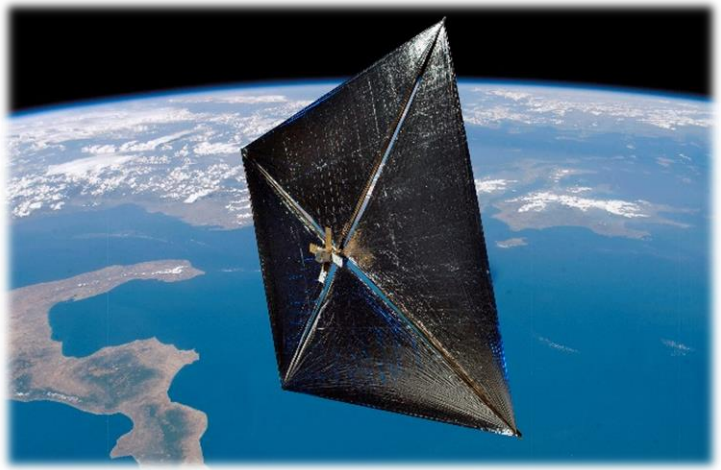

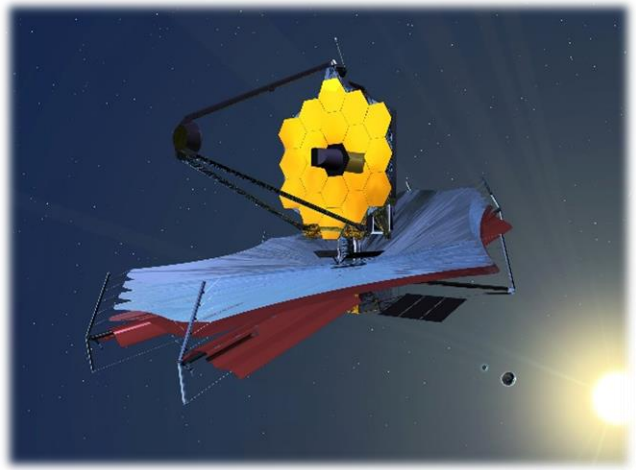

NeXolve
Technology for Today & Tomorrow

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

By: Kirk Maddox
6/6/23

Agenda

1) Overview
2) Requirements Development
3) Sail Quadrant (SQ) Design
4) Key Enabling Structures and GSE
5) Manufacturing
6) Direction of Technology Development
7) Conclusion

1) Overview

NeXolve has successfully developed and demonstrated the capability to manufacture large solar sails and sail quadrants (SQ), such as Solar Cruiser, as well as many other large deployable thin film structures.

Presenter:
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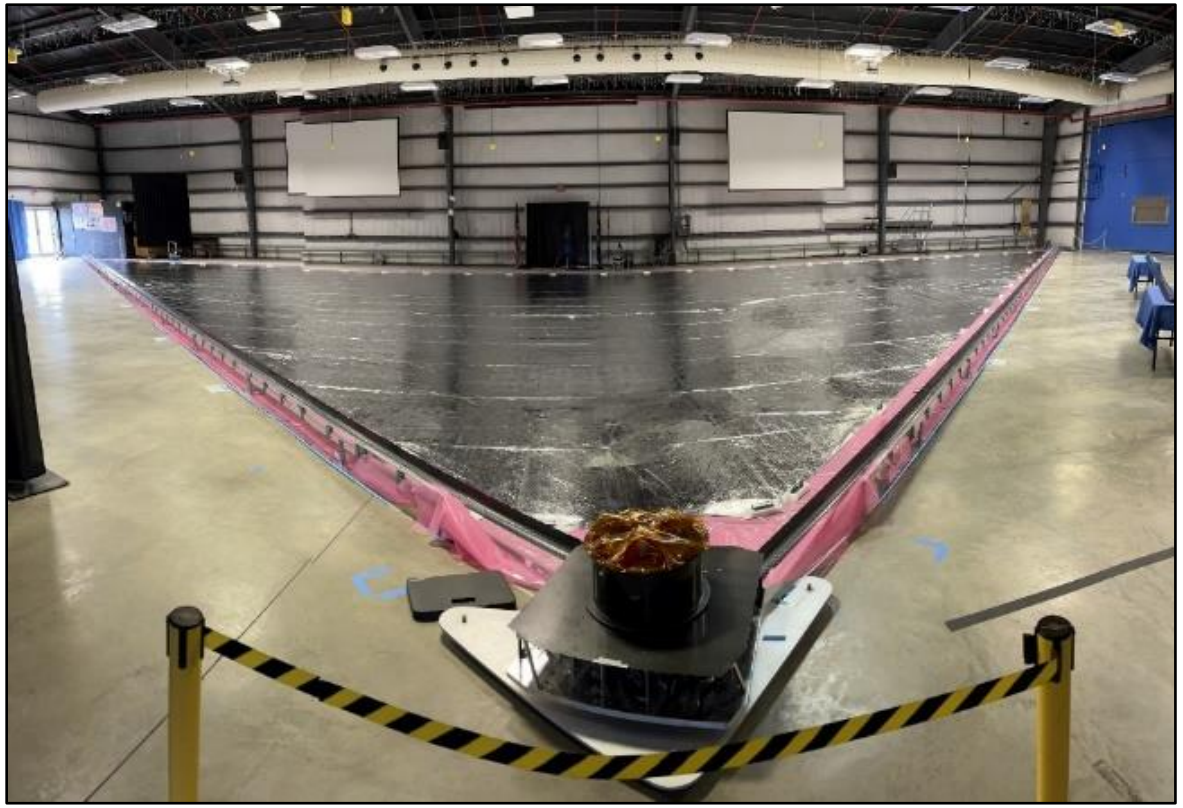


Photo from Solar Cruiser Prototype Deployment Test at NASA-MSFC (Nov 2022). Credits: Redwire

NeXolve Solar Cruiser Manufacturing Team

Below
Mark Johnson
Chris White
Jim Pearson
Antoine Parnell
Sage Johnson
Kirk Maddox
Daniel Hutchins
Robbie Eichman
Seth Gipson
Adam Callis

Not Pictured
Jim Moore
Isabel Nield
Tony Ewing
Debbie Gulas
Mona Gatlin
Bruce Buckner
Brandon Farmer

Shoutout to the NeXolve Manufacturing Team!!

*Picture taken 7/29/22 with the completed and spooled Prototype SQ.

2) Requirements Development

- Requirements defined to support membrane manufacturing
- Requirements drove the SQ design, size, and feature install/construction
- Most all requirements for NeXolve manufacturing can be summarized in the list below.

