National Aeronautics and Space Administration

NASA Armstrong Flight Research Center (AFRC) Fiber Optic Sensing System (FOSS) Technology

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Information Updated

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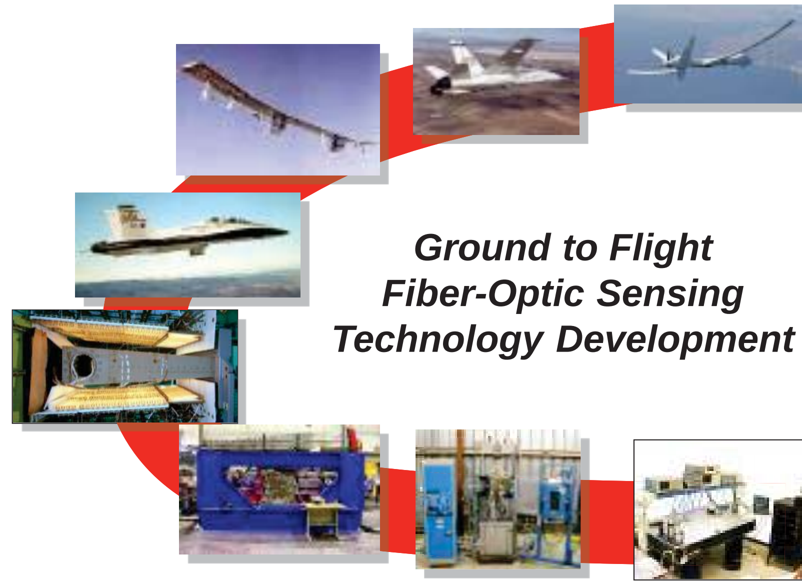
National Aeronautics and Space Administration

The FOSS Team

	Team member	Background/ experience	Contributions to Fiber Optics Team
	**Patrick Chan**	Optics Engineer	Optics Development, laser research and development
	**Phil Hamory**	Electrical Engineer	Advanced System Algorithm Development
	**Allen Parker**	Electrical Engineer	Systems design & development, data processing and visualization
	**Frank Pena**	Structures Engineer	Mechanical design & development, Structural Simulation and Testing
	**Anthony Piazza**	Instrumentation Specialist	Sensor characterization, application, & interpretation
	**Lance Richards**	Structures Engineer	Aircraft structures, strain measurement

Background

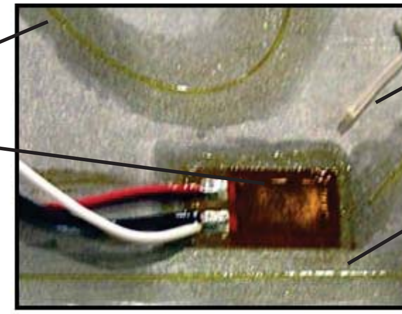
- **AFRC initiated fiber-optic instrumentation development effort in the mid-90's**
  - **AFRC effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique**
- **AFRC focused on developing system suitable for flight applications**
  - **Previous system was limited due to laser technology**
  - **System limited to 1 sample every 90 seconds**
- **AFRC initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight**
- **As a result, AFRC has developed a comprehensive portfolio of intellectual property that is now ready to be commercialized by the private sector.**



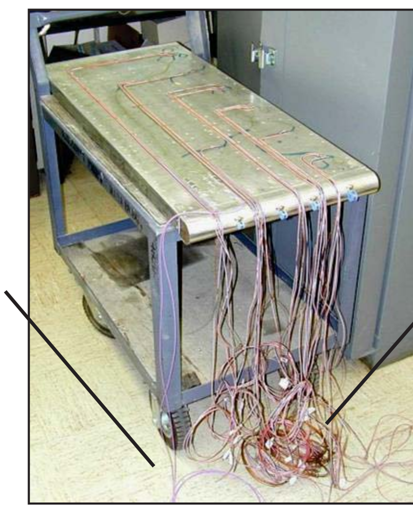
X-33 IVHM Risk Reduction Experiment

Fiber Optic Sensor Advantages

- **Advantages of FO sensors over conventional technology**
  - **Light weight**
    - **Increased payloads**
    - **Increased range**
  - **Serial multiplexibility**
    - **Full-field strain mapping**
    - **Reduced bundle sizes**
    - **Reduced time to install/troubleshoot**
  - **Small size (about the size of human hair)**
  - **Embeddable**
    - **Damage detection**
    - **Internal health assessment**
  - **Compatibility with telecom**
  - **No sparking, no ground loops**
  - **Chemically inert**
  - **No EMI or EMP**
- **Wide application potential**



Strain sensor comparison



X-33/SRA flight test fixture

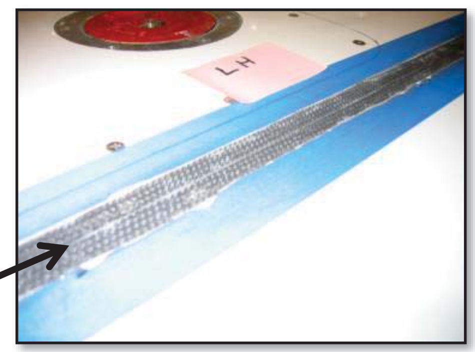
Installation Advantages and Limitations

Installation Advantages

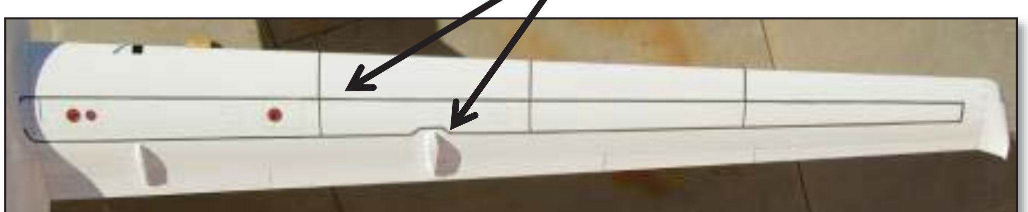
- **Greatly reduced installation time compared to conventional strain gages**
  - **2 man days for 40' fiber (2000 strain sensors for a continuous surface run)**
  - **Multiple sensors installed simultaneously**
  - **Same surface preparation and adhesives as conventional strain gages**
  - **Minimal time spent working on vehicle**
  - **All connectors can be added prior to installation, away from part**
  - **No soldering, no clamping pressure required**
- **Can be installed on aerodynamic surfaces with little to no impact on performance**

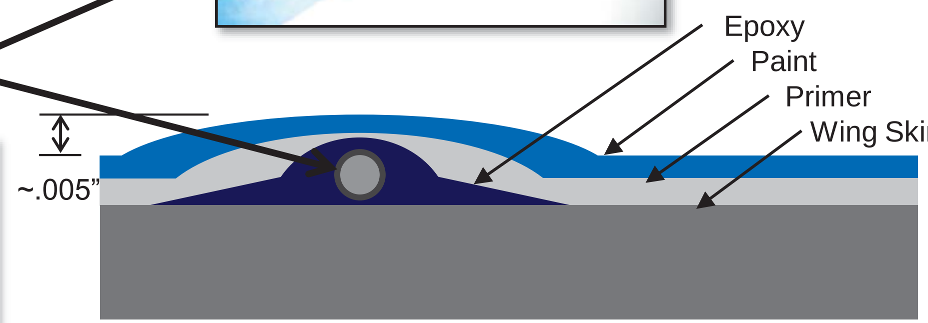
Installation Limitations

- **Optical fiber more fragile than conventional strain gages**
- **Some measurement locations not practical due to fiber minimum bend radius**
- **Not practical if only interested in spot measurements**



