Test of a Full-Scale Quadrant for the 1,653m^2 Solar Cruiser Sail

Zachary McConnel [a]*, Brian Sanders [a], Anan Takroori [a], Craig Hazelton [a], Jim Pearson [b], Carlos Diaz [c], Ashley Benson [c]

[a] *Redwire Space Systems, Longmont, Colorado, USA*
[b] *NeXolve, Huntsville, Alabama, USA*
[c] *NASA Marshall Space Flight Center, Huntsville, Alabama, USA*
* Corresponding Author email: zachary.mcconnel@redwirespace.com

NASA Marshall Space Flight Center (MSFC), in collaboration with Redwire and NeXolve, is advancing the design of a 1653 m^2 Solar Sail System (SSS) for the Solar Cruiser mission; a technology demonstration mission to enable missions to high solar inclination orbits, sub-L1 halo orbits, non-Keplerian solar and other planetary orbits. Since 2019, the program has been developing key components, including: the Sail Deployment Mechanism (SDM), high strain composite Triangular Rollable and Collapsible (TRAC) booms, and the ~ 413 m^2 thin film sail quadrants. This effort has culminated in the successful ground deployment demonstration of a flight-scale prototype quadrant in late 2022. This paper provides an overview of the results from this test. This paper also outlines critical lessons learned that will inform ongoing efforts to further develop the technology towards flight.

Keywords: Solar Cruiser, Redwire, NeXolve, MSFC, Solar Sail

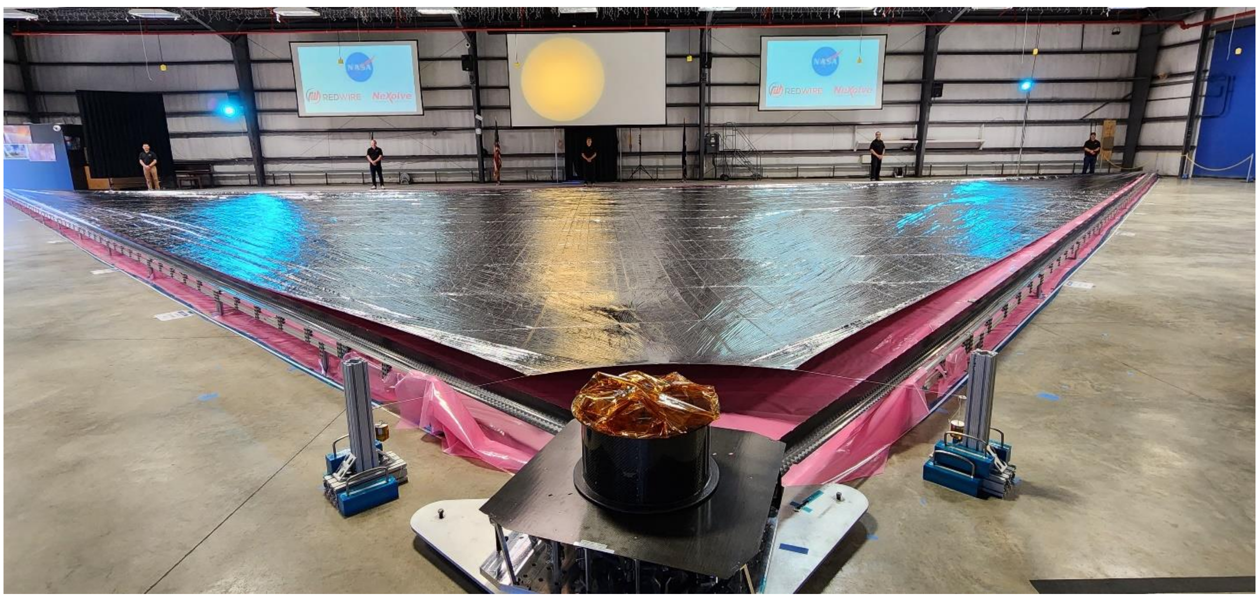

Fig. 1. Fully Deployed Single Quadrant Prototype Sail, TRAC-Booms and Deployer

1. Introduction

This paper summarizes a test program to deploy a single full-scale quadrant of the sail designed for NASA's Solar Cruiser Mission [1]. This test consisted of fully deploying two booms perpendicular to one another with a 413m^2 (4435ft^2) sail quadrant tensioned in between (Fig. **1**). The primary objectives of this test were to demonstrate the operation of key features of the Sail Deployment Mechanism (SDM) and evaluate design concepts for critical ground support equipment (GSE) and procedures for full-scale sail testing, hence pushing the limits of solar sail technology forward for 2,000 m^2 class sails. This demonstration included many stage gates through which associated risks were mitigated. The team built on the preliminary sub-scale tests to verify hardware and procedures for the full-size deployment test. Ultimately, the test campaign confirmed that the designed hardware is mature, while identifying several design features that can be improved in the next hardware maturation cycle towards flight.

