6th International Symposium on Space Sailing (ISSS 2023), New York, USA, 5-9 June 2023

Development of a Flight-Like Solar Sail Quadrant for NASA's Solar Cruiser

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Abstract

In 2021 and 2022, NeXolve successfully collaborated with their NASA Solar Cruiser (SC) partners, NASA Marshal Space Flight Center (MSFC) and Redwire Space, to design, develop, fabricate, package, and test a flight-like Prototype Sail Quadrant (SQ) designed for NASA's Solar Cruiser solar sail mission. The SC solar sail system includes 4 right triangular quadrants, deployed radially from a central spool by 4 equally spaced deployable booms. The total SC sail area is 1653 m^2, with each quadrant having a design area of 413.25 m^2. NeXolve was responsible for the Prototype SQ design, development, manufacturing, and packaging as well as supporting a deployment test of the Prototype SQ at NASA MSFC. NeXolve developed all manufacturing process and mechanisms to support the Prototype SQ manufacturing flow [1] which enables NeXolve to design and build solar sails with a larger footprint than the facility in which they are manufactured. This is successfully accomplished by a delicate balance of sail fabrication and sail folding, simultaneously. The sail is made from NeXolve's 2.5-micron thick CP1 [2] polyimide film with a 1000Å aluminum coating. The Prototype SQ has surface features including edge and corner reinforcements for structural loading, electrical jumpers for continuity, ripstops for tear-propagation, and seams that join the 60-inch-wide rolls of material together. These features are installed by a resin bonding process developed by and propriety to NeXolve. Following sail manufacturing, the Prototype SQ was spooled and packaged at NeXolve and delivered to Redwire Space.

Keywords: NeXolve, Solar Cruiser, Solar Sail, CP1, Large Deployable Thin Film Structures

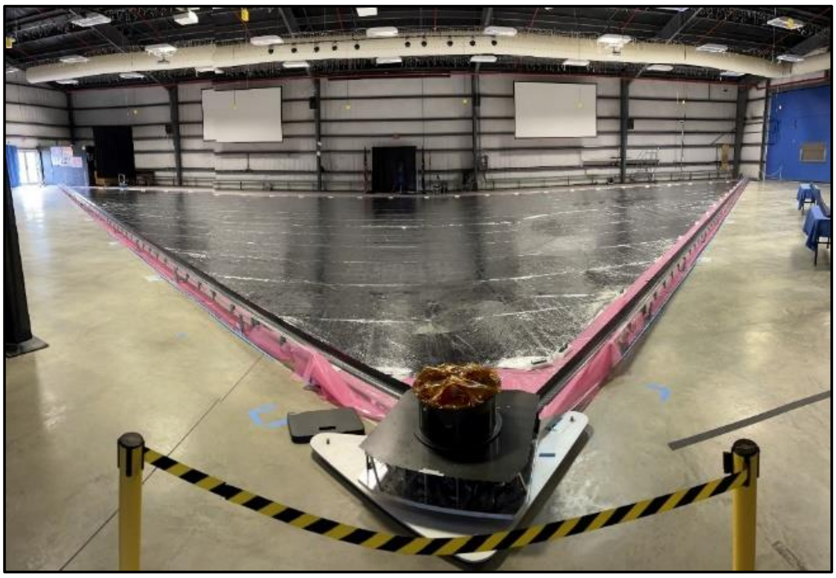

Figure 1. SQ deployed at NASA MSFC building 4316 (non-tensioned)