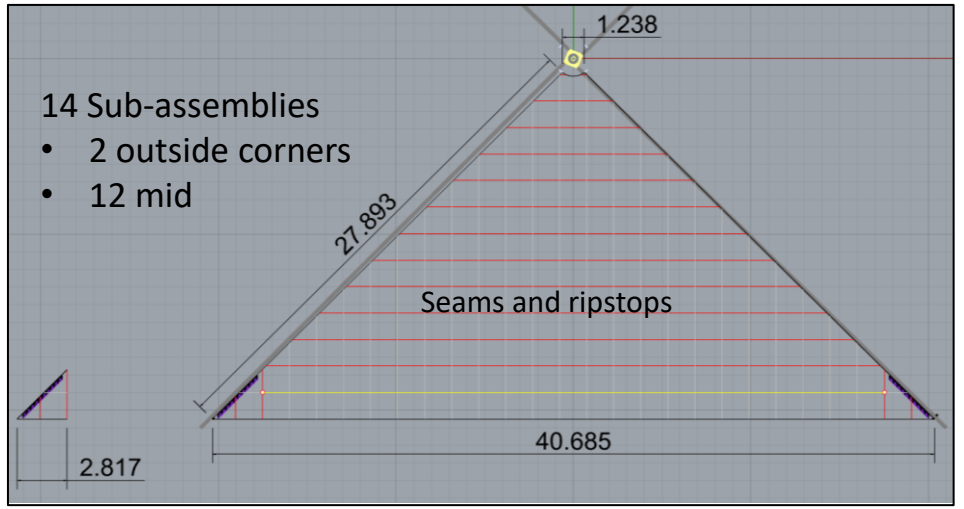
Make it:
- ✓ **Big**
- ✓ **Strong**
- ✓ **Shiny**
- ✓ **Lightweight**
- ✓ **Clean**

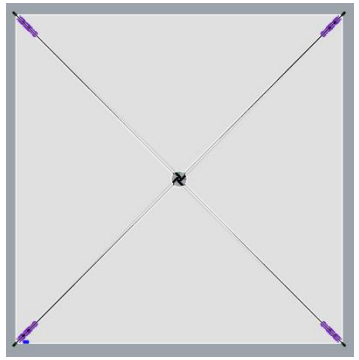
Description	Requirement	Capability	Verification	Approach
Solar Sail System shall have a four-quadrant architecture with a total deployed area of 1,653 m^2, with each quadrant having dimensions and architecture as defined in ICD ✓ **Big**	1653 m^2, +0%, -1%	1653 m^2	Inspection/Test	MIPs by customer at completion of SQs; inspection of released design drawings, inspection of ICD, inspection using CAD models, inspection of manufacturing records/travelers. EDU test plan to provide for verification of quadrant size.
All Sail Quadrant mechanical interfaces and features shall be designed to be able to accommodate a <=3N axial boom load with a factor of safety >3 (TBR) ✓ **Strong**	< 3 Nt	< 3 Nt	Analysis/Test	Analysis (FEA) to determine on-orbit stresses. Coupon testing of main constructions such as corners (grommet), seams, ripstops, edge reinforcement for BOL ambient(TBD)
Sail membrane shall be manufactured using VDA/CP1 with prior test data demonstrating no more than 5% reflectivity degradation after exposure to radiation and UV. ✓ **Shiny**	< 5%	TBD	Analysis/Similarity	Analysis; similarity to previous S4 program (MSFC data) Apply EOL knockdown to BOL capability
Membrane assembly mass shall be less than 13.12 kg including embedded features ✓ **Light**	<= 13.12 kg	<= 13.12 kg	Test	Test; weigh as-received spool for tare then weigh completed/spooled 4 SQ+spool. EDU quadrant weight.
Sail Quadrants shall be manufactured and delivered at a cleanliness level meeting 300A/2 standards ✓ **Clean**	300A/2	TBD	Inspection/Test/ Analysis	Analysis, coupon testing (see CC plan for specifics)

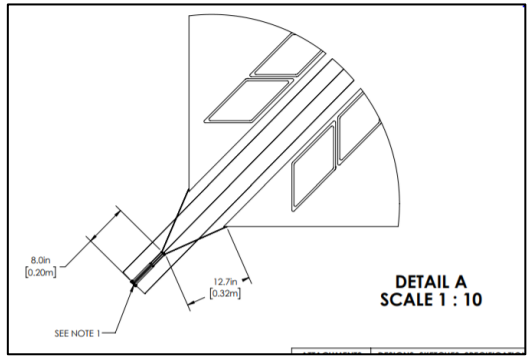
**SQ design passed Critical Design Review (CDR) on 10/14/21.*