2. Test Unit

Fig. **2** illustrates the test unit in its stowed configuration. The test unit consists of the Sail

Deployment Mechanism (SDM) and two TRAC booms [2] manufactured by Redwire and a 2.5 micron thick Colorless Polyimide -1 / Vapor Deposited Aluminium (CP-1/VDA) sail quadrant manufactured by NeXolve. To achieve the single quadrant deployment, the assembly contains two nearly 30m TRAC booms and one full-scale sail quadrant. When stowed the system occupies roughly 1/3m^3, after deployment the full sail spans 1,653m^2, with a single quadrant measuring 413m^2 in area.

The sail quadrant was spooled onto a flight-like sail spool designed to accommodate four sail quadrants. To adjust for a single quadrant deployment test, an Adjoining Sail Simulator was constructed to simulate the packaged volume of the three remaining sail quadrants. Similarly, a Sail Ramp was constructed to ease the transition of the sail from the upper deck to the ground deployment area, preventing the sail quadrant from folding onto itself. The sail hub spins freely on a set of trundle bearings, only moving once the booms pull on the sail through distal end connections.

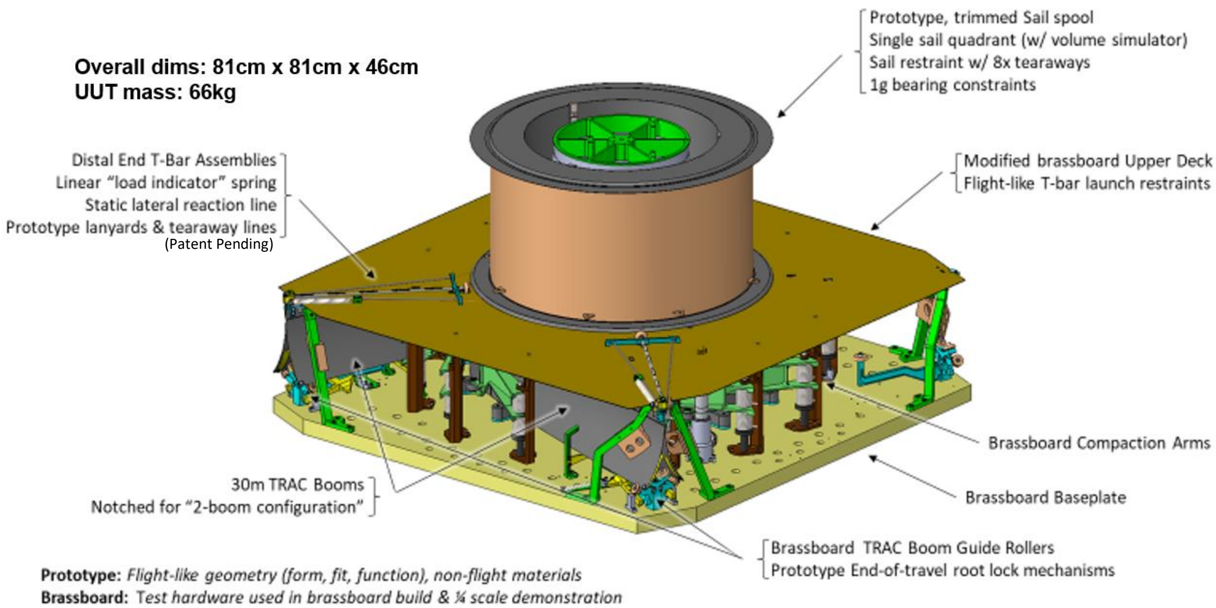

Fig. 2. Test unit components.

Fig. 3. Panoramic view and floor layout of test facility (MSFC B4316).

The key structural elements of the flight sail system are four 30m-long, high-aspect ratio TRAC booms [3] that serve as the sail's skeletal system and are designed to *deploy* the packaged reflective sail membrane as well as *provide* operational sail tension loads for flight. The full-scale quadrant test unit incorporated two full-scale TRAC booms manufactured to meet the flight system structural, thermal, and packaging requirements.