Optical Fiber





Strain Sensing – Ground System

Current Capabilities

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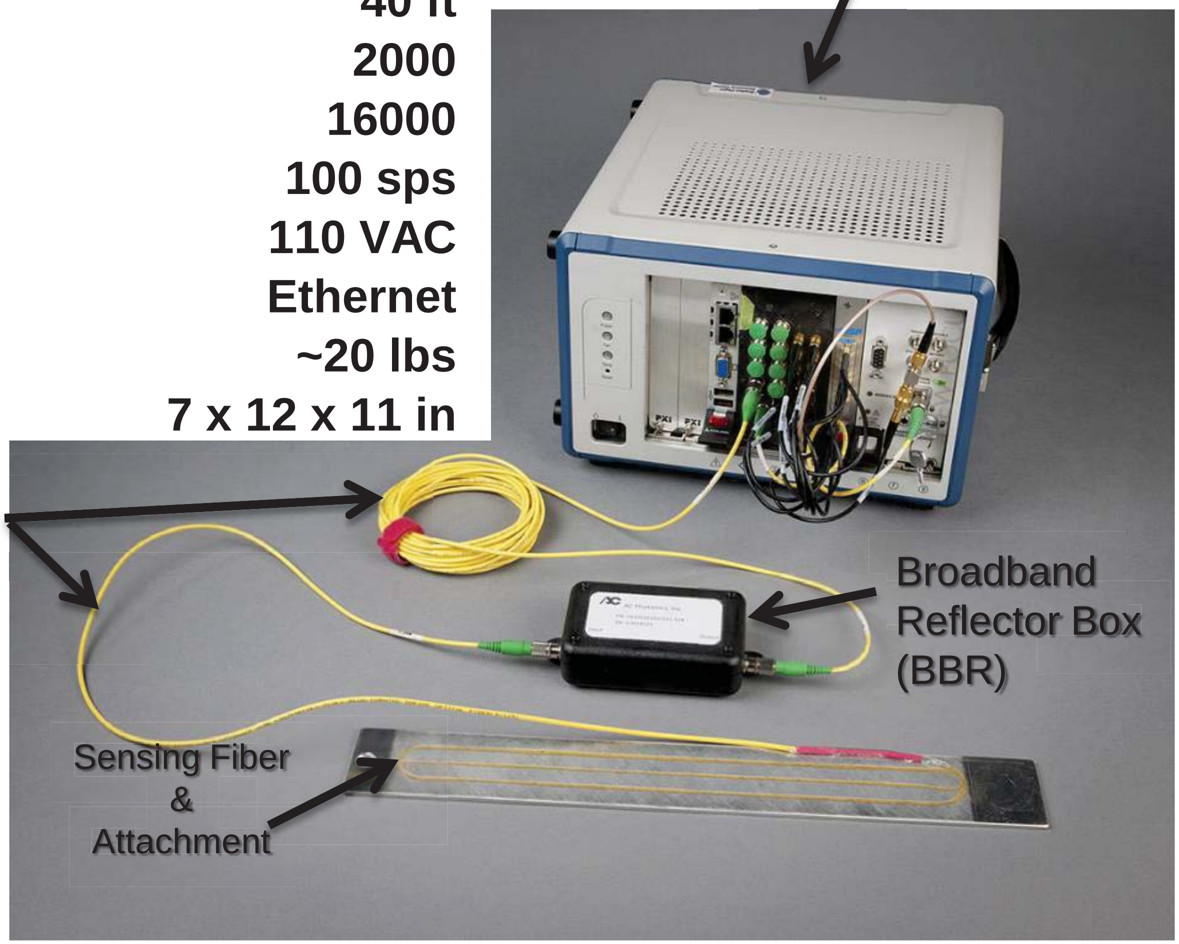
Current system specifications

• Sensor Range	+/- 12,000 micro Strain
• Resolution	2 micro Strain
• Accuracy	5%
• Fiber count	8
• Max sensing length / fiber	40 ft
• Max sensors / fiber	2000
• Total sensors / system	16000
• Max sample rate	100 sps
• Power	110 VAC
• User Interface	Ethernet
• Weight	~20 lbs
• Size	7 x 12 x 11 in



Strain Sensing – Flight System

Current Capabilities

Current system specifications

• Sensor Range	+/- 12,000 micro Strain
• Resolution	2 micro Strain
• Accuracy	5%
• Fiber count	8
• Max sensing length / fiber	40 ft
• Max sensors / fiber	2000
• Total sensors / system	16000
• Max sample rate	100 sps
• Power	28VDC @ 4.5 Amps
• User Interface	Ethernet
• Weight	~30 lbs
• Size	7.5 x 13 x 13 in

Flight System

Fiber Installed on Wing

Environmental qualification specifications for flight system

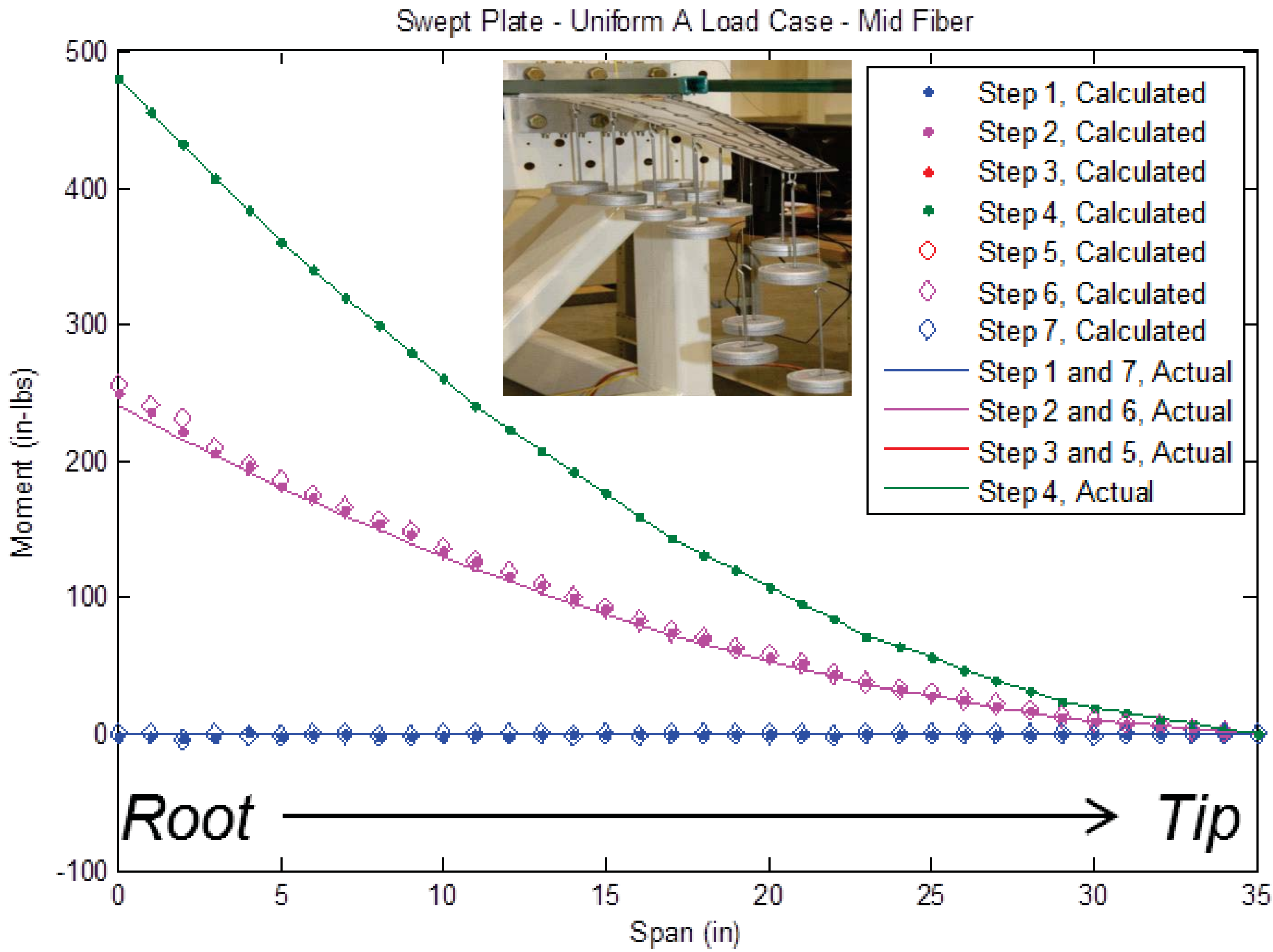
• Shock	8g
• Vibration	1.1 g-peak sinusoidal curve
• Altitude	60kft at -56C for 60 min
• Temperature	-56 < T < 40C