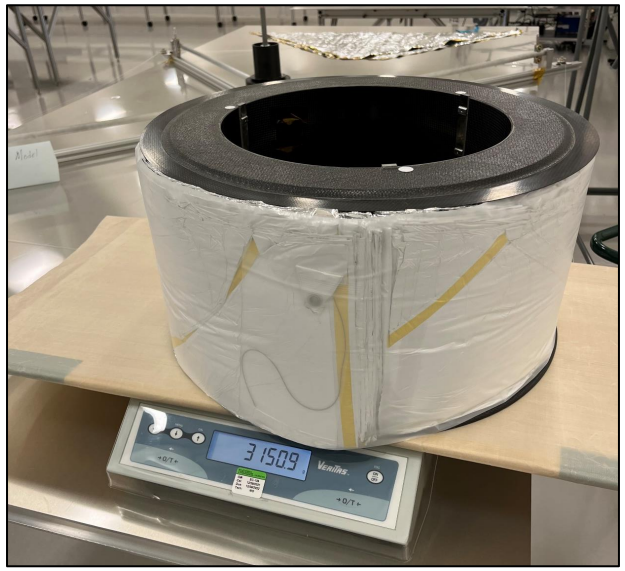
3) SQ Design - Overview

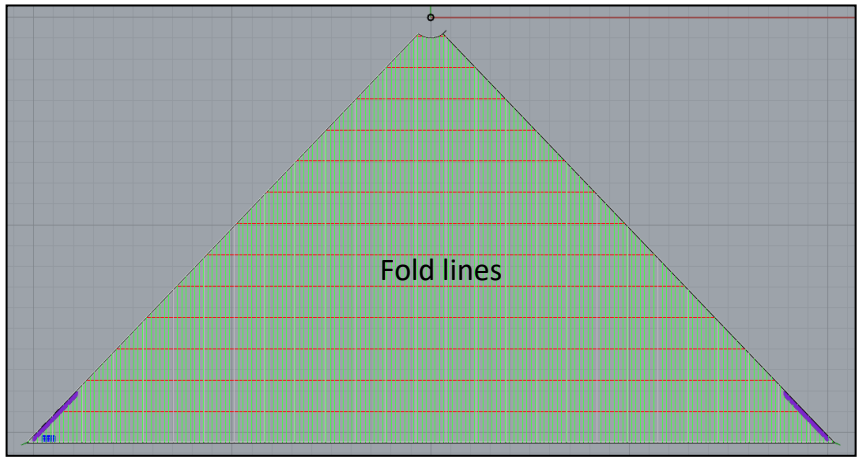
- Total sail area (4 SQ) = 1653 m^2 ... Total sail mass (4 SQ) = 6.91 Kg
  - Prototype (1 SQ) area – 413.25 m^2 … Prototype (1 SQ) mass = 1730 g
- 4 identical right triangular SQs from VDA-coated CP1 film with 2m diameter center-hole
  - VDA-coated CP1 film (sail film) is 2.5 µm thick
- Sail Features: seams, rip-stops, edge reinforcements, edge reinforcement covers, grounding seam jumpers corner reinforcements, and cross-ties
- Completed sail wraps onto and deploys from a 30cm diameter, 22.5 cm composite spool
  - Sail fold width is ~22 cm
- The sail is divided into 14 sub-assemblies approximately the size of the table work surface
  - 2 corner subassemblies (SA1 & SA14)
  - SQ midspan (SA2 - SA13)



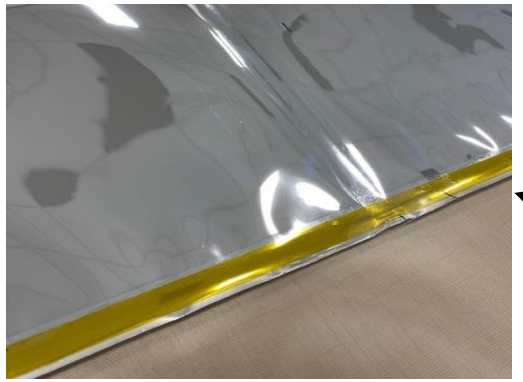






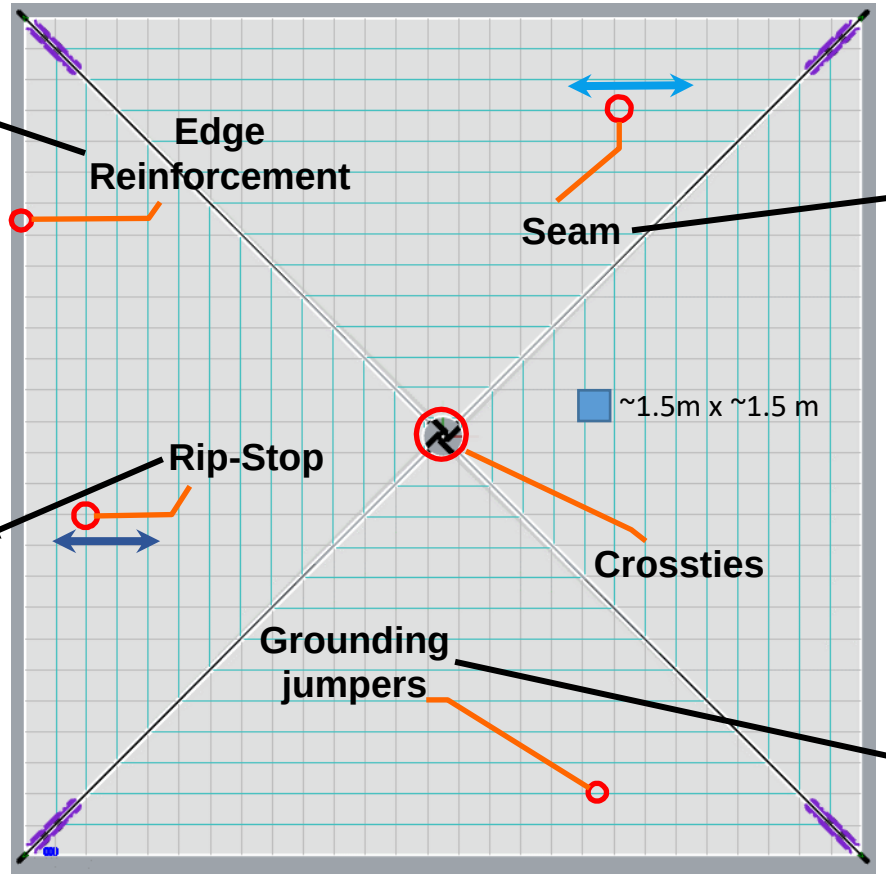


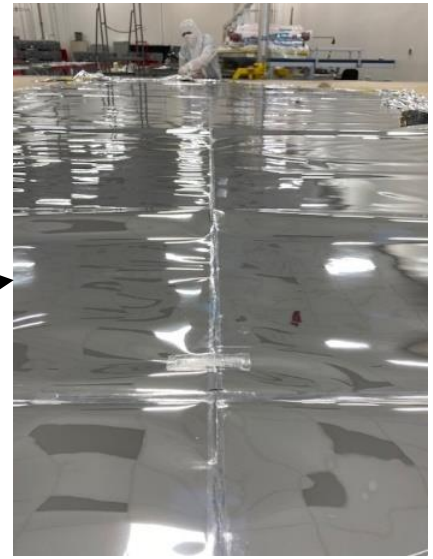
3) SQ Design – Key Features & SQ Layout



Reinforced edges:
- 0.5 mil Kapton tape with 3 µm TCP1 cover
- Cover prevents adhesive leach out
- Load bearing path around perimeter of SQ

Ripstops:
- Resin bonded 3 µm TCP1 on base material
- Prevents tear propagation





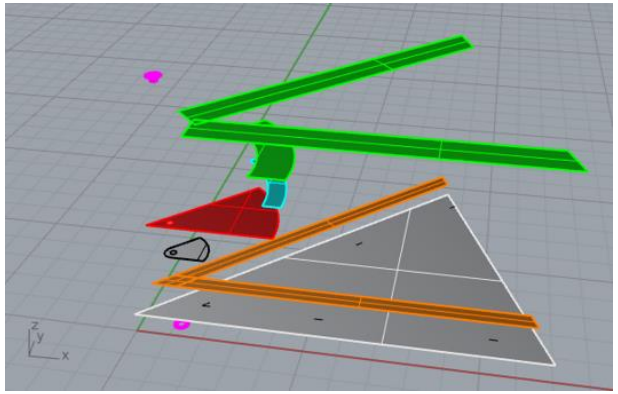
Seams:
- Resin bonded 3 µm TCP1 on base material
- Butt-joint joining gores of film together