3. Description of Facility and Test Setup

The full-scale quadrant deployment test took place in Building 4316 at NASA's Marshall Space Flight Center (MSFC, Fig. 3). The open layout of B4316 provided sufficient floor space for the full quadrant test as shown in the floor layout sketch in Fig. 3.

Prior to the test, the facility was cleaned, and ground support equipment was put in place. This includes the SDM base, the boom support sections and the ground cover material. The ground cover material, ULINE Anti-Static Poly Sheeting, was determined to be the best option due to its low coefficient of friction, its ability to dissipate static charges which could provide additional drag on the sail and relatively low cost for area needed. Other design options were traded for the sail deployment surface, such as an air hockey table-like structure that would provide a cushion of air beneath the sail, however this method would have been prohibitively expensive. Small scale tests were used to determine the lowest friction against other materials. The material was also used in all preliminary deployments on smaller scale tests. The material would serve the critical role of a uniform surface for the sail to slide across throughout deployment.

The TRAC booms were offloaded with support tracks with the TRAC boom flanges gliding along a series of rollers. A horizontal rail and trolley assembly was installed on the outer edges of these support sections (opposite side of the sail, between boom support sections) along the length of the booms. This rail assembly balanced the lateral loads the sail put on the distal ends of the booms. This is necessary when testing a single quadrant, as there are no other sail quadrants to balance this adjoining sail lateral load.

The test unit (Fig. **2**) was positioned on top of a turntable that allowed for its rotational alignment to the rest of the GSE during the test to be adjusted. As the booms deploy, the tangent angle between the boom and the hub changes, as the boom's spooled diameter decreases. This change in boom angle was accommodated by manually rotating the test unit periodically during the test.

4. Preliminary Deployment Tests

Leading up to the full-scale deployment test, a series of five preliminary tests were conducted to validate the ground support equipment and expose test process risks. Three quarter-scale sail deployment tests were conducted at Redwire's facilities in Longmont, Colorado on a complete sail with four quarter-length booms and four quarter-scale sail quadrants (Fig. **4**) to facilitate development of the ground support equipment. Once the ground support equipment was finalized and installed at MSFC B4316 a full-length boom deployment test was conducted without the sail, and an additional quarter-scale mylar sail quadrant deployment test was done to ensure the alterations to ground support equipment were effective in reducing deployment risks.

Fig. 4. Quarter-scale sail deployment test.

The quarter scale sail deployments were done with mylar sails roughly eight meters on each side (being referred to quarter scale by deployment length). These tests provided critical understanding of the deployment dynamics of the sail in a 1g environment. The mylar material is stronger than the CP-1/VDA material being used on the full-scale deployment but showed the unfolding movements that could be expected. Any snagging risks observed in these preliminary deployments, due to test conditions, were recorded and mitigated with additional MGSE for the last quarter scale deployment and the full sail deployment. These test conditions are due to deploying in a 1g and with only a single quadrant.

The TRAC booms themselves were also load tested prior to the deployment testing to ensure they wouldn't buckle under the testing conditions in gravity. The booms proved to be extremely robust, only buckling at loads 19x nominal operating load in flight. These results validated analysis models which predicted very similar performance and buckling dynamics.

The lessons learned from these preliminary deployment tests, both at Redwire's facility and the deployments prior to the CP-1/VDA sail, informed refinements to the GSE and procedures for the full-scale test that minimized snagging and damage to the ultra-thin CP-1/VDA quadrant.

5. Full-Scale Quadrant Deployment Test

The full-scale single quadrant prototype sail deployment test began on October 12th 2022 and was completed on October 14th 2022. While the deployment time alone is less than an hour at full speed, the close monitoring, 1g environment and testing procedures increased the time necessary to complete the program. The following sections describe the deployment test steps.

5.1 Test Day One. As per the test plan, the team started with a review of the test plans for the day to ensure the test team was well coordinated. NASA, NeXolve and Redwire were present. Test personnel were in place and first motion was commanded to the SDM to deploy the booms. The booms moved approximately 2cm and the boom distal end features disengaged from the SDM's launch stowing location. This then caused successful release of the sail restraint (Fig. **5**).

