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

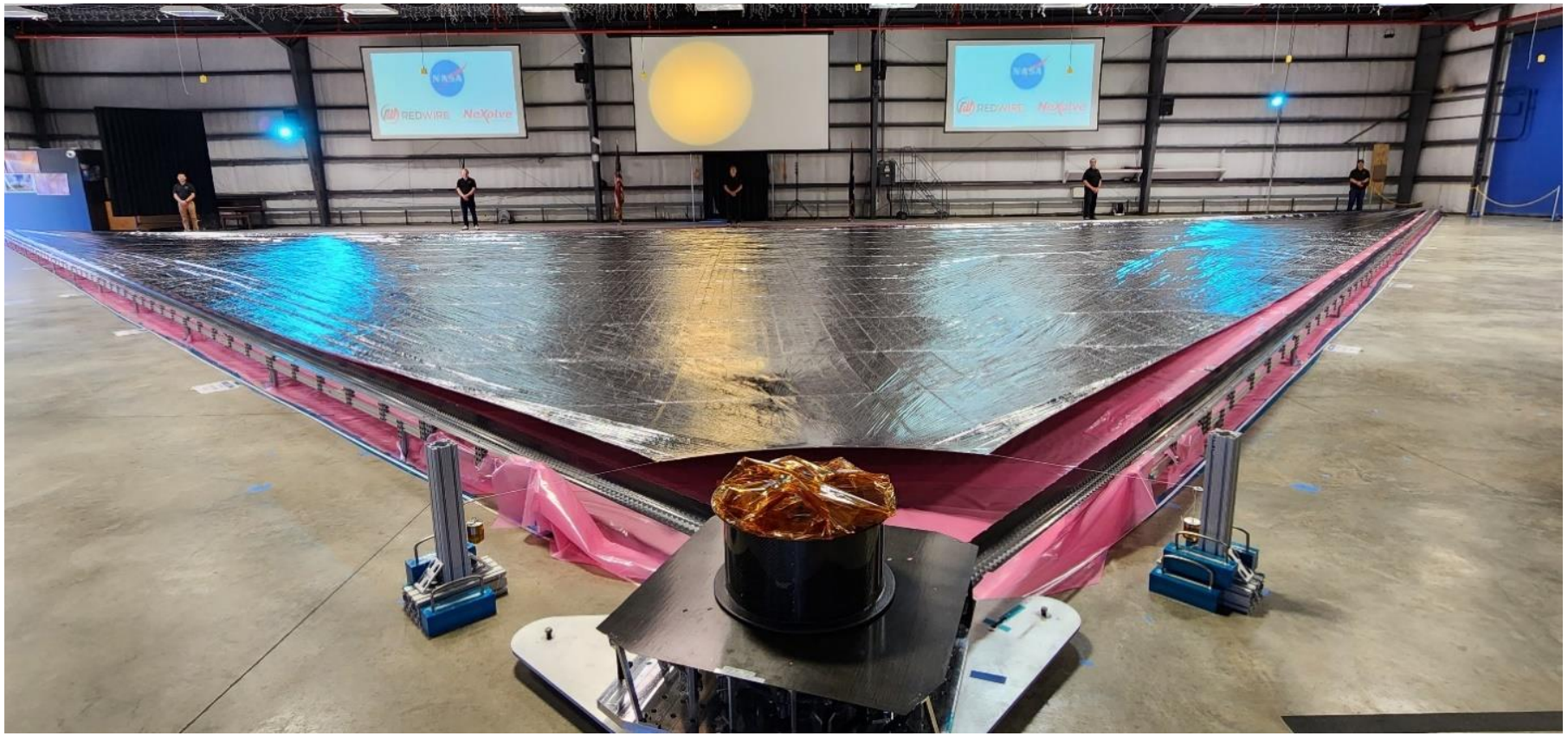
6th International Symposium on Space Sailing (ISSS 2023)

New York, USA

Zachary McConnel June 6, 2023

Overview

1. Background
2. Test Preparation
3. Deployment Test
4. Conclusion
5. Questions

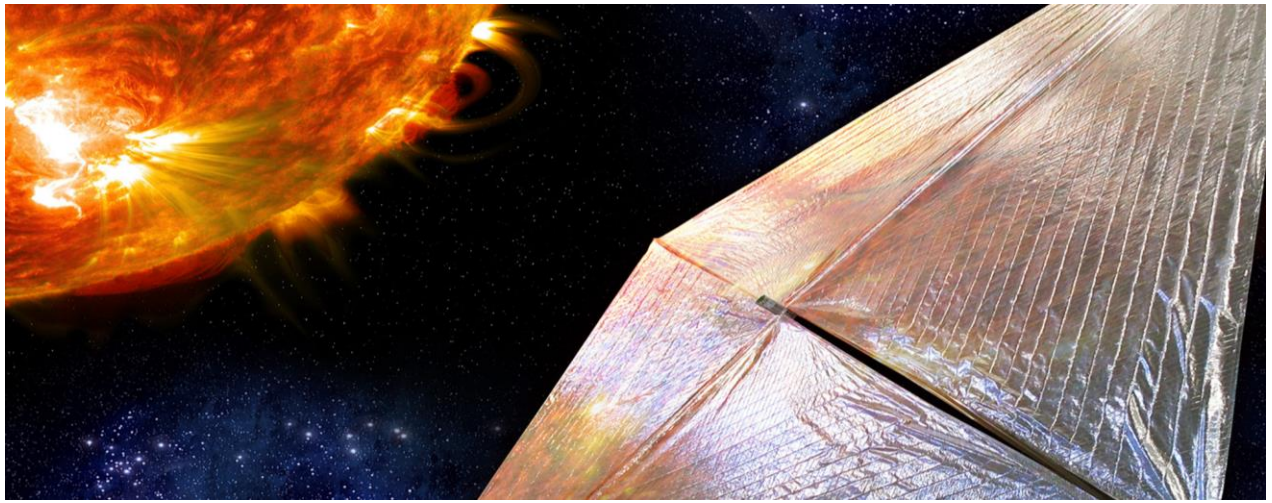


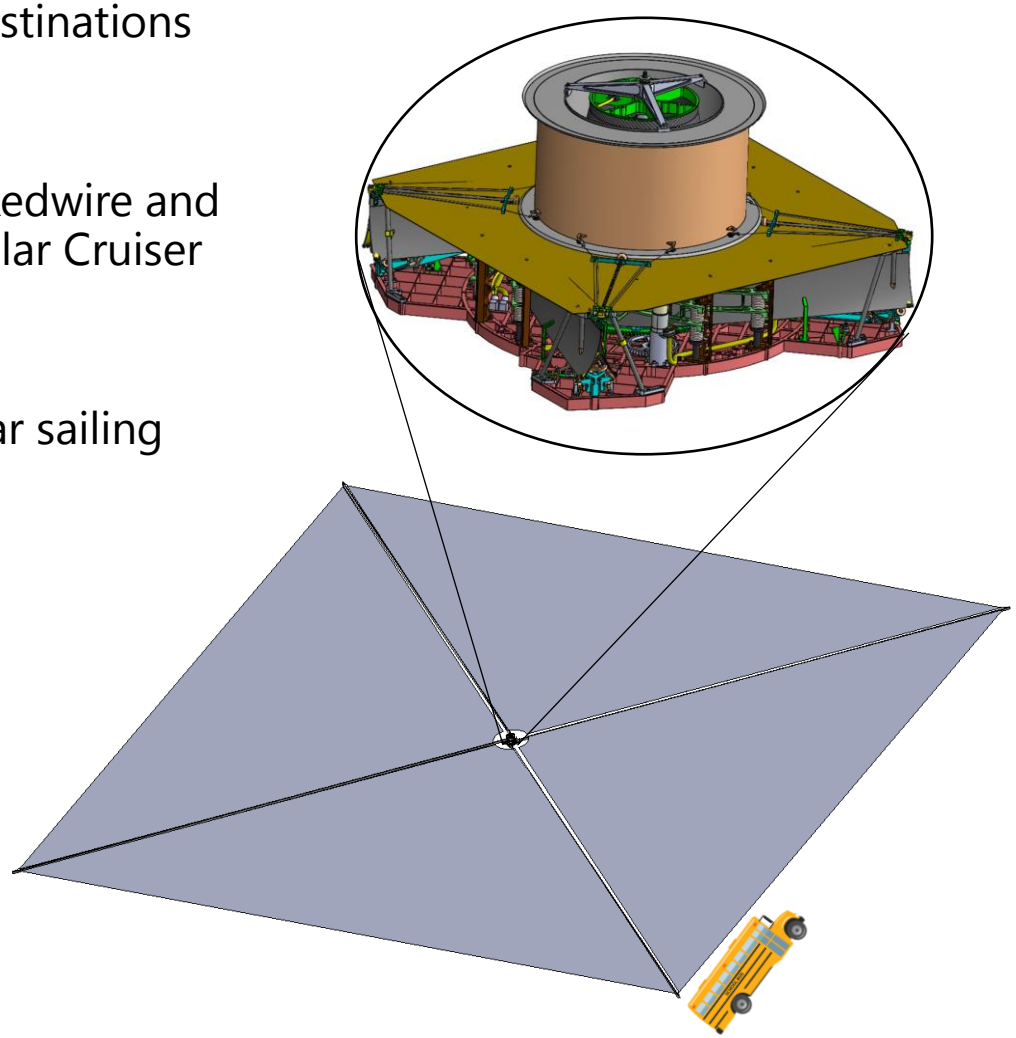
Introduction – Solar Cruiser

- Why Solar Sails? - Enables near term missions to address high priority science questions by enabling access to novel and propulsion intensive destinations including national security uses.