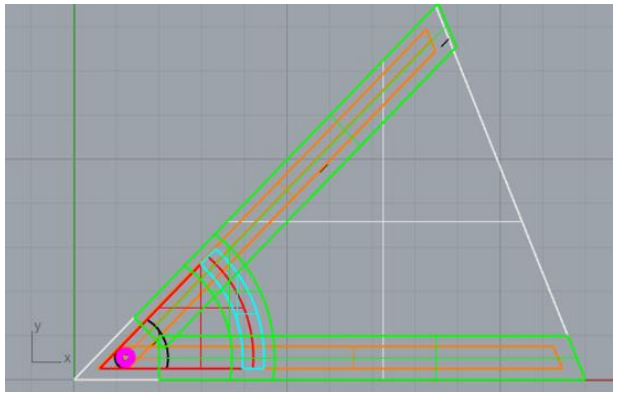
Grounding jumpers:
- Sail film & conductive PSA with a 3 µm TCP1 cover
- Cover prevents adhesive leach out
- Allows for surface ESD bleed off and continuity across seams

3) SQ Design – Corner Reinforcement

- Mechanical interface via grommet
- Outer corners attaches to booms via lanyard
- Inner corners attach to adjacent quadrant via crossties

Outer corner (distal)

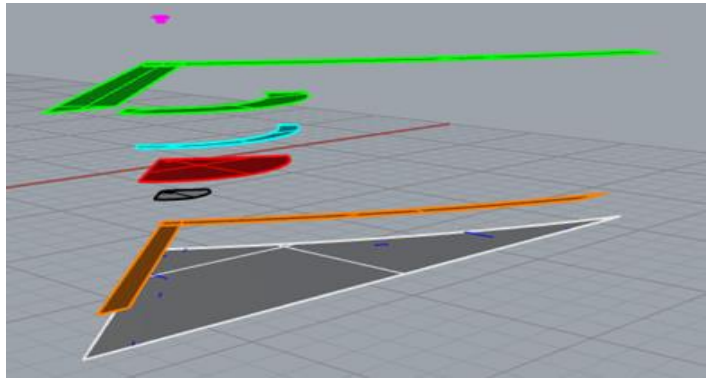


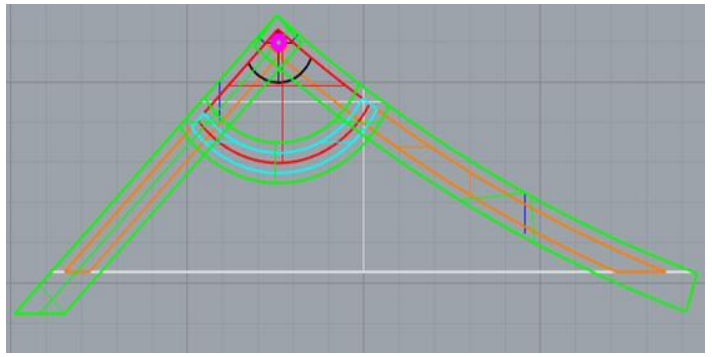


Corner stack-up

3.0 μm TCP1
1 mil Kapton w/VDA
1 mil conductive PSA
1 mil Aluminum
1 mil conductive PSA
0.5 mil Kapton tape (Si PSA)
0.5 mil Kapton tape (Si PSA)
2.5 μm CP1 w/1000Å VDA

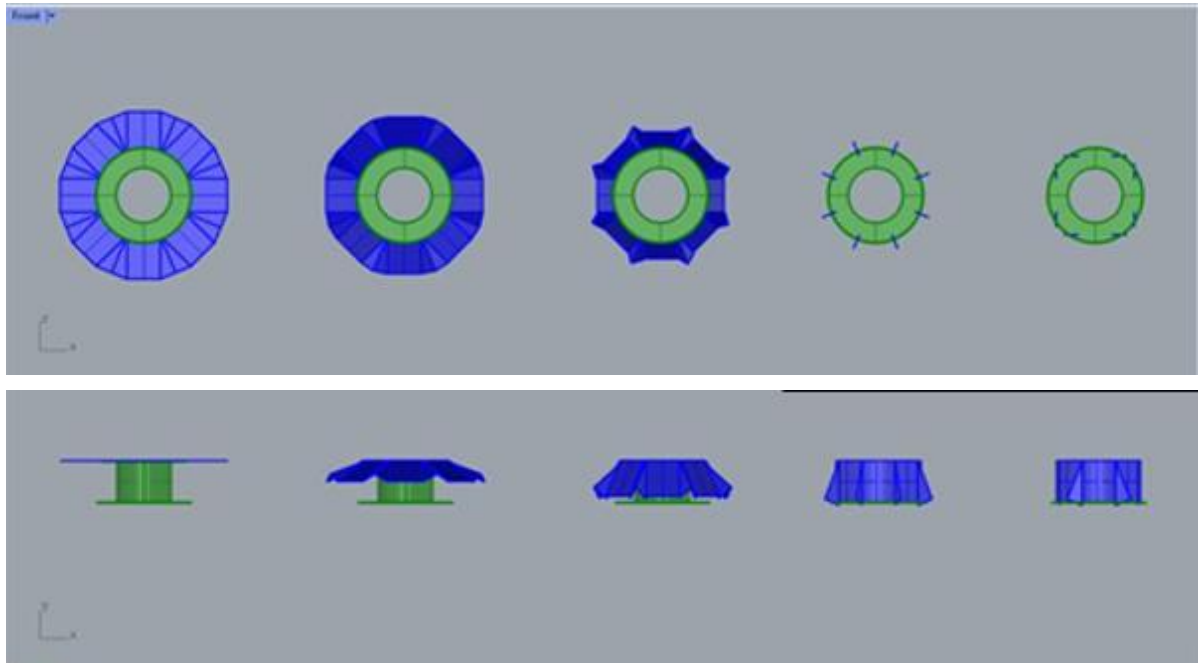
Inner corner (hub)

