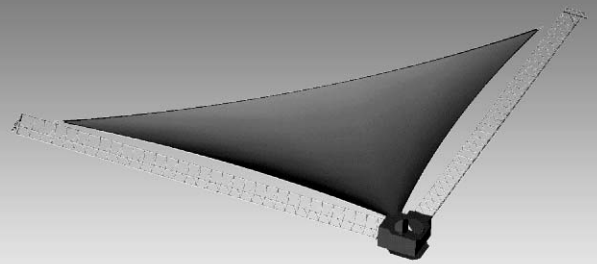
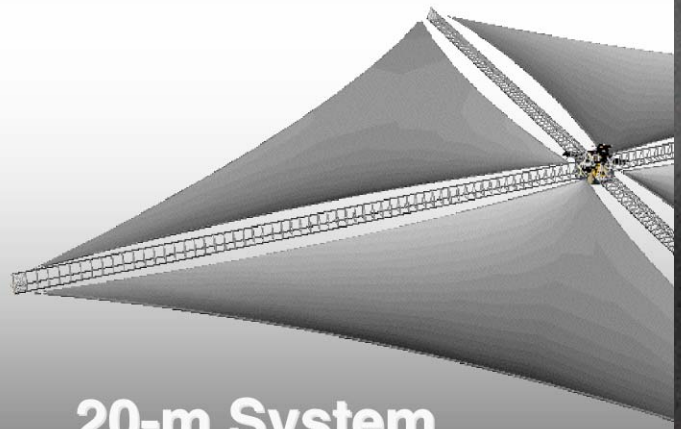
Solar Sail System Development

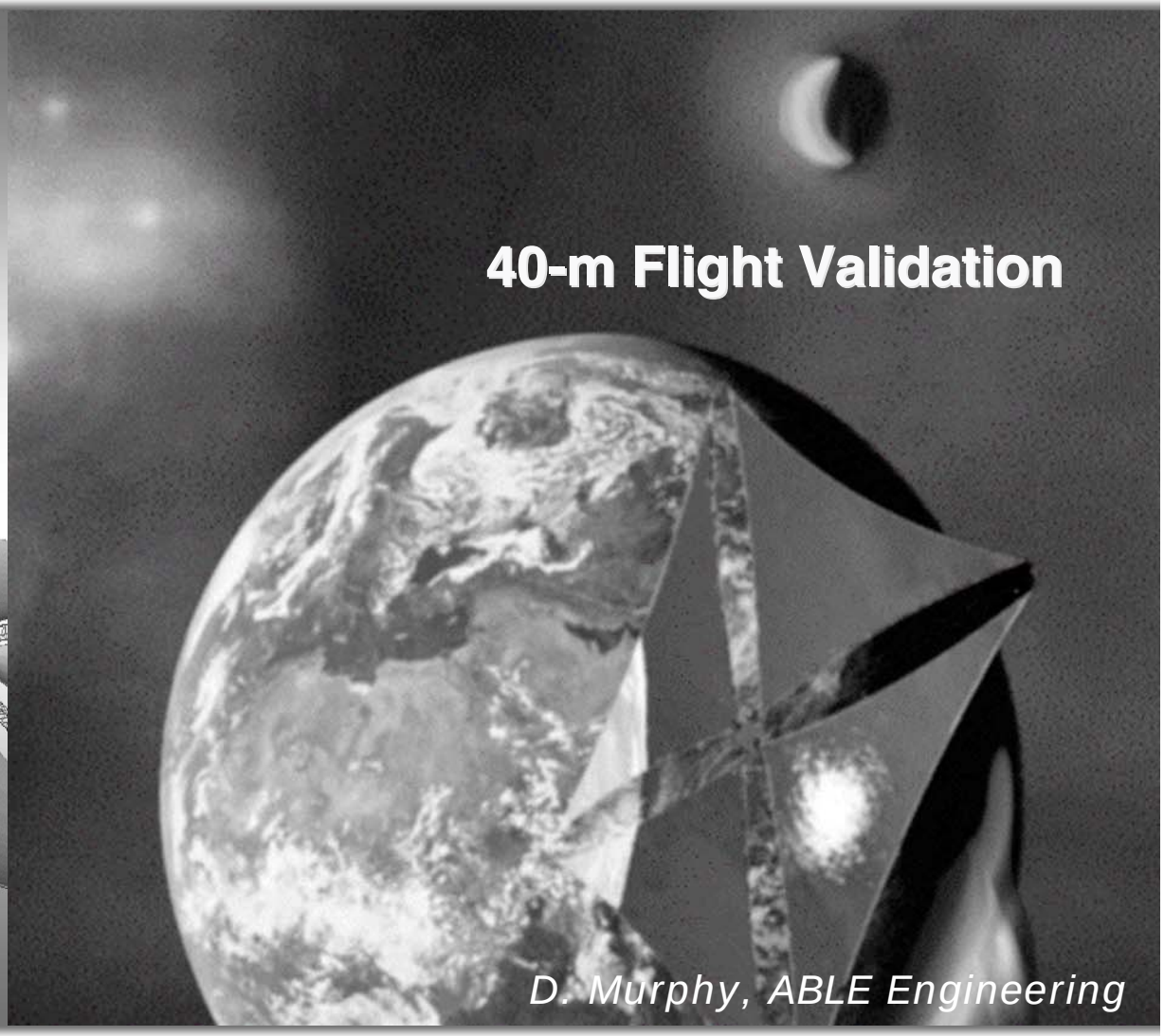
Solar Sail Technology and Applications Conference



10-m Quadrant ✓



20-m System



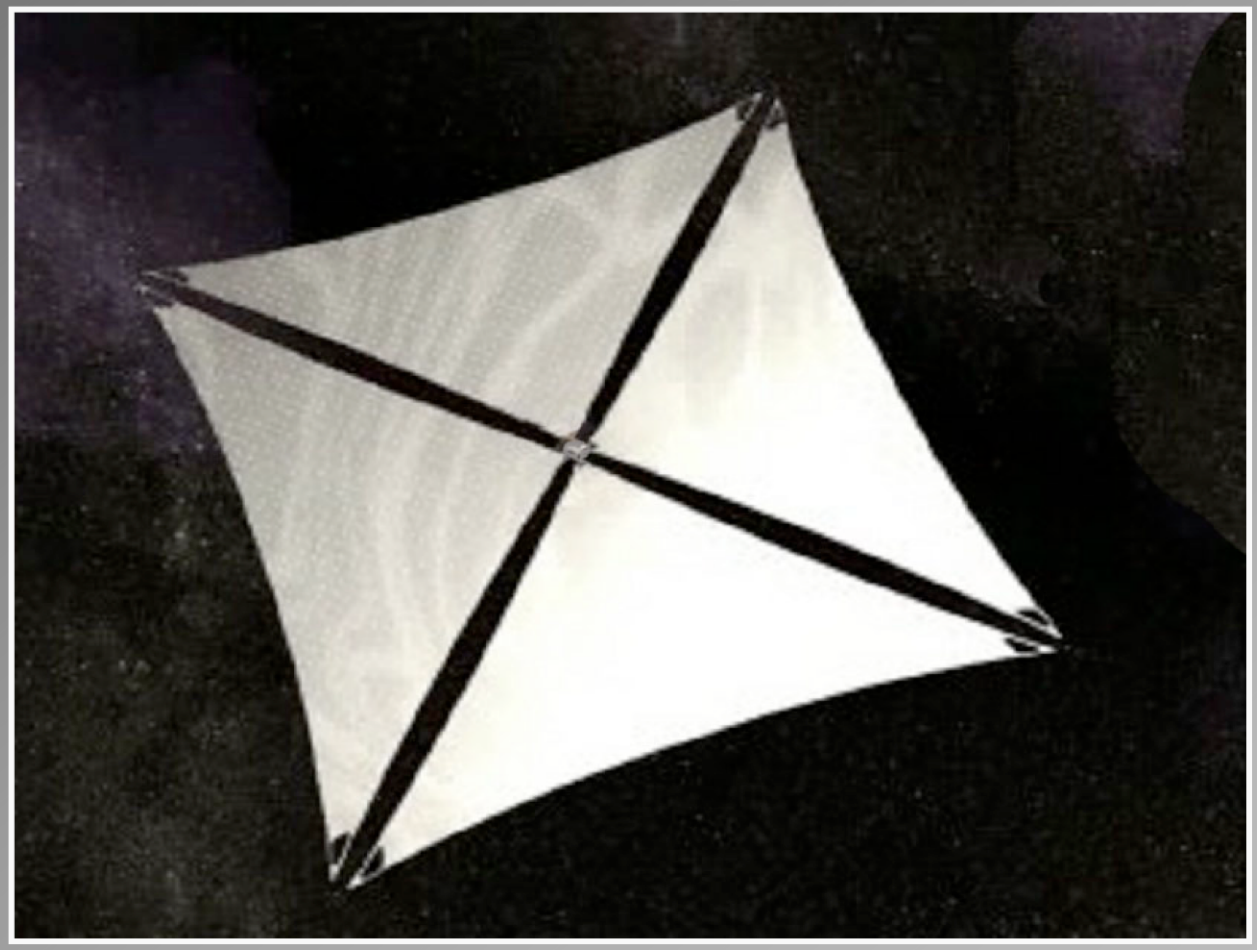
D. Murphy, ABLE Engineering

ABLE SRS NASA ASU PrincetonSATELLITE SYSTEMS

9-29-04, Greenbelt, Maryland

Solar Sailing!

The S^4 System



Scalable Square Solar Sail

ASNAP Team: S^4 Development and Ground System Demonstration (GSD)

NASA: ISP Program Leadership

MSFC: ISP Project Management

AEC-Able Engineering
Sail System Ground Demonstration Lead

SRS Technologies
Sail Assembly Provider Development & Validation

S. Montgomery
Project Manager

D. Messner
Program Director

P. Gierow
Co-I

A. English
COTR

D. Murphy
PI - Technical Director

G. Laue
Program Lead

ASU - PSS
ACS Trades, Modeling, and Implementation

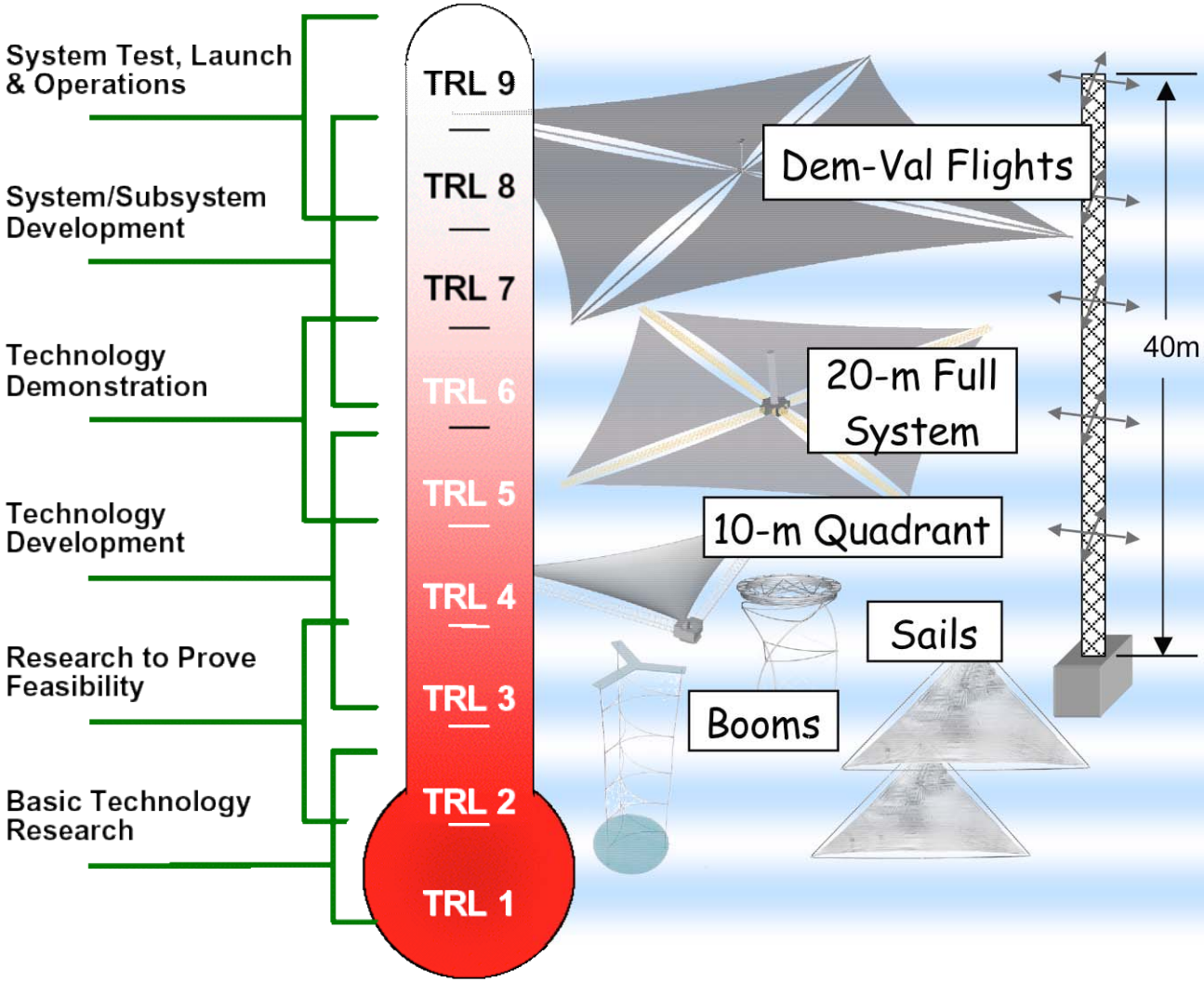
NASA – MSFC SEE
Materials Evaluation and Life Testing

NASA - LaRC
Modeling and Dynamics Testing

NASA - JPL
Missions, Materials, and Environmental Issues

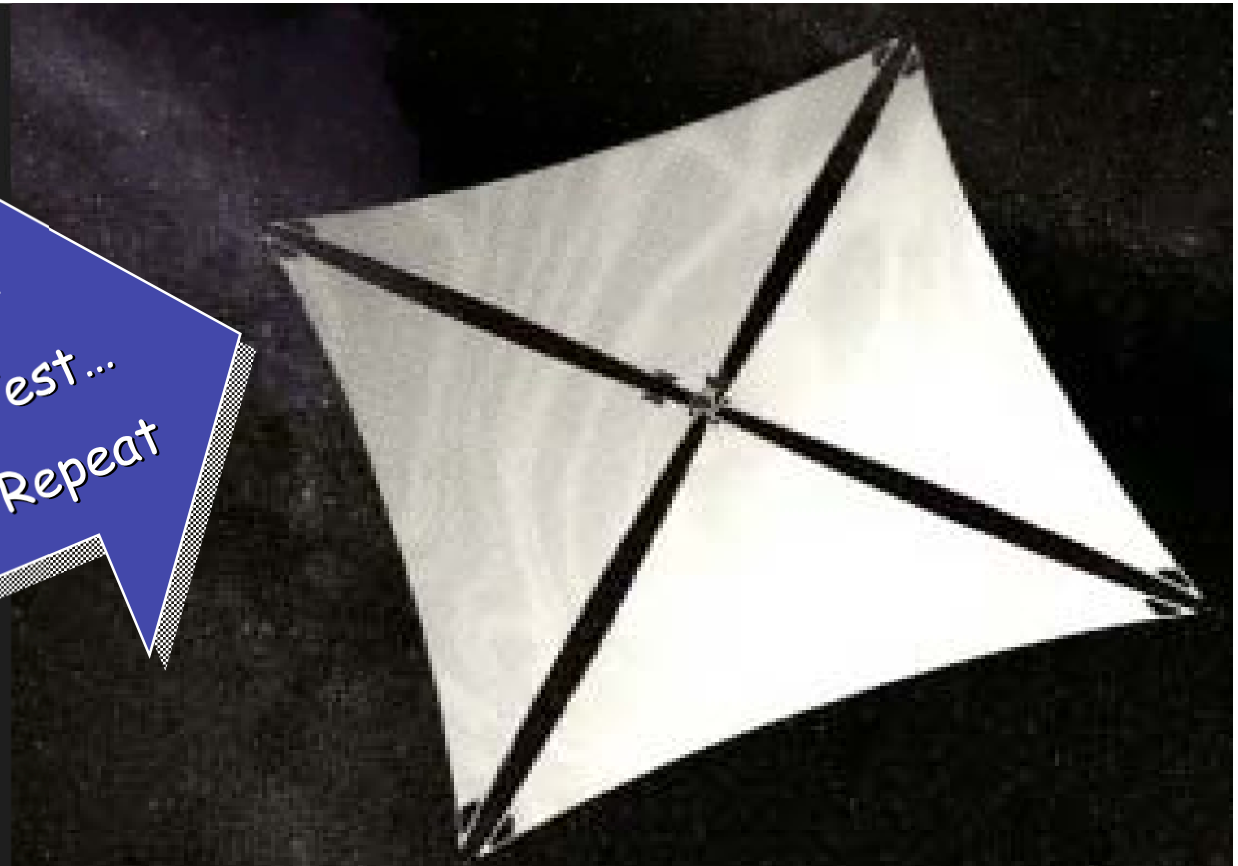
Technology Readiness Level (TRL)

Advancing the TRL to Prepare for Science Missions



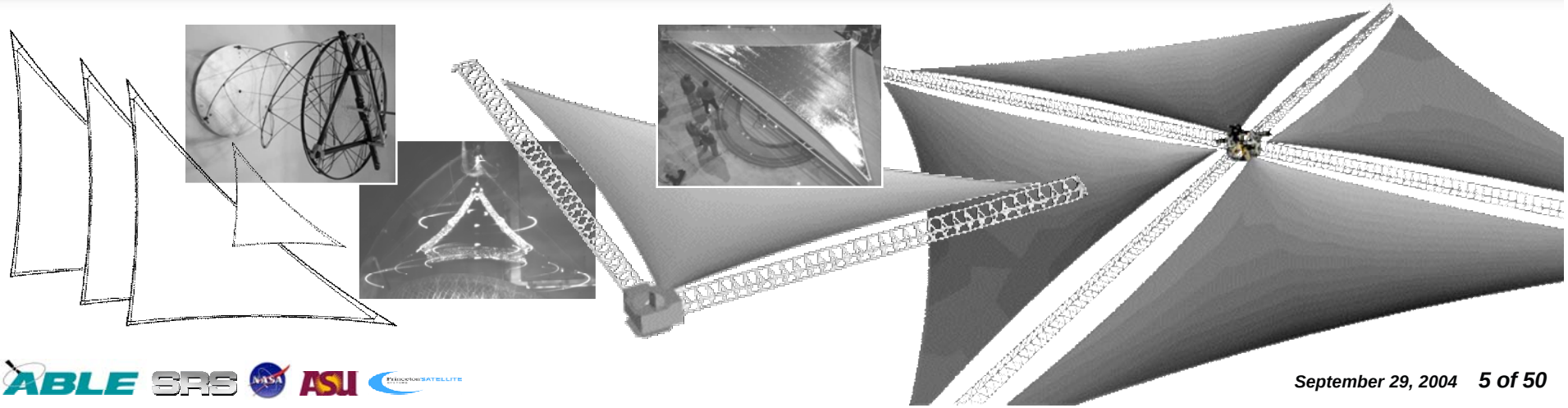
- **TRL 9** — Actual system "flight proven" through successful mission operations
- **TRL 8** — Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)
- **TRL 7** — System prototype demonstration in a space environment
- **TRL 6** — System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
- **TRL 5** — Component and/or breadboard validation in relevant environment
- **TRL 4** — Component and/or breadboard validation in laboratory environment
- **TRL 3** — Analytical and experimental critical function and/or characteristic proof-of-concept
- **TRL 2** — Technology concept and/or application formulated
- **TRL 1** — Basic principles observed and reported