- NASA Marshall Space Flight Center (MSFC), in collaboration with Redwire and NeXolve is developing a 1,653m^2 Solar Sail System (SSS) for the Solar Cruiser Mission to a TRL6

- Solar Cruiser is a technology demonstration mission to enable solar sailing missions on a much larger scale





Introduction – Redwire Longmont, Colorado

Solar Cruiser Specific capabilities

- Uniquely equipped to provide the deployment mechanism
- Space mechanism design
- High Strain Composite design and composite in-house manufacturing

Longmont

- Large aperture deployable structures for RF systems
- Responsive Space Antenna Systems,
- Solar Power Products and Thermal control

Across the Country

- Star Trackers
- Roll Out Solar Arrays – ROSAs
- Additive Manufacturing
- Robotics Systems

Deployment Efforts

Brassboard Deployment

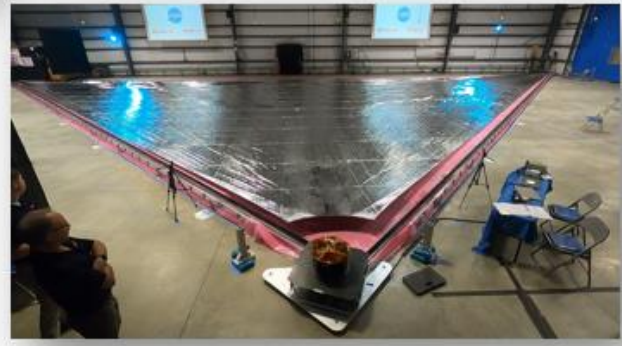
2021
10m²

Prototype Mini Deployment

2022
20m²

Prototype Full Deployment

2022
409m²



Full Scale Test Deployment – Objectives and Description

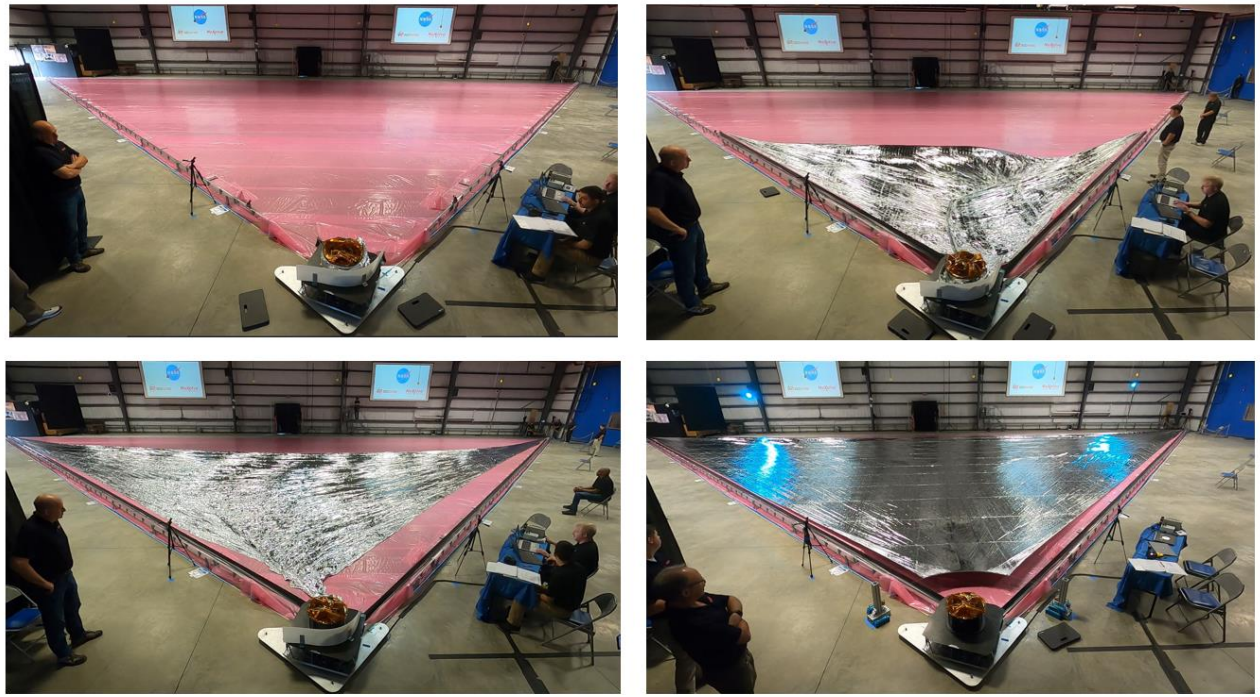
Sail Deployment Mechanism (SDM), Triangular Rollable and Collapsible (TRAC) Booms, and Sail quadrant were all tested in a single ground deployment

Primary objectives

- Demonstrate the operation of key features of the SDM
- Evaluate design concepts for critical Ground Support Equipment (GSE) for full scale sail testing

Test Description

- Full-scale deployment of sail quadrant and 2 adjacent TRAC booms
- Linear force springs for max load condition will be monitored



Deployment Test Background

Why one quadrant?

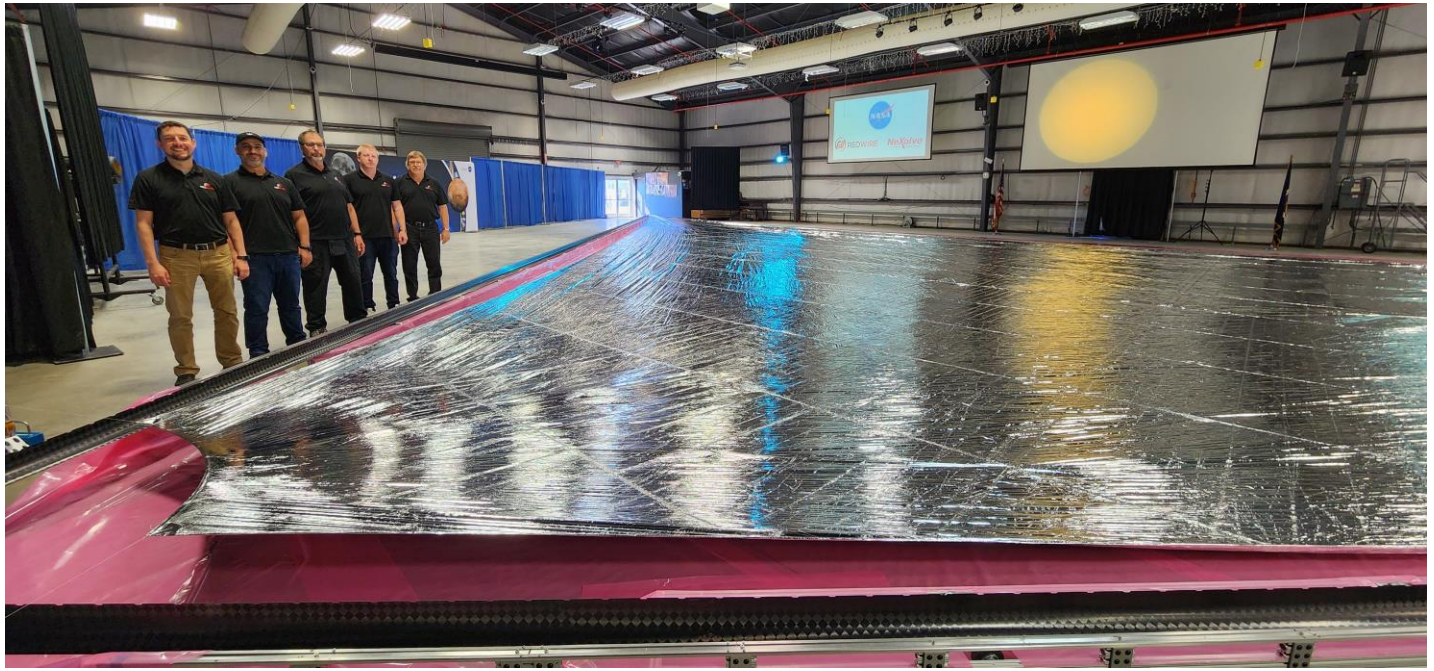
- Cost and test space availability
- Still proving hardware capabilities

Why only two booms?

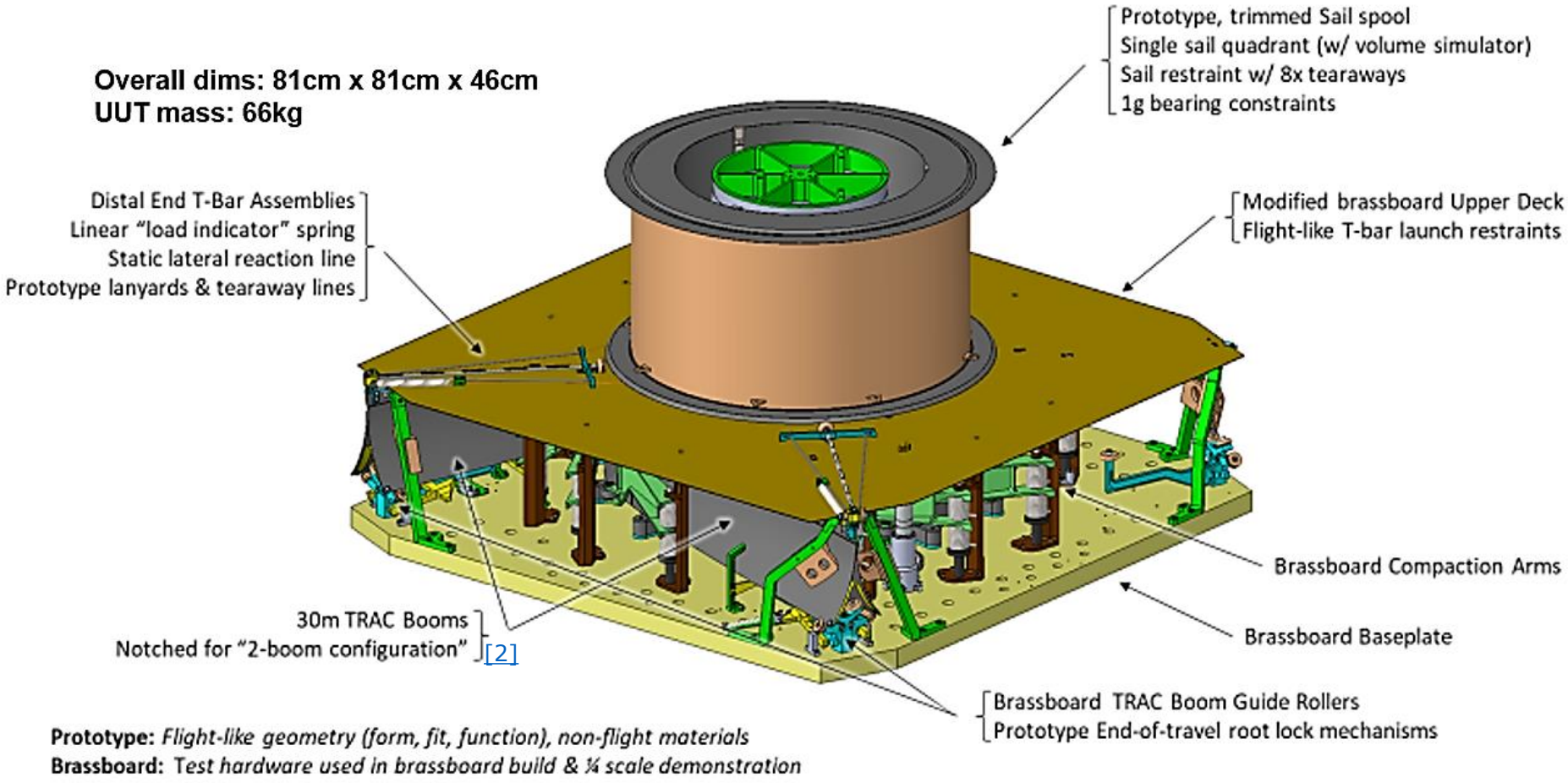
- Cost and test space availability
- Possible to deploy 4 booms in future single quadrant testing