Predator -B in Flight

Strain and Applied Loads

Aluminum Flat Plate Validation Testing

Applied Loads Results

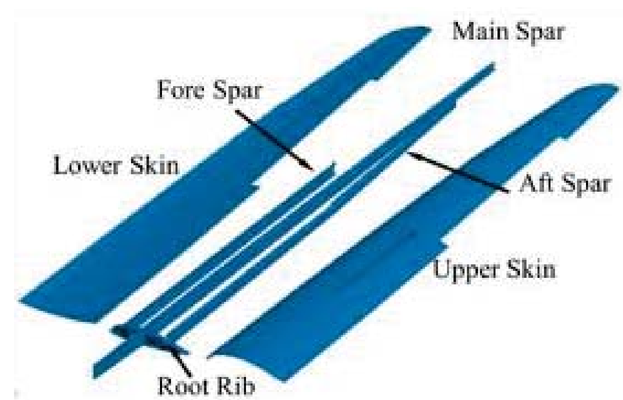


Strain and Applied Loads

Large-Scale Composite Wings - Mississippi State Univ

ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

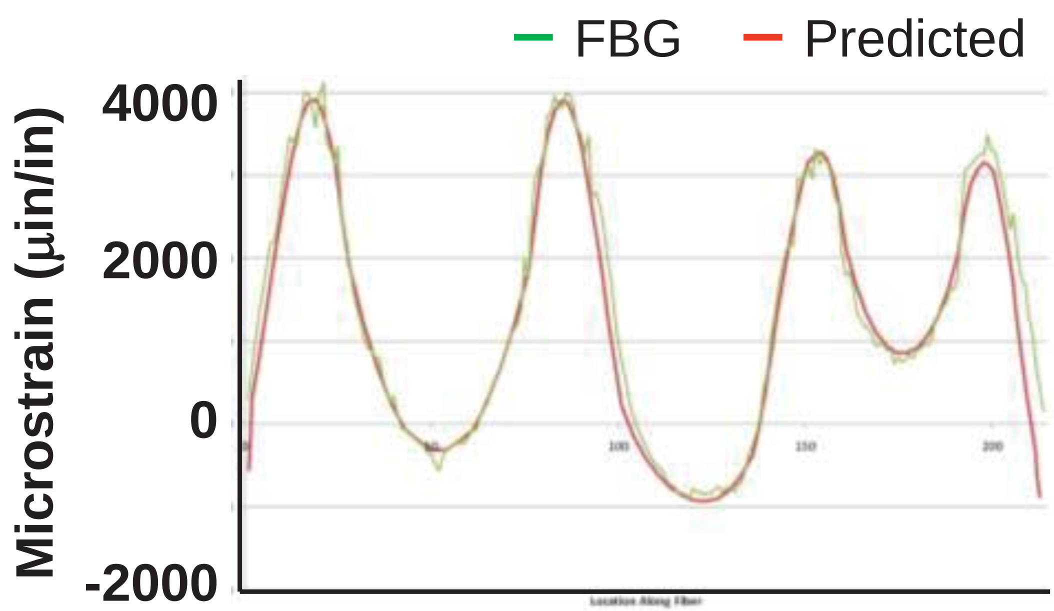
Material Properties	Woven fabric Toray-T700G	Unidirectional fabric Toray-T700S	Foam core DIAB Divinycell HT 50
E_{11}, GPa	5.54×10^{1}	1.19×10^{2}	8.50×10^{-2}
E_{22}, GPa	5.54×10^{1}	9.31×10^{0}	--
G_{12}, GPa	4.21×10^{0}	4.21×10^{0}	--
ν_{12}	3.00×10^{-2}	3.10×10^{-1}	3.20×10^{-1}
ρ, kg/m^3	1.49×10^{3}	1.52×10^{3}	4.95×10^{-1}



Strain Sensing

Composite Crew Module

- **Four fibers were installed around the module's three windows and one hatch**
- **3300 real-time strain measurements were collected at 30Hz as the module underwent 200%DLL pressurization testing**
- **Measured strains were compared and matched well to predicted model results**
- **Project concluded:**
  - **"Fiber optics real-time monitoring of test results against analytical predictions was essential in the success of the full-scale test program."**
  - **"In areas of high strain gradients these techniques were invaluable."**



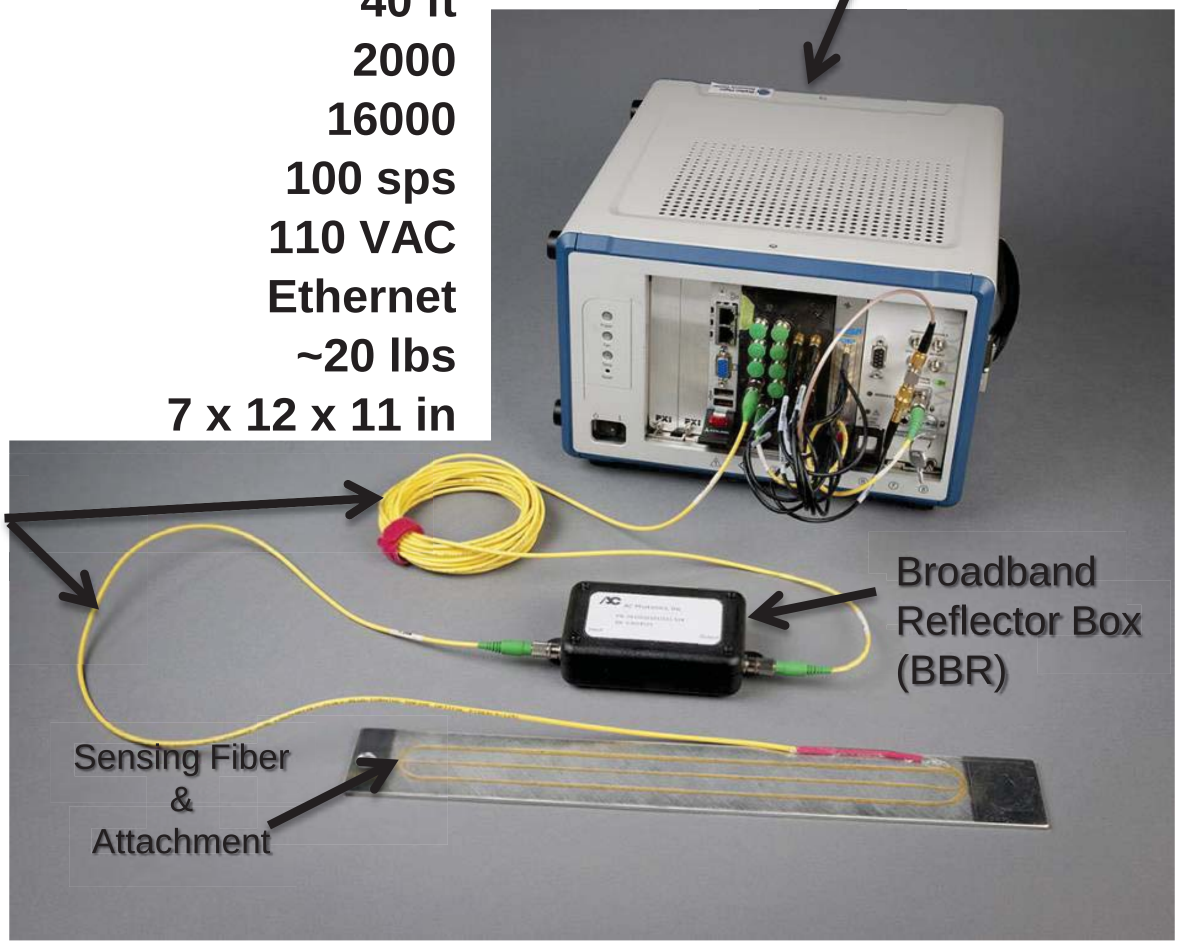
Inner Hatch FBG Strains, Max Pressure

Temperature Sensing

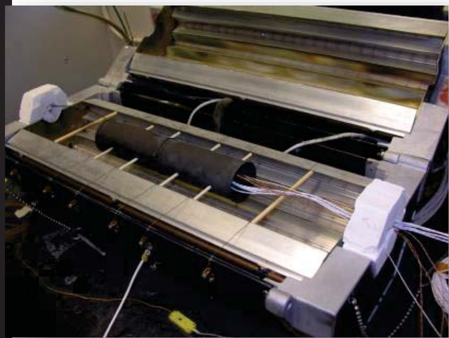
Current Capabilities

Current system specifications

Sensor Range	- 425 deg F to 550 deg F
Resolution	1 deg F
Accuracy	5%
Fiber count	8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Total sensors / system	16000
Max sample rate	100 sps
Power	110 VAC
User Interface	Ethernet
Weight	~20 lbs
Size	7 x 12 x 11 in