ISP S^4 Roadmap

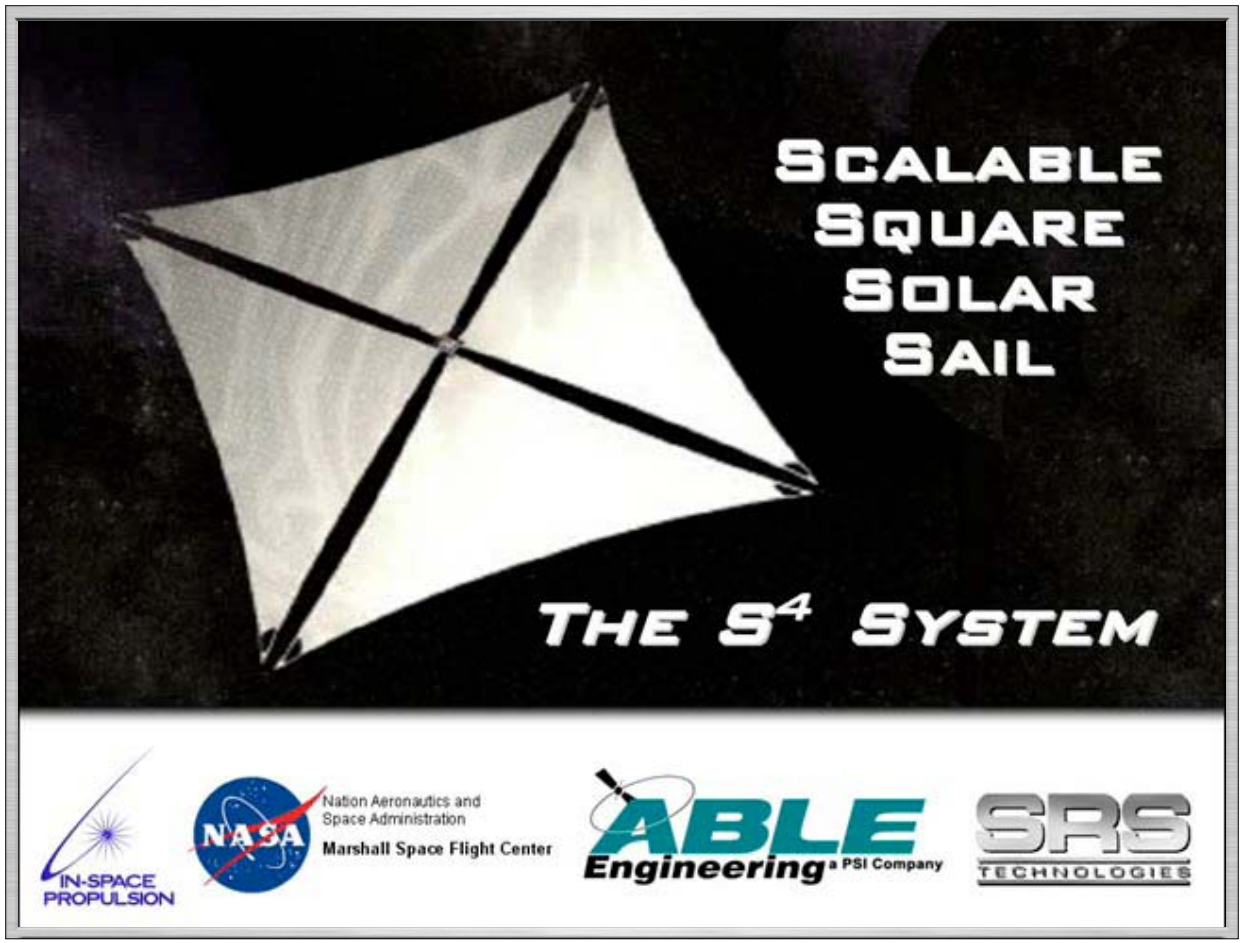


Refine Design, Build, Test…
Validate, Scale Up, Repeat

Sails… Masts… 10-m Quadrant System 20-m Full S^4 System



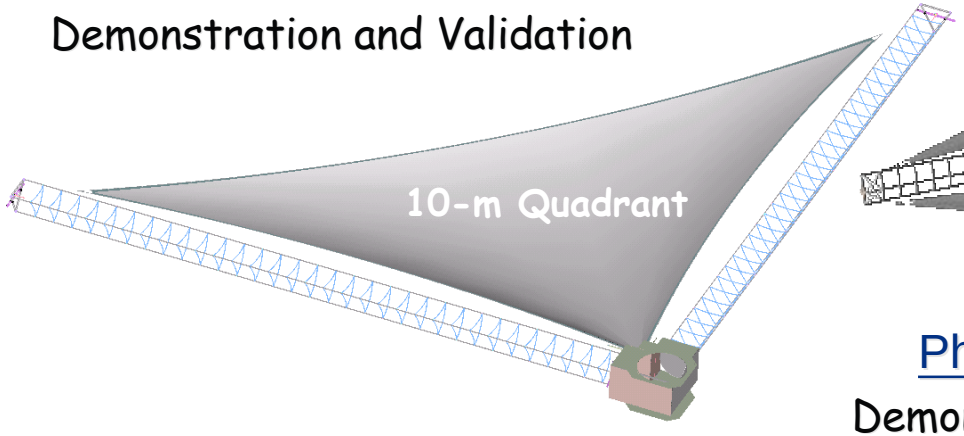
S^4 Sail Technology

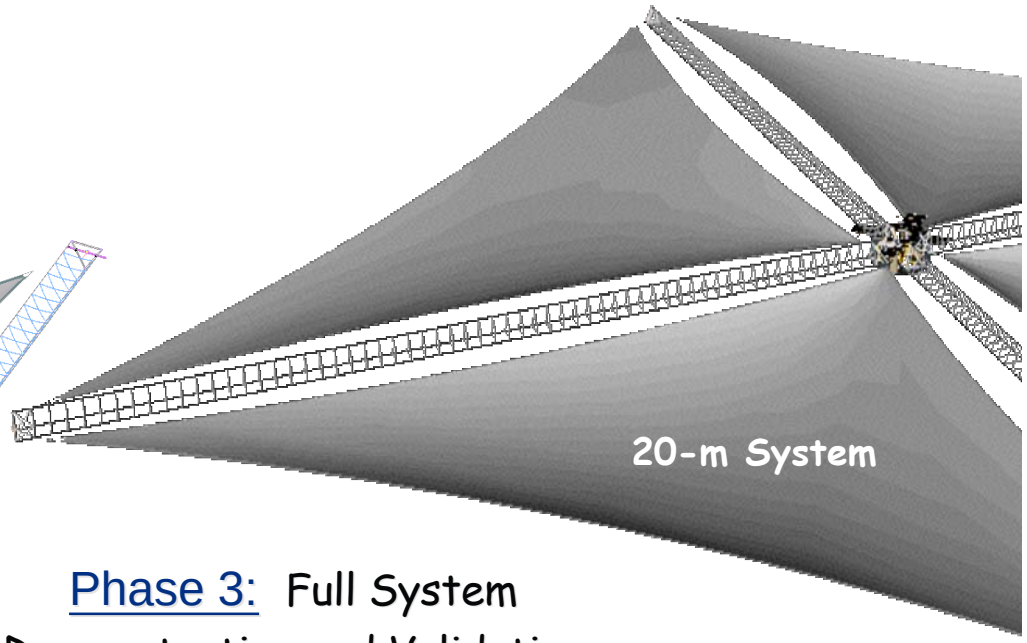


ISP S^4 GSD Program Overview

- Conduct **solar sail development and demonstration activities** in three phases to increase TRL of a **scalable solar sail *system***
  - Program Phases:
    - ✓ 1. Concept Refinement (CR) 6 months
    - ✓ 2. Hardware Development (HD) 13 _ months
    - ➢ 3. System Demonstration (SD) 1 year

Phase 2: Hardware Development and 1/4 Symmetry System Demonstration and Validation

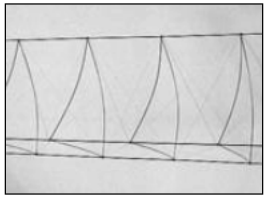




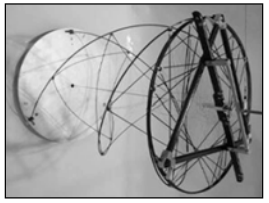
Phase 3: Full System Demonstration and Validation

Phase 2 Development & Demonstration Milestones

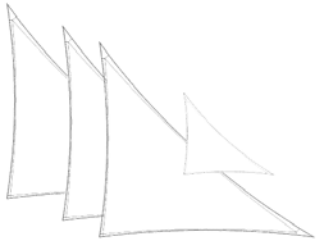
- Mast Development
  - EDU1, EDU2, 7-m masts (2)
  - Functional, stiffness, strength, alignment
- Sail Development
  - Workhorse, Refined Sail (RS5), Refined Sail (RS3), Performance Sail
  - Process Development
  - Material Testing
- System Demonstration
  - Packaging, Deployment Control, Ascent Venting, Quadrant Functional (ambient and vacuum), Shape and Dynamics Measurement
- Modeling
  - Correlations with mast and system testing results
- **Summary**
  - We did what we were asked to do:
    - Validate a *sail system in the LaRC vacuum chamber*
  - We did it within (the original) budget



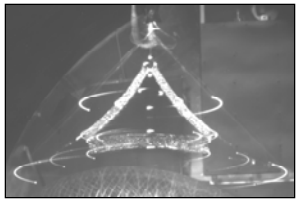
Mast EDU1



Mast EDU2



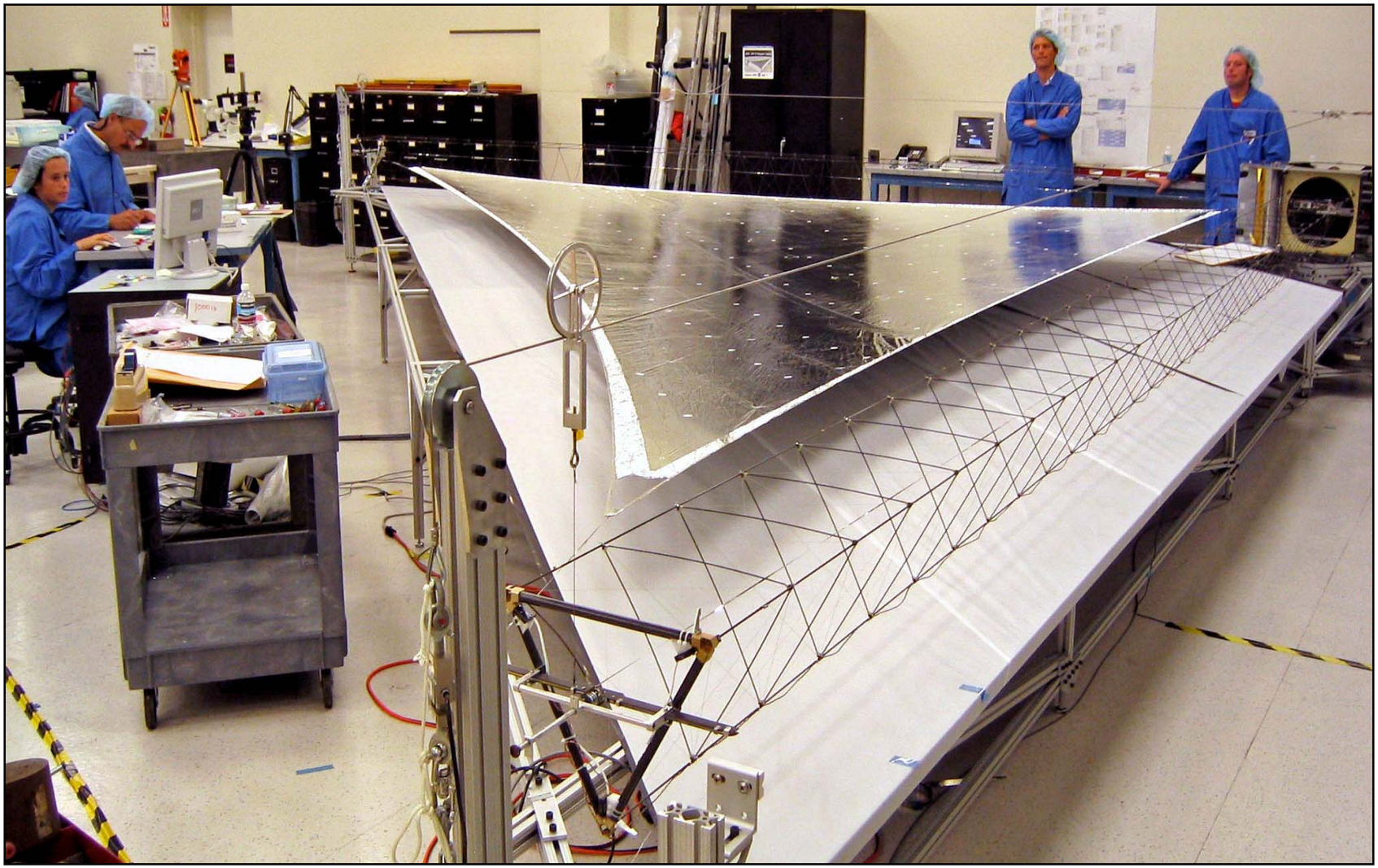
10-m Sails (3)