Why Deploy on the ground?

- Cost and simplicity
- Accessibility and visibility



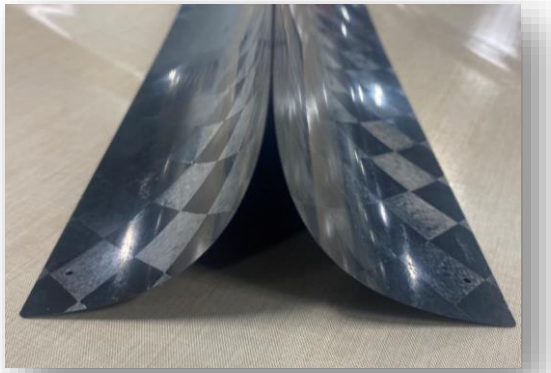
Test Unit -SDM

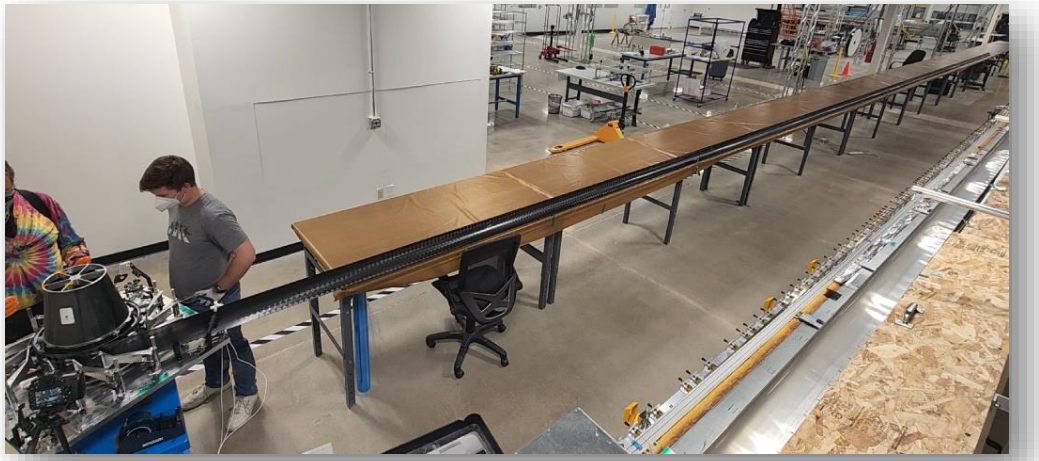


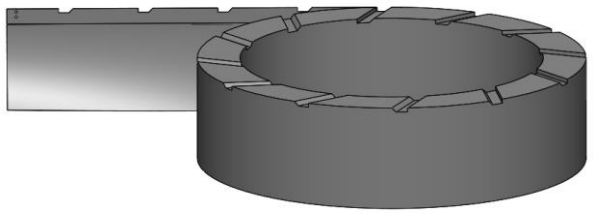
[Patent pending]

TRAC Booms

- Triangular Rollable and Collapsible booms [2]
- 29m long, 12.7cm tall
- High strain composite laminate architecture
- Required custom 30m mold, oven, and layup table to be built on site







CAD Image of Spooled Boom

CAD image of Deployed Boom

Preliminary Tests – Brassboard ¼ Scale Deployment

Objectives

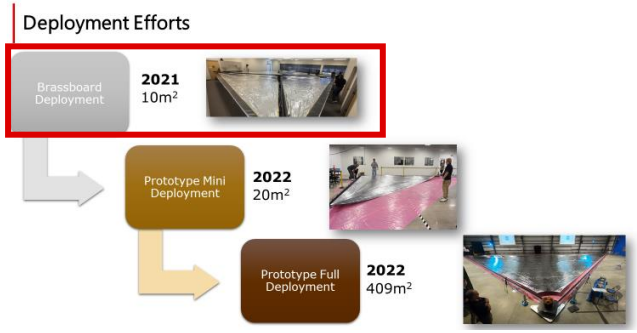
- Learning about kinematics
- Sail deployment behaviors
- Root lock development

Test

- 7.5m booms
- 1 CP1/VDA sail and 3 Mylar
- 1/16th by area sails

Lessons Learned

- Surface-Sail cling effects
- Root Locking of booms is highly desired
- Mylar and CP1/VDA differences
- Complexity of the test setup

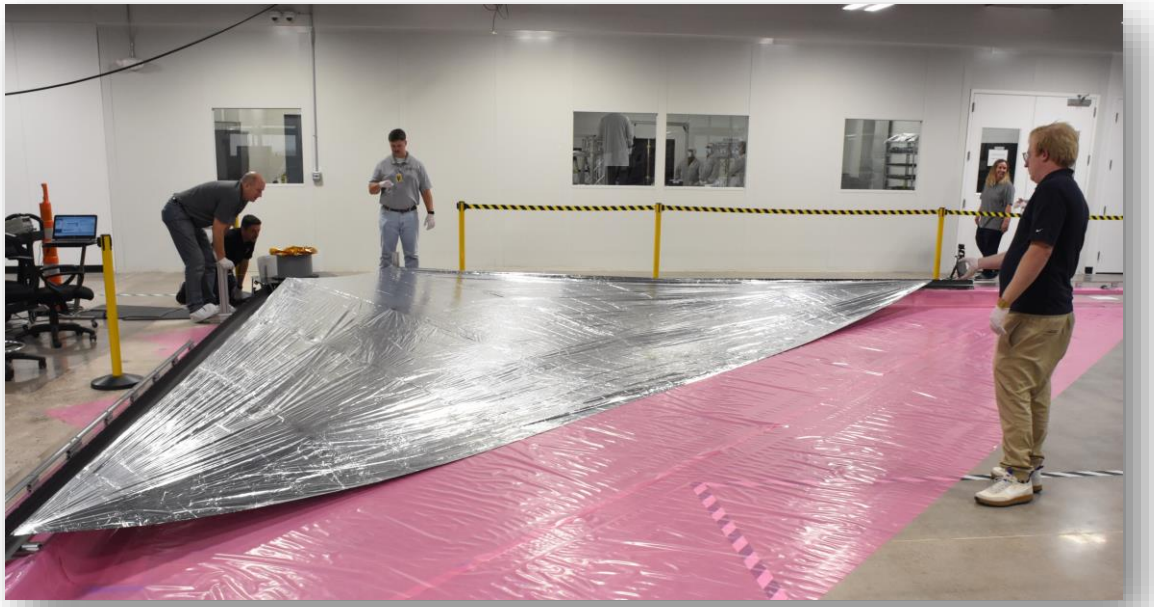


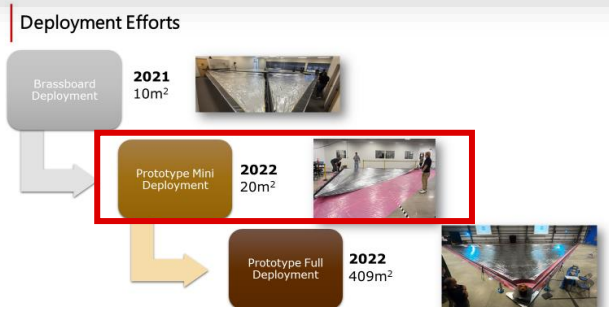
Brass Board ¼ scale deployment video

Preliminary Tests – Quarter scale deployment at Redwire Longmont

Primary objectives

- Ensure SDM functions nominally under deployment loads
- Validate GSE design on a smaller scale
- First testing of tearaway tabs on sail restraint membrane
- Training the team for deployment logistics
- Watching for sail membrane and GSE interactions.