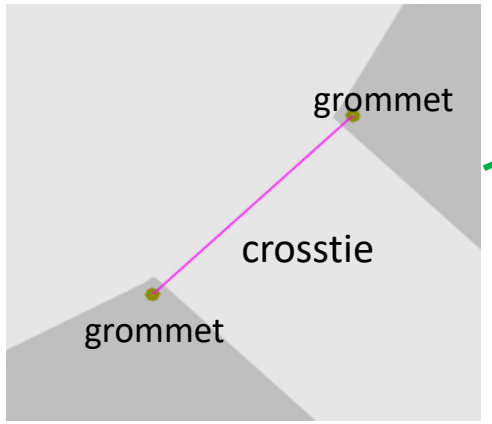


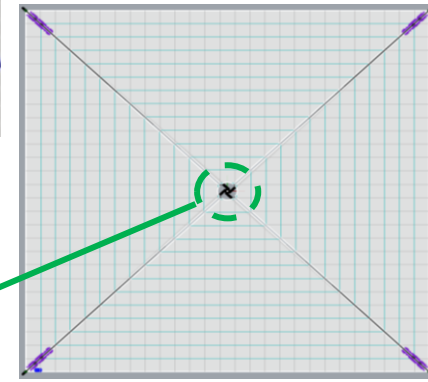


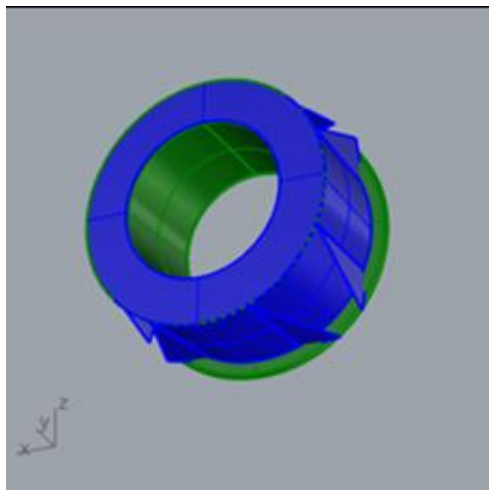
1 μm = 3.93701 x 10^{-5} inch

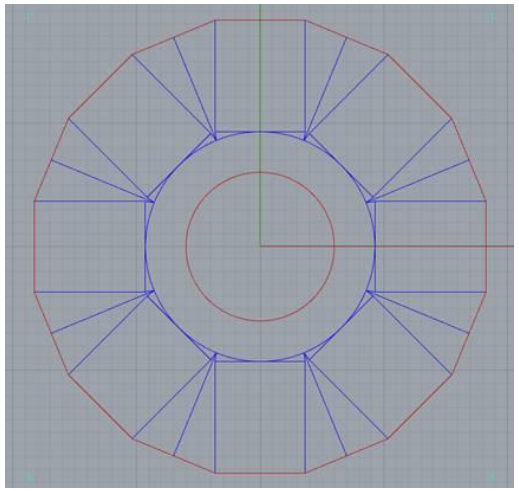
3) SQ Design – Sail Restraint and Crossties











- Restraint (left)
  - BB – Clean Poly
  - Prototype – Kapton
  - Flight – VDA/Kapton
- Works like a cupcake wrapper to keep the sail from “blooming”
- Crosstie (Above)
  - Prototype – Braided line
  - Flight – Nitinol wire
- Allows the sail to act like a monolithic structure

4) GSE - Overview

NeXolve's solar sail manufacturing facility is a 12,000 ft^2 class 10K/class 7 cleanroom. NeXolve's Quality Management System (QMS) is compliant with ISO 9001:2015 + AS9100D standards.

GSE:

- Eastman Cutting Table
  - CNC machine with cutting, punching, and drawing capabilities
- Marking Gantry
  - Structure that spans the width of the work surface and uses an automated arm equipped with a pen to mark key locations and feature indications on the SQ surface
- Fabrication & Folding (F&F) Table
  - Worksurface where sub-assemblies SA2 – SA13 are manufactured
  - Transport system
  - Folding station where the SQ is folded to the 22 cm fold width
- Working Gantries
  - Allows technicians do perform tasks and build the SQ from above the table surface where it cannot be reached from the ground
- Spooler
  - Spooling trough
  - Spooling mechanism – series of cranks, pulleys, and bars that compresses the SQ while also wrapping onto the spool