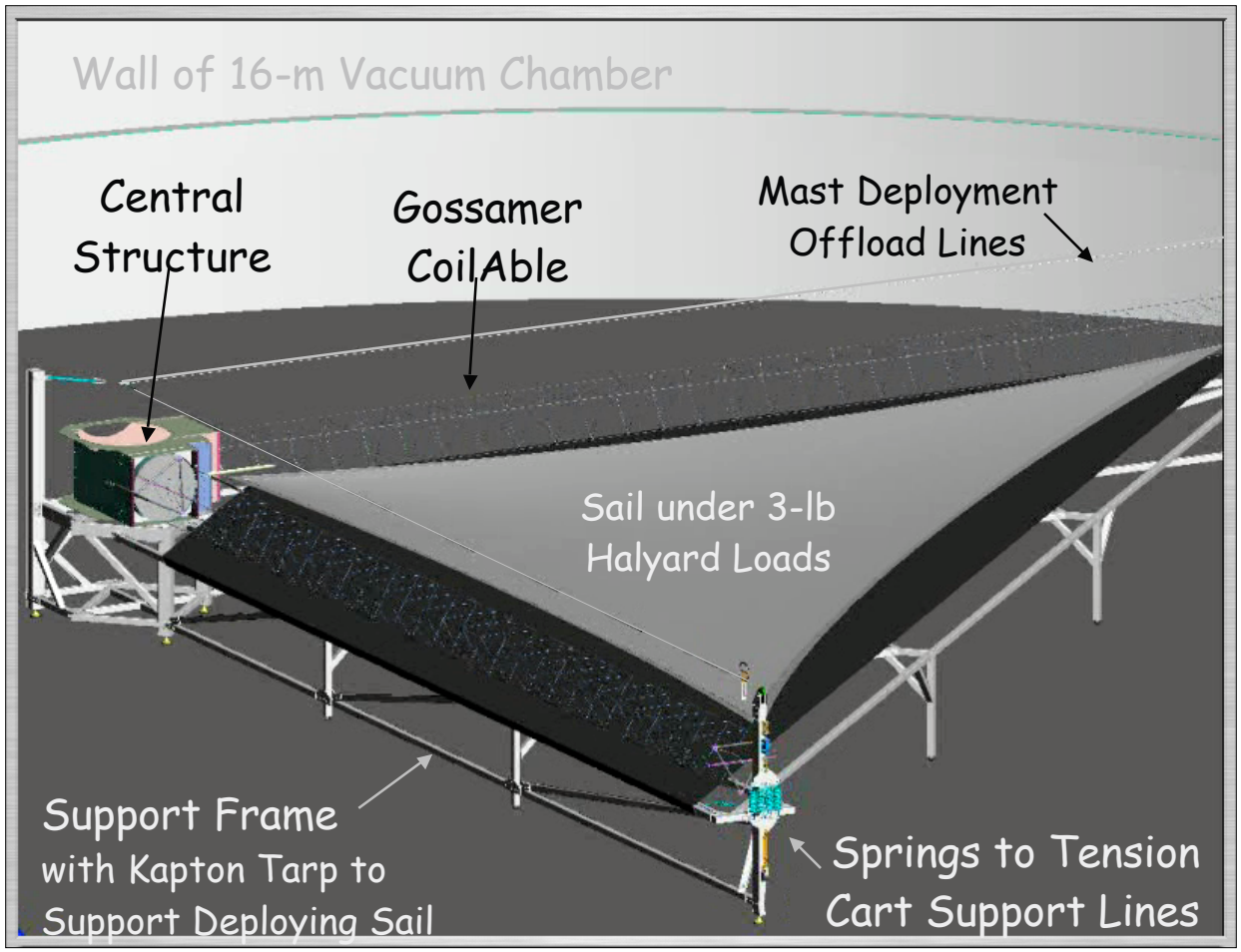
1.5-m Sail at GRC

10-m S^4 Sail System at NASA LaRC

10-m Quadrant System



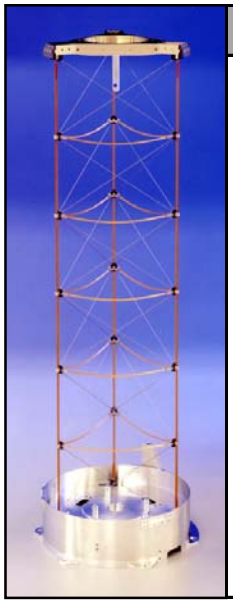
10-m Quadrant in LaRC Chamber



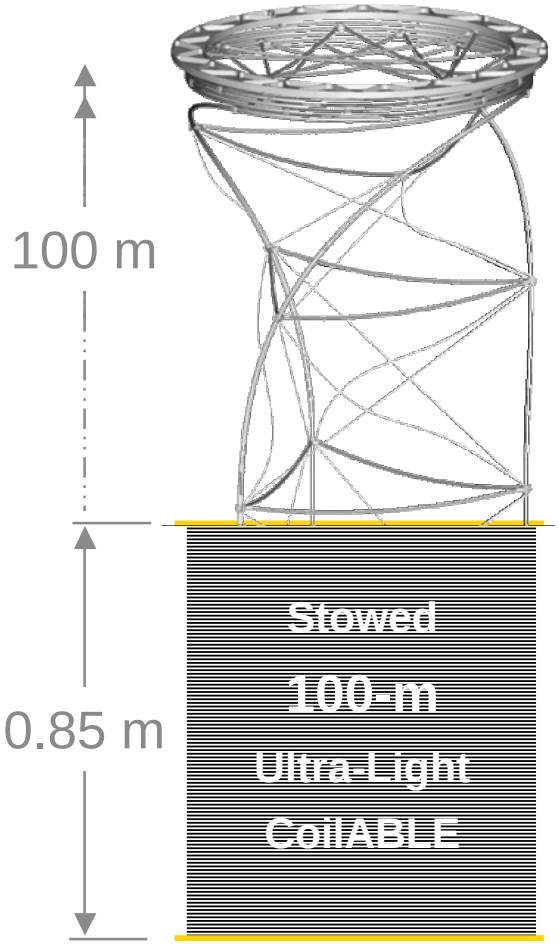
Mast Technology Maturation

CoilAble Mast Heritage

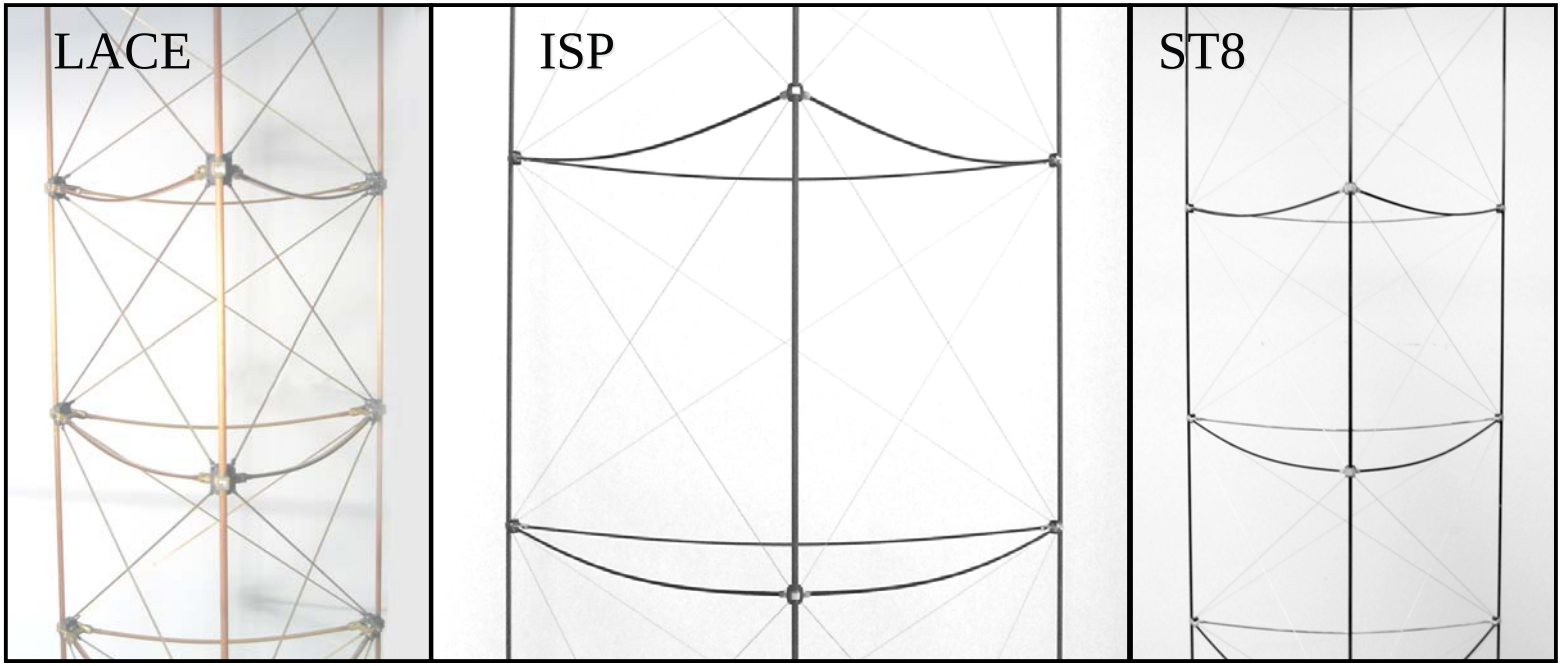
- 30 CoilAble systems have been flown to date
  - A phenomenal Stiffness to Weight ratio, High Dimensional Stability, Robust deployment, and Compact Stowage
- Recent flight mast designs
  - Mars Pathfinder (1999) 7-in.-dia. boom: 130 g/m



Program	Hardware	Customer
SAFE	Solar Array Deployment Boom	LMSC/MSFC
Galileo	Magnetometer Booms (2)	JPL
SOOS	Gravity Gradient Booms (6)	RCA/USN
UARS	ZEPS Deployment Boom	GE/GFSC
LACE	150 ft Booms (3)	NRL
EUVE	High Gain Antenna Deployer	Fairchild/GSFC
GGS	Polar and Wind Instrument Booms (2)	Martin/GSFC
IMP	Imager Boom for Mars Pathfinder	Martin/JPL/U. of A.
IPEX	Boom Micro-dynamics Experiment	JPL
CASSINI	Magnetometer Booms (2)	JPL
Lunar Prospector	Instrument Booms (3)	Lockheed Martin
Mars Polar Lander	Boom for Stereo Surface Imager	LMA/JPL/UA
Terra (EOS –AM)	Solar Array Deployment Boom	TRW/LM/GSFC
IMAGE	10 m spin axis booms (2)	Univ. of Mass. Lowell

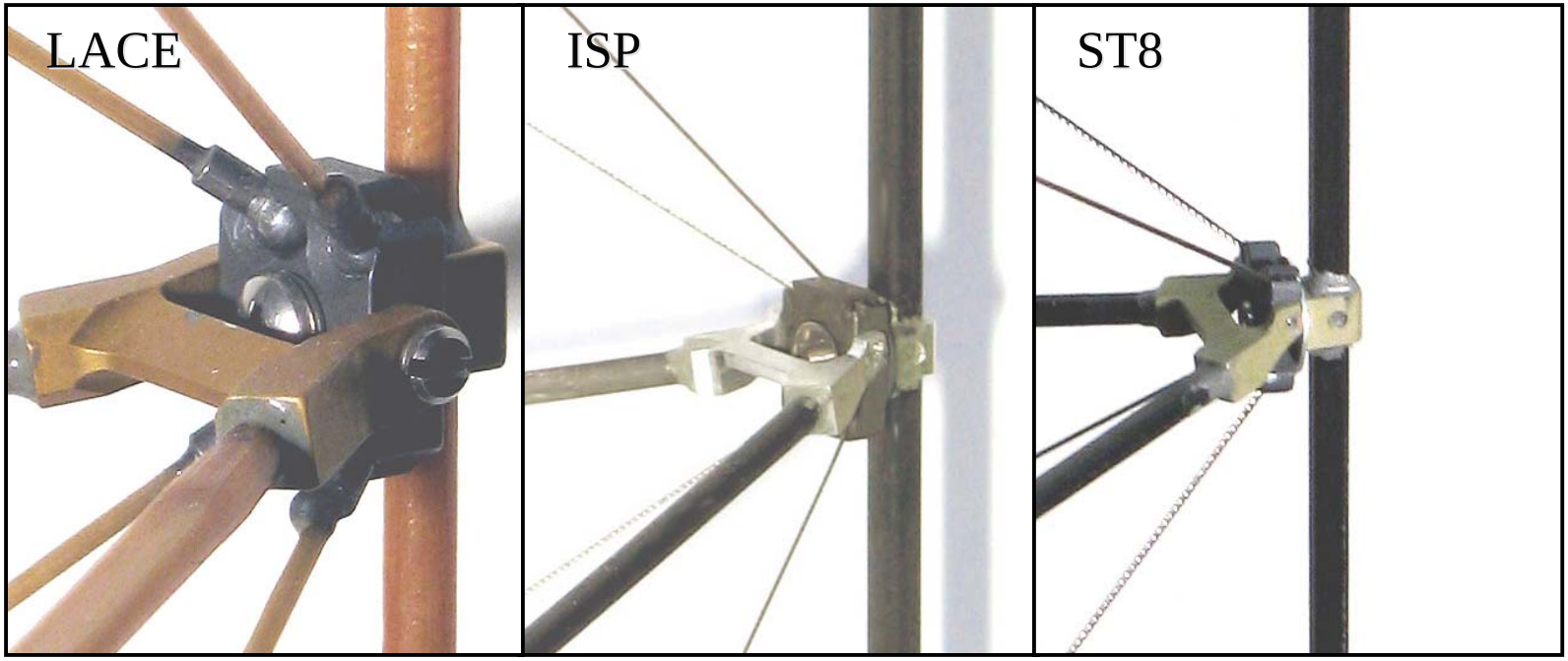


Comparative Mast Properties



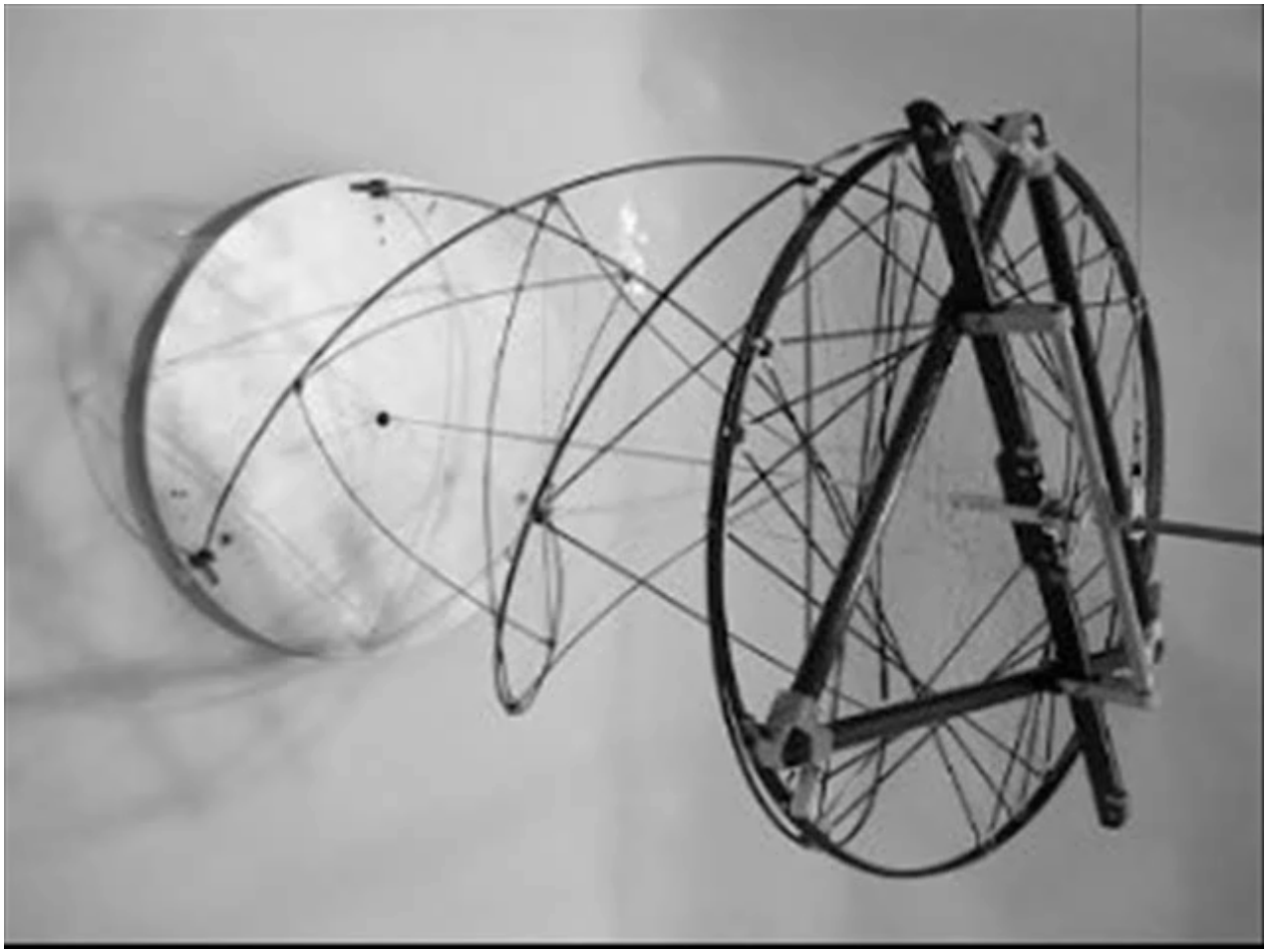
LACE	ISP	ST8
$\varnothing_M$ = 25.5 cm	$\varnothing_M$ = 39.5 cm	$\varnothing_M$ = 24.0 cm
L_S/L_D = 2.0%	L_S/L_D = 0.85%	L_S/L_D = 0.88%
ρ_L = 240 g/m	ρ_L = 70 g/m	ρ_L = 34 g/m

Comparative Fitting Sizes



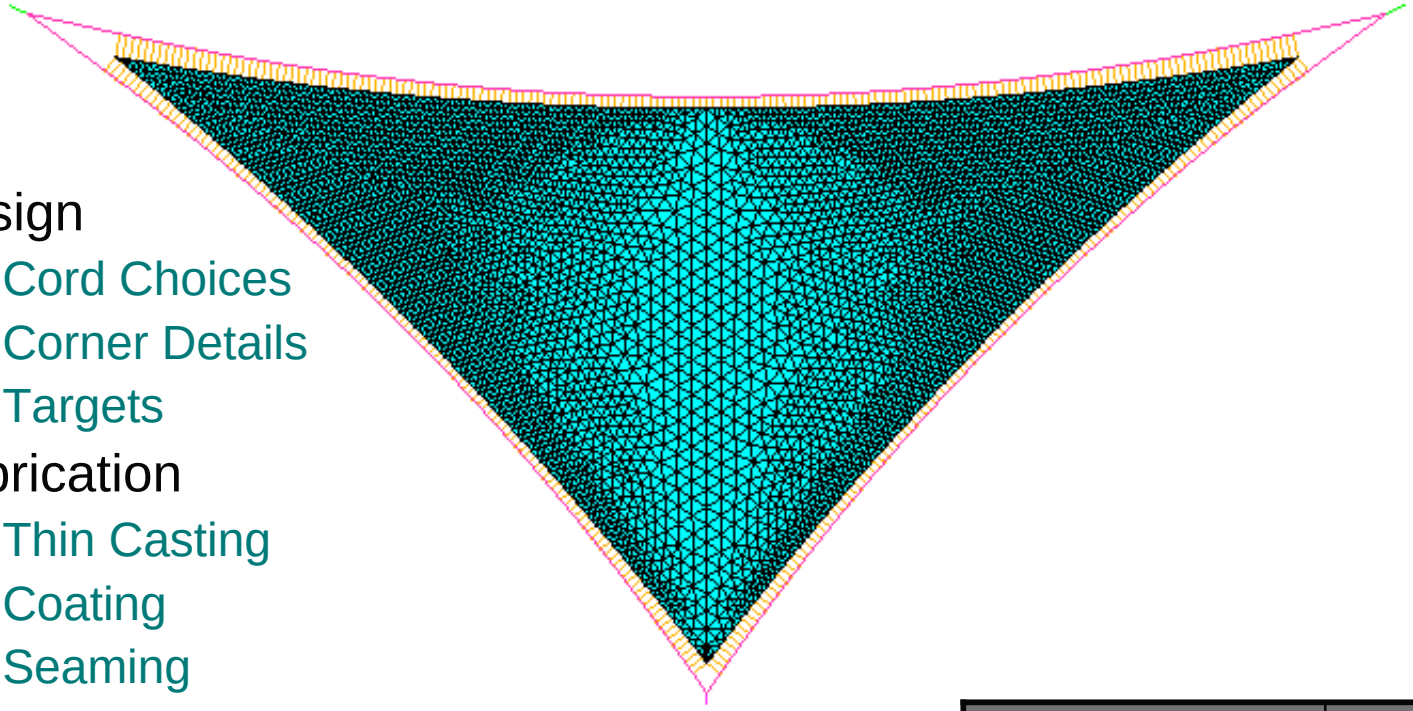
LACE	ISP	ST8
$\varnothing_L$ = 3.8 mm	$\varnothing_L$ = 2.8 mm	$\varnothing_L$ = 2.0 mm

Video of Mast Deployment



Sail Technology Maturation

Challenges Overcome

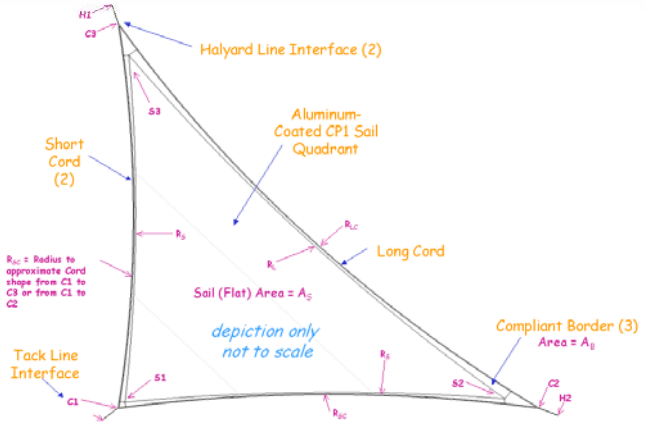


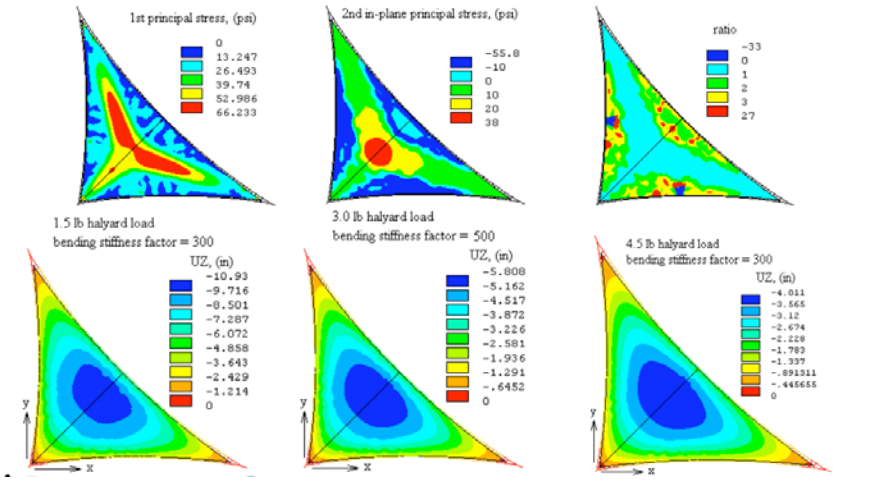
- Design
  - Cord Choices
  - Corner Details
  - Targets
- Fabrication
  - Thin Casting
  - Coating
  - Seaming
- Analysis
  - Mechanics of shear in compliant border
  - Efficient 3D nonlinear models, with gravity
- Functionality
  - Packaging, Folding
  - Deployment Sequencers