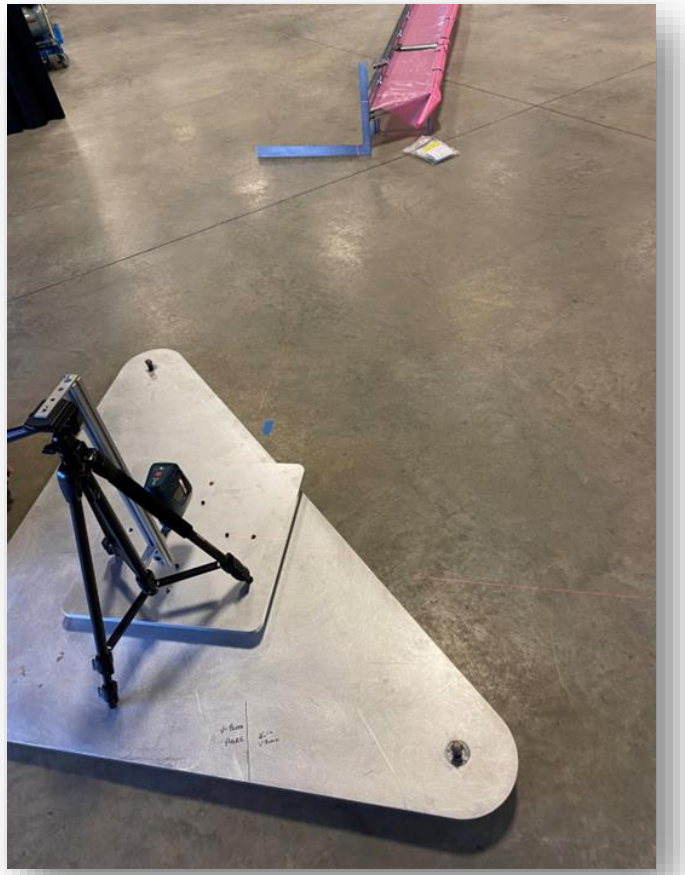
Test Preparation – GSE Boom Support Tracks and SDM Base

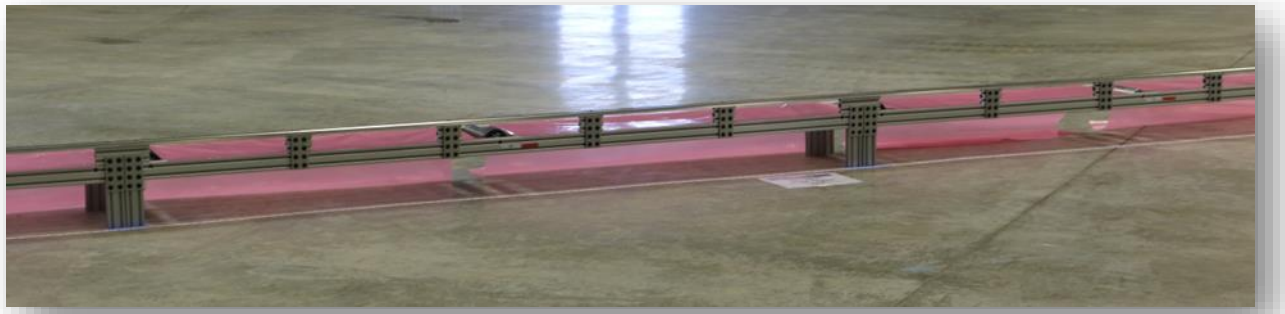
Boom Support Tracks

- Supported the TRAC booms with rollers during deployment
- Roughly 30cm off ground
- Trolley connected to distal end of boom to react loads of sail on ground

SDM Base

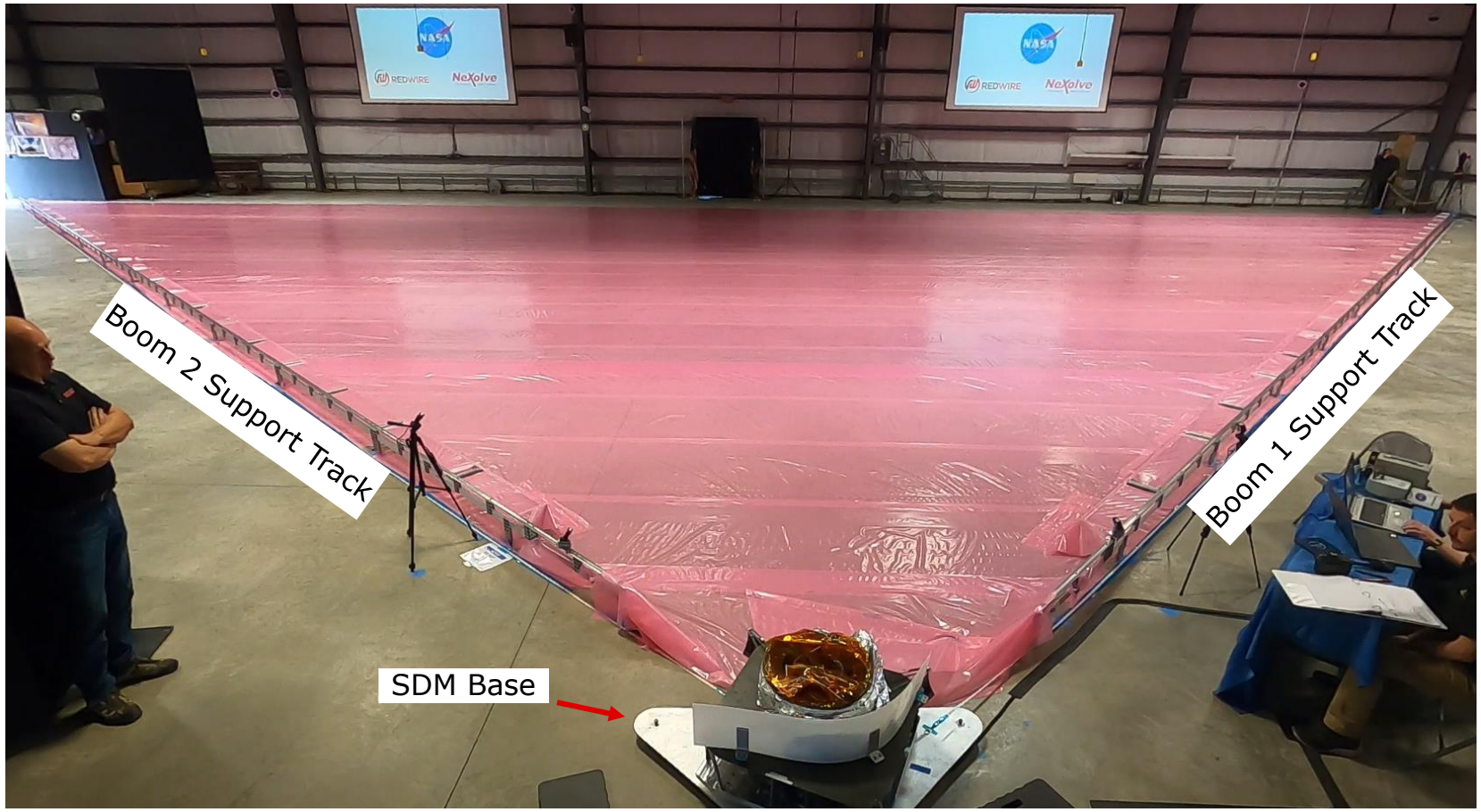
- Supports SDM
- Able to rotate and tilt as needed during deployment and stow





Test Preparation – GSE Floor Covering

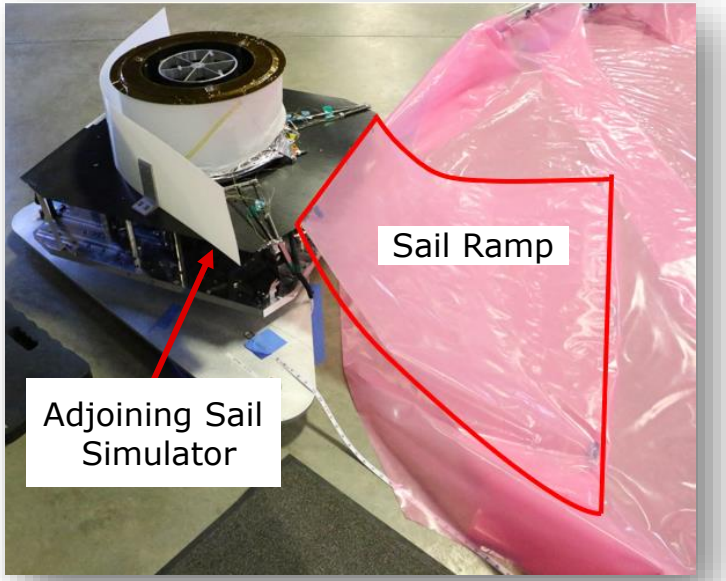
- ULINE Anti-Static Poly Sheeting was selected as the low-friction ground covering
- Trade study concluded deploying on the ground was the most cost effective and simple
- Massive “air hockey” table concept was considered

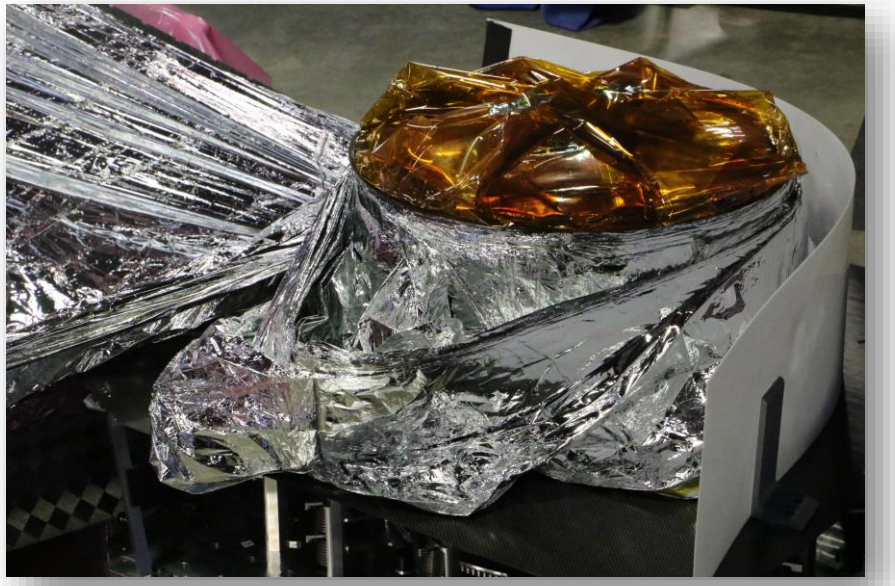


Additional GSE
Sail Ramp and Adjoining Sail Simulator

- Sail Ramp prevented the sail from folding over itself on the ground
  - Only necessary when deploying in 1g