After successful release of the booms and sail quadrant from their retention devices, deployment continued with a goal to extend the system initially to 5m (roughly 1/6 of the full deployment distance). During this phase, the unfurling sail quadrant was observed to migrate between the upper deck of the SDM (Fig. **5**) and the Adjoining Sail Simulator. The sail migrated between the Adjoining Sail Simulator and the test article due to gravity and raised a concern that pinching of the quadrant could cause the sail to rip. The situation was monitored until the test was stopped to assess changes to the ground support equipment and test procedures to mitigate the issue.

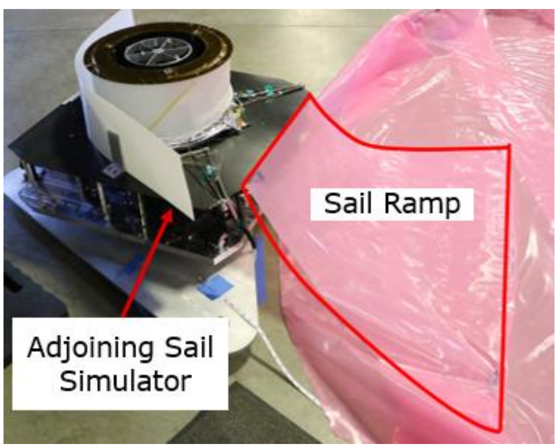

Fig. 5. Sail test unit after first motion.

The root cause of the sail migration problem was ultimately attributed to the design of the Adjoining Sail Simulator (i.e., the material designed to fill the volume of the three adjoining sail quadrants left out of the present tests). In space, and with the adjoining sails present, the Adjoining Sail Simulator would not be necessary. So the issue was purely a result of the single-quadrant test configuration. To complete the test, an additional ground support equipment feature, referred to as the Adjoining Sail Simulator Extension, was installed to prevent the sail test quadrant from getting pinched.

The test resumed with the boom deployment to 3m. Deployment then continued without significant issues to 27m. The local time was 4:00pm and test was halted for the day. Data and pictures were saved, and the hardware was safed with the sail quadrant tensioned.

5.2 Test Day Two. The team reconvened at the test site and the daily planning meeting was held. Hardware was inspected, all appeared normal, and in the state it was left in the previous evening. The test resumed at 9:11am on October 13th, 2022. The first motion resulted in disconnection of one of the TRAC boom distal end fittings and the sail. The test was halted, and the situation was assessed. Upon inspection it was discovered that a solder bead in the sail clevis had separated from the stainless-steel cable. This was likely due to the connection only being proof tested in short term loading conditions, unlike the overnight loading that took place between test days. The design deficiency was noted, and a field repair was affected involving the use of a compression sleeve in place of the failed solder bead. Then the repaired connection was proof tested using spare materials to ensure the fix would hold for the duration of the test under expected loads.

With the distal cable fitting anomaly repaired the final deployment and sail tensioning proceeded nominally. The team slowly tensioned the sail at slow deployment rates and continually monitored the booms and sail tension. This was a key factor to monitor throughout deployment was the load imparted on the sail from the distal end hardware of the booms. In flight this load would be negligible, but in gravity the force of friction between the sail and deployment area put tension in the corners of the sail attached to the booms. The sail corner fittings are designed to withstand 22 newtons (5lbs) of load from the distal end chords. Indicator springs were integrated into the boom's distal end hardware to monitor this load and partial results are presented in Fig. **6**. Test team members followed the ends of the booms and called stop to deployment when the tension hit 18 newtons (4lbs). On these occasions, sail luffing methods were used to break the sail free from the deployment surface and reduce static cling that had built up to that point in the test. A few luffing methods were tried, but the most successful was directing an ionizing fan beneath the edge of the sail near the connection to the boom.

The tension at each boom was near zero for the first quarter of deployment but the tension loads increased as more of the sail's mass left the spool and was resting on the ground. The tension spiked at 27.7m of deployment, and the luffing method was used to prevent damage to the sail. Once the tension was reduced and the sail settled back to the ground, the deployment continued. The two corners experienced different tensions throughout, but both steadily increased throughout the test. The distribution of the folding pattern on the deployment surface likely explains why the two booms experienced different loads.