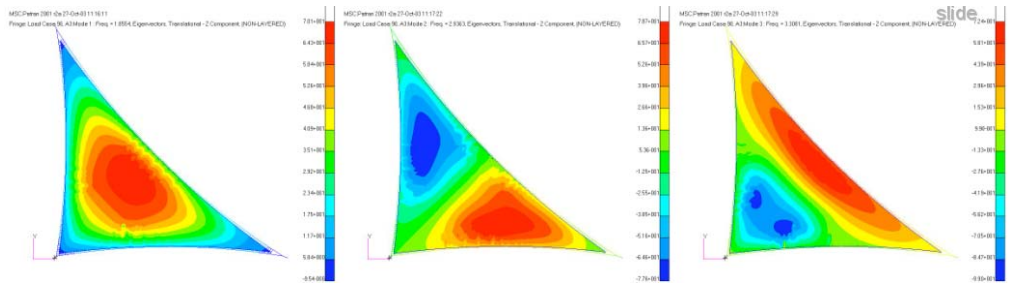
Sail Description	Completed
Workhorse Sail	12/03/03
Refined Sail 5	03/9/04
Refined Sail 3	04/3/04
Perf. Sail (1.5-m)	2/15/04

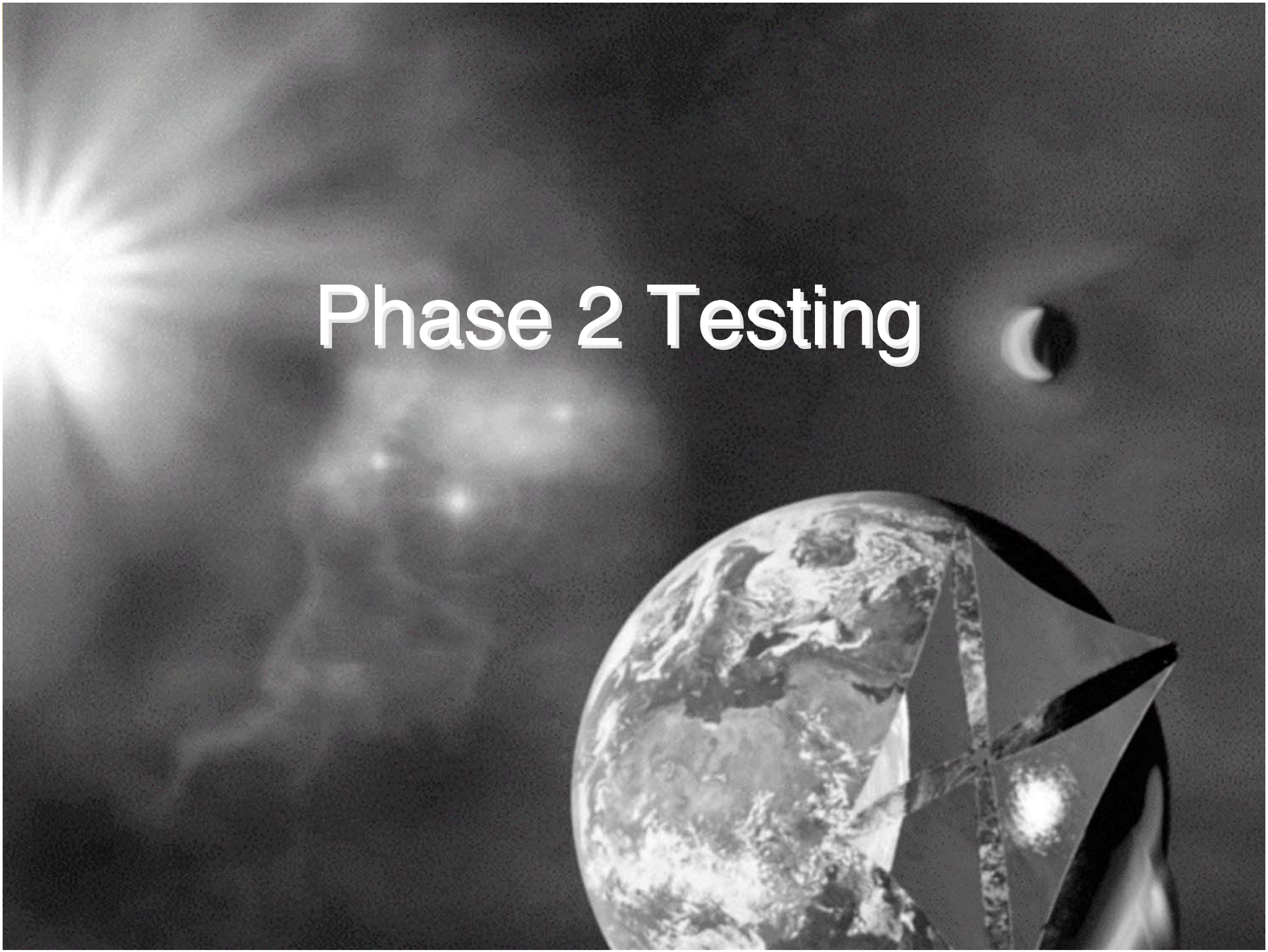
Analysis Development

- ABLE-LaRC-SRS Team Effort
- Convergence of models challenging
- Methods for sail membrane and compliant border modeling developed
- Cases run for:
  - Zero-g large sails (40-100 m)
  - Gravity-loaded sails (10, 20 m)
  - Horizontal and vertical testing
- 3-d wrinkling predictions achieved
- Models rerun as designs evolved
  - Workhorse, RS5, RS3
  - Predicted and Actual thicknesses
  - As-built mass with add-ons
  - Stress, Sag, Modes

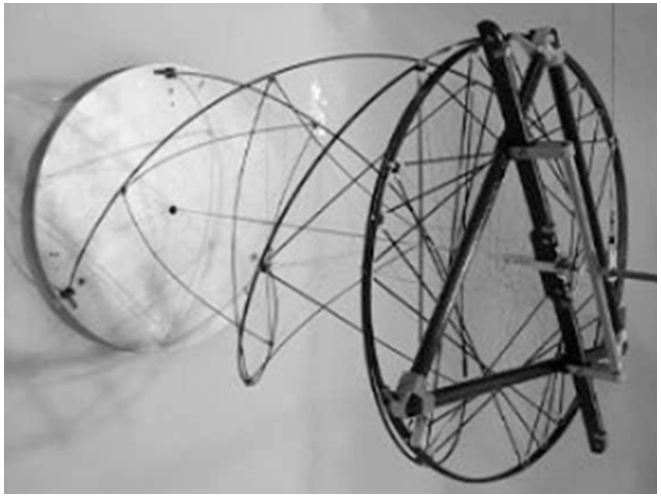


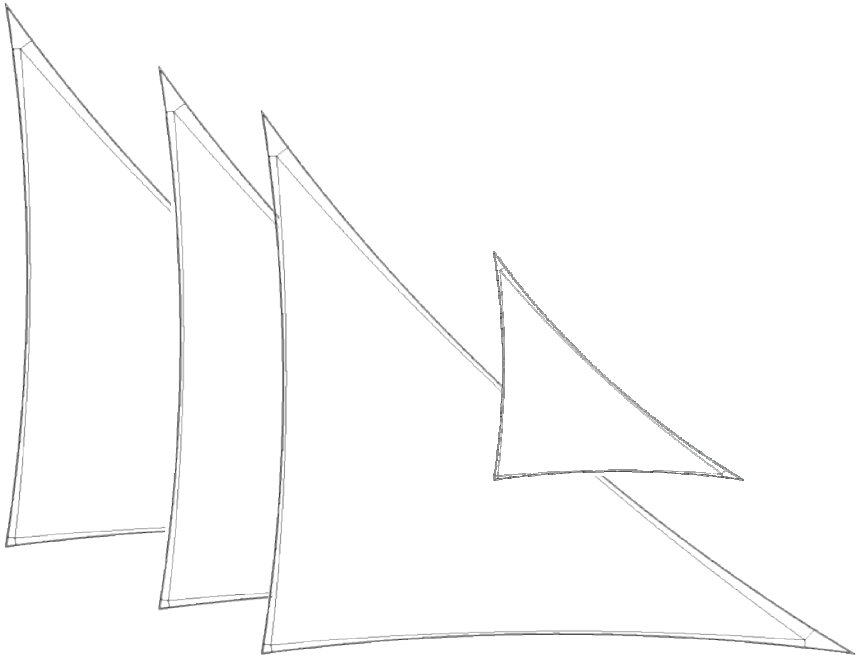





Phase 2 Testing

Flow Diagram for Mast & Sail Testing

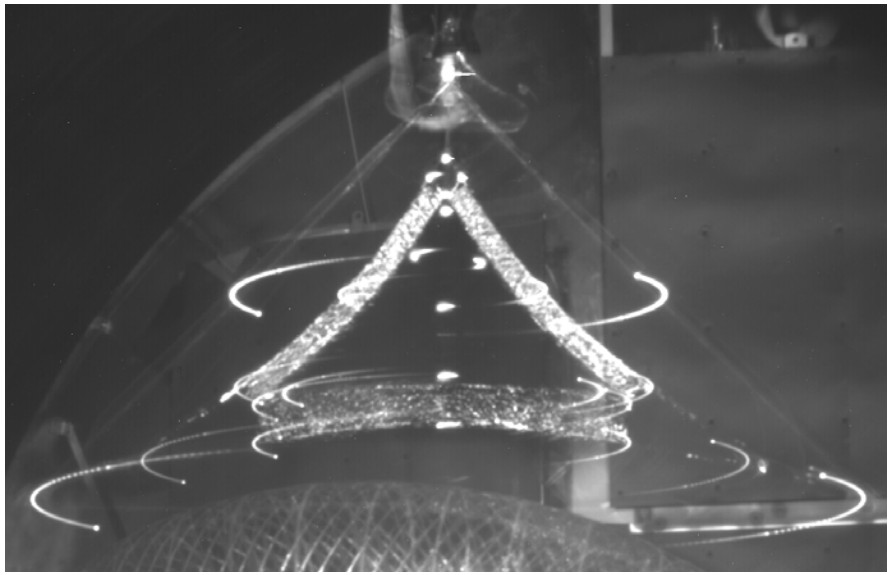




Sail Thermal Vacuum Test

- Test set up at GRC Tank 6
  - Vacuum Solar Simulation
- Chamber extremes
  - Pressure at 10^{-6} torr range
  - Cold soak at -128°C
- Successfully Completed
  - 0-4 sun intensity

Image shows rotation of sail under long exposure



Photogrammetry Courtesy of Dr. Mike Holmes, AFRL

Poster – Sail T/Vac. Testing

Thermal Vacuum Testing of Subscale Solar Sail at NASA GRC Tank 6 Facility

Testing Performed February–March 2004

SRS TECHNOLOGIES

ATK ALLIANT TECHSYSTEMS

Goal

Conduct Pathfinder Tests of a Subscale Solar Sail Test Article in a Relevant Environment

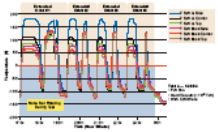
Test Objectives

- Measure Sail Temperatures at 1-Sun, Over Orbital Thermal Cycles, in Vacuum, and at Various Sun Angles
- Evaluate 6-Inch Diameter Film Samples at 3-Sun and 4-Sun Intensities
- Verify Operation of Compliant Border in a Thermal Vacuum
- Evaluate and Compare Performance of Diffuse versus Retro-Reflective Targets

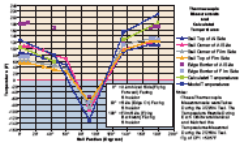
This technical effort is conducted under the MSFC ISP Program. Participants for this Test Included SRS Technologies, NASA MSFC, NASA GRC, and AFRL.

Solar Sail Thermal Characterization

Sail Temperatures Over 4 Orbital Thermal Cycles



Sail Steady State Temperature versus Sail Position

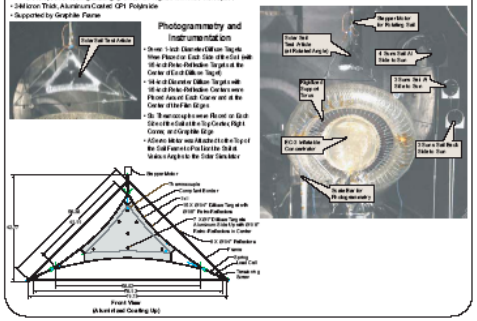


Test Hardware

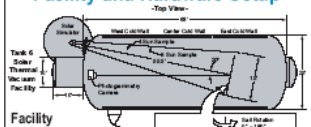
Test Article

- Triangular Sail (1.5m Hypotenuse x 1m Sides)
- Design and Dimensions are a Scale Down of a 10m Sail Design Developed for Testing at Langley Under a Program with Able Aerospace
- 2 Mil Iron Thick, Aluminum Coated CP1 Polyimide
- Supported by Graphite Frame

Photogrammetry and Instrumentation



Tank 6 Thermal Vacuum Test Facility and Hardware Setup



Facility

- Tank is 18 Feet Long x 25 Feet in Diameter
- Solar Simulator Has Over 36 Arc Vessel Lamps Capable of Providing 1.2 Suns at 36 Feet from the Simulator
- Twelve Cryopumps Provide 10⁻⁶ Torr Level Vacuum
- Liquid Nitrogen Cold Walls Simulate Space Thermal Environment (Aft Center and East Cold Walls were Operational During this Test)

Camera Setup

- ARRI Supplied Vacuum-Grade Enclosure Containing a CCD Camera and a Video Camera
- Halogen Lights (for Retro-Reflective Target Illumination) were Placed on Top of the Camera Enclosure
- An IR Camera was Used to Measure Sail Temperatures, However this was Not Possible Due to the Reflective Nature of the Sail (the Camera Could Not Distinguish Between Actual Sail Radiance and Reflected Radiation)

Testing

- Performed Three Long Tests (Two at Full Sun and One at 1/3-Sun)
  - Each Test Included 4 Orbital Thermal Cycles
  - Each Orbital Cycle Included 60-Minute Co-Sun, 30-Minute Eclipse
- Sail was Rotated 180° During Each Co-Sun and Eclipse Cycle
- Photogrammetry Measurements of Diffuse and Retro-Reflective Targets were Taken at Several Angles

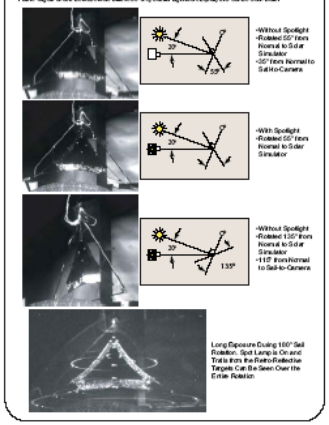
Date	Test Summary
23 Feb	Hardware Checkout — Full and Partial Sun, without Cold Walls, Ambient Pressure
25 Feb	Full Sun, with Cold Walls, Vacuum, 4 Orbital Cycles
3 Mar	1/3-Sun, with Cold Walls, Vacuum, 4 Orbital Cycles
20 Mar	Full Sun, with Cold Walls, Vacuum, 4 Orbital Cycles

Photogrammetry Target Evaluation

- SRS Currently Uses Retro-Reflective Photogrammetry Targets to Measure the Shape of Thin Films
- Discussions of Using Retro-Reflective Targets
  - Effects on Wrinkles in Thin Film Where They Are Placed
  - Add Extra Weight to Film
  - Requires High-Intensity Light Source Located at the Camera Position to Illuminate the Targets
- Advantages of Diffuse Targets
  - Can Be Cast into the Film Thereby Adding No Additional Weight or Irregularities
  - Do Not Require a High-Intensity Light Source as the Light Source Does Not Need to Be Located at the Camera Position, Therefore Sun Can Be Used as the Light Source

Test Results

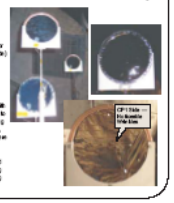
- Diffuse Targets Could Be Detected Within 15° of Sail-to-Camera Orientation
  - Could Have Been Closer at Even Lower Sail-to-Camera Angles but No Measurements were Taken at Less Than 10°
- Future Targets Should Be Fabricated so Diffuse Co-Dot Is Darker Light Intensity and Can Be Even Better



Sail Samples

Thermal Characterization of Film Samples at 3-Sun and 4-Sun Intensity

- Tested Three 6-inch Sail Film Samples
- Two Samples were Placed at 3-Suns Intensity
  - One Front Side (Aluminized Side) Facing Solar Simulator and One Backside (CP1 Side) Facing Solar Simulator
- One Sample was Placed at 4-Suns Intensity
  - Front Side Facing Solar Simulator
- Samples were Instrumented with Thermocouples (Also for Use in Determining with Increasing Thin Film with Thermocouples, the Resulting Temperatures were Not Accurate
- All Sail Samples, 3-Suns and 4-Suns Exposure, Experienced Retraction from Mounting Ring and Some Holes in the Wrinkling in the Film