- Adjoining Sail Simulator kept the sail from falling off the back edge of the SDM as it unwinds
  - The adjacent sails will accomplish this in four quadrant deployments



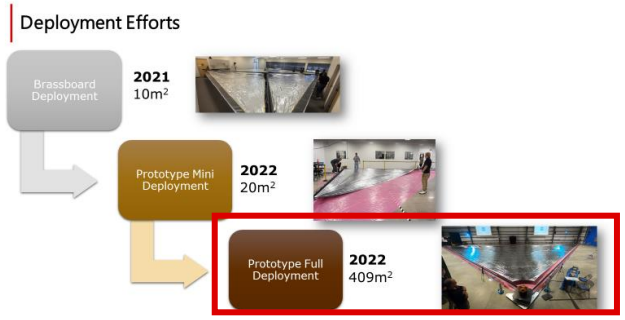


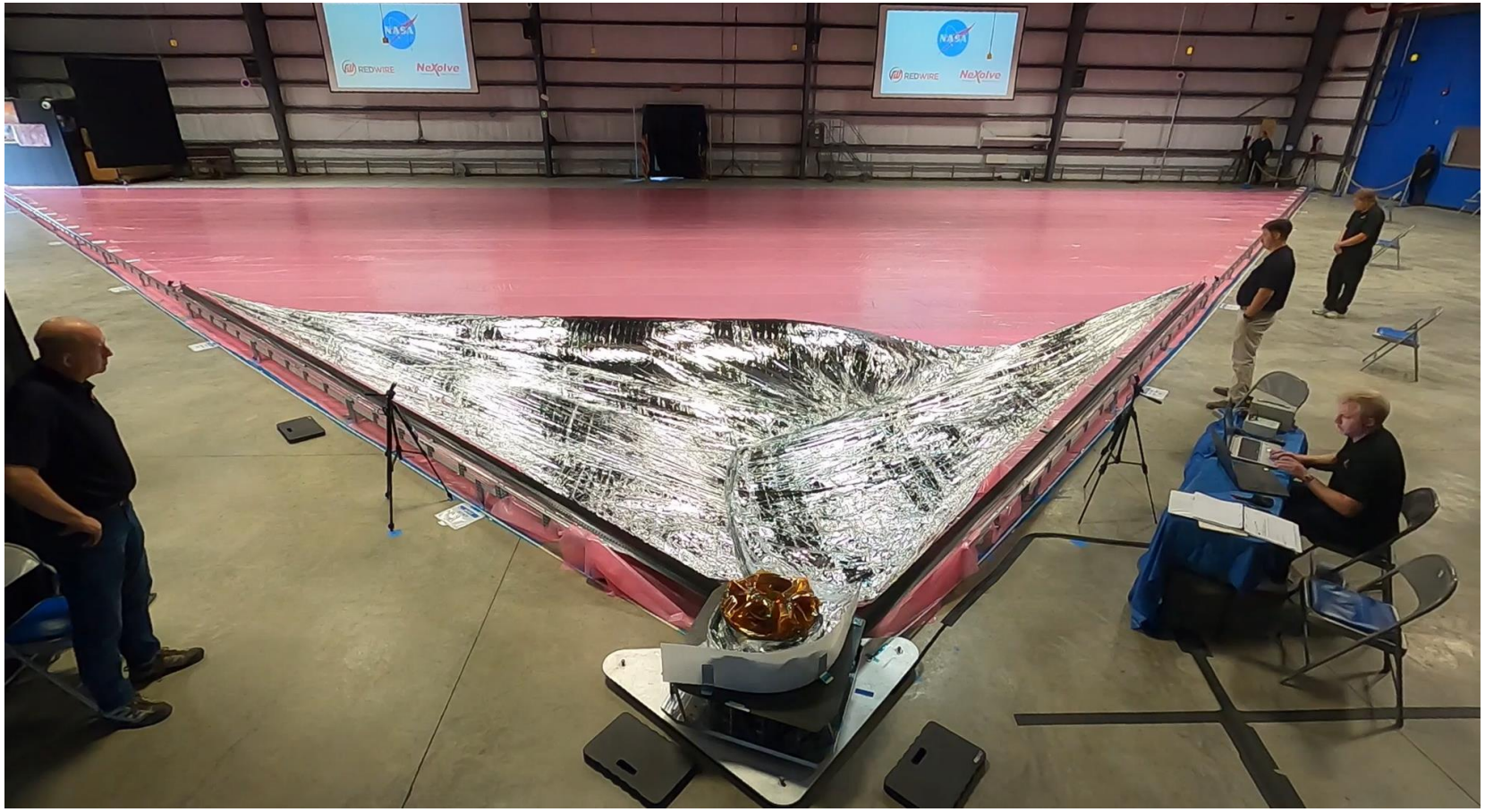
Full-Scale Quadrant Deployment Test

- Planned for 2 weeks test on site at NASA Marshall Space Flight Center
- Finished in 3 days thanks to a cohesive team effort!

Deployment Test: Day 1 - October 12th 2022

- Began first motion
- Tearaways
- Sail Snag Mitigation
- Monitoring Sail induced loads during deployment



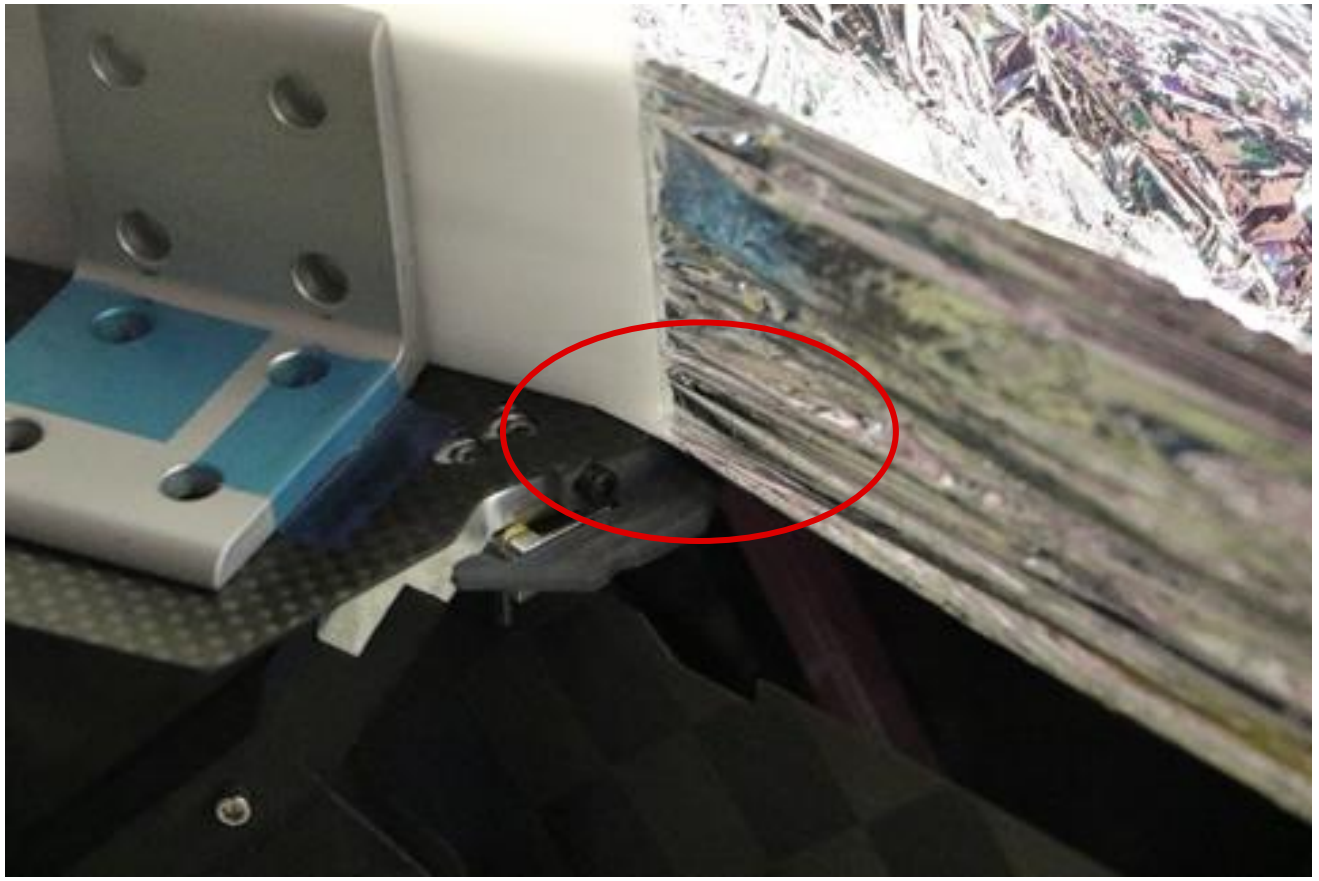


Deployment Test: Day 1 – Tearaways

- Tearaway tabs hold the sail restraint membrane in place during assembly
- In the first 2cm of deployment, a latch is released to pull the tearaways
- Tearaways successfully functioned on every test opportunity