1. Introduction

This paper outlines the successful development of the Prototype Sail Quadrant (SQ) for NASA's Solar Cruiser mission. The Prototype SQ matches the design accepted by NASA at the Sail Quadrant Membrane Assembly Critical Design Review (SQ MA CDR) in October of 2021. The full design is a 4-quadrant architecture consisting of 4 identical right-triangular quadrants. Each quadrant is approximately 413 m^2 made from NeXolve's 2.5-micron thick Colorless Polyimide 1 (CP1) film with a 1000Å Vapor Deposited Aluminum (VDA) coating, with the full size 4-quadrant structure totalling 1653 m^2. Included in the quadrant design are corner reinforcements, edge reinforcements, ripstops, seams, and electrical seam jumpers. NeXolve, in partnership with MSFC and Redwire Space, led the efforts for the design, development, manufacturing, and packaging of the SQ as well as the 4-quadrant solar sail architecture. This design and development effort included SQ requirements development, sail membrane thermal and structural analysis, key enabling infrastructure and GSE development, manufacturing process development and documentation, key techniques and procedures that are essential for the quality and accuracy of the SQ fabrication, as well as final verification, testing, and shape measurements.

2. Development of the Prototype SQ Requirements

NeXolve provided significant support and key inputs to the development of Solar Cruiser SQ requirements, SQ design, and analysis of Solar Cruiser Sail Quadrants (SQ)s. Typically, requirements would have "flowed down" to NeXolve but, based on the uniqueness of this development, NeXolve worked with Redwire and NASA to define the set of flight SQ requirements and verification plans, and presented them at SQ Membrane Assembly (MA) Critical Design Review (CDR) in October of 2021. Following SQ MA CDR and the closure of several related Request for Action (RFA), Redwire provided NeXolve with the Authority to Proceed (ATP) into flight SQ manufacturing, following the completion of the Prototype SQ [3]. However, the flight program for Solar Cruiser was not confirmed at a key decision point due to programmatic constraints. The SQ Requirements including system performance, interfaces, environments, and key constraints were presented at the SQ MA CDR and are summarized in Figure 2.

SQ Requirements (Assumed)

Architecture
- 4 right triangular sail quadrants (SQ) oriented symmetrically about a centrally located sail spool
- 1-m diameter center hole
- SQ diagonal edge spacing equal to ¼ sail spool circumference
- Outer corners of sail (2) are connected to distal end of respective TRACBooms
- Inner corners of sail (2) are connected to adjacent inner corners via a "cross tie"
- Sail area: 1653m2.

Sail features / materials
- Sail: <3 micron CP1 with ~1000Å VDA on 1 side
- Seams: resin bonds
- Rip-stop: TCP1, 60 inch spacing
- Edge reinforcements (4): 1-mil 0.5" wide Kapton tape, ¾" wide TCP1 covers resin bonded to sail
- Corner reinforcements (4): 2-mil Kapton film with PSA, ¾" wide TCP1 covers resin bonded to sail, aluminum grommets
- Jumpers: sail film + ¾" wide TCP1 covers, resin bonded to sail
- Catenaries (if included):
    - 1-mil 0.5" wide Kapton tape, ¾" wide TCP1 covers resin bonded to sail, circular profile with 3% depth
    - Outer edge (1)
    - Diagonal edge (2)
    - No catenary on inner edge
- Cross tie: length is ¼ sail spool circumference, material is tbd
- RCD Deployment Mechanism: 10 per corner, <22cm x 22cm (there are more RCD requirements)
- LISA Photovoltaic cell: 19.5cm x 31cm CIGS, 1 per corner (there are more LISA PV requirements)

Figure 2. Initial SQ requirements

3. Analysis Completed for the Development of the Prototype SQ

The main objective of our analysis was to support the decision for not using catenaries. It became apparent that catenaries would not be beneficial for this sail because of the corner tensions and stresses. We also used analysis to ensure we meet our strength and stress requirements for the non-catenary model we're moving forward with.

Initially we thought we would use catenaries to tension the membrane, however our analysis showed the loads for catenary tensioning at this size become prohibitive. After we decided to go with the non-catenary model, we focused our analysis on the four-corner tensioning approach along with the reinforcements and features required to react the loads in the corners. For NEASCOUT, the sail was monolithic, but because of the requirement for a hole to be cut into the center of the sail for Solar Cruiser, and the need to fabricate this in a quadrant architecture due to its size, we developed a unique design feature to enable it to behave like a monolithic sail [3]. These features are called cross ties and they aren't connected to the space craft but to each adjacent sail instead.