Conclusions

Advanced TRL of Solar Sails by Demonstrating in a Relevant Environment

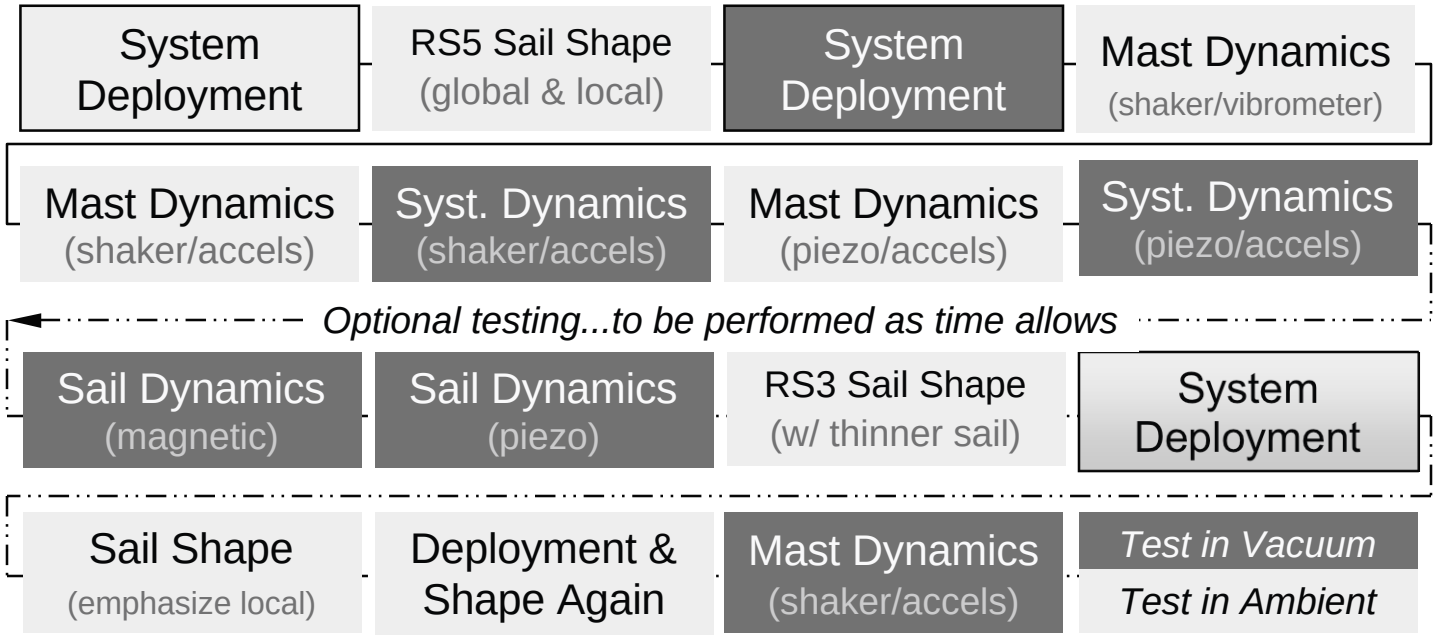
- Sail was Cycled Through Eight Orbital Thermal Cycles at 1-Sun, Four Orbital Thermal Cycles at 1/3-Sun, Over 15 Hours of Testing, at Vacuum Pressures Down to 1x10⁻⁶ Torr, and Performed Over a Thermal Range of -130°F To +180°F
- Sail Film Temperatures Closely Matched Thermal Models
  - All Temperatures were Well Under the T_g of CP1 (505°F) Thus Maintaining Shape Throughout Simulated Orbit Cycles
  - Variation Between Actual and Calculated Temperature is Due to Thermocouple Method of Measuring Film Temperatures
- Sail Samples Did Not Degrade at 3-Sun And 4-Sun Intensities
- Compliant Border Performed As Designed
  - No New Sail Wrinkling Was Observed Throughout Thermal Cycling
- Diffuse Photogrammetry Targets Worked to Within 10° Sail-to-Camera Orientation

Compliant Border Verification

- Compliant Border is Designed to Compensate for Any Thermal or Mechanical Shrinkage Between the Sail Film and the Edge Due to Stiffening Cause Wrinkling
- Border Performance Designed Throughout the Thermal Cycling
- No Wrinkles Due to Thermal-Induced Shrinkage Observed
- Reflection from the Compliant Border Could Be Clearly Seen at Certain Sun Angles
  - This Can Be Used in Addition to the Photogrammetry Target(s) to Determine Position of the Sail

Quadrant Testing at LaRC

- Top-Level Test Goals
  - Demonstrate deployment in vacuum of mast and sail system
  - Provide data for modeling evaluation & correlation on:
    - Sail and mast shape and mast/sail/system dynamics



Summary of Phase 2 Testing

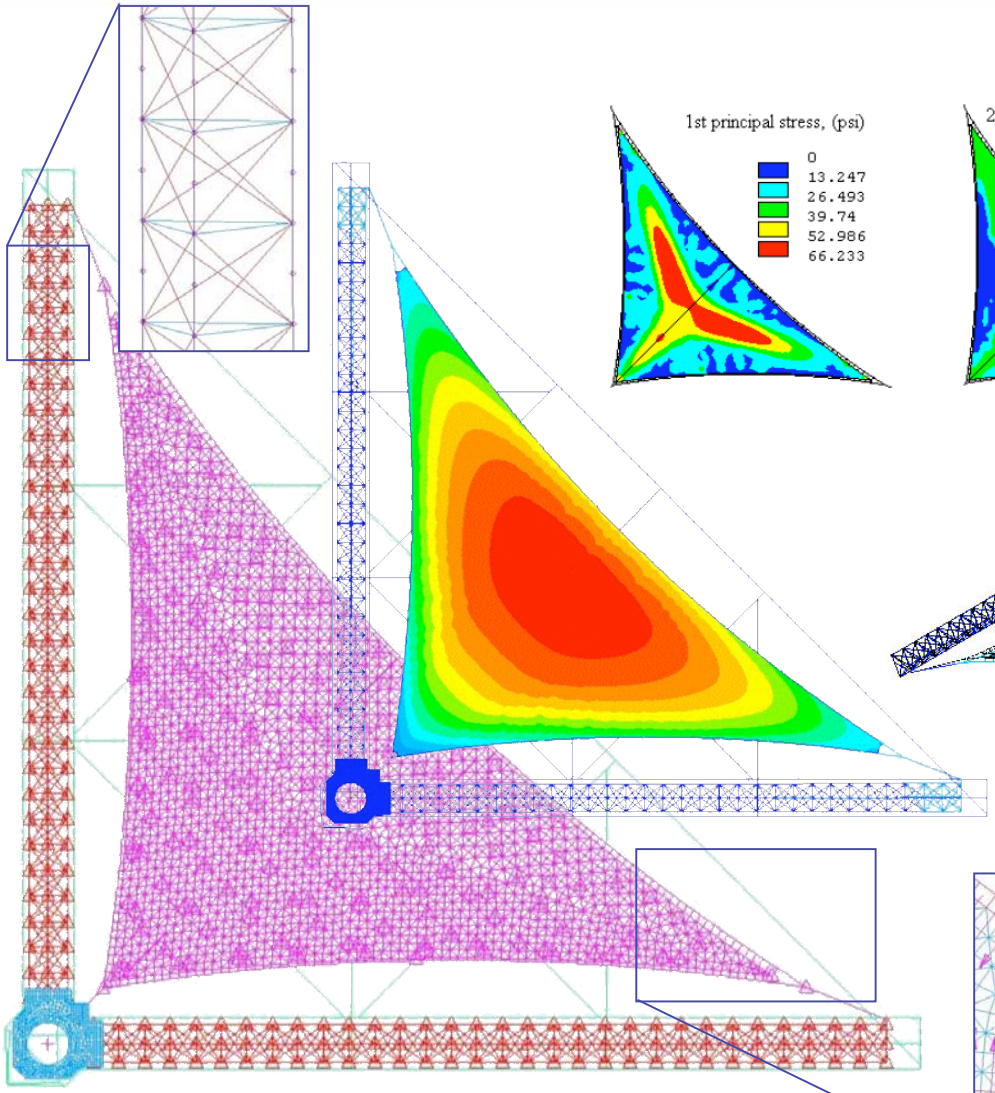
- Testing priorities all successfully achieved:
  - ✓ Demonstrated deployment in vacuum of S^4 Quadrant System
  - ✓ Measured global sail shape (3 loads)
  - ✓ Measured mast, sail, and system modes
- Data for modeling evaluation & correlation:
  - ✓ Telemetry and Imagery of deployment recorded (see video)
  - ✓ Operational deflection shapes and freq. response functions
  - ✓ Detailed dynamics test data analysis in process
  - ✓ Shape data received and analysis complete
- Goals of Optional Testing also all achieved:
  - ✓ Piezo excitation (flight traceable dynamic input method)
  - ✓ Mast dynamics in vacuum (for precise measure of damping)
  - ✓ RS3 shape measurement and deployment

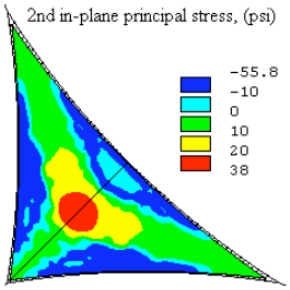
10-m Quadrant in LaRC Chamber*

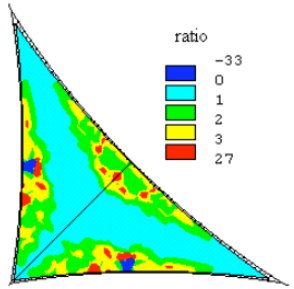
*In-vacuum deploy video will play automatically

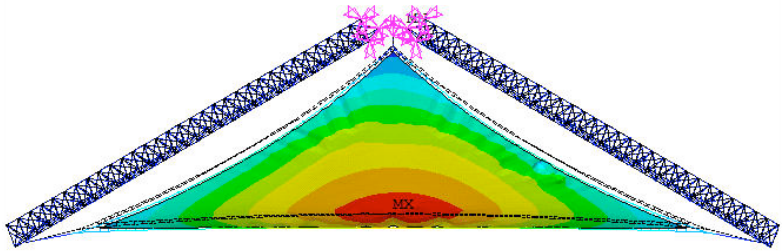
S4 Vacuum Deployment at LaRC

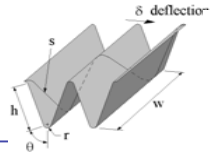
System Analysis

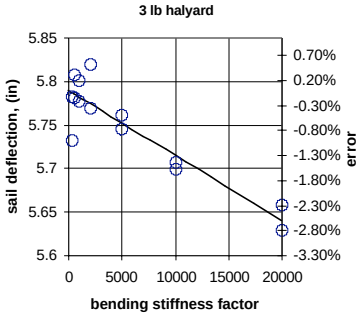








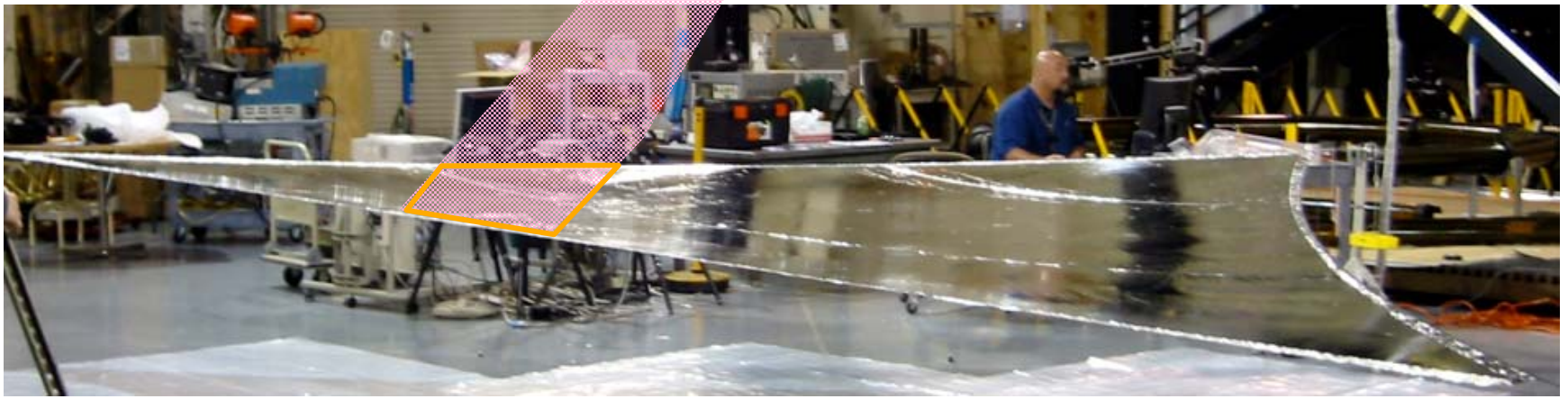




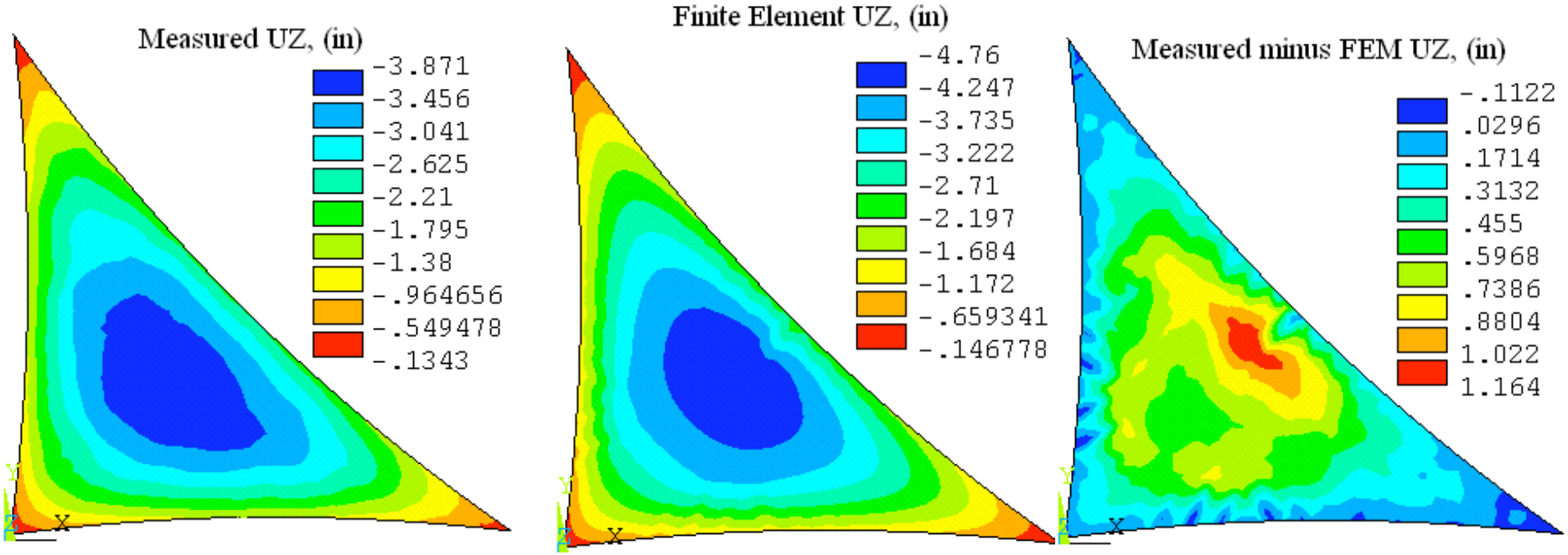
Sail Shape Testing

- Global and local shape measured
  - Sag in 1-g correlated to FEA models
- Local testing documented creasing effects from folding and rolling
  - Allows identification of sail topology (propulsiveness) at 0-g stress levels

Leica Laser Radar



Sail Deflections (2.5 lb Tack Load Case)



Poster – Propulsion Modeling

Solar Sail Propulsion Evaluation Tool

SRS TECHNOLOGIES

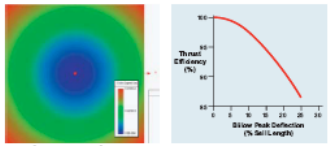
NASA

Goal

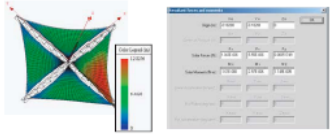
Develop a Method to Enable High Fidelity Thrust Vector and Torque Predictions Including the Effects of Sail Billow, Wrinkling, Reflection, Emission, and Absorption

Initial Studies and Verification

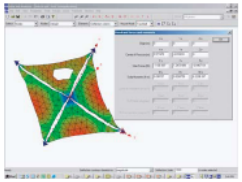
Sail Billowing Effect



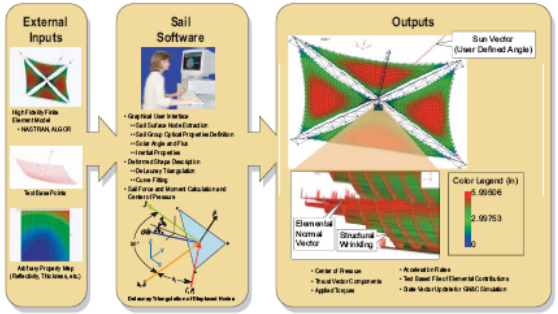
Sail Structure Interaction



Modeling of Sail Damage and Deployment Errors



Approach

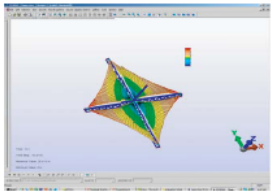


Extract Sail Operational Geometry from High Fidelity FEM Analysis or Points Cloud and Perform Element by Element Thrust Vector Calculation. Elemental Thrusts Are Summed to Obtain:

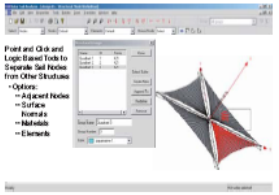
- Resultant Thrust Vector Magnitude and Direction
- Center of Pressure
- Vehicle Torques

Sail Software Features

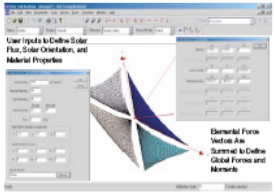
Finite Element Model Results



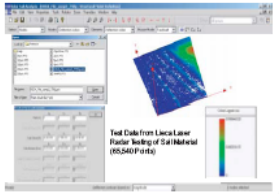
Extraction of Sail Surface Nodes from Complex FEM Model