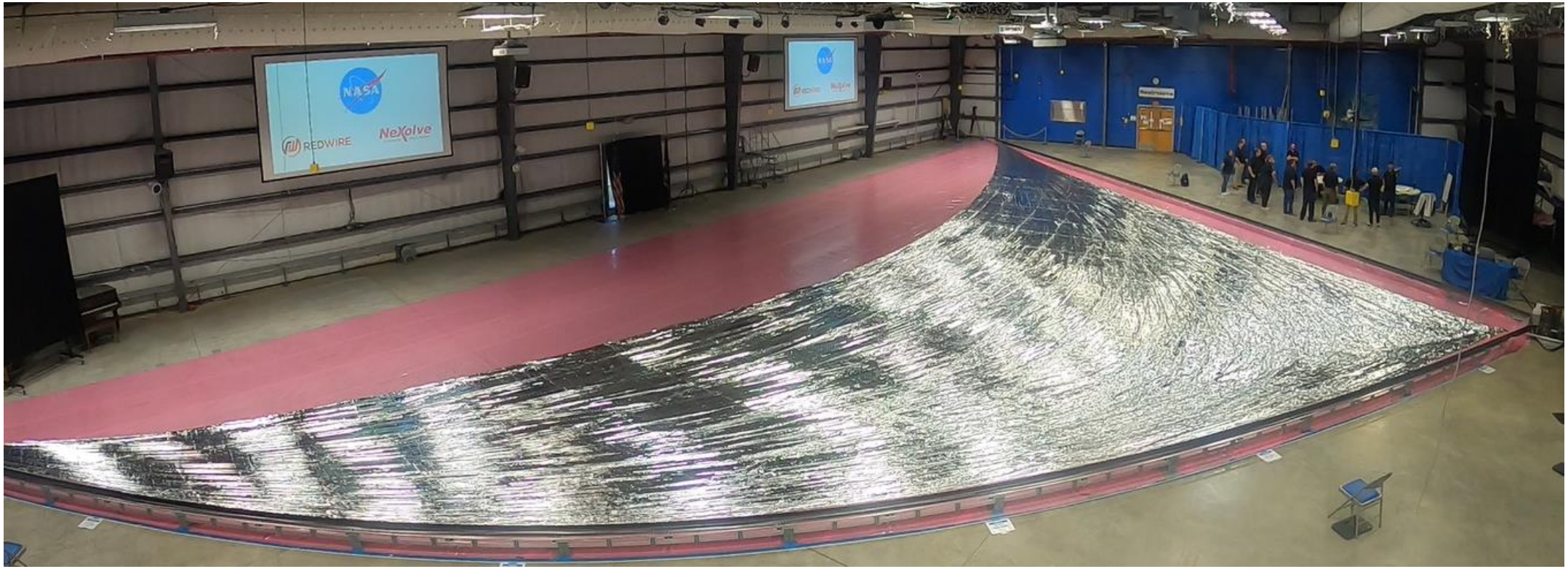
Deployment Test: Day 1 – Sail Snag Mitigation

- The sail traveled under the leading edge of the Adjoining Sail Simulator in first 3m of deployment
- GSE was extended to below the upper deck to mitigate this sail tearing risk



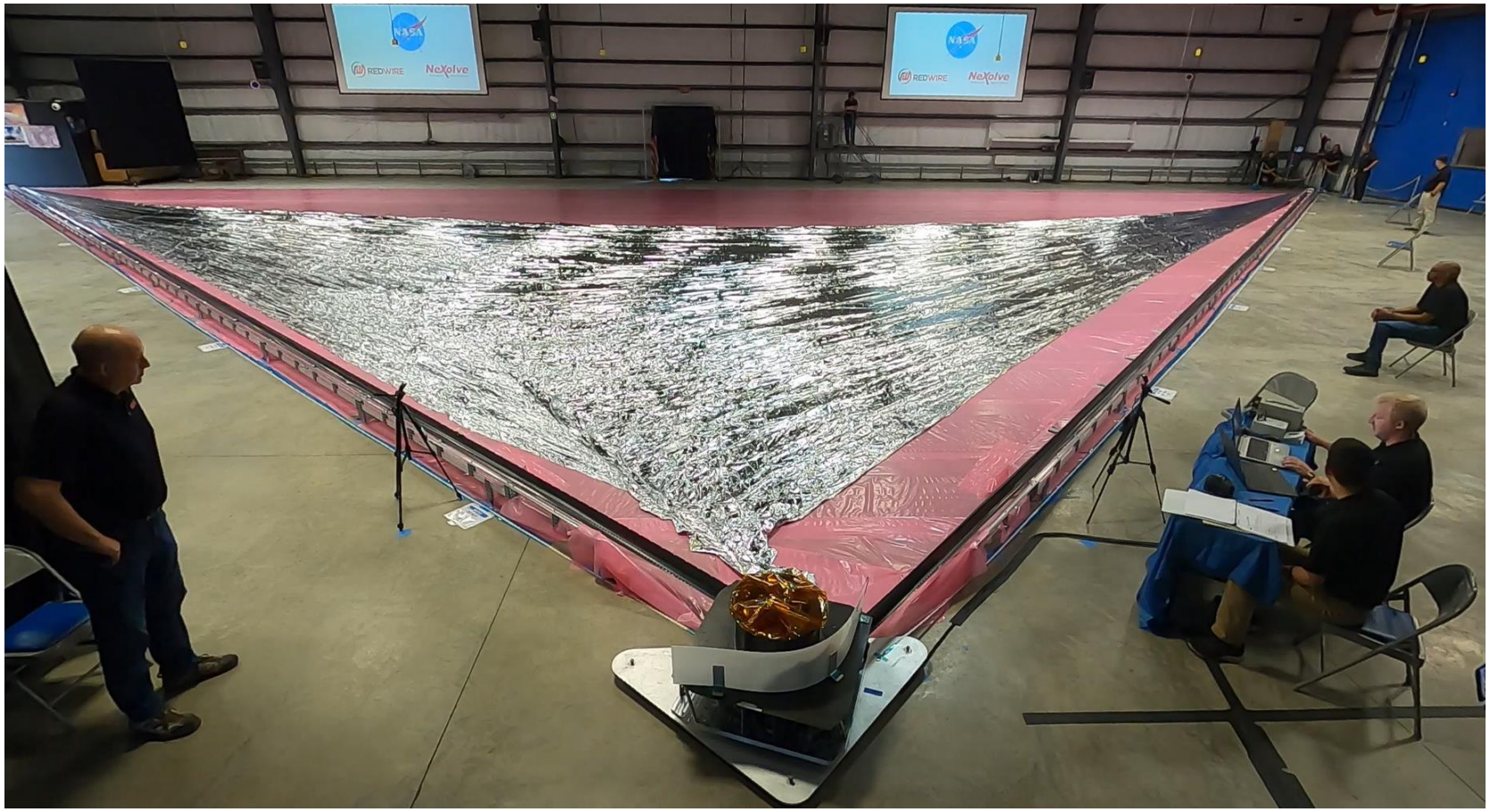
Deployment Test: Day 1

- Outside of snagging mitigation, the deployment went nominally
- Completed 27m of boom deployment in the first day