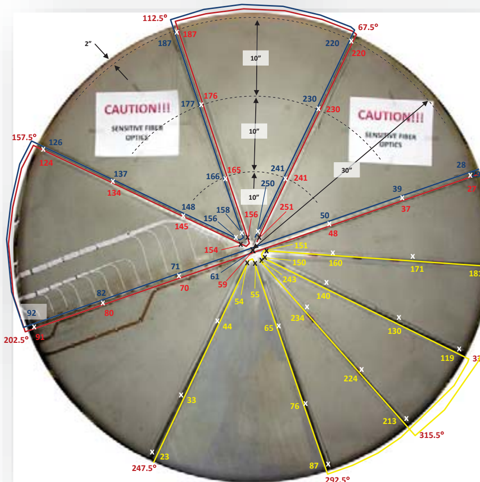


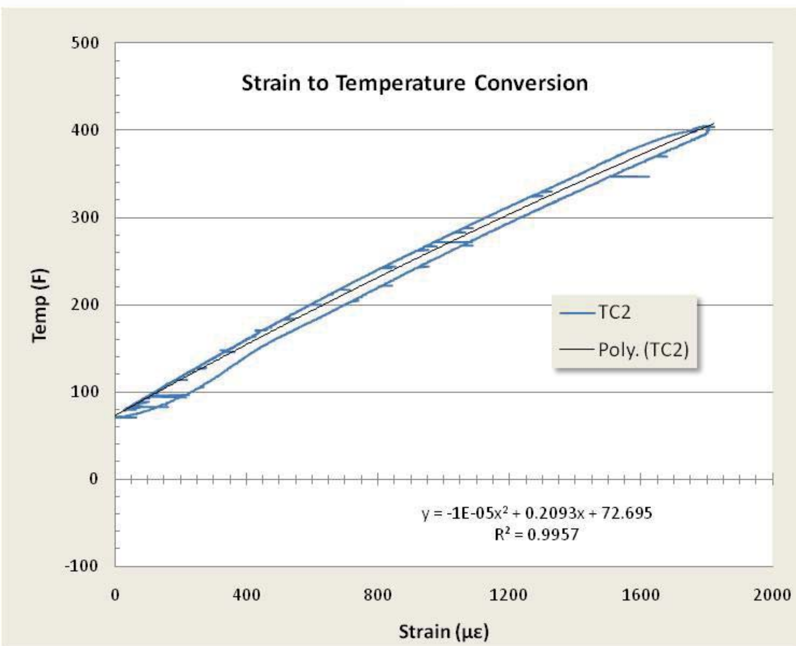
Temperature Conversion

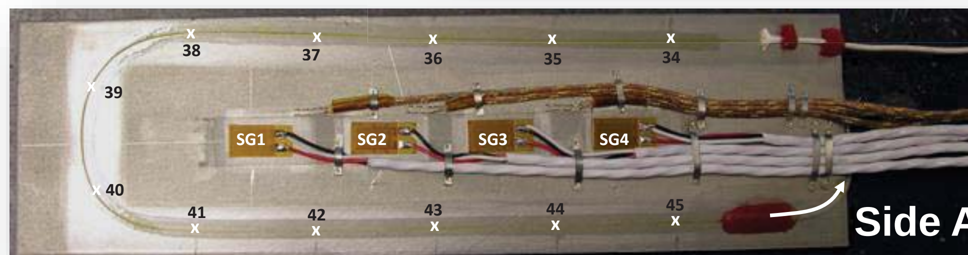


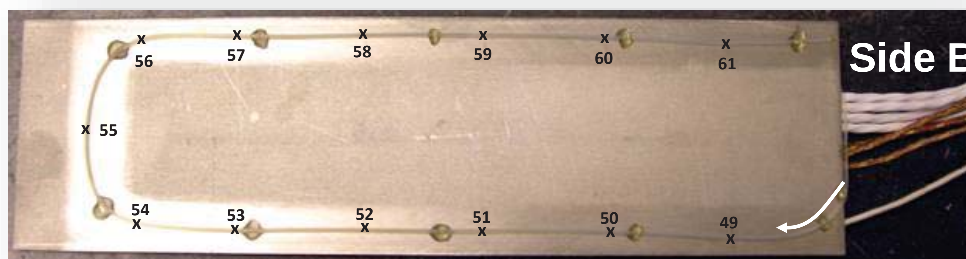
Test Notes

Eleven FO FBG’s, decoupled from substrate in polyimide tubes, were averaged to generate coefficient to convert strain to Fahrenheit









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2D Shape Sensing
Current Capabilities

Current system specifications

- Max sensing length / fiber — 40 ft
- Resolution — ~ ¼ in.
- Accuracy — 2%
- Max sensing fibers — 8
- Max sensors / fiber — 1000
- Total sensors / system — 8000
- Max sample rate — 100 sps
- Power (flight) — 28VDC @ 4.5 Amps
- Power (ground) — 110 VAC
- User Interface — Ethernet
- Weight (flight, non-optimized) — 27 lbs
- Weight (ground, non-optimized) — 20 lbs
- Size (flight, non-optimized) — 7.5 x 13 x 13 in
- Size (ground, non-optimized) — 7 x 12 x 11 in

Environmental qualification specifications for flight system

- Shock — 8g
- Vibration — 1.1 g-peak sinusoidal curve
- Altitude — 60kft at -56C for 60 min
- Temperature — -56 < T < 40C

Flight System

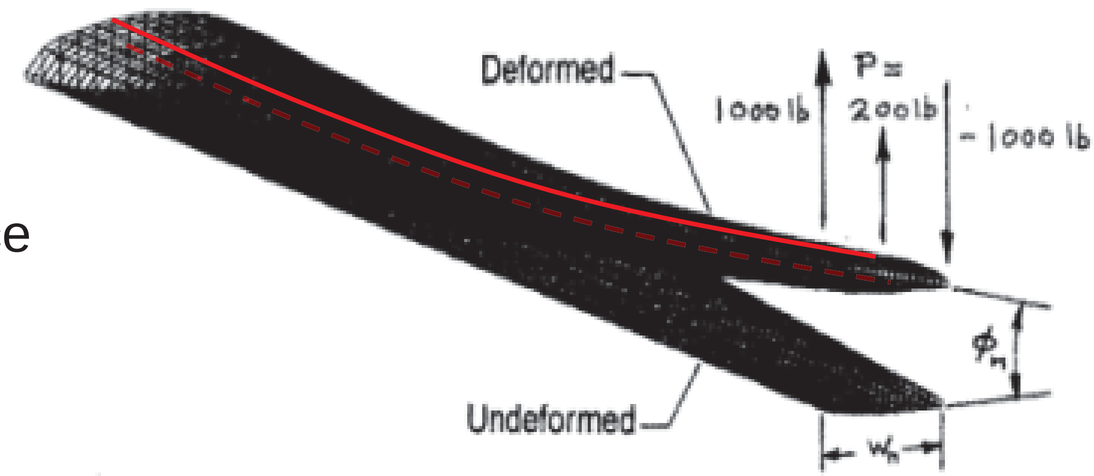
Ground System

Requires knowledge of the structures centroid

2D Strain-Based Deflection Methods

2D Shape Sensing Method

- Uses structural strains to get deflection in one direction
- Fibers on top and bottom surface of a structure (e.g. wing)



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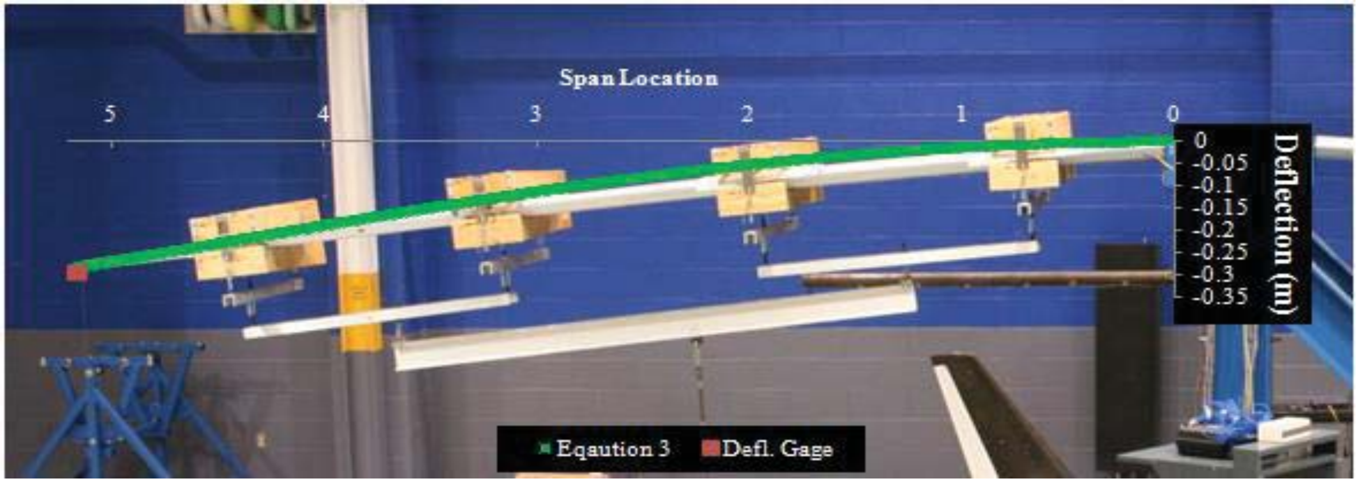
Strain, Applied Loads, and 2D Shape

Large-Scale Composite Wings - Mississippi State Univ.



