separation has been incorporated so that testing in the flight configuration can be conducted. Hardware has been incorporated to stow and constrain the spreader assembly for launch and deployment.

<u>Launch Environment Testing</u>
In order to show system compatibility with the Delta-2 launch environment a series of launch environment tests were planned and executed. An Ascent Vent test was conducted to show that all components of the solar sail are capable of venting any gasses present in the structure during booster ascent. A launch vibration test was completed exposing the stowed configuration to the Delta-2 launch vibration profile in all axes. Finally, an ambient deployment test was conducted to demonstrate successful operation after exposure to the vent profile and launch vibration loads. Detailed inspections were carried out at all phases of the environment testing to identify any issues, however, certain areas inside of the booms, tip mandrels, and internal sail folds were not accessible for inspection. A post launch environment deployment test was conducted to identify any anomalies encountered in these areas.

Ascent Vent Test
The fully stowed configuration was installed in LaRC's 8'x15' thermal vacuum chamber for the ascent vent testing, see Figure 8. The chamber was evacuated at a rate similar to the payload fairing on a Delta-2 booster during ascent. This test demonstrated that the stowed configuration is compatible with this launch environment and that all residual trapped gasses in the sail folds and stowed beams and vanes can vent without causing any damage or disturbances to the stowed configuration.

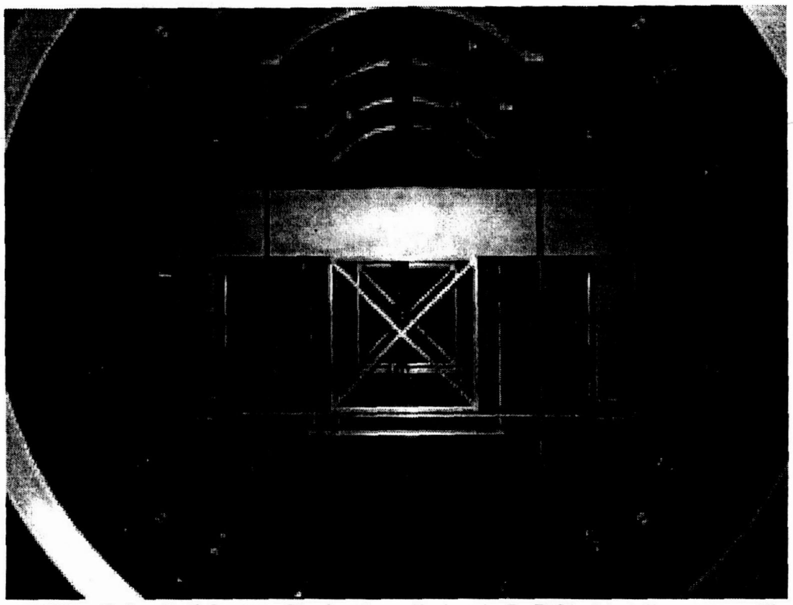
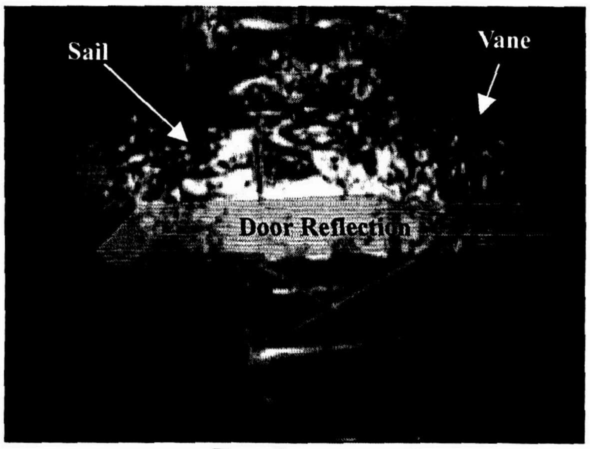


Figure 8. 20 m Solar Sail System During Installation in LaRC's 8'x15' Vacuum Chamber

Once the chamber achieved hard vacuum, the walls were cooled to 0°C, the expected on-orbit equilibrium deployment temperature, and one of the doors was actuated to demonstrate functionality in a relevant environment. The door opened nominally, and the stowed sail quadrant and vane boom are clearly visible with the door open, see Figure 9. The successful outcome to this test demonstrated that the stowed configuration is compatible with the launch environment of the Delta-2 booster, and that the doors can operate in a relevant on-orbit deployment environment.