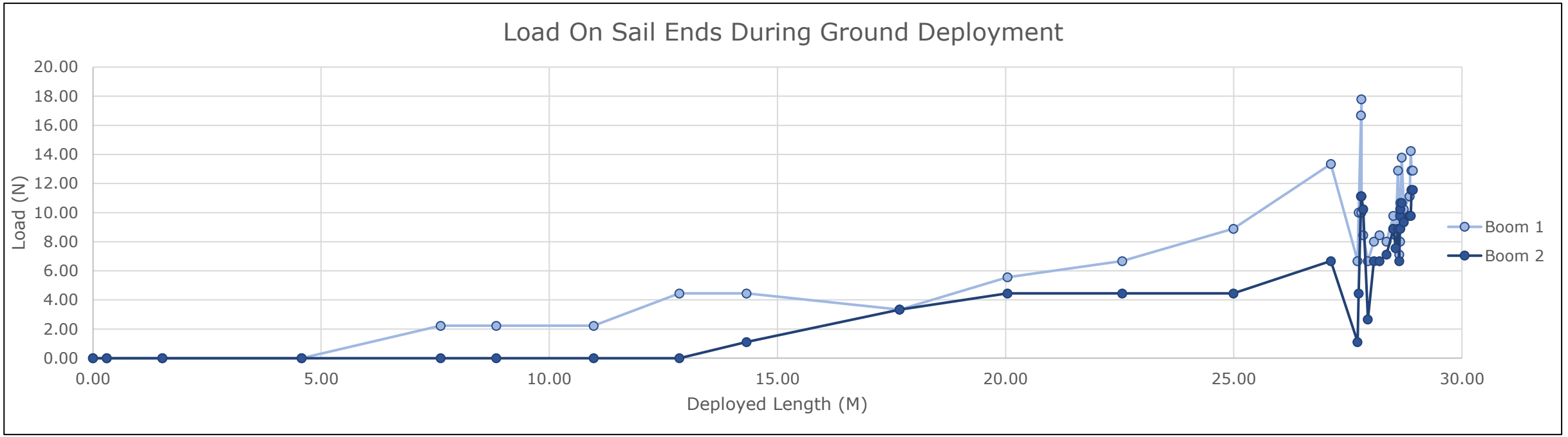


Deployment Test: Day 2 - October 13th 2022

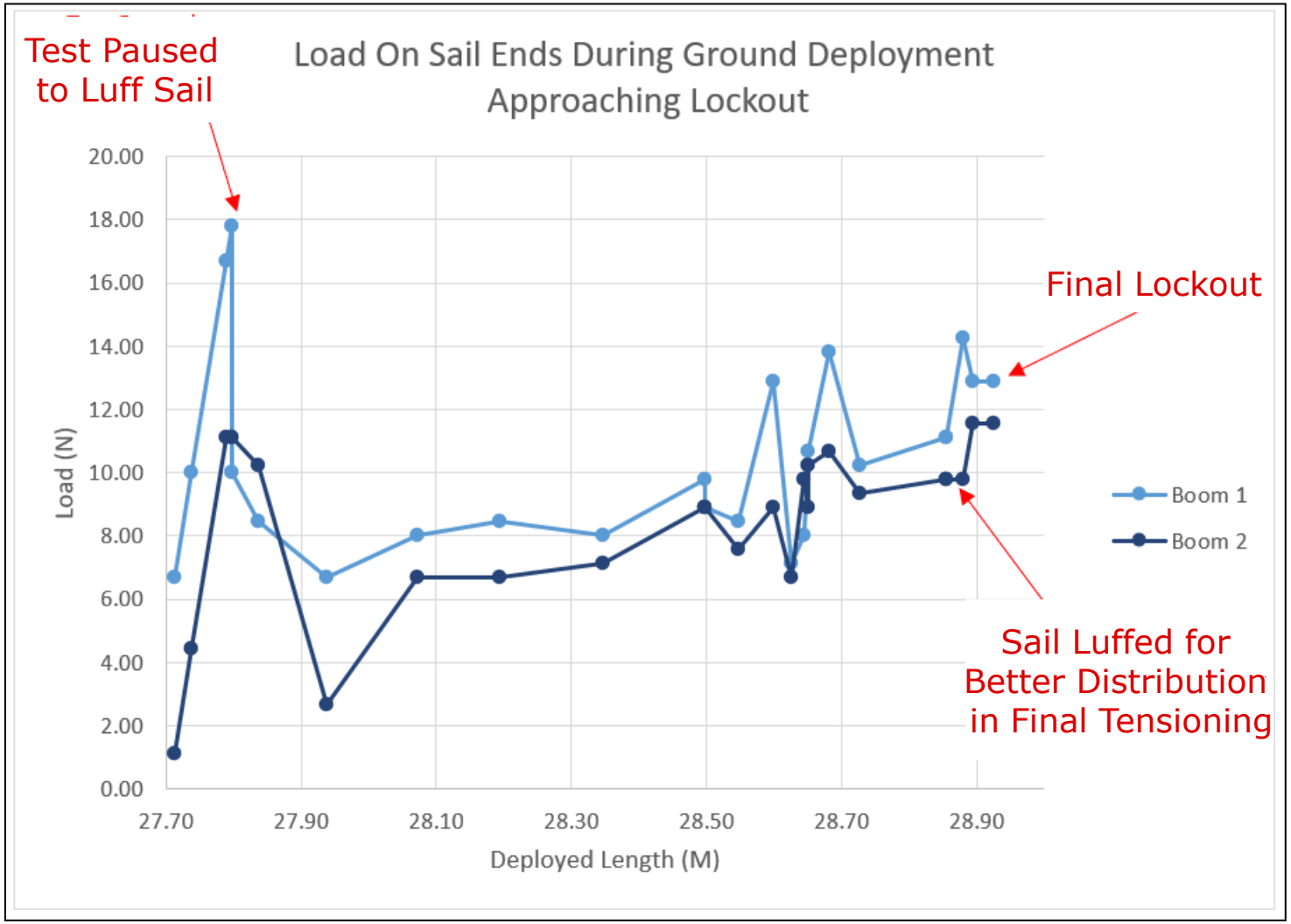
- Continued deployment
- Distal Connection repair
  - Sail to boom connection failed after first movement
- Continue Monitoring Sail induced loads
- Sail “Luffing” activities



Monitoring Sail Induced Loads

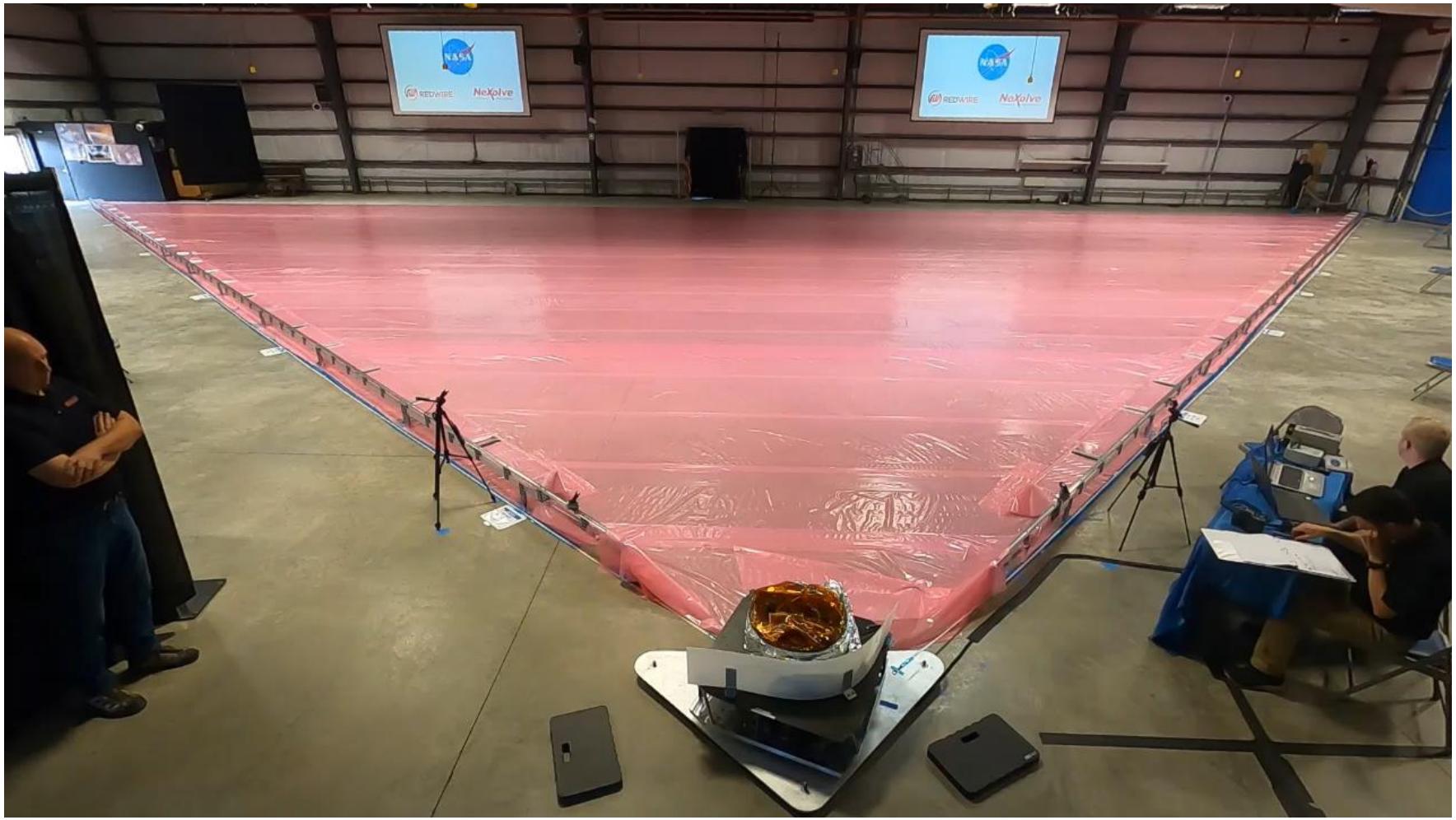


Monitoring Sail Induced Loads – Approaching Lockout



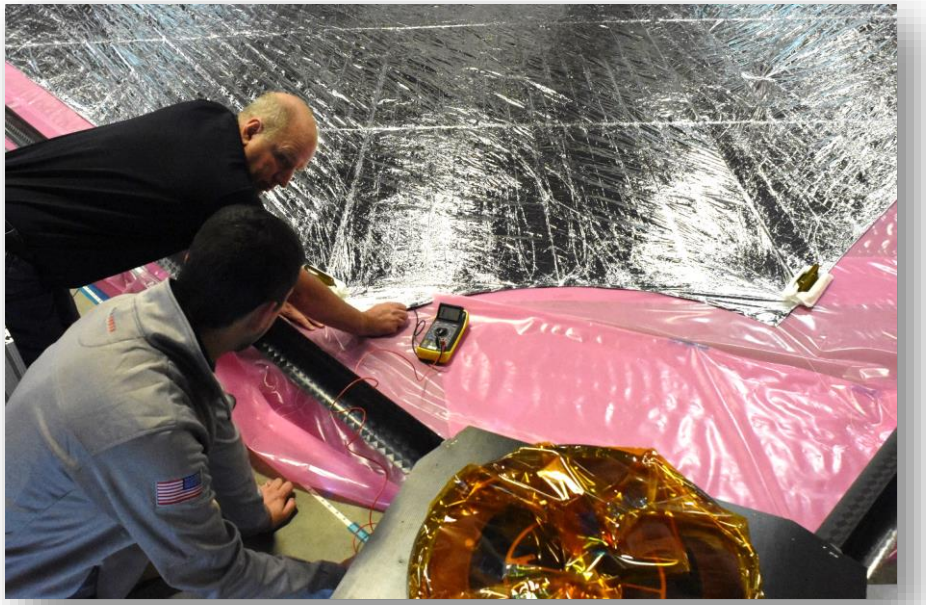
Deployment Test: Day 3 - October 14th 2022

- Tensioning
- Photos and Measurements taken



Deployment Test: Day 3

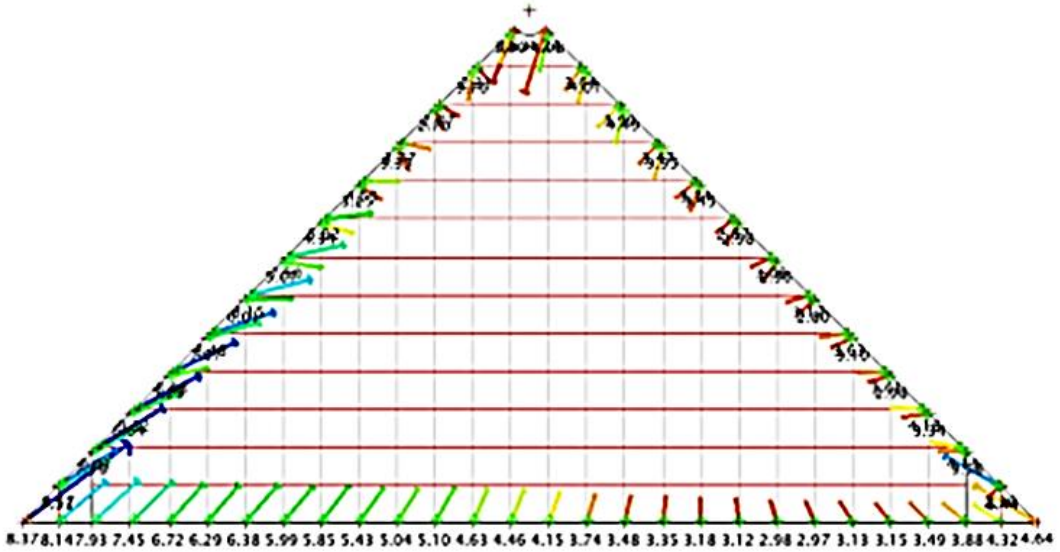
- Electrical conductance measurements taken
- Tensioning
  - Cross tie simulators hold the root of the sail in the same position as the adjacent sails would in a 4 quadrant system