MEASURED AND CALCULATED WING TIP DEFLECTIONS

F, N	Measured δ_L, m	Calculated δ_L, m	**Error, %**
1373	-0.184	-0.178	**3.02**
1592	-0.209	-0.205	**2.29**
1837	-0.241	-0.231	**4.08**
2036	-0.265	-0.257	**3.23**
2269	-0.295	-0.284	**3.75**

Test Procedure for displacement

- Collect FBG strain data
- Use displacement Eq. and Strain data to calculate deflection

OUT-OF-PLANE APPLIED LOAD

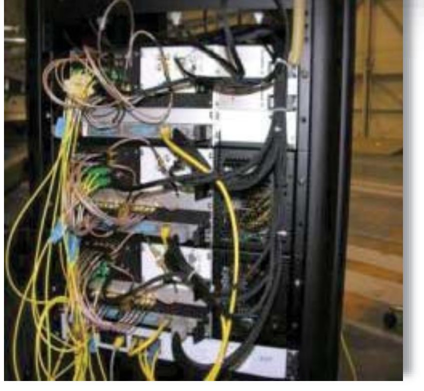
Applied Load, N	Calculated Load, N	**Error, %**	Difference, N
-185.5	-178.8	**3.60**	6.7
-194.4	-210.0	**7.98**	15.5
-241.5	-252.0	**4.35**	10.5
-288.5	-291.5	**1.05**	3.0
-333.3	-332.9	**0.12**	0.4
-378.1	-381.1	**0.80**	3.0
-422.9	-435.9	**3.07**	13.0
-472.2	-486.4	**3.01**	14.2
Average EI=98728.2-N*m^2			

Test procedure for out-of-plane loads

- Determine EI for the wing
- Determine moment acting on wing
- Determine Load applied

Strain and 2D Shape Sensing
Global Observer UAS

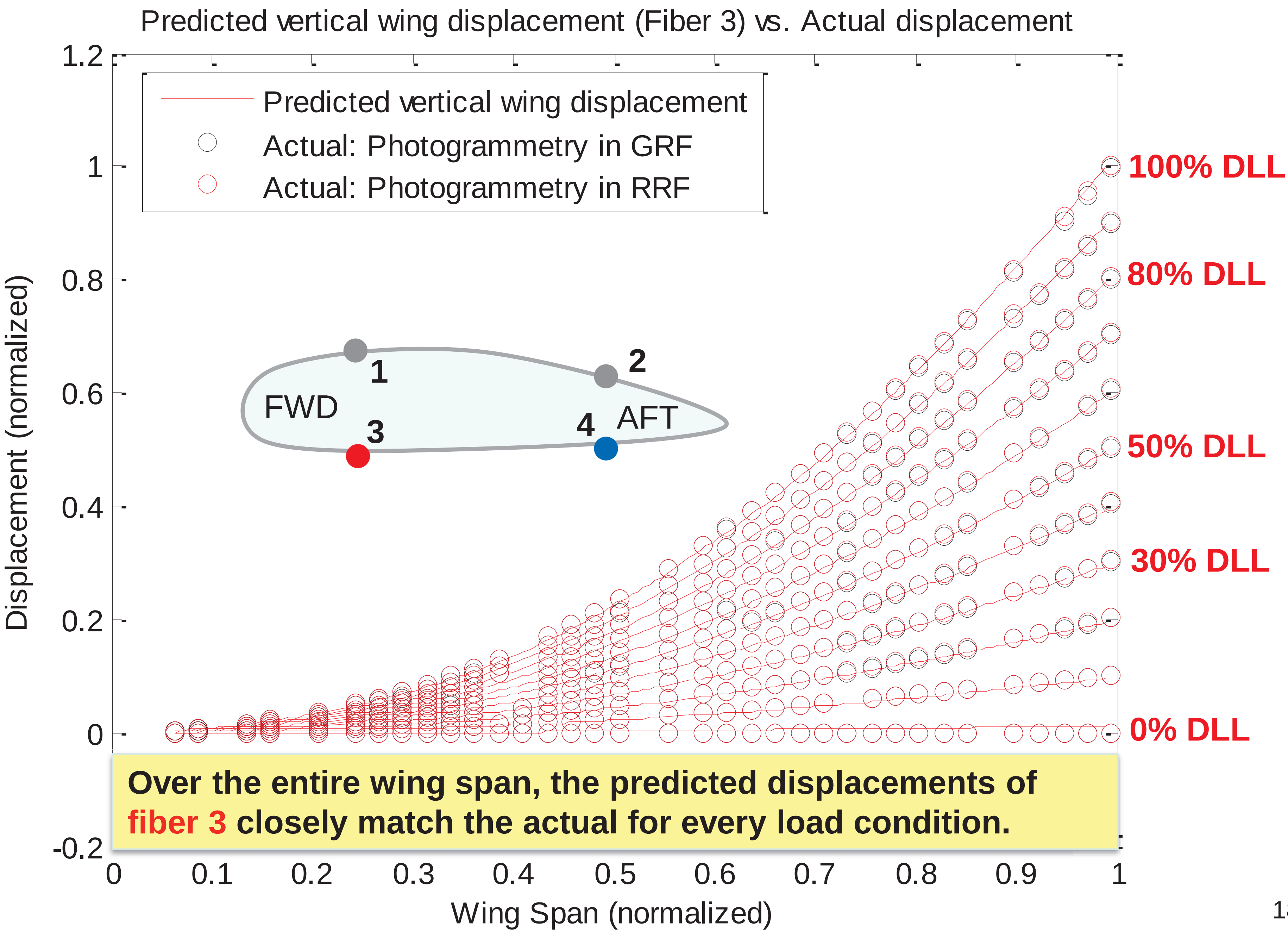
- **Validate strain predictions along the wingspan**
- **Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.**
- **FO Strain distribution measurements are being used to interpret shape using AFRC's 2D shape algorithm**
- **A 24-fiber system was designed of which 18, 40ft fibers (~17,200 gratings) were used to instrument both left and right wings**



Strain and 2D Shape Sensing
Global Observer UAS

- **Proof-load testing of components and large-scale structures**

2D Shape Sensing Results
Global Observer UAS



Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

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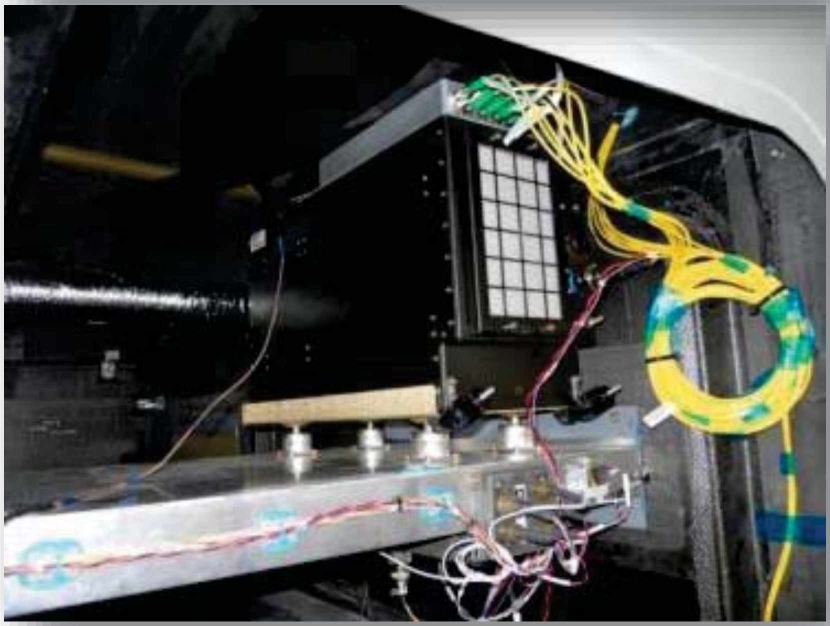
Strain and 2D Shape Sensing