As our level of analysis began to mature, we added solar sail features to our model. This includes 1-mil thick, 0.5"-wide Kapton tape acting as an edge reinforcement along with a specifically designed corner reinforcement (Shown in Figure 3) including a stainless-steel stiffener, VDA-coated Kapton for loading, electrical jumpers for surface conductivity, and a grommet for a connection point to connected to either a crosstie or a distal end spring to be attached to the booms. This corner reinforcement was loaded with a distributed load from the location of the grommet the sail will be pulled from to simulate on-orbit film stress fields across the quadrant. The loading value input is based on the axial capability of the TRAC-boom provided by Redwire Space which was determined to be approximately 3 Newton's for on-orbit conditions.

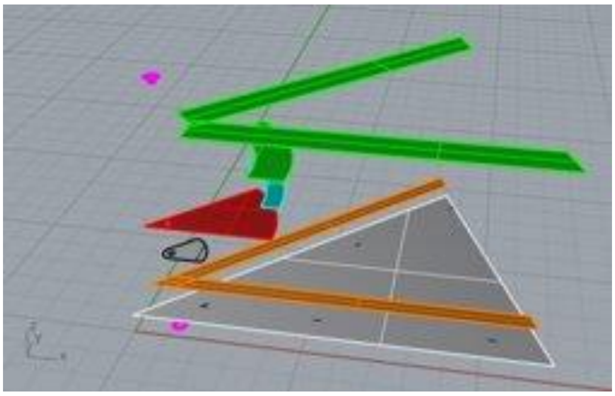

Figure 3. Sail corner features stack-up (side view)

4. NeXolve's Manufacturing Facility

The flight scale footprint of the NeXolve solar sail fab and fold mechanism was established along with the placement of all Ground Support Equipment (GSE) elements including the Fab and Fold table, the corner Sub-assembly tables, a sail spooler, and the marking gantry. Figure 4 is a photo of NeXolve's solar sail manufacturing facility located at 355 Quality Circle in Huntsville, AL. This facility is a 12,000 sq. ft. cleanroom compliant with ISO Class 7/10K class cleanroom standards and requirements. The photo also shows the Z-folded Prototype SQ on the edge of the fab and fold table. Although tweaks to the fab and fold table continued throughout Prototype SQ fabrication, as part of the vetting process, the mechanisms were used effectively to support prototype SQ fabrication.