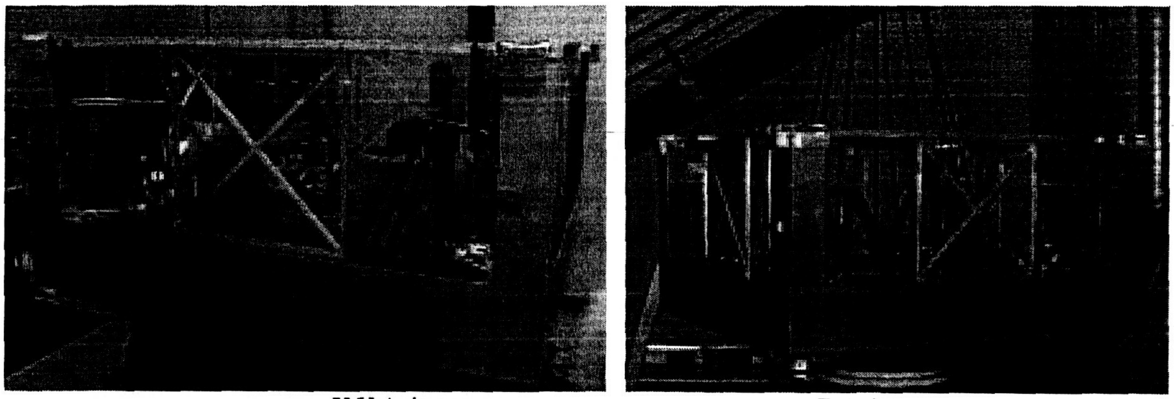


Door Closed Door Open

Figure 9. Ascent Vent/Door Actuation Test at Hard Vacuum

Launch Vibration test

To demonstrate compatibility of the stowed solar sail with the launch vibration environment of the Delta 2 booster, launch vibration tests were conducted. L'Garde's vibration table was utilized and applied relevant vibration loads to the stowed configuration in the X, Y, and Z orientations. The lateral and longitudinal test setups are shown in Figure 10. After applying the Delta-2 launch loads in the X, Y, and Z-axis no damage was apparent to the canister, stowed configuration, and stowed spreader lines. A subsequent ground deployment confirmed that the stowed configuration is compatible with the Delta-2 launch environment.

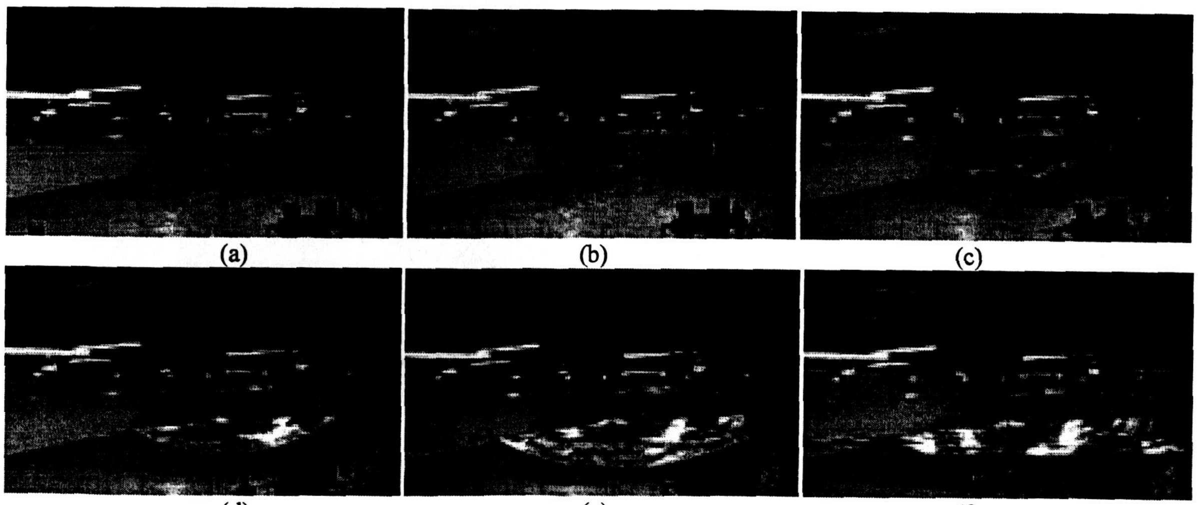


X,Y-Axis Z-Axis

Figure 10. Vibration Test Setups

Ambient Deployment

To complete the launch environment testing a successful ambient deployment of the 20m system was demonstrated at L'Garde. This successful deployment verified that the stowed configuration is compatible with the Delta-2 ascent vent and launch vibration environment simulated during earlier environment tests. The deployment was initiated with the vane components rotated from the stowed configuration into the plane of the sail (a). The vane booms were fully inflated deploying the subscale vane (b). The main beams were deployed under computer control until the 20m beams, sail quadrants, and subscale vane reached their fully deployed geometries (c)-(f). The updated deployment control algorithm kept the beams within 1m in deployed length during the sequence. The deploying sail quadrants were supported only by the beams and were only briefly in contact with the chamber floor 2m 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) (e) (f)

Figure 11. 20m Ambient Deployment Sequence

The successfully deployed 20 m solar sail is shown in Figure 12. This important test was a milestone for the technology and was the first time the full system including vane components was deployed. This deployment completed the ambient test sequence and validated the launch environment testing. The 20 m system was re-packaged and sent to NASA's Plum Brook facility for upcoming vacuum deployment and structural tests.