Post Deployment Activities

- VIP tours given and Media day hosted to build excitement for the Solar Cruiser Mission

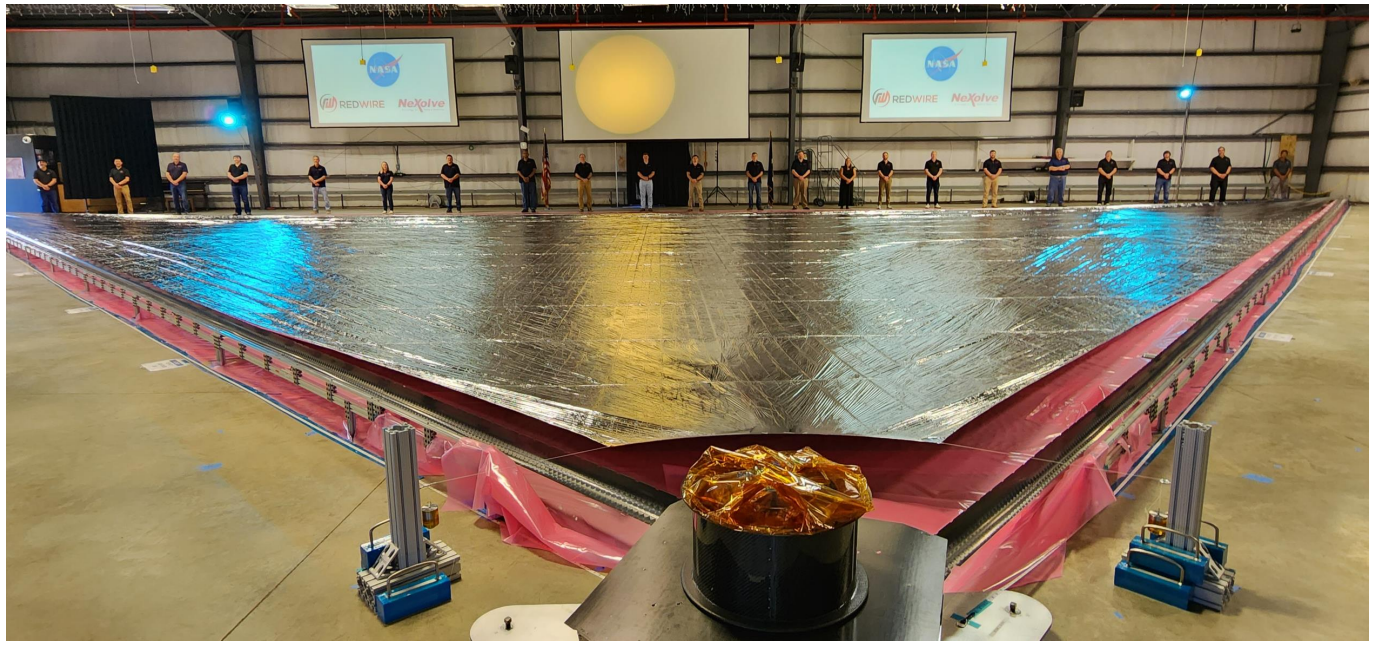
- Full Quadrant Measurements gave valuable insight in the as designed and as deployed sail quadrant that will help inform future sail production



Vector plot of Sail from Laser Tracker Measurements

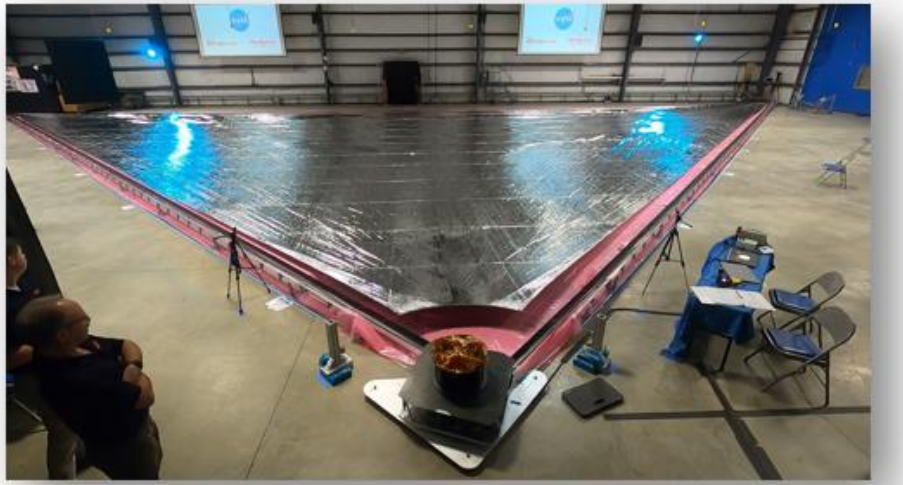
Conclusion and Key Takeaways

1. Designing the deployment key objectives to be in scope with gravity and program constraints
2. MGSE design for boom offloading
3. Sub-Scale Testing and building to a large test
4. Sail to Ground interfaces were important
5. Sail size and ICD impacts were captured
6. All of the above lessons learned will help to inform the next sail deployment in 2024!

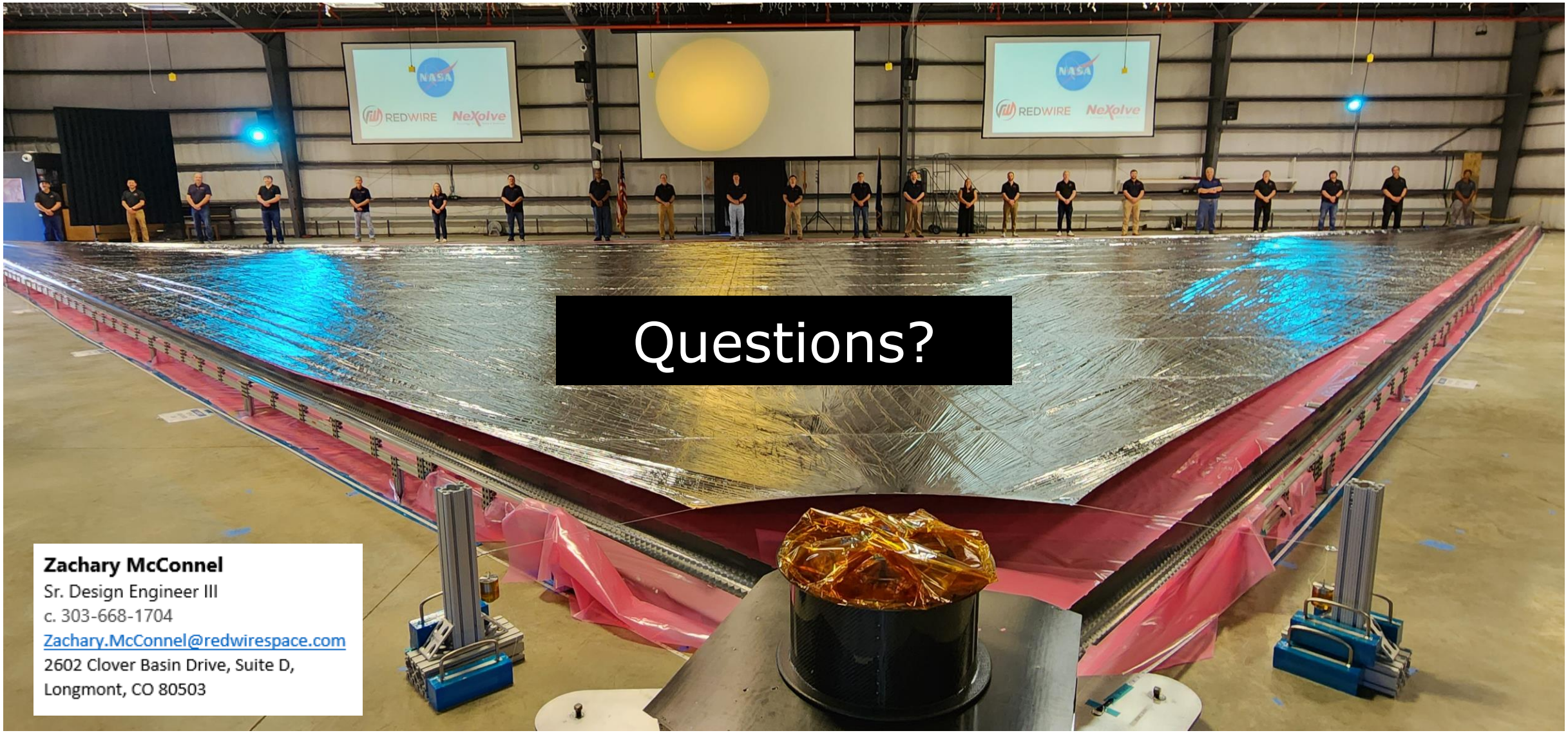


Post Deployment Efforts

- Prototype Full Deployment — Oct 2022
- TRL6 Hardware Development — Oct 2022 - May 2023
- TRL6 Hardware Build and Test — May 2023 – Oct 2023
- TRL6 Sail Deployment — Nov 2023 - Feb 2024



Supporting the team to enable a flight by 2028



Questions?

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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.

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!