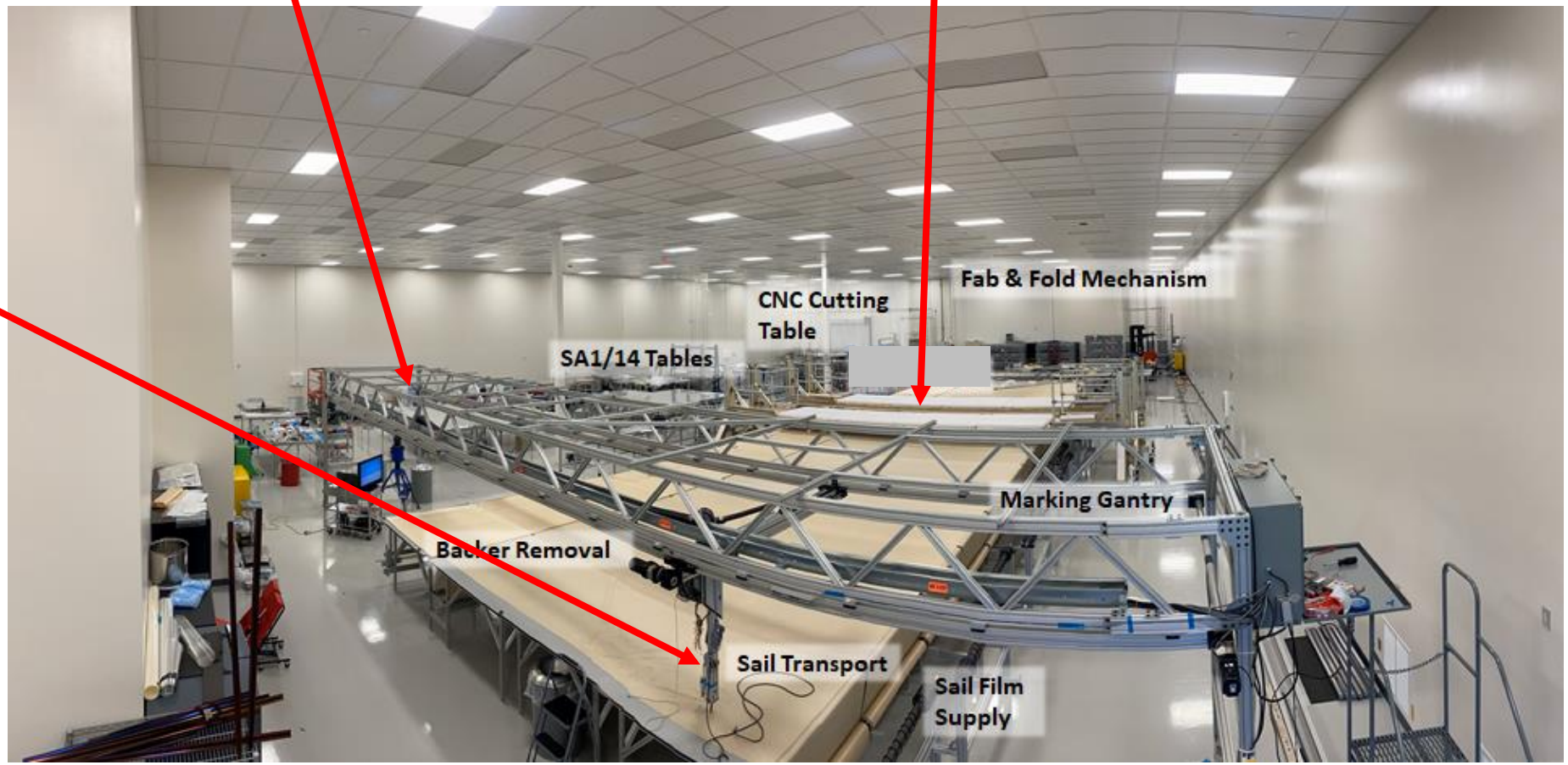
4) GSE – Marking Gantry

Large gantry structure spanning the width of the table surface.

Working gantries (2)

Automated arm w/ pen to mark key locations and feature indicators on SQ surface.

Key markings:
- Ripstop locations
- Edge reinforcement line
- Fold lines
- Fiducial targets



4) GSE - Fab and Fold Table

NeXolve's cleanroom facility
12,000 ft^2 10K facility (ISO class 7)

Prototype SQ Manufacturing Flow

Corner SAs
SA-1
SA1
Folded SQ Stack
Backer Removal
SA2
SA-3
SA fab area
SA-4+
Gore #
Gore #1
Mfg Flow
Marking Gantry
Clamping Bar
Transport Film Supply Rollers
Sail Film Supply Rollers

4) GSE – Transport System

Clamping bar in the “up” position.

Clamping bar in the “down” position.

The transport system moves the sail across the table after a sub-assembly has been complete so that it can be folded. The clamping bar shown is part of the transport system. It is a bar that spans the length of the F&F Table and “clamps” the Armalon (brown “transport” material shown above) and pulls it down. The clamping bar is fully automated by 6 actuators that moves the bar up and down in unison and in increments equal to the SQ fold width.

4) GSE - Fab and Fold Table (4SQ)

NeXolve's cleanroom facility
12,000 sq. ft. 10K facility (ISO class 7)

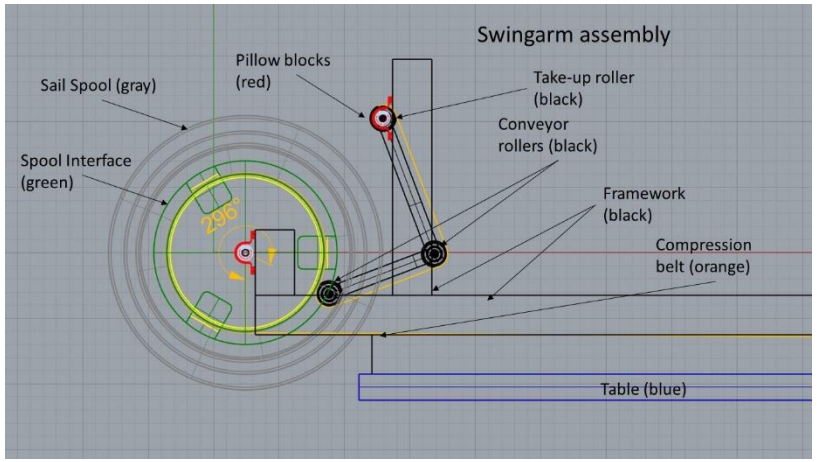
Prototype SQ Manufacturing Flow

Corner SAs
SA-1
SQ2
SA-11
SQ2
SA1
Folded SQ Stack
Backer Removal
SQ3
Mfg Flow
Marking Gantry
SA2
SA-3
SA fab area
SA-4+
Gore #
Gore #1
Clamping Bar
Transport Film Supply Rollers
Sail Film Supply Rollers

4) GSE - Spooler

- Legacy design from previous sails such as NanoSail-D, NEAScout, and Solar Cruiser BrassBoard.

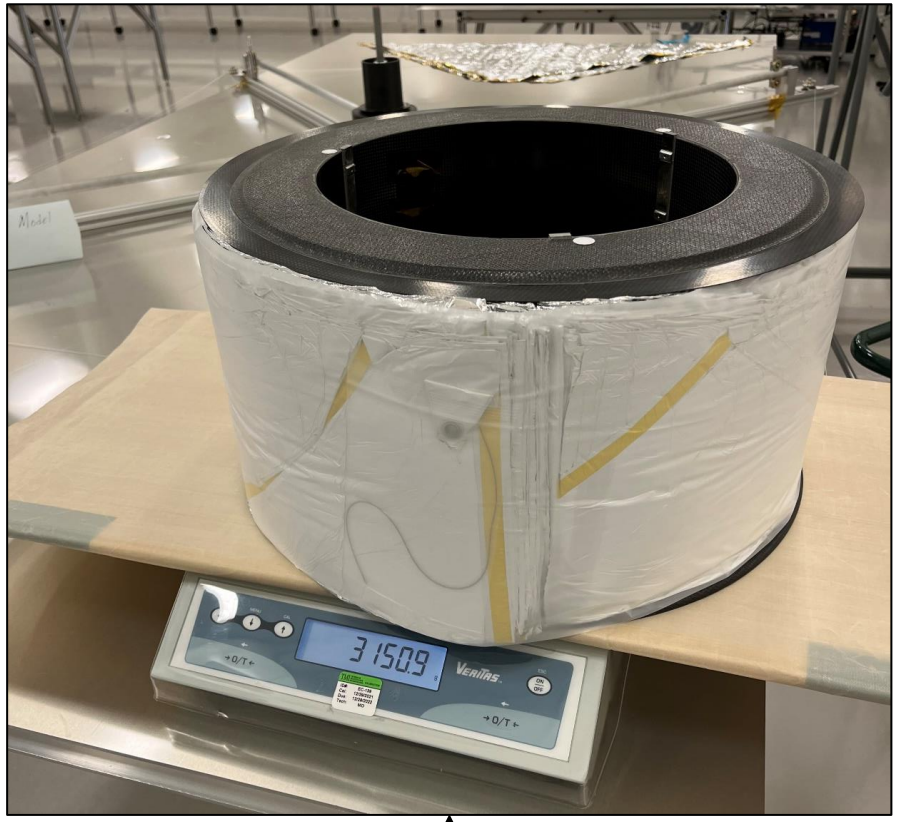
- Spooling Mechanism:
  - 70’+ long “trough”
  - Compression layer
  - Spooling mechanism



7/29/22 Prototype SQ Spooling Pictures

Completely folded Prototype SQ on edge of F&F table ready to move to spooling trough.