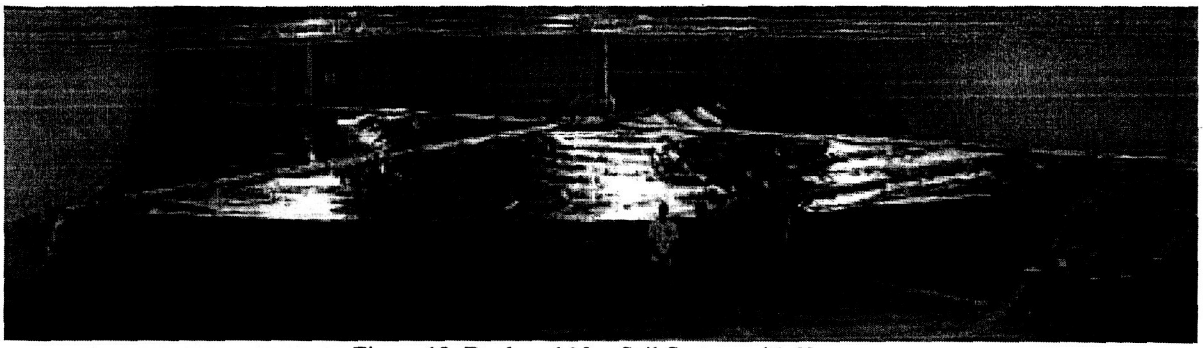


Figure 12. Deployed 20m Sail System with Vane

20m Vacuum Deployment Test

The 20m ambient tests prepared the configuration for deployment at NASA's Plum Brook 30m vacuum chamber. This important test will raise the full system TRL level to near 6. The test will be very similar to the 10m deployment conducted at the facility in June of 2005, Figure 13. The 20m tests will be 4 times larger in area, and will include the subscale vane to demonstrate the vane control system in as near a relevant an environment as possible on the ground.

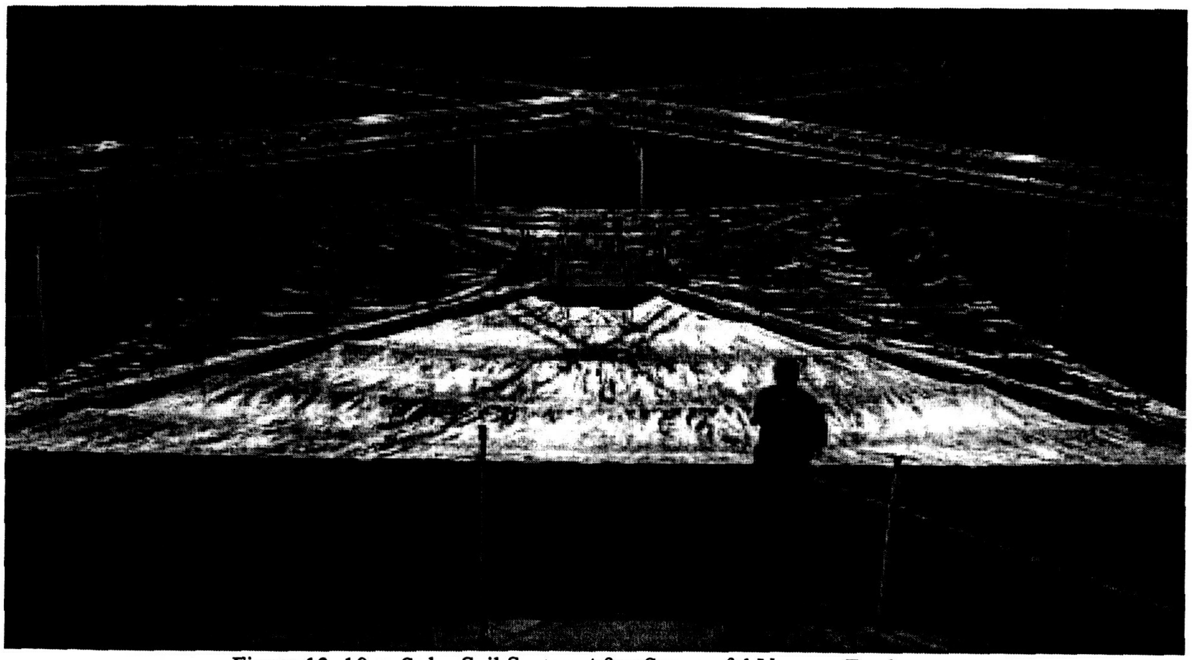


Figure 13. 10 m Solar Sail System After Successful Vacuum Deployment

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 20 m 4-quadrant 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

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