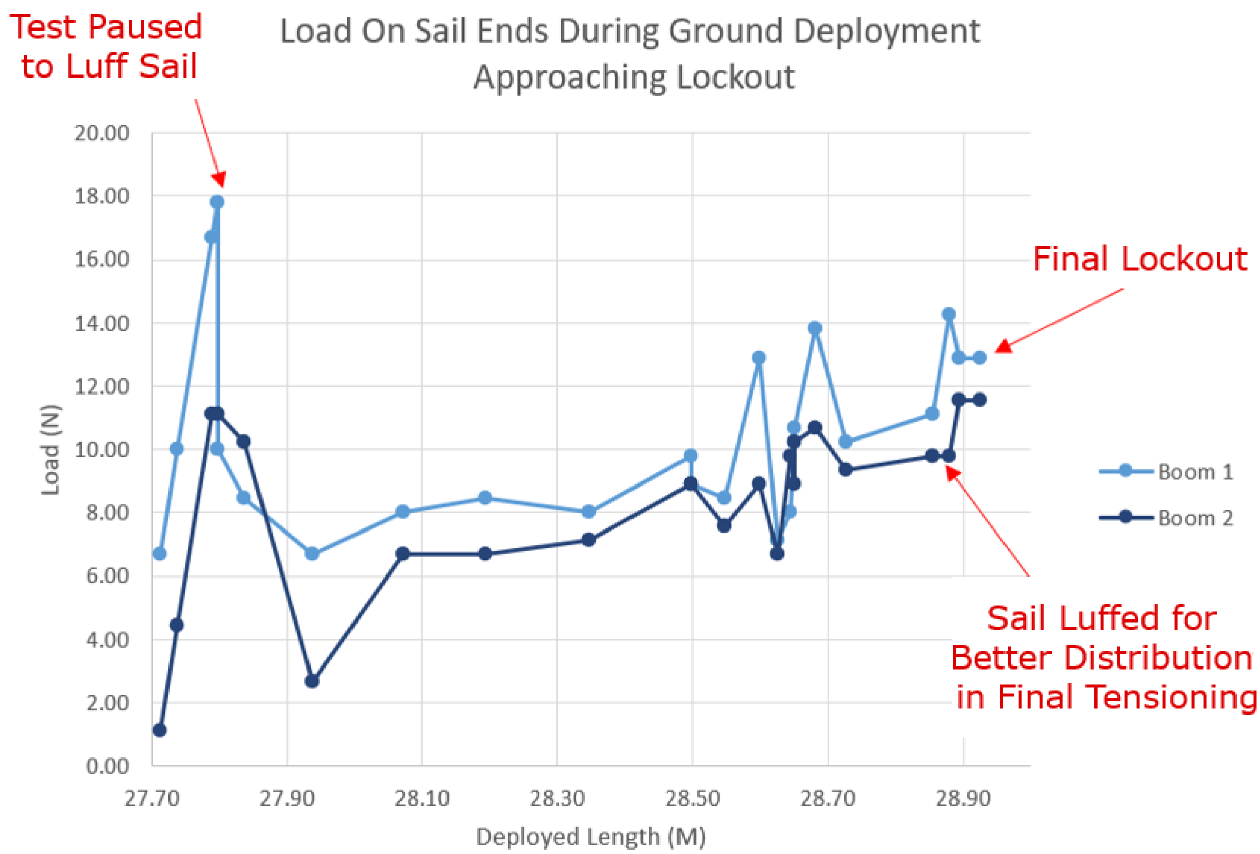

Fig. 6. Loads on sail ends during the final few meters of deployment, with some key events labelled in red.

Deployment to a full length of 28.9m was achieved with the final lock out of the booms in the Sail Deployment Mechanism observed by the test team at 5:34pm. End of deployment was determined by observing the boom lockout with the full engagement of the root support mechanism. The fully deployed quadrant is shown in Fig. **7** prior to tensioning of the sail, which involved the use of additional ground support equipment.

5.3 Test Day Three. The team reconvened at the test site and the daily planning meeting was held. Hardware was inspected and all appeared normal and in the same state it was left in the previous evening. The test resumed at 6am on October 14th, 2022. The primary objective of the third day of testing was to fully tension the quadrant with the additional ground support equipment that simulate the root connections of the sail quadrant to adjacent sail quadrants (Fig. **8**).