Calculation of Solar Pressure Forces and Torques

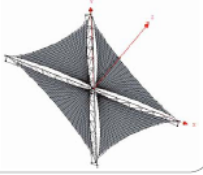


Alternate Input Method - Import Geometry from Points Cloud



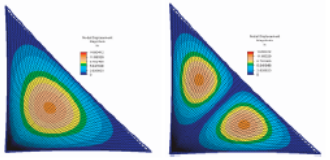
Current Development Status

Initial Release Capabilities

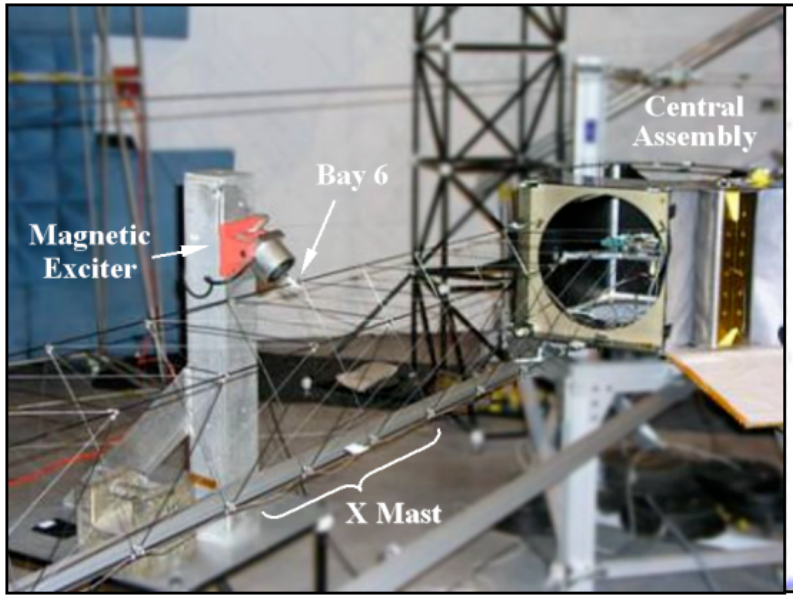


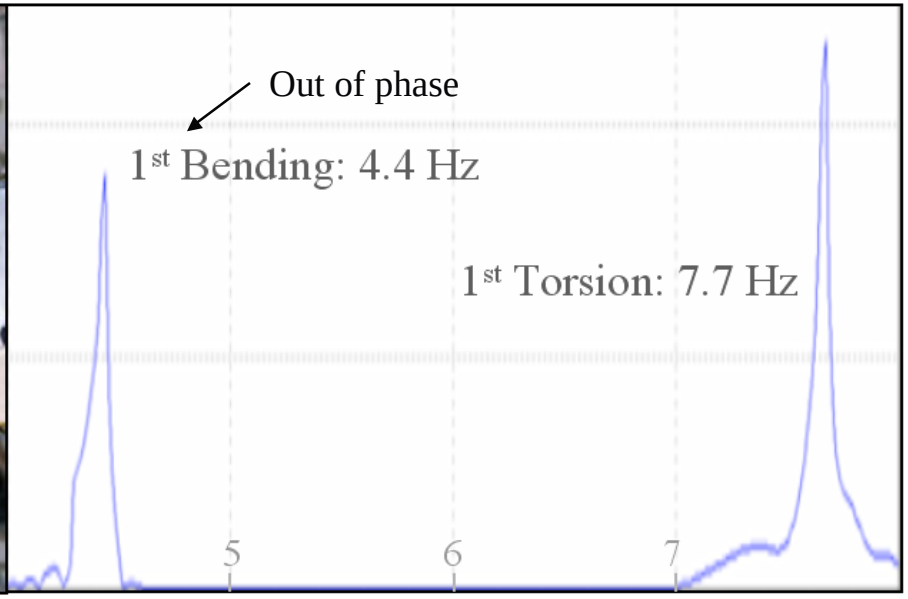
Sail Software Benefits

Future Enhancements

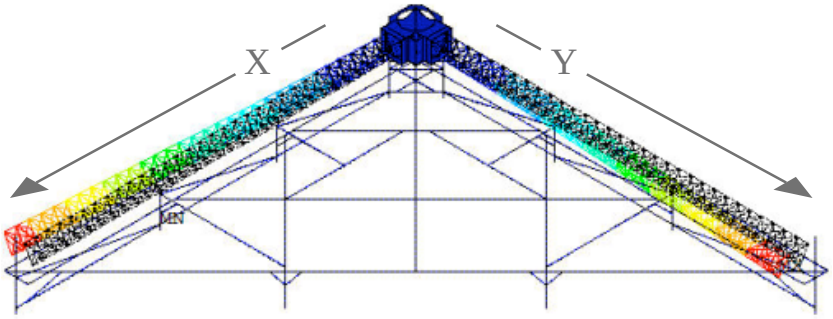


Dynamics Testing: Quick Look Data

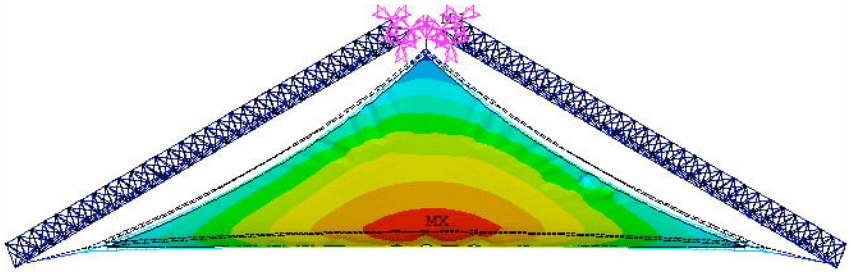




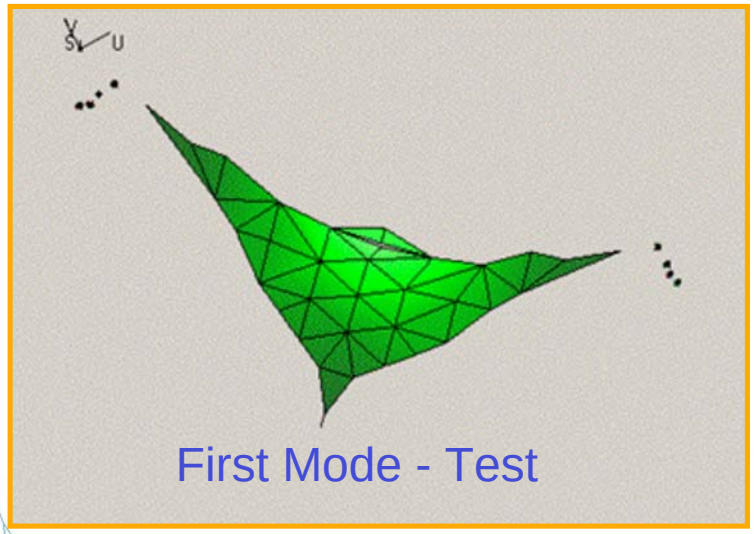
Mode 1: Prediction: 4.6 Hz

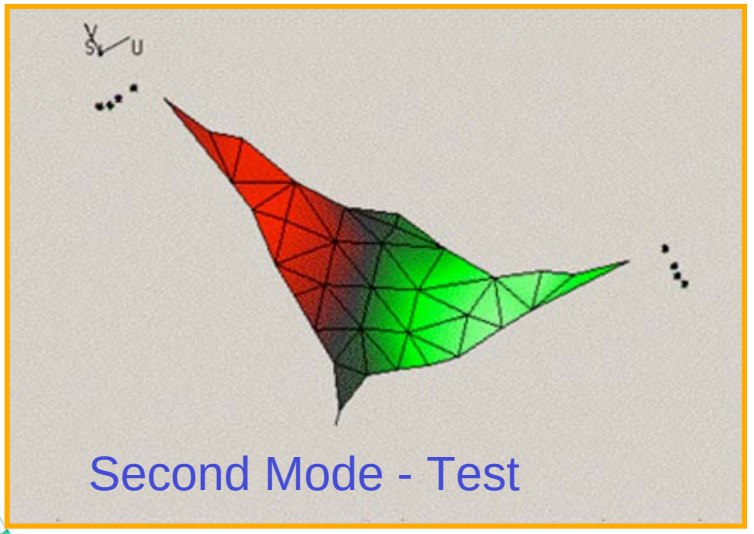


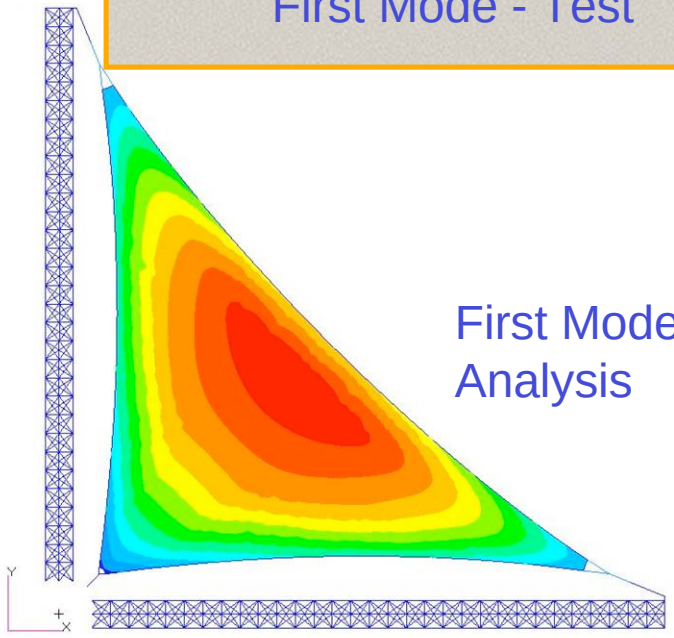
Mode 1: Prediction: 1.3 Hz



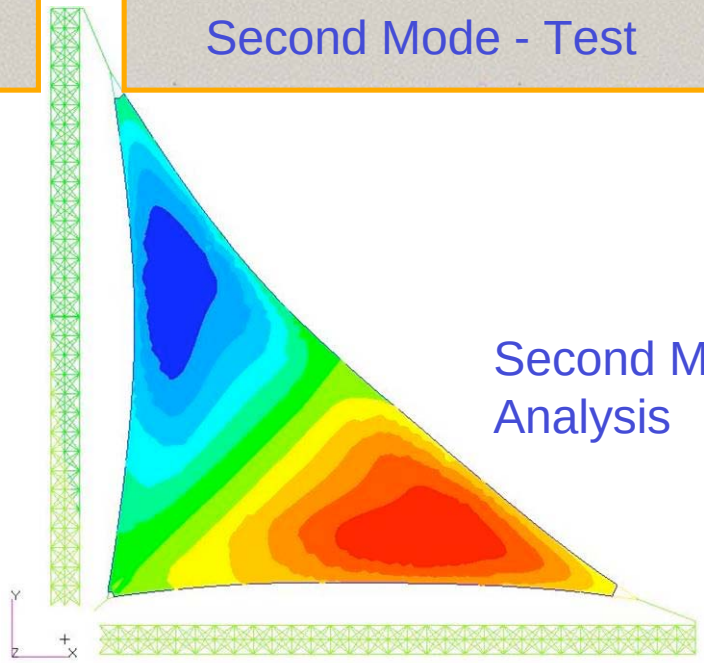
System Modes: Test/Analysis Comparison





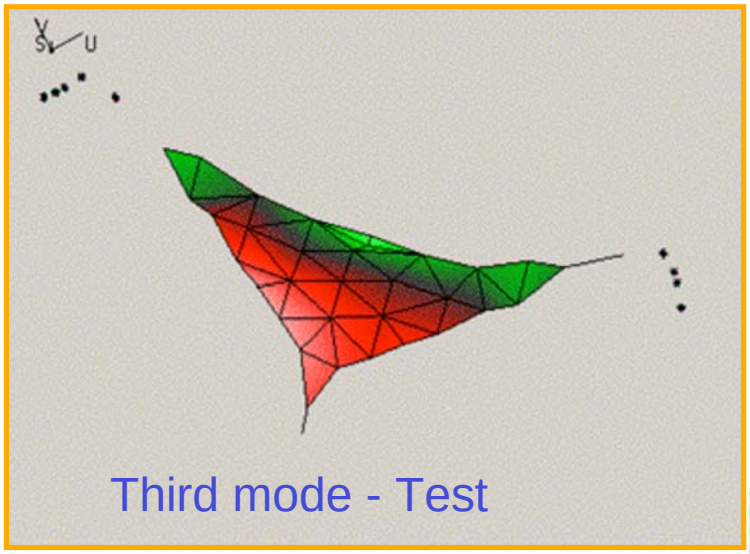


First Mode Analysis

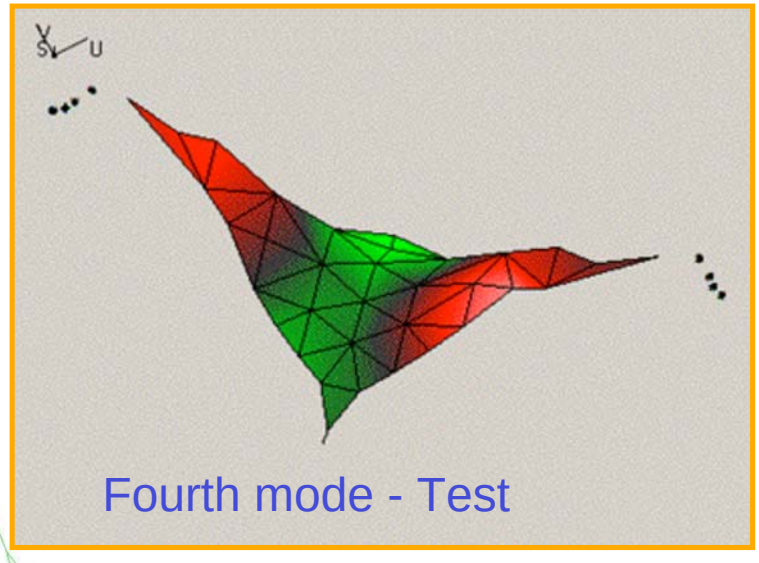


Second Mode Analysis

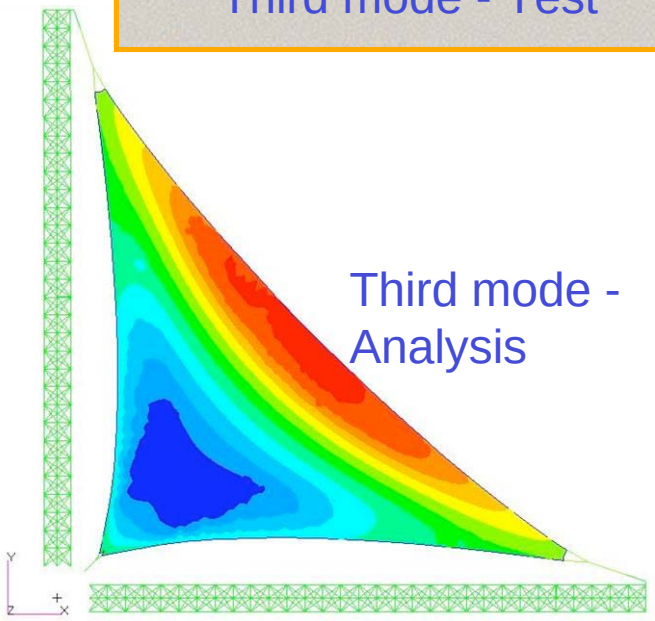
System Modes: Test/Analysis Comparison



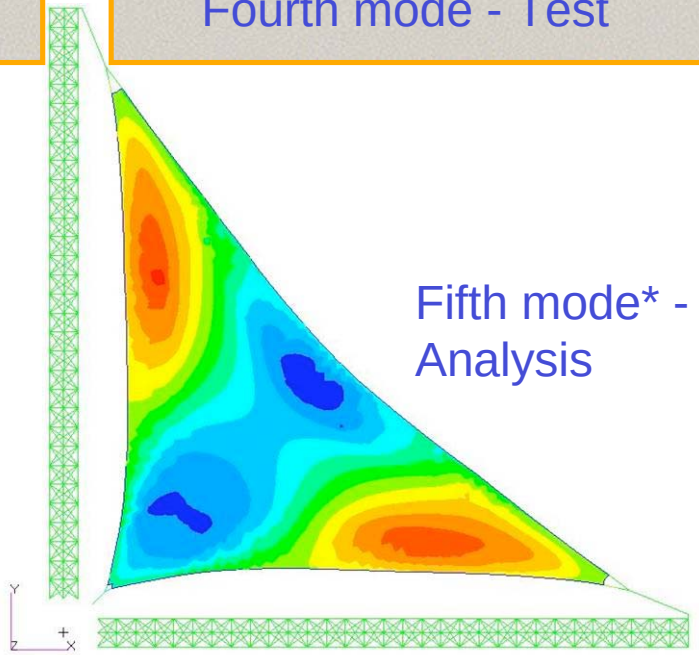
Third mode - Test



Fourth mode - Test



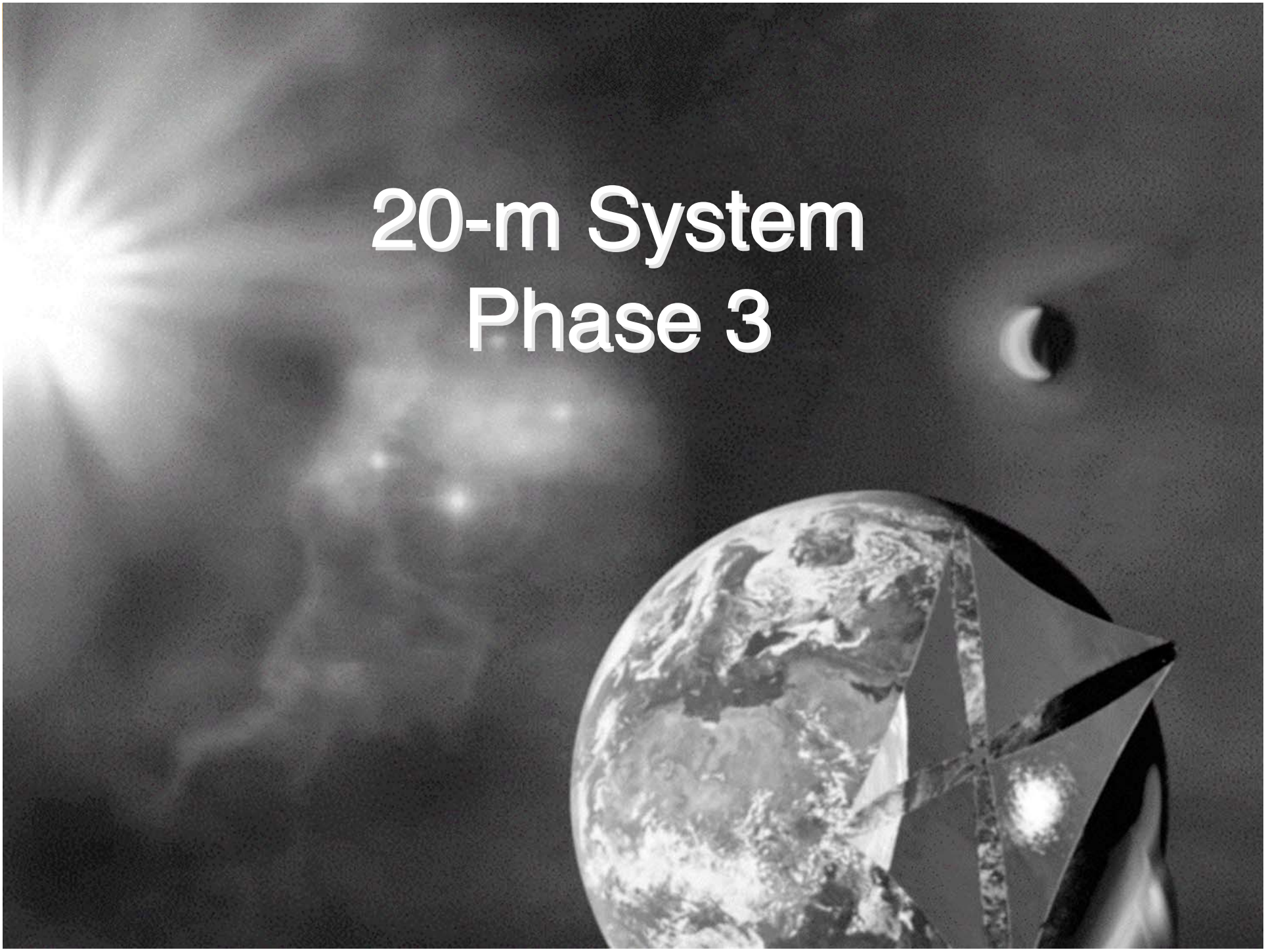
Third mode - Analysis



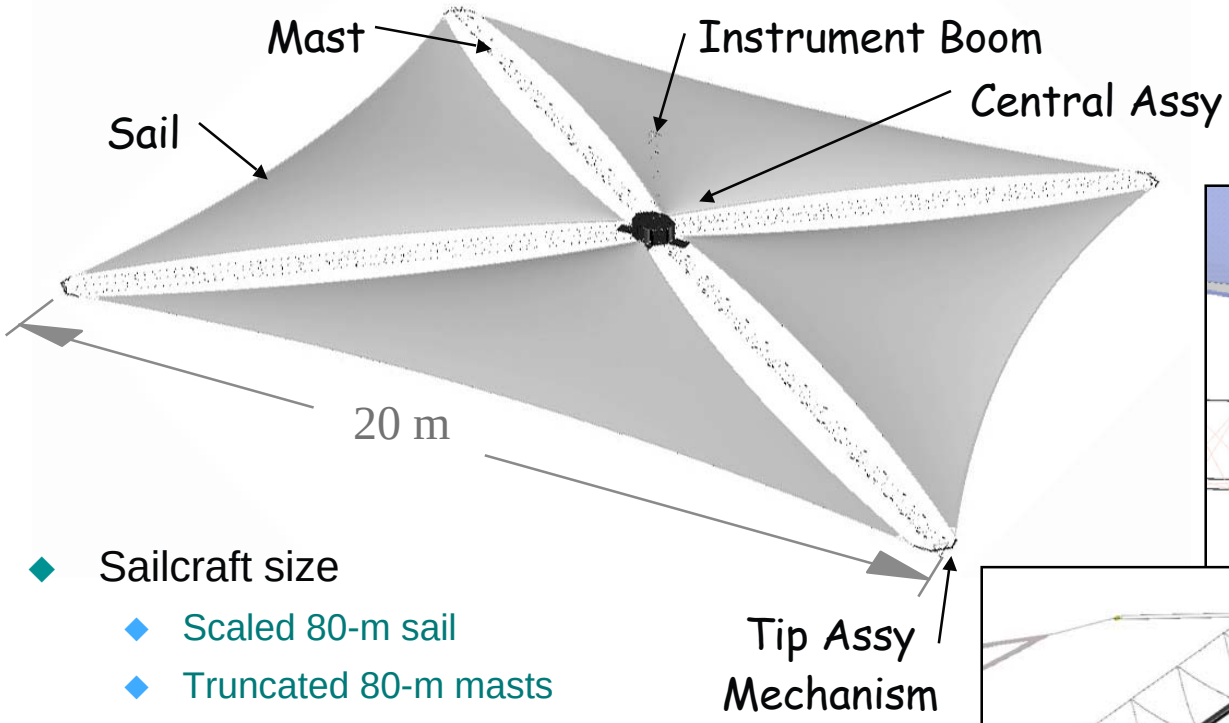
Fifth mode* - Analysis

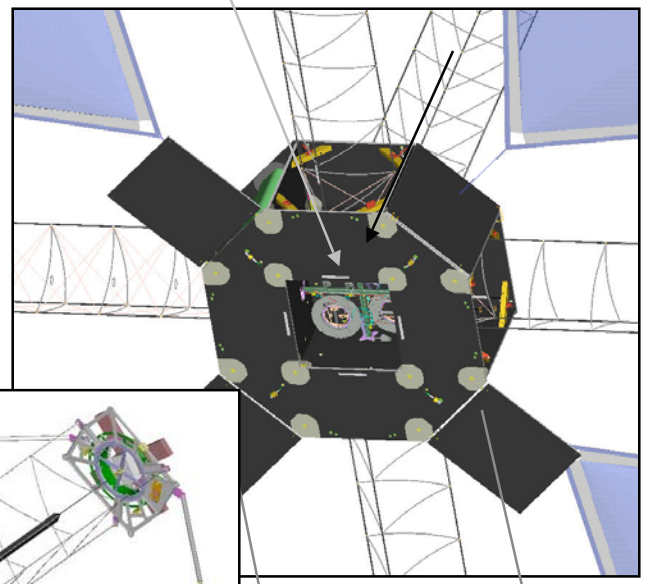
* 4th mode of test corresponds to 5th mode of analysis

20-m System
Phase 3



20-m S⁴ GSD General Design





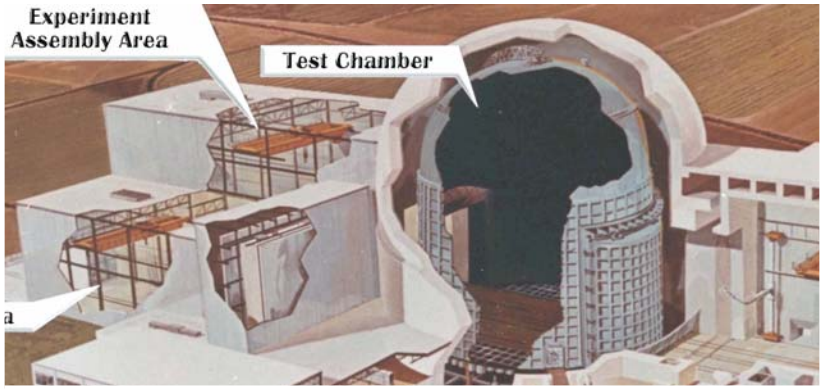
- Sailcraft size
  - Scaled 80-m sail
  - Truncated 80-m masts
  - Volume of 40-m flight system
- Methodology
  - Minimal weight
  - Scalable sailcraft