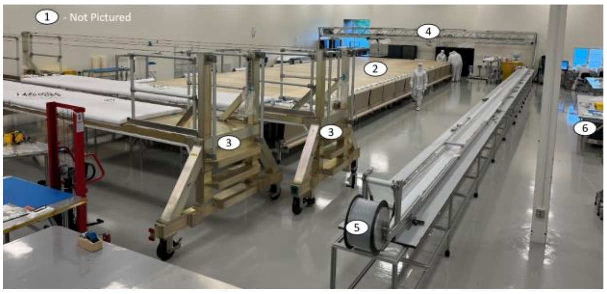

Figure 4. NeXolve's cleanroom manufacturing facility and key enabling GSE

5. Key Enabling Ground Support Equipment (GSE) for SQ Manufacturing

1. The Eastman Cutting Table (#1 in Figure 4 not pictured) is a CNC machine with cutting, punching, and marking capabilities. NeXolve has used the Eastman Cutting Table (ECT) for many different applications as it is a very versatile piece of equipment. For Solar Cruiser, the sail film panels that form the corner subassemblies (SA1 and SA14 pictured in Figure 5) are produced.
2. The Fabrication and Folding (F&F) Table (#2 in Figure 4) is arguably the most important piece of GSE for sail manufacturing. This table contains the rolls of sail material, the work surface where the SQ midspan (SA2 thru SA13 in Figure 5) is formed and features are installed, the backer removal system, the transport system, where the corner subassemblies are integrated to the SQ midspan, as well as the SQ folding area.
3. The working gantries (#3 in Figure 4) are the GSE that enable the manufacturing staff to reach the work surface and execute the tasks to build the SQ.
4. The Marking Gantry (#4 in Figure 4) is a large bridge-like structure that spans over the F&F Table and houses an automated arm that is equipped with a sail marking pen that marks sail feature locations.
5. The Spooling Mechanism (#5 in Figure 4) allows the SQ folded stack to maintain the right amount of compression while being wrapped onto the spool with extreme accuracy.
6. The corner subassembly fabrication tables (#6 in Figure 4) allow for the corner subassemblies to be built in parallel to the SQ midspan. This was necessary in order to install Reflectivity Control Devices (RCDs) and Lightweight Integrated Solar Array (LISA) panels on each of the (8) corner subassemblies of the full sail. The RCDs and LISAs were descoped from the program in April of 2022 due to programmatic cost restraints and risk mitigation.

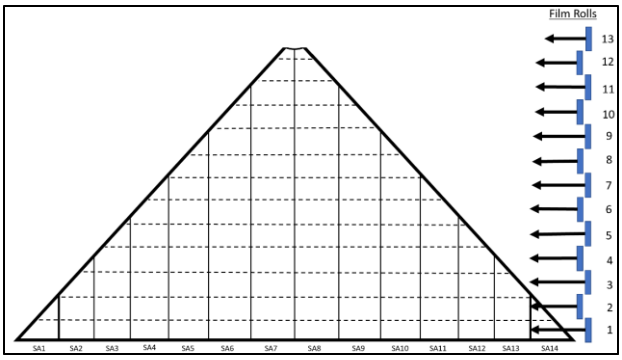

Figure 5. Sail quadrant sub-assembly layout.

6. SQ Manufacturing Flow and Manufacturing Processes

The SQ is broken up into 14 subassemblies (SAs) numbered 1 through 14 from left to right, shown in Figure 5. Each subassembly is approximately 10 feet wide so that it can fit on the 15 feet wide work surface of the F&F Table. The corner subassemblies are SA1 and SA14, and the SQ midspan is made up of SA2 through SA13. The SQ contains corner reinforcements at each of the 4 corners (2 inner corners, 1 on SA1, and 1 on SA14), edge reinforcements with covers along the perimeter of the SQ, seams joining the 60"-wide rolls of sail film together (the dotted lines shown in Figure 5), ripstops that are also placed 60" apart from each other but perpendicular to the seams, and electrical seam jumpers for surface continuity and electro-static discharge (ESD) bleed off. The base material sail film is NeXolve's VDA-coated CP1 polyimide film which is produced on a backer. This backer allows the manufacturing staff to be able to handle such thin film with precision, and it allows the resin bonding process to be possible. The edge reinforcements are made of 0.5" wide Kapton tape to act as a reinforcement but also a load bearing path around the perimeter of the SQ. The edge reinforcements are also covered with a polyimide film to encapsulate any potential adhesive leach out over time or in the harsh environments of space, as any uncovered adhesives have proven to be extremely damaging to these films. The seams, ripstops, and edge reinforcement covers are made from NeXolve's Toughened CP1 film (TCP1) which is the base uncoated CP1 material infused with PTFE for tear resistance and durability.