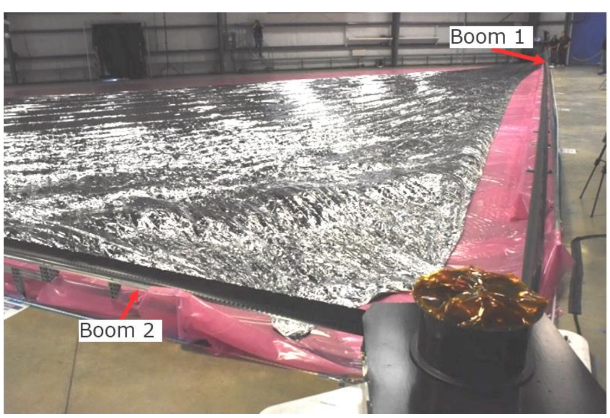

Fig. 7. Sail after full deployment, before manual tensioning (end of test day two), with booms labelled.

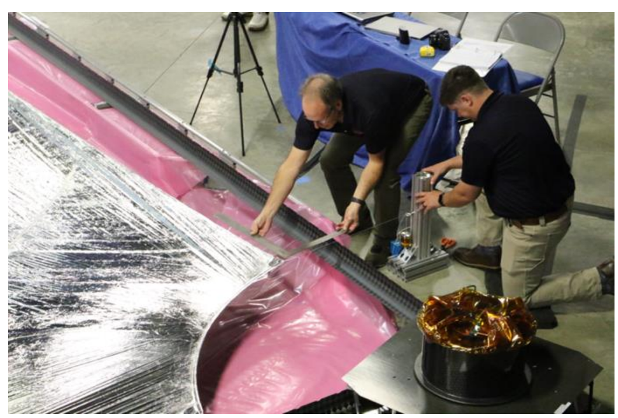

Fig. 8. Sail root cross-tie simulators being installed to tension the sail quadrant.

The final steps of the test included measuring electrical resistance across key reference points of the system to establish the performance of static grounding treatments applied to the hardware. The sail was found to exhibit several open circuits associated with minor damage to the hardware primarily from interactions with the ground support equipment. Importantly, the electrical resistance from the SDM to the distal end of the TRAC booms was found to satisfy the grounding requirement. Fig. **9** presents a sequence of images captured throughout the full-scale quadrant deployment test.

5.4 Follow on Activities. After the test had commenced the sail remained in its tensioned state to present to interested parties.

A final set of measurements were taken to validate the size of the sail as manufactured. Each section of the sail was folded as it was adhered together, so the first opportunity to measure its full area was after the deployment. The sail was detached from the distal ends of the booms and the cross-tie simulators, then laid flat on the ground. The NeXolve team members took extensive measurements, by use of a laser tracker, at key points along the edges of the sail to compare with the designed specifications.

6. Key Takeaways

Throughout this deployment test the team encountered and overcame many challenges, developing lessons learned which can be applied to Solar Cruiser testing and other space sail technology. Redwire is currently developing a TRL 6 (Technology Readiness Level 6) prototype for ground qualification testing of flight loads and environments.

The boom offloading system was extensive and not without its flaws. The team improvised solutions during assembly to ensure few to none snags could occur between the hardware and GSE. These included shingling the low friction film across the TRAC boom offloading structure, over metallic elements that could potentially damage the booms, minimizing friction on all sliding surfaces that the booms or sail may encounter.

Deploying a single sail quadrant out of four, a testing condition that would seem to simplify the procedure, presented a need for more GSE to simulate the effects the adjacent sails would have on the existing quadrant. These structures include the aforementioned Adjoining Sail Simulator, the cross-tie tensioning system as well as the trollies on the TRAC boom offloading system. These trollies road along a rail during deployment, reacting the loads put on the distal end of the boom by the sail. An action which in flight would be done by the adjoining booms and sail quadrants.

The team's diligence in recording data during the test, which was predominantly a technology demonstration, helped to inform analysis models that are currently in development to understand the dynamics of sail flatness on orbit, and the resultant design modifications to ensure flatness. This data includes the final measurements of the sail quadrant dimensions and the loads imparted on the distal end of the boom from the sail (despite those loads being mostly a result of gravity).

Qualitative observations of the system led to innovative design changes for future prototypes.