Folded Prototype SQ in spooling trough ready to begin spooling.



Spooled Prototype SQ with compression layer installed (pre-restraint).

5) Manufacturing – Manufacturing Flow

Manufacturing Flow of **SQ**:

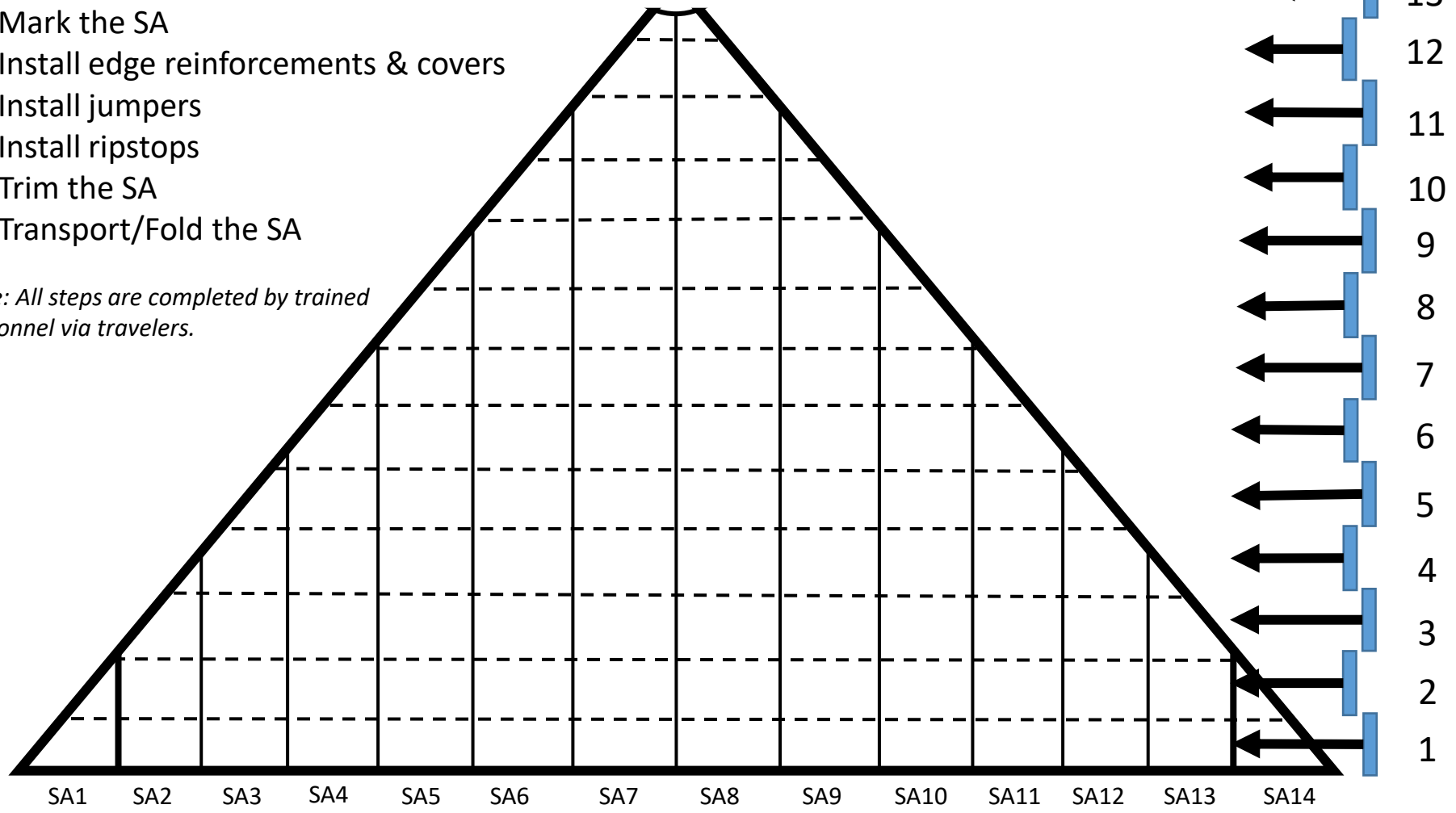
- Build SA1 on side table
- Build SA2 on F&F Table
- Integrate SA1 to SA2
- Transport & Fold SA1/SA2
- Build SA3
- Transport & Fold SA2/SA3
- …
- *Repeat through SA12*
- …
- Build SA13 on F&F Table
- Build SA14 on side table
- Integrate SA14 to SA13
- Transport & Fold SA13/SA14
- “Flop” fold SQ
- Move SQ to spooling trough
- “Un-flop” the SQ
- Spool the SQ
- SQ Complete

Note: 7 Transport/Fold cycles complete one SA.

Manufacturing Flow of **Sub-assembly**:

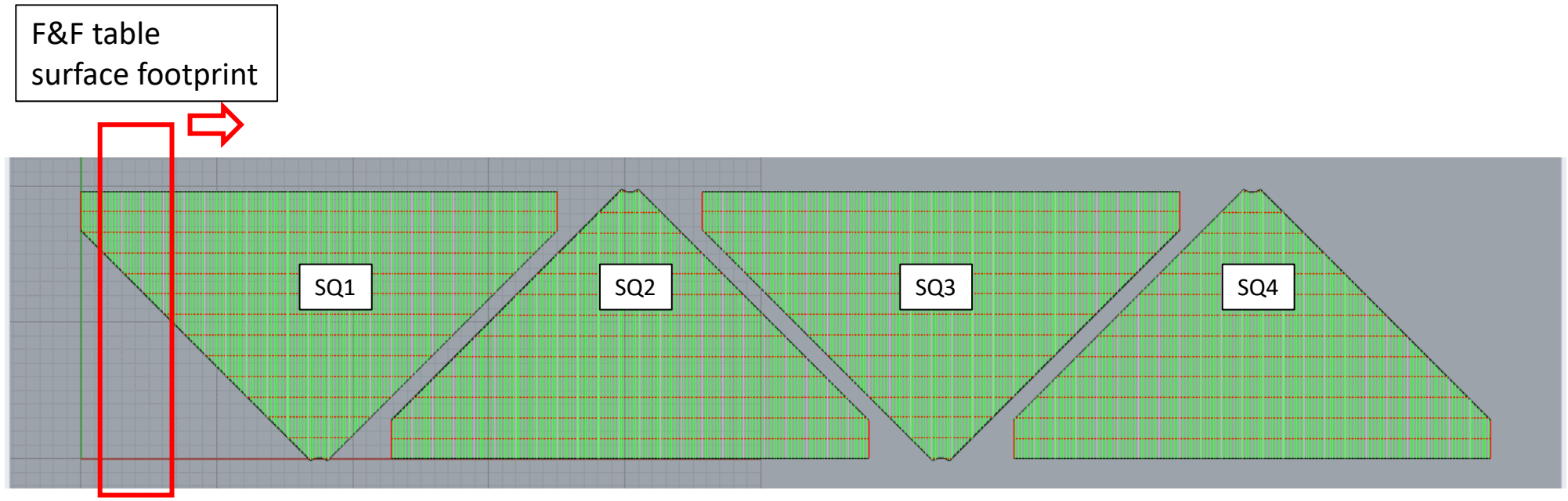
- Laser align film with FARO
- Install seams to the SA
- Mark the SA
- Install edge reinforcements & covers
- Install jumpers
- Install ripstops
- Trim the SA
- Transport/Fold the SA

Note: All steps are completed by trained personnel via travelers.

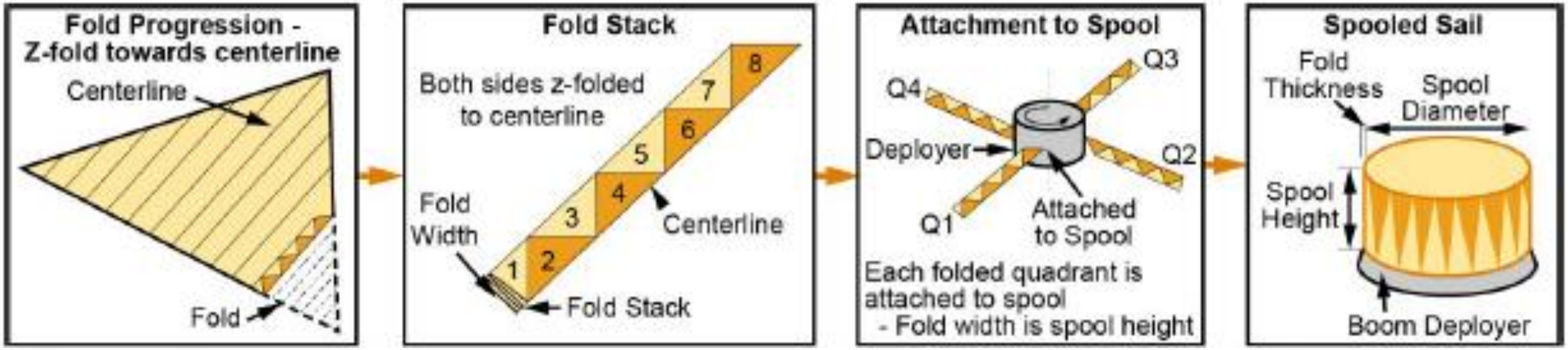


5) Manufacturing - Staggered 4SQ Approach

- Two SQs will be worked on at once
  - Can improve schedule and decrease the 4SQ build duration; inherits more risk
- Just past the halfway point of SQ1 manufacturing, SQ2 manufacturing will begin. This pattern continues through SQ4.
- When SQ1 is finished, it will be “flop” folded out of the way of SQ2. This pattern continues through SQ4.
- All work occurs on the F&F Table.



5) Manufacturing - 4SQ Approach



- Same Fabrication & Fold Manufacturing flow, repeat 4x
- Stack and stagger the 4 z-folded SQs by 1/4th the circumference of the spool
- Spool the 4 SQs just as we would with 1 SQ and secure with the sail restraint

6) Direction of Technology Development

1) NeXolve is currently in the contracting phases of manufacturing the full Solar Cruiser design 4-quadrant sail.

2) NeXolve is currently under contract for work to develop Reflectivity Control Devices (RCDs). NeXolve is using their expertise in thin film structures to develop a very special and delicate balance of thin films and coatings so that the devices can be tunable to potentially spin, roll, and maneuver a sail once deployed in space.

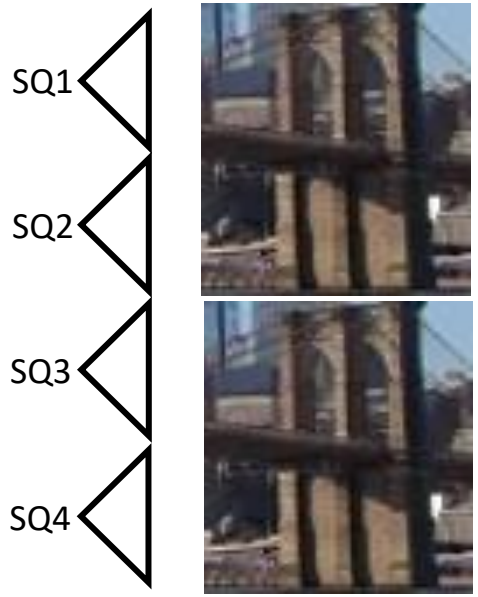
3) NeXolve has done extensive research on the expansion of solar sail technologies by looking at current facilities and GSE, sail architecture, as well as manufacturing methods.
   - NeXolve's current manufacturing facility and F&F table can be expanded to support a 4-quadrant sail design up to 4000 m^2.

7) Conclusion

The NeXolve facilities, mechanisms, processes, design, and materials were implemented to produce a large flight-like Solar Cruiser Sail Quadrant. The in-process data collection plus the SQ Ascent Vent test and SQ Deployment demonstration test validated that the manufacturing flow and method produces a flight-like SQ within tolerance.

NeXolve is currently manufacturing a second SQ, of the same size, to undergo another testing campaign with plans of achieving TRL6 for the Solar Sail System. NeXolve plans to assist Redwire Space with the deployment test of this quadrant scheduled for January 2024.

Fun fact: If the 4 Solar Cruiser SQs were stacked vertically by each hypotenuse, it would be approximately the same height at TWO Brooklyn Bridge towers.



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Thank you!
Go Cruiser!