  - Robust and reliable
- Design Life
  - > 10 Years

- Key Environmental Validations
  - Vibration per enveloping launch specification
  - Deployment under thermal gradient extreme

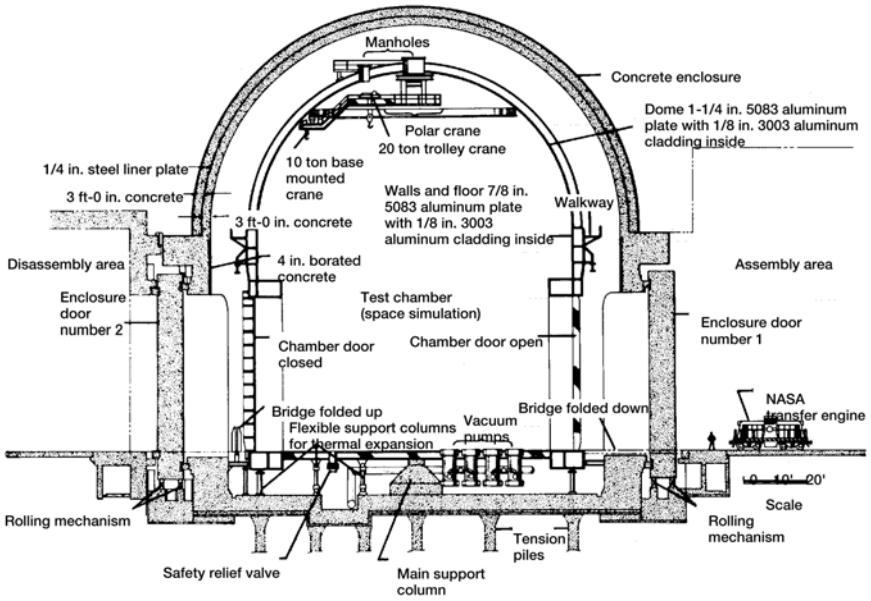
Testing at NASA Glenn – Plum Brook

- Plum Brook Test Objectives:
  - Deploy in Vacuum
    - Ambient Temperature
    - Cold (Thermal Gradient)
  - Demonstrate ACS Function
  - Measure Sail Shape
  - Measure System Dynamics

- Result:
  - Full system functionality… in vacuum…at temperature

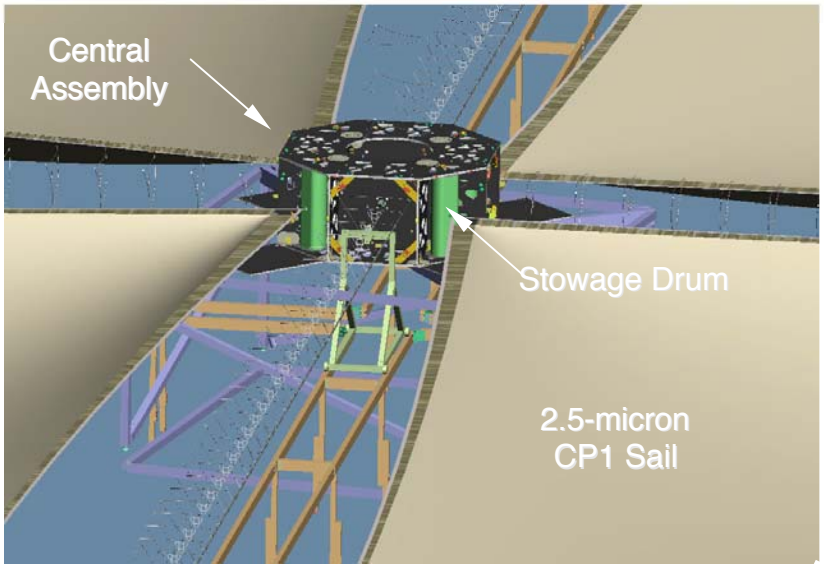


NASA GRC - Plum Brook

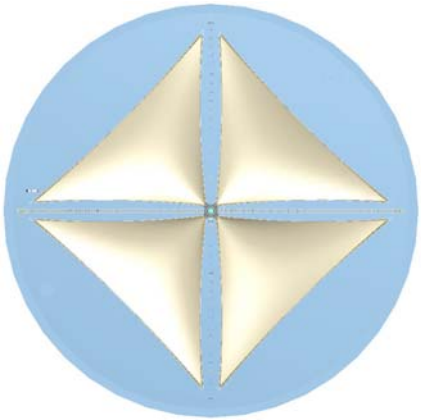


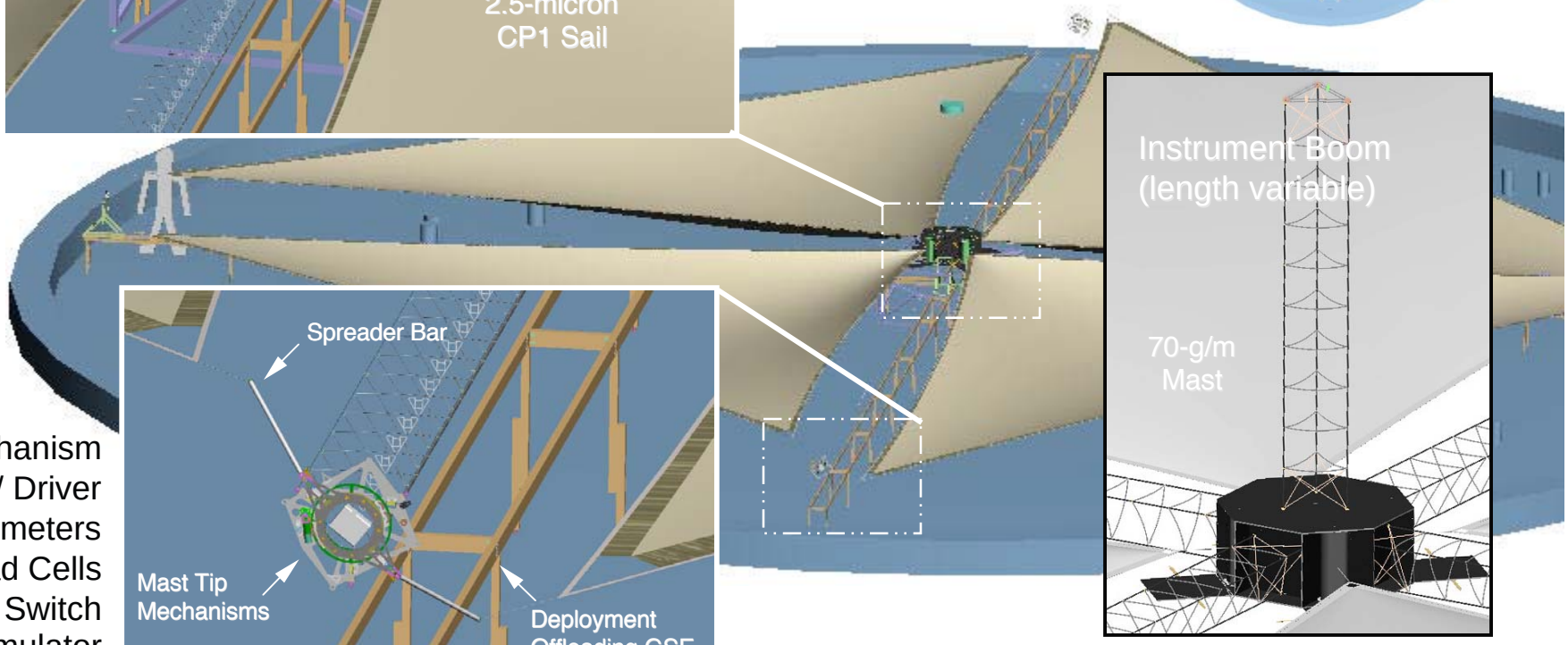
Cutaway view of test chamber.

20-m S^4 System Overview



Drive Mechanisms
Motors / Drivers
Electronics controls
Position Sensors
Mast Tip Release Actuators
Load Cells (Tack line)
Piezos

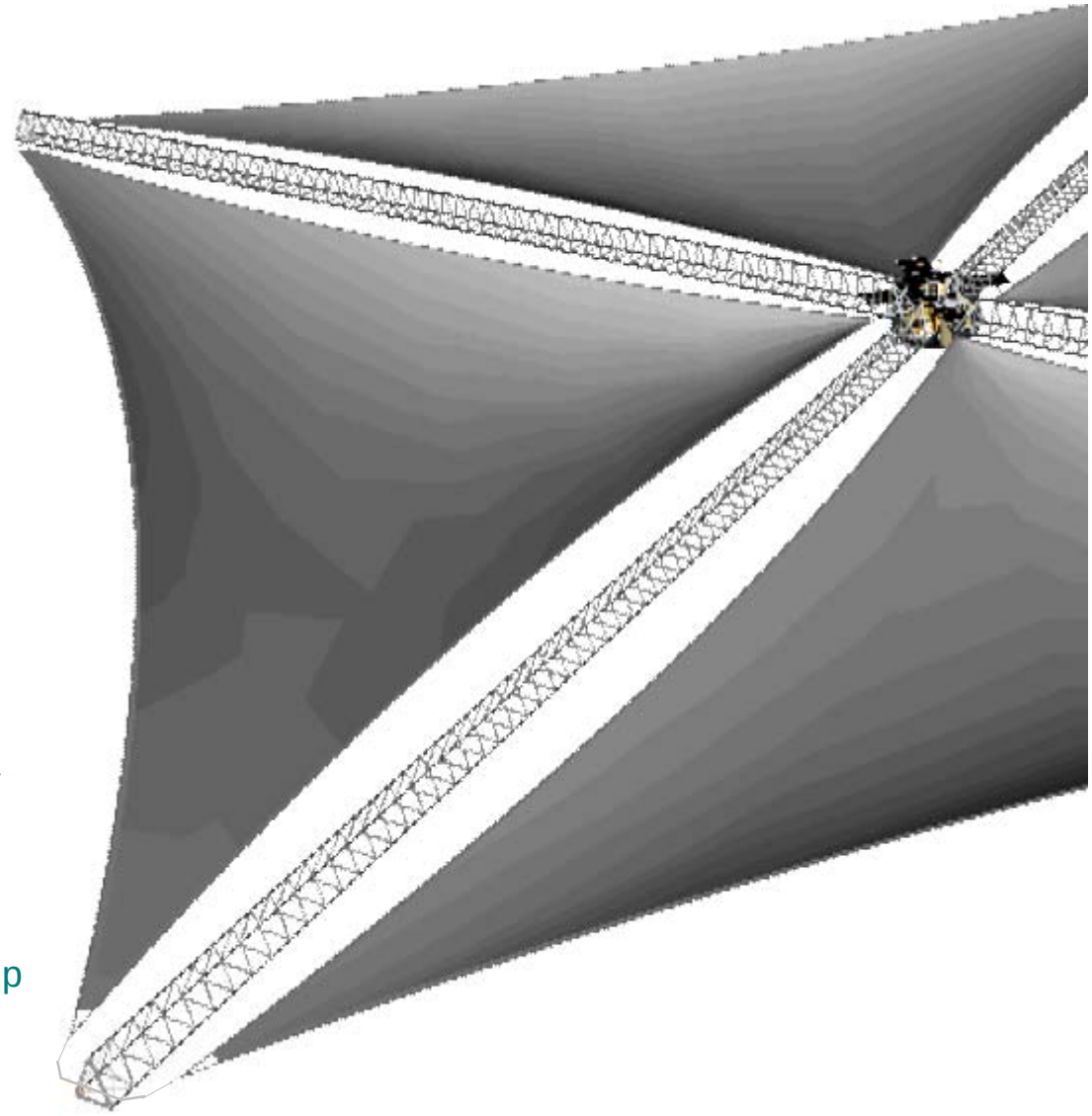




ACS Mechanism
& Motor / Driver
Accelerometers
Load Cells
Limit Switch
μPPT Simulator

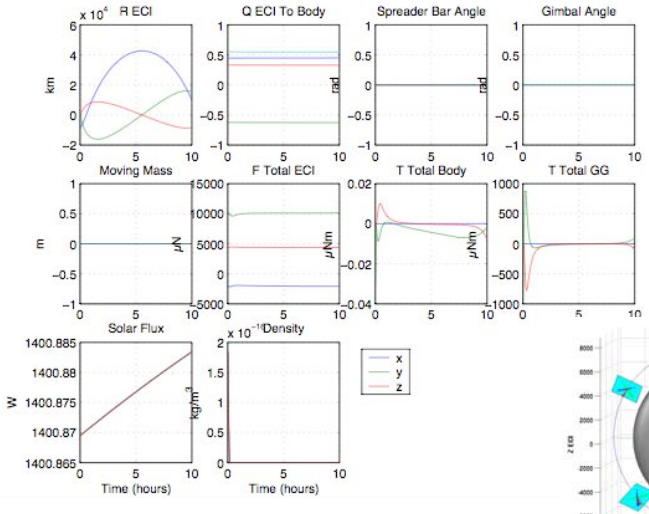
Deployment Sequence

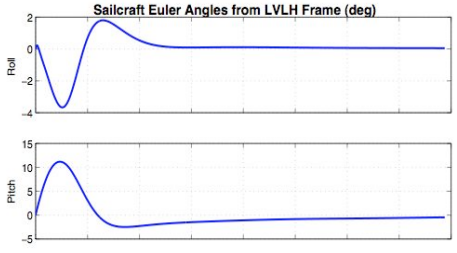
- Release launch vehicle ties
  - Stabilize in 3-axes
- Release mast tips
  - Simultaneous release (4x)
- Deploy masts
  - Mass runner/CA mechanism
  - Doors released by mast root
- Deploy sails
  - Mast tip motor
  - Spools
  - Sail sequencers
  - Sail deployment loads monitored via spreader load cells
- Sail Operation
  - Roll control via spreader rotation
  - Tension maintained by negators at tip
  - Sail operational loads monitored via tack line load cells