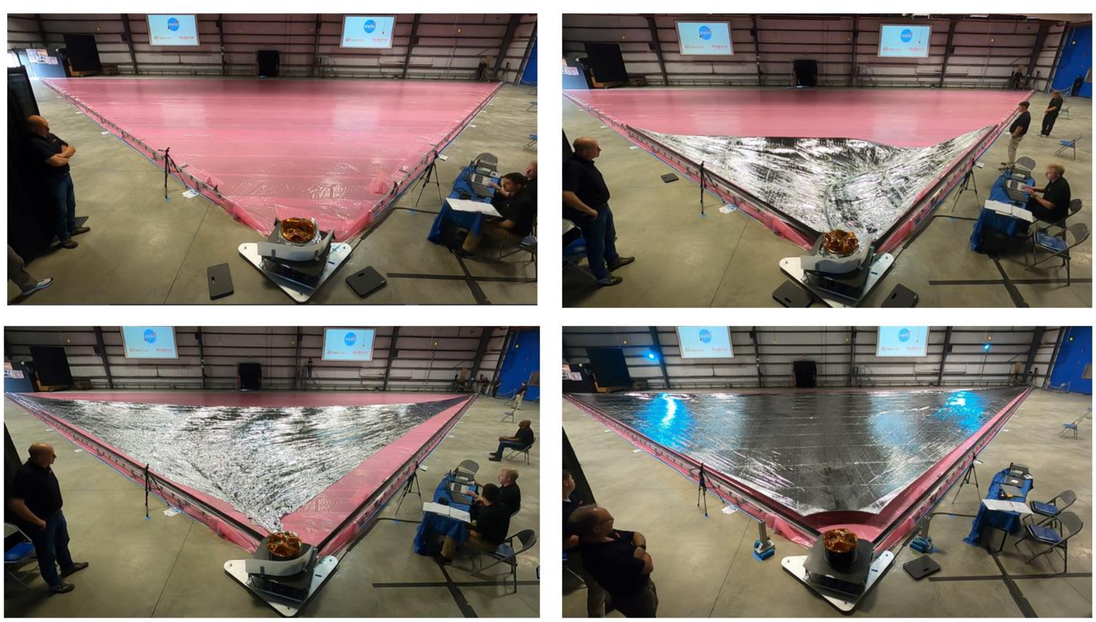

Fig. 9. Full-scale sail quadrant deployment images captured throughout deployment.

The nature of the sail quadrant's wrinkles concluded a greater nominal tension would be required to optimize deployed sail flatness. Additionally, as a result of the testing, the TRAC boom root lockout system was modified for reliability in the TRL 6 prototype.

Also significant was the confidence and cohesiveness this test instilled in the team members who developed the technology and ran the deployment. A technology demonstration of this magnitude not only proves it is possible, it established the foundation for future prototype testing, in both technology and team dynamics.

7. Conclusion

The deployment of the prototype full-scale sail quadrant was successful, with the sail deployment mechanism (SDM) and TRAC booms performing as designed and sail quadrant movement and management working mostly as planned with minor issues encountered related to the interactions of the sail quadrant with ground support equipment. The 1g environment created many challenges to demonstrating this technology, however the ground support equipment performed sufficiently to validate all critical elements of the system design towards flight.

At present, the nearly 1,700m^2 sail system is undergoing continued development through TRL 6 ground qualification to flight loads and environments. The design has been updated for functional reliability and mass efficiency, with intention to repeat the single quadrant deployment test in a similar fashion. This next iteration will have four booms installed instead of the two, requiring additional GSE to be developed in parallel. The manufacturing of the TRAC booms has also been refined for consistency and are currently being manufactured for the TRL 6 prototype.

Redwire, NASA and NeXolve are collaboration to developing analytical models to predict the behavior of Solar Cruiser in flight. This is critical to provide feedback on the latest design which will enable a future Solar Cruiser flight opportunity.

Acknowledgements

The work herein was funded by NASA under Marshall Spaceflight Center contract 80MSFC21CA008. Thank you to team members from NASA, Redwire and NeXolve who made this test possible. Go Cruiser.

References

[1] Johnson, L., Curran, F., Dissly, R., Heaton, A., Turse, D., The Solar Cruiser Mission: Demonstrating Large Solar Sails for Deep Space Missions, December 2020, https://www.researchgate.net/publication/347079622 (accessed 03.02.23)

[2] Murphey, T. W. and Banik, J., "Triangular rollable and collapsible boom". US Patent No. 7,895,795, March 1, 2011 (licensed exclusively by Redwire 08.12.16)

[3] Nguyen, L., McConnel, Z., Medina, K., and Lake, M., Solar Cruiser TRAC Boom Development, Presented at AIAA SciTech 2023, AIAA Paper No. 2023-1507.