Global Observer UAS - Flight Testing

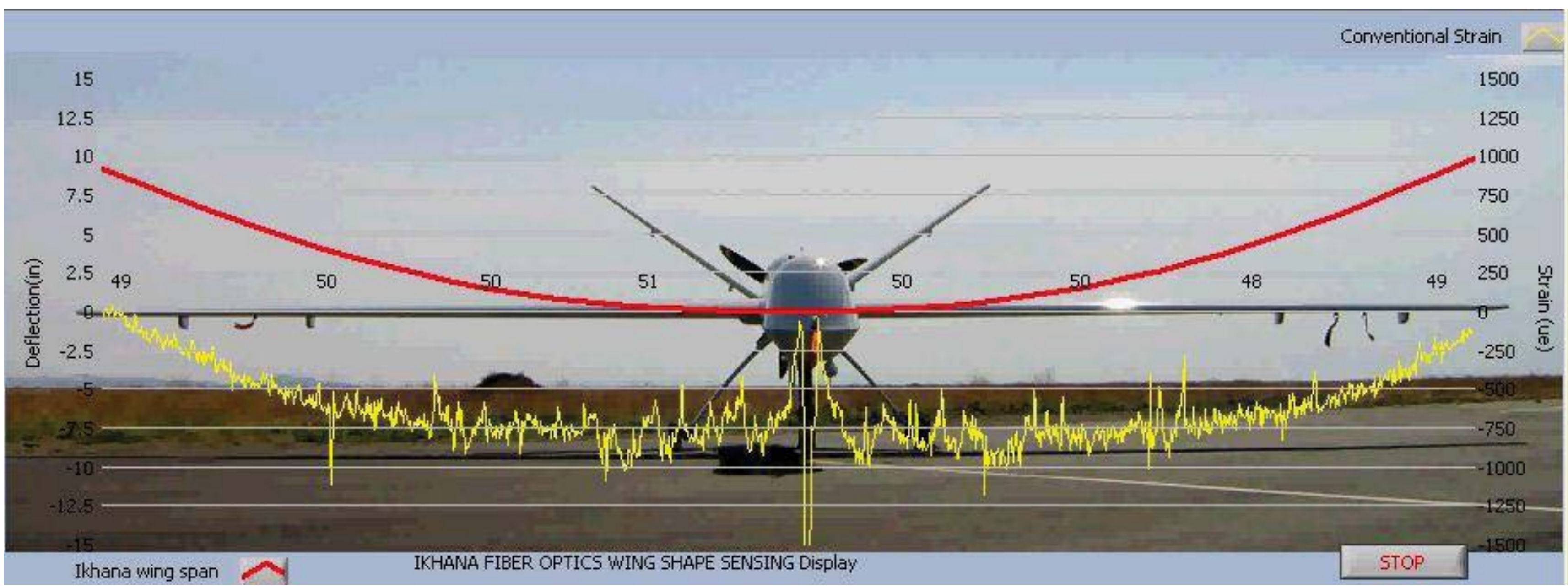
- **Validate strain predictions along the left wing in flight using 8, 40ft fibers (~8000 strain sensors)**
- **An aft fuselage surface fiber was installed to monitor fuselage and tail movement**
- **Strain distribution were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.**
- **8 of the 9 total fibers are attached to the system at any give time**
- **The system performed well and rendered good results**



Strain and 2D Shape Sensing

Predator-B UAS - Flight Testing

- 18 flights tests conducted; 36 flight-hours logged
- Conducted first flight validation testing April 28, 2008
- Believed to be the first flight validation test of FBG strain and wing shape sensing
- Multiple flight maneuvers performed
- Total of 6 fibers (~3000 strain sensors) installed on left and right wings
- Fiber optic and conventional strain gages show excellent agreement
- FBG system performed well throughout entire flight program



Video clip of flight data superimposed on Ikhana photograph

3D Shape Sensing

Current Capabilities

Current system specifications

• Max sensing length / fiber	40 ft
• Resolution	~ ¼ in.
• Accuracy	5%
• Max sensing fibers	8
• Max sensors / fiber	1000
• Total sensors / system	8000
• Max sample rate	100 sps
• Power (flight)	28VDC @ 4.5 Amps
• Power (ground)	110 VAC
• User Interface	Ethernet
• Weight (flight, non-optimized)	27 lbs
• Weight (ground, non-optimized)	20 lbs
• Size (flight, non-optimized)	7.5 x 13 x 13 in
• Size (ground, non-optimized)	7 x 12 x 11 in

Flight System

Ground System

Environmental qualification specifications for flight system

• Shock	8g
• Vibration	1.1 g-peak sinusoidal curve
• Altitude	60kft at -56C for 60 min
• Temperature	-56 < T < 40C

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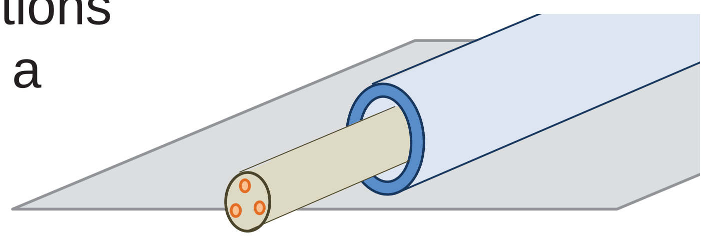
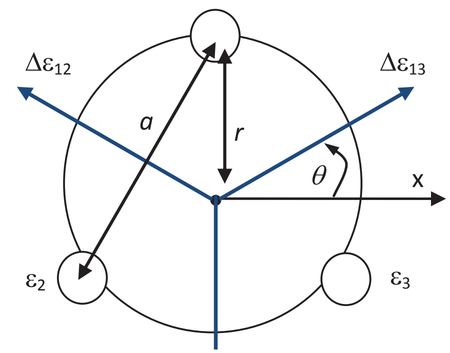
3D Strain-Based Deflection Methods

3D Shape Sensing Method

- Uses strains on a cylindrical structure to get 3D deflections
- 3 fibers 120 deg apart on a structure or a lumen





3D Shape Sensing

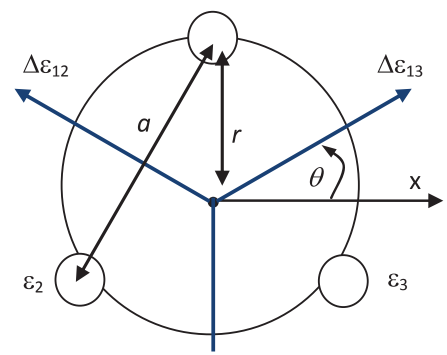
Prototype Quiet Spike Testing

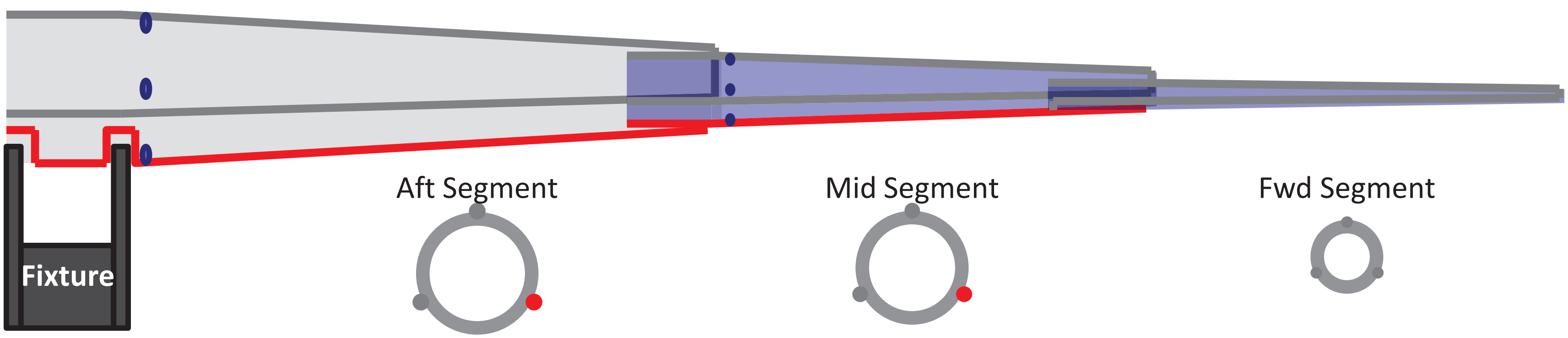
- **Fibers are installed on the prototype of 35ft quiet spike at Gulfstream in Savannah GA**