The SQ corner subassemblies (SA1 and SA14) are manufactured in parallel to the midspan on the corner subassembly fabrication tables. This was originally planned to accommodate the installation of RCDs and LISAs in each of the (8) corner subassemblies of the full sail. When the RCDs and LISAs were descoped from the program, NeXolve elected to continue to fabricate the corner subassemblies in parallel due to consistency and that it had no negative effect on production schedule. The corner subassemblies are made up of (2) panels produced on the ECT and transported to the fabrication table. These panels are then seamed together with CP1 resin produced by NeXolve by utilizing a NeXolve proprietary process of an adhesiveless bonding technique. This bonding technique can also be thought of as a resin weld or polymerization process. This same process is also used to install the ripstops, to prevent tear propagation, which are perpendicular to the already-installed seams and are also spaced 60" apart. The corner subassemblies also contain corner and edge reinforcements. The corner reinforcement construction is shown in Figure 3 utilizing a stainless-steel plate (grey part in Figure 3) and VDA-coated Kapton doubler (red part in Figure 3). These reinforcements provide the additional support needed for the added loads introduced by the radially deployed TRAC booms that are connected through a grommet embedded in the corner construction.

The SQ midspan is fabricated completely on the F&F Table from the time the material comes off the film rolls until the sail gets z-folded for spooling. The process begins on the "feed out" side of the table shown in Figure 6 where the sail film is introduced to the F&F table (Figure 7) as it comes off the material rolls shown. The film is then brought out onto the table surface by hand and laser aligned to be parallel to one another. When the material is aligned and on the work surface, the rolls are then seamed together using TCP1. After the seams have been installed, the sail is then marked by the marking gantry. The marking gantry is first aligned to the roll 1 portion the subassembly (the bottom edge of the SQ triangle) and will mark edge lines, fold lines, and ripstop locations. The marking gantry will then be positioned on the roll 2 portion of the sub assembly by using fiducial marks made in the previous step so that it can "lock" into the correct position. This process is repeated until the whole sub assembly has been marked. The edge reinforcements, edge reinforcement covers, ripstops, and seam jumpers are then installed, also by using CP1 resin and NeXolve's adhesiveless bonding technique, based on the markings to complete the build of the subassembly. All features installed to the midspan are the same as the features installed to the corner subassemblies. All bonding steps and feature installation occurs while the film is still on the backer.

Figure 6. The "feed out" side of the F&F table

Figure 7. The F&F table

Once the subassembly construction is complete and all features have been installed, the subassembly is then transported and folded. The transport system is a key inhibitor of the F&F Table as it transports the sail across the table so that the already-completed subassembly can be moved through what is called the backer removal station. The system works such that the Armalon (the brown material) in Figure 8 is strung through a series of rollers and pulleys in a certain fashion that allows a "clamping bar" to clamp the material in the region where the slacked Armalon is on the left side of Figure 8. Once the clamping bar is clamped onto the material, a series of actuators move the bar downward in unison so that it pulls the Armalon across the whole F&F Table as the Armalon is also fed onto the table on the "feed out" side in sequence with the sail film. A certain load of weight must be sitting on each panel of the sail (seen in Figure 8) so that there is minimal if any slippage between the Armalon and sail. Approximately 5 feet from the clamping bar side of the F&F Table is what is called the "separator board" which separates the film from the backer. At the beginning, and as a new roll of material is added to the SQ, the backer is slightly peeled off by hand and fed underneath the separator board so that throughout the rest of that roll of material for that SQ the backer will continue to be peeled off at the separator board. This process is repeated throughout the duration of the SQ until completion.

Since the corner subassemblies are built in parallel to the SQ midspan, they must be integrated at a certain point in the flow of production. SA1 is completed first or in parallel with SA2 such that they are both completed at the same time. SA1 is attached with a vertical seam joining the two along with connecting edge reinforcements and covers, and seam jumpers. These two, now-joining, subassemblies will be transported and folded as one. A similar process is used to integrate SA14. Once SA13 is finished and ready to begin transport, it will be transported just enough that SA14 can fit on the F&F Table work surface and then joined to SA13 with the same steps as SA1 was joined to SA2. Once this is complete, final integration will be complete with only the final transporting and folding left to finish.