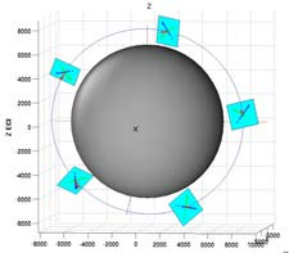


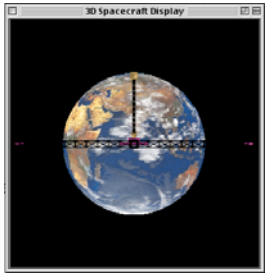
Attitude and Orbital Modeling

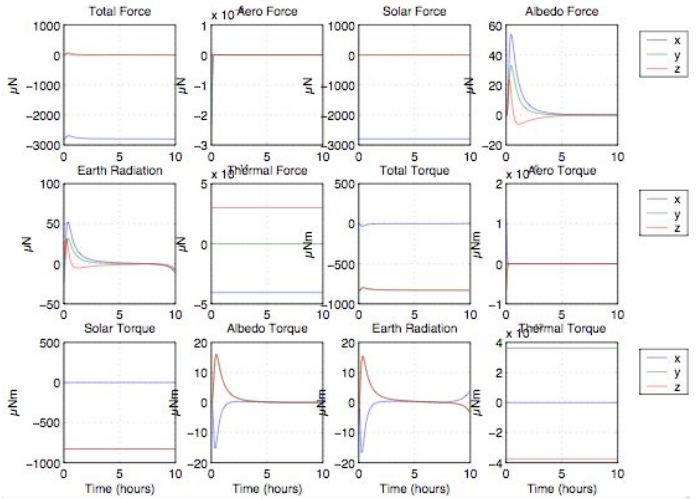
- Attitude Control Analysis
- High-Fidelity Orbit and Disturbance Modeling
  - Orbits studied to date: GTO, Sun-Synch, SPI
  - Propagated trajectories with detailed Sailcraft model & Disturbances:
    - Sailcraft Model: Component-Level Mass, inertia, center-of-mass, optical and thermal properties, Mesh of areas and normal vectors, RF and magnetic properties,…Power and Thermal Analysis, Multi-body Dynamics
    - Disturbances: SRP, Albedo, ACS, Aero, GG, Elliptic, RF, Magnetic…Sun, Moon, Earth Oblateness





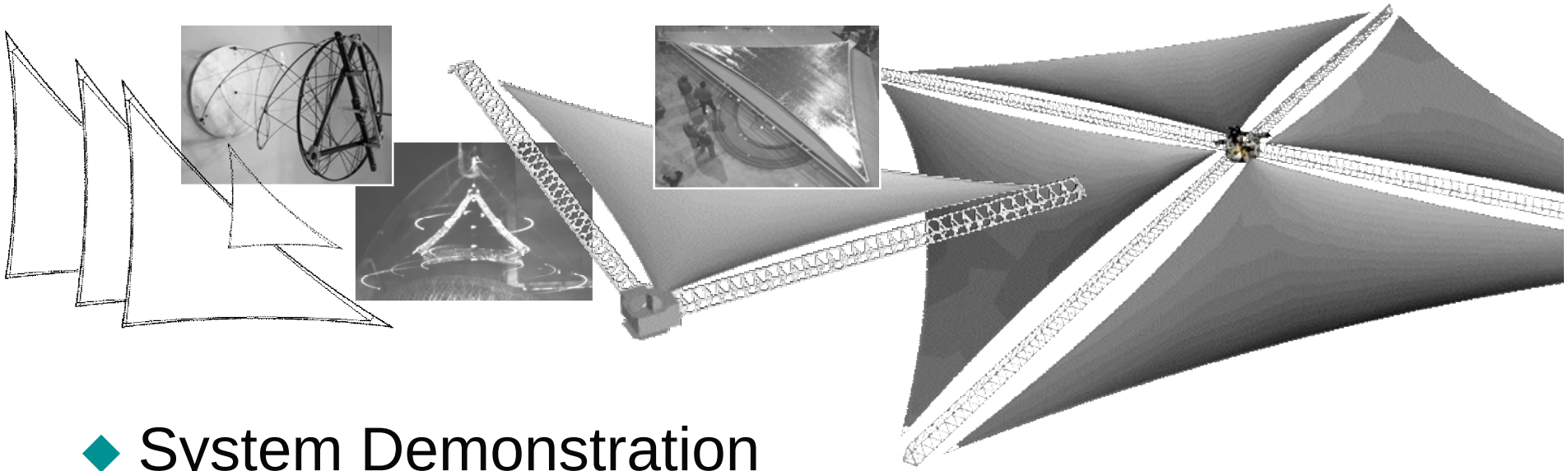






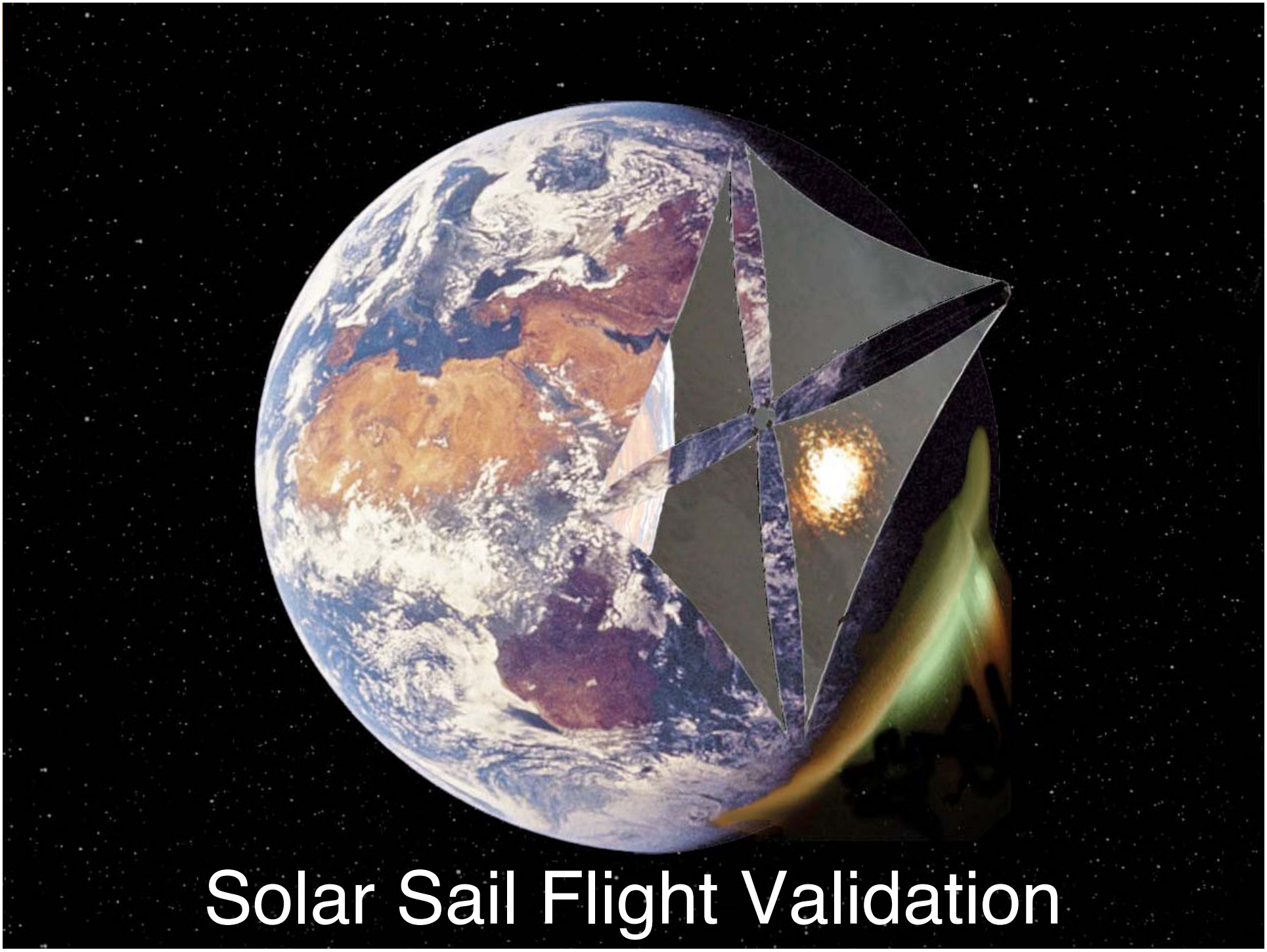
ISP S^4 GSD Program to Date

- Hardware development
  - Progressing on schedule and on budget
- Test and analysis
  - Correlation excellent, fidelity increasing



- System Demonstration
  - Planned for March 2005

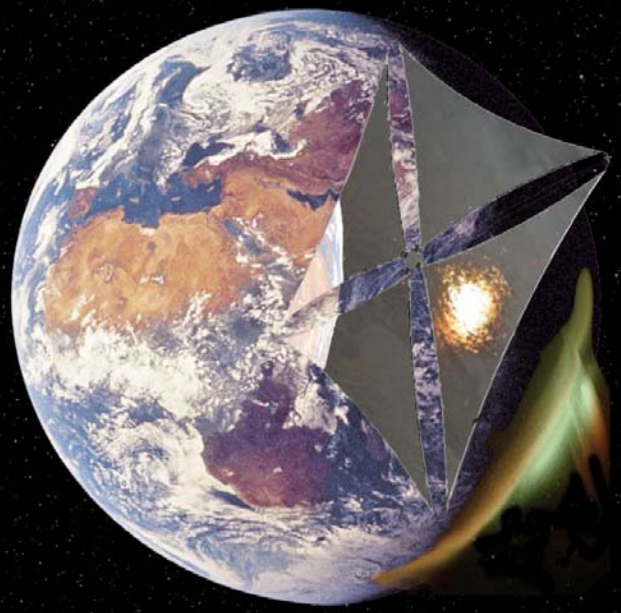

Time to Set Sail


Solar Sail Flight Validation

Looking Forward to Flight Validation

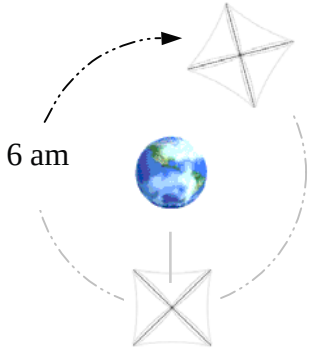
- The flight validation activity will greatly benefit from cost and risk reduction with the ISP S^4 design because the 10 and 20-m system design elements are directly applicable:
  - Simple transitional step given the truncated masts, geometrically scaled sails, and 40-m central structure design in process on the 20-m system
  - Alternately, A mass-optimized system can be demonstrated

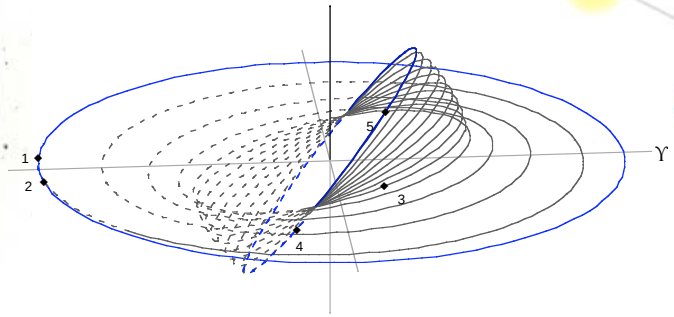
- The validation of 10 and 20-m systems *– followed by flight on ST9 –* prepares solar sailing propulsion technology for **the direct, low cost, low risk insertion into evolving missions**

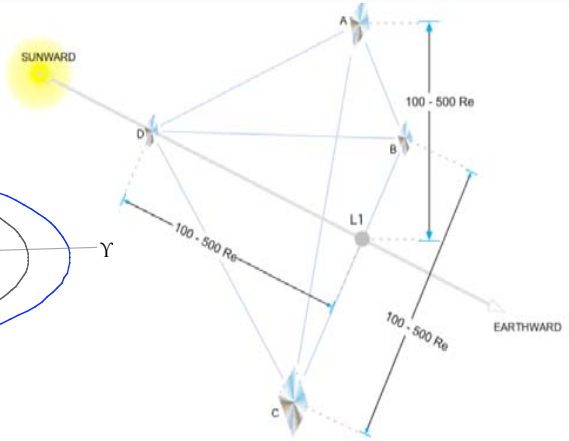


NASA Roadmap

40-m Validation 80-m Explorer 160-m Solar Polar Imager Lagrangian Sentinels







Merger News

ABLE is now part of ATK

- **ATK: *Shaped by experience. Driven by vision.***
  - **Corporate Profile**
    - $2.7 billion aerospace and defense company
    - 12,000 employees
    - Ranked 10th largest U.S. space company by *Space News*
- Full capability for technology and product development, design and analysis, component fabrication, subsystem integration and test
- Integrated site approach allows customers to seamlessly “plug and play” into capabilities of the corporation

ABLE Integrated Under:

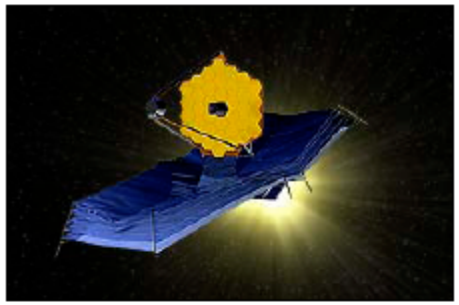
Precision Structures, ATK Composites

Experience and Capability

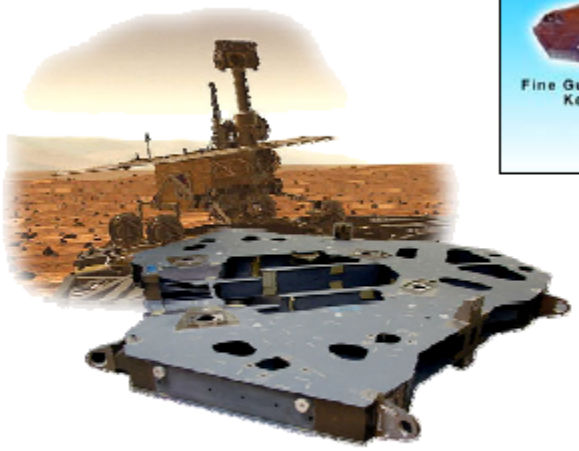
- Hubble
- Chandra X-ray telecope
- Mars lander
- JWST

Vision

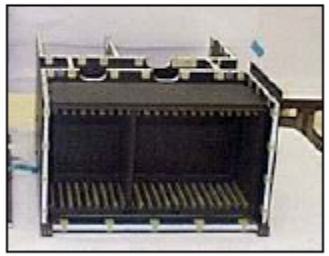
- Parts per billion accuracy
  - Test capability
- Multifunctional structures



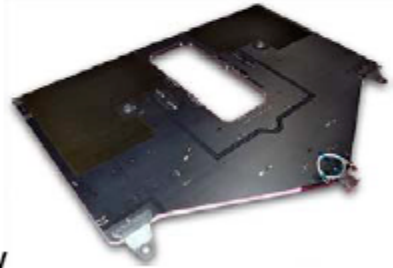
JWST



Mars Rover Deck and PanCam Mast



Integrated Solar Array, Battery And Power Electronics



GOES Yoke Platform

S4 Team Sail Technology Papers

1. Murphy, D., et al, ***Scalable Solar Sail Subsystem Design Considerations***, AIAA-2002-1703, , 43th AIAA Structures, Structural Dynamics, & Materials Conference, 3th Gossamer Spacecraft Forum, Denver, CO, April 22-25, 2002.
2. Murphey, T., et al, ***A Method to Quantify the Thrust Degradation Effects of Structural Wrinkles on Solar Sails***, AIAA-2002-1560, 43th AIAA Structures, Structural Dynamics, & Materials Conference, 3th Gossamer Spacecraft Forum, Denver, CO, April 22-25, 2002.
3. Murphy, D., et al, ***Scalable Solar-Sail Subsystem Design Concept***, AIAA Journal of Spacecraft and Rockets, Volume 40, No. 4, pp. 539-547, July-August 2003.
4. Murphy, D., et al, ***Progress and Plans for System Demonstration of a Scalable Square Solar Sail***, AAS 04-105, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, HA, February 8-12, 2004.
5. Murphy, D. and Wie, B., ***Robust Thrust Control Authority for a Scalable Sailcraft***, AAS 04-285, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, HA, February 8-12, 2004.
6. Murphy, D., et al, ***Demonstration of a 10-m Solar Sail System***, AIAA 2004-1576, 45th AIAA Structures, Structural Dynamics, & Materials Conference, 5th Gossamer Spacecraft Forum, Palm Springs, CA, April 19-22, 2004.
7. Gaspar, J., et al, ***Development of Modal Test Techniques for Validation of a Solar Sail Design***, AIAA 2004-1665, 45th AIAA Structures, Structural Dynamics, & Materials Conference, 5th Gossamer Spacecraft Forum, Palm Springs, CA, April 19-22, 2004.
8. Laue, G., et al, **Innovative Structural Design Features for a 10m Solar Sail Demonstrator**, AIAA 2004-1508, 45th AIAA Structures, Structural Dynamics, & Materials Conference, 5th Gossamer Spacecraft Forum, Palm Springs, CA, April 19-22, 2004.
9. Moore, J., et al, ***High Fidelity Finite Element Based Modeling for Solar Sail Thrust Vector Prediction from Flexible Sail Models,*** 52nd Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting, Las Vegas, Nevada, May 10-13, 2004.
10. Thomas, S., et al, ***Design and Simulation of Sailcraft Attitude Control Systems Using the Solar Sail Control Toolbox***, AIAA 2004-4890, AIAA/AAS Astrodynamics Specialist Conference, Providence, RI, August 16-19, 2004.
11. Wie, B., et al, ***Robust Attitude Control Systems Design for Solar Sails, Part 1: Propellantless Primary ACS***, AIAA 2004-5010, AIAA/AAS Astrodynamics Specialist Conference, Providence, RI, August 16-19, 2004.
12. Wie, B., et al, ***Robust Attitude Control Systems Design for Solar Sails, Part 2: MicroPPT-based Secondary ACS***, AIAA 2004-5011, AIAA/AAS Astrodynamics Specialist Conference, Providence, RI, August 16-19, 2004.

Murphy, D., et al, ***Demonstration of a 20-m Solar Sail System***, AIAA 2005-TBD, 46th AIAA Structures, Structural Dynamics, & Materials Conference, 6th Gossamer Spacecraft Forum, Austin, TX, April 18-21, 2005.

Murphy, D., et al, ***Validation of a Scalable Solar Sail System***, AIAA 2005-TBD, 41st AIAA Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

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Poster – S^4 Development