- **Performed tests to determined benefits of deploying FOSS on Low Boom Experimental Vehicle**

- **Installed a total of 5 fibers measuring strain at ½” increments (2,570 strain sensors)**

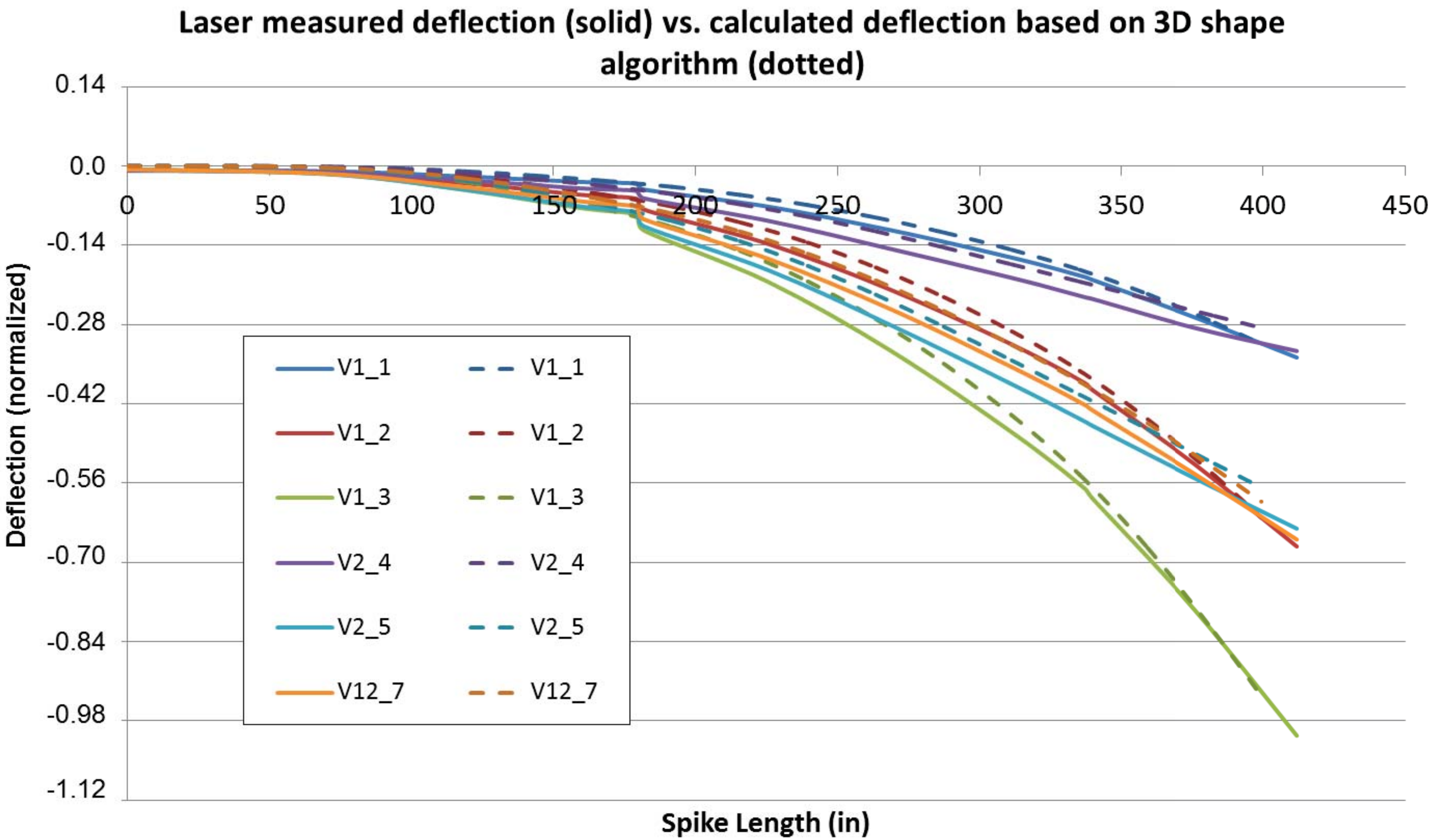
- **Deflection shape of the Quiet Spike evaluated through the 3D shape algorithm**





3D Shape Sensing

Quiet Spike Testing Results – lateral deflection

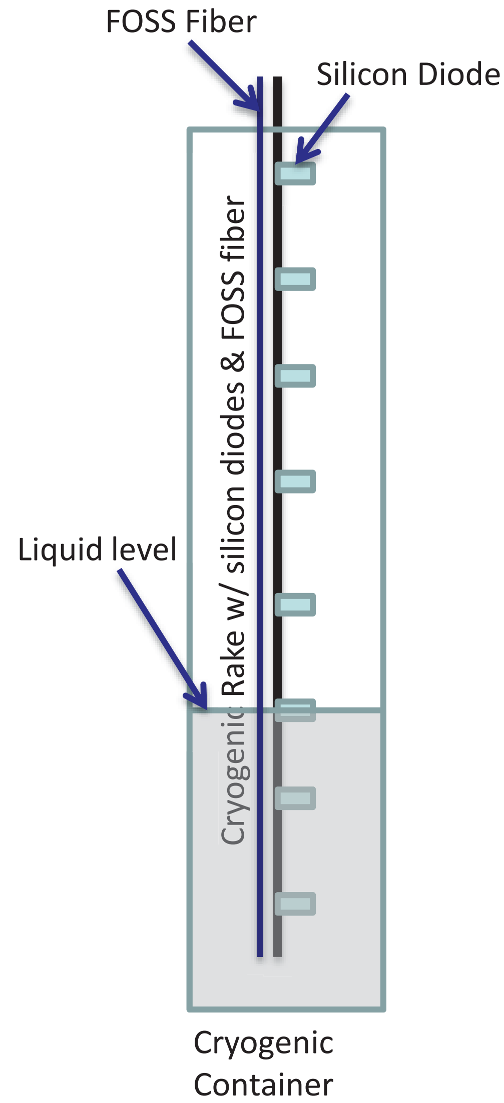


Liquid Level & Cryogenic Liquid Level Sensing
Current Capabilities

National Aeronautics and Space Administration

Current system specifications

Specification	Value
Max sensing length / fiber	40 ft
Resolution	~ ¼ in.
Accuracy	~ ¼ in.
Max sensing fibers	8
Max sensors / fiber	2000
Total sensors / system	16000
Max sample rate	0.5 Hz
Power	110 VAC
User Interface	Ethernet
Weight	~ 20 lbs
Size	7 x 12 x 11 in



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Cryogenic Liquid Level-Sensing

The Challenge

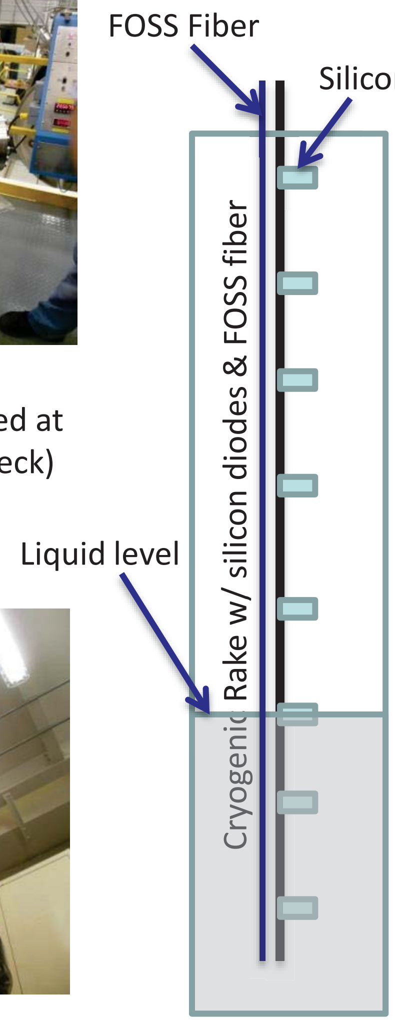
- The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements
- Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level along with high wire count