Throughout the duration of the SQ build, it is also folded. The design of the SQ is to be z-folded such that once it is deployed it will unfold and open out to full deployment in a controlled and orderly manner. NeXolve has developed a proprietary process that is semi-automated, semi-manual for folding a sail this large. This process enables NeXolve to successfully build solar sails and solar sail quadrants larger than the facility they are manufactured in. The Prototype SQ for example, if fully deployed would not fit in NeXolve's manufacturing facility. The fold pitch or fold width for the Solar Cruiser Prototype SQ is 22 cm, or ~8.66 inches. The z-folded stack and fold width is shown in Figure 8. This entire process would repeat 4 times for a 4-quadrant full size sail for the Solar Cruiser mission as all 4 quadrants are identical.

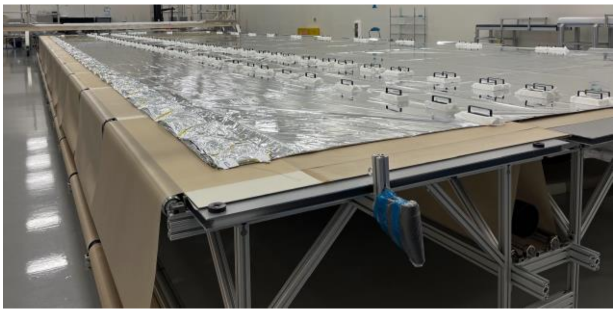

Figure 8. The transport system on the F&F table

7. Prototype SQ Spooling and Final Packaging

Once all fabrication is complete, the sail quadrant(s) are then spooled onto a carbon fiber spool, provided by Redwire Space, and packaged with a sail restraint attached. The spooling mechanism is shown as GSE #5 in Figure 4. The spooling mechanism is a piece of GSE hardware that is built and designed by NeXolve through previous solar sail programs such as NEAScout. This mechanism is wrapped with a thin mostly static-free material called Syntrex and designed such that a series of cranks, turns, and bars being leveraged against one another wraps the z-folded stack of the SQ around the spool as well as collects the Syntrex material away from the sail at the same time. The Syntrex material is extremely important as it is wound through the spooling system in such a way that is maintains the correct amount of pressure on the SQ so that it doesn't blossom or balloon with air pockets throughout the entire process. When spooling 4 SQs onto a single spool for a flight size sail, the 4 z-folded SQs are laid on top of each other in a staggered fashion spaced out by ¼th the circumference of the spool and then spooled in the same way. Once the SQ or SQs have been spooled the inner crossties are attached joining adjacent SQs. For the Prototype SQ and the upcoming Ground Test Quadrant to be deployed in January of 2024, a crosstie simulator will be installed given that there is only one SQ being spooled and will not have any adjacent sails.

After the SQ has been spooled, the sail restraint is installed. This restraint is produced from uncoated 2-mil Kapton for its mechanical properties. The restraint is designed such that it is attached to the top of the spool with pressure sensitive adhesive (PSA) and wrapped around the circumference of the sail with a slight gap at the bottom of the sail for venting. For visual purposes, the restraint performs similar to how a cupcake wrapper works. The function of the restraint is so that throughout the lifetime of the spooled sail, the sail does not blossom, entrap any unwanted air, nor become slack and release from the spool at an undesired time. Figure 9 below shows a sequential picture collage of the Prototype SQ build, spool, and package. The far bottom right image in Figure 9 shows the restraint installed to the spooled Prototype SQ.

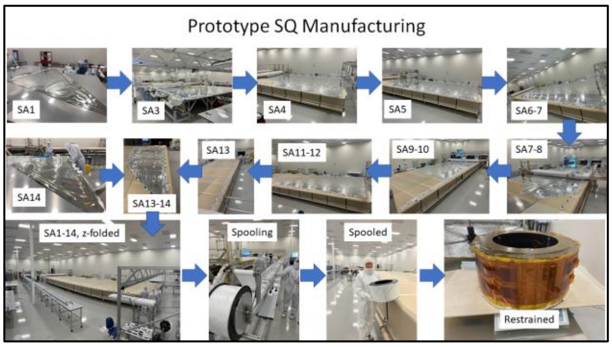

Figure 9. Collage of prototype SQ manufacturing and packaging

8. Verification Testing

Over the life of the Prototype SQ after manufacturing, folding, and packaging, the NASA, Redwire, and NeXolve teams conducted multiple verification tests involving SQs including [3]:

- 4-SQ architecture BrassBoard (1/16th scale) deployment test at Redwire Space led by NeXolve
- (1) spooled Prototype SQ with 3SQ volume simulator Ascent Vent Test led by NeXolve
- 4-SQ architecture BrassBoard deployment test at NASA MSFC led by Redwire Space
- (1) Prototype SQ ground deployment test at NASA MSFC led by Redwire Space

9. Post-Deployment SQ Shape Measurement Process

Prior to measuring the quadrant, the long edge was aligned with a tensioned string that spanned from grommet to grommet on the long edge. A weight was placed near each ripstop/edge intersection on the long edge to reduce wrinkles introduced in the deployment process and to keep the sail from moving during the measuring. After securing the long edge, the short edges of the quadrant were flattened and weights were added. No string was used on the short edges [3].

The four grommet locations were measured with the laser tracker by placing a 0.5" Spherically Mounted Retroreflector (SMR) seated in the center of each grommet. A best fit algorithm located the CAD model relative to the physical sail quadrant. Measurements around the perimeter were made by mounting the 0.5" SMR into a clear acrylic tool which enabled positioning the SMR above the points of interest [3].

7. July-August 2022 - Ascent Vent Testing of the Spooled Prototype SQ at NASA MSFC
8. September 2022: BrassBoard SQ Deployment at Redwire and NASA MSFC to verify the prototype deployment configuration
9. September / October 2022 – Prototype SQ Deployment Demonstration at NASA MSFC

10. Conclusion

NeXolve has successfully developed the capability of manufacturing large solar sails, such as Solar Cruiser, as well as many other large deployable thin film structures. NeXolve's current manufacturing facility setup and operating GSE is expandable and scalable to support the production of a 4-quadrant solar sail up to 5000 m^2. Architectures other than a 4-quadrant structure are supported as well. In partnership with MSFC and Redwire Space, NeXolve led the efforts for the design, development, manufacturing, and packaging of the SQ as well as the 4-quadrant solar sail architecture. The Solar Cruiser design 4-quadrant architecture totals 1653 m2 and has a total sail mass of 6.91 kilograms The single Prototype SQ came to a total ~1730 grams. The Prototype SQ took approximately 7 months to complete. After incorporating lessons learned and completing some observed areas for improvement, the Ground Test Quadrant is on track to be completed in approximately 6 months and NeXolve believes that we can achieve a full future SQ build in 5.5 months. The Prototype SQ successfully completed an Ascent Vent test, led by NeXolve, and conducted at NASA MSFC facilities as well as a ground-based deployment test in November of 2022, led by Redwire Space and conducted at NASA MSFC. The Ground Test Quadrant is currently underway as its purpose is for technology advancement of the entire Solar Sail System (SSS) to achieve TRL6. This system includes the Sail Deployment Mechanism, Active Mass Translator, and TRAC booms provided by Redwire Space along with the Sail Quadrant provided by NeXolve. The Ground Test Quadrant will be integrated with the rest of the SSS to undergo a full testing campaign of Thermal Vacuum, Vibration, and Deployment Testing. The deployment test for the Ground Test Quadrant is planned for January of 2024 at NASA MSFC.

Acknowledgments

The completed and ongoing work described in this paper was funded by NASA's Marshall Space Flight Center, where NeXolve supported Redwire Space as a subcontractor under Redwire Subcontractor Agreement RCSC717-10066-2. Thank you to all team members involved from NASA, Redwire Space, and NeXolve.

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