FOSS Approach

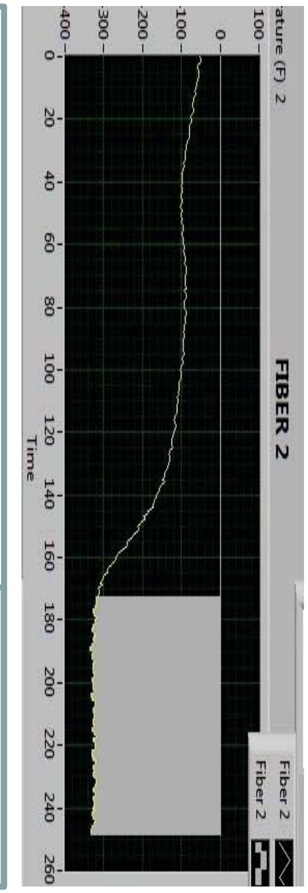
- While using a uniquely developed fiber optic structure (CryoFOSS), the transitional phase can be mapped more accurately
- Using a single continuous grating fiber, a high degree of spatial resolution can be achieved, as low as 1/16”

Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)



Cryogenic Container



1st Gen CryoFOSS Test Results

LH_2 Testing of CryoFOSS at MSFC

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Objective

- Experimentally validate CryoFOSS using AFRC's FOSS technology

Test Details

- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of 20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope with a ruler (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH_2 liquid level sensor(CryoFOSS)

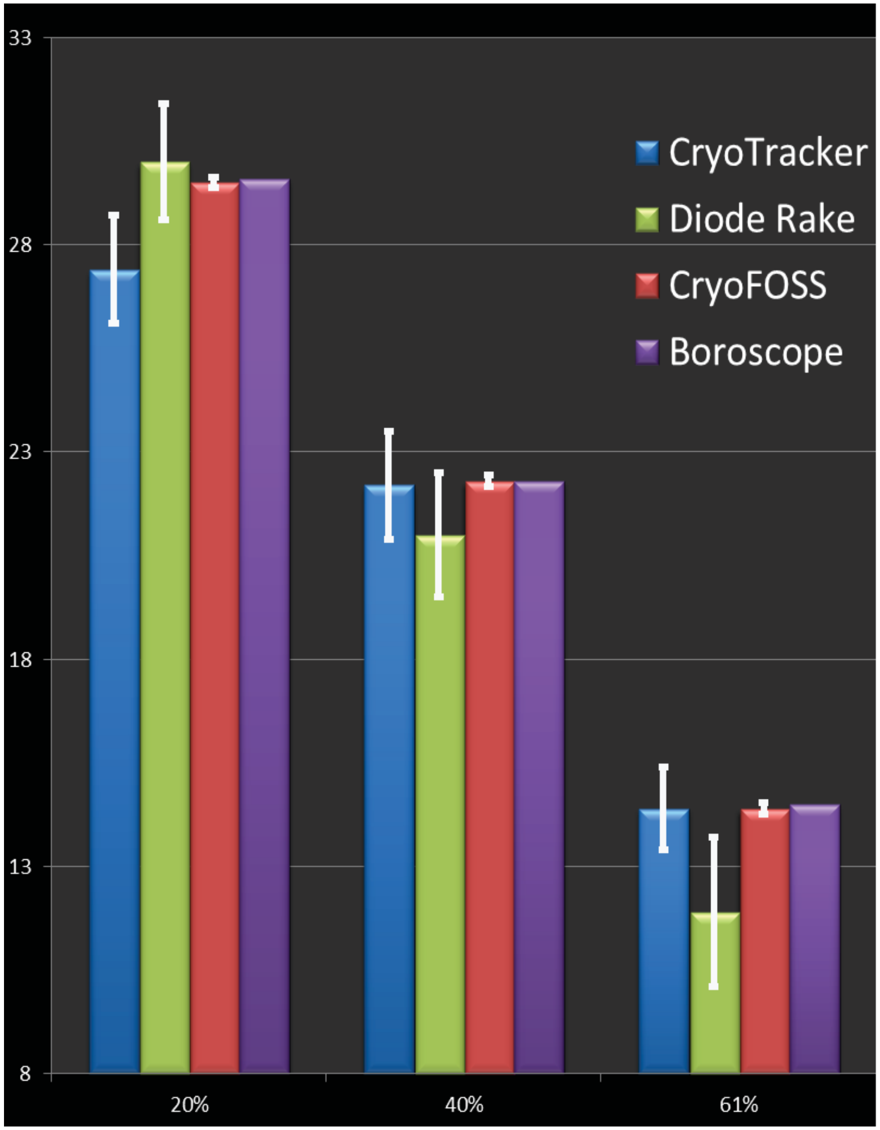
Results

- CryoFOSS sensor discerned LH_2 level to ¼" in every case
- Excellent agreement achieved between CryoFOSS, boroscope, and silicon diode Cryotracker

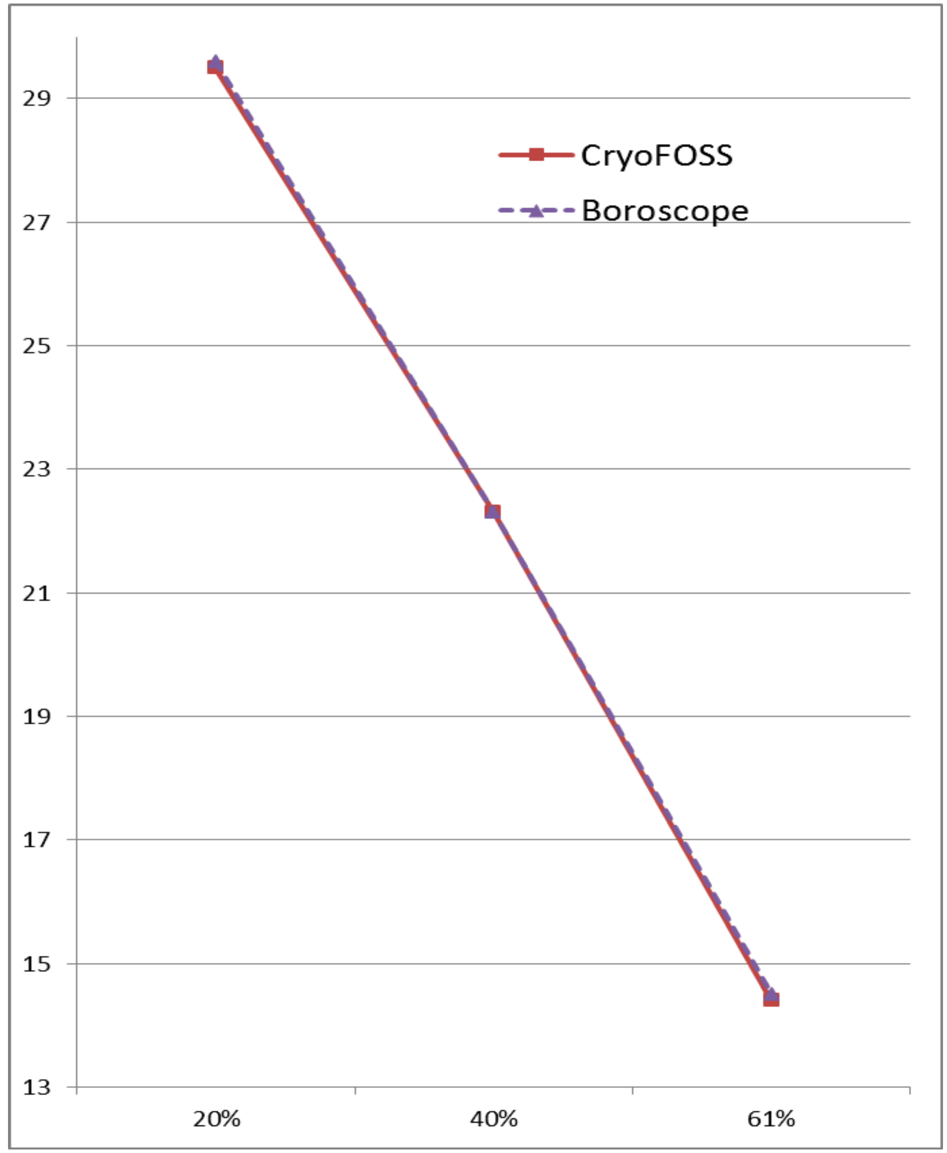
Bottom line

- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for ground and in-flight cryogenic fluid management systems

LH_2 Liquid Level Results



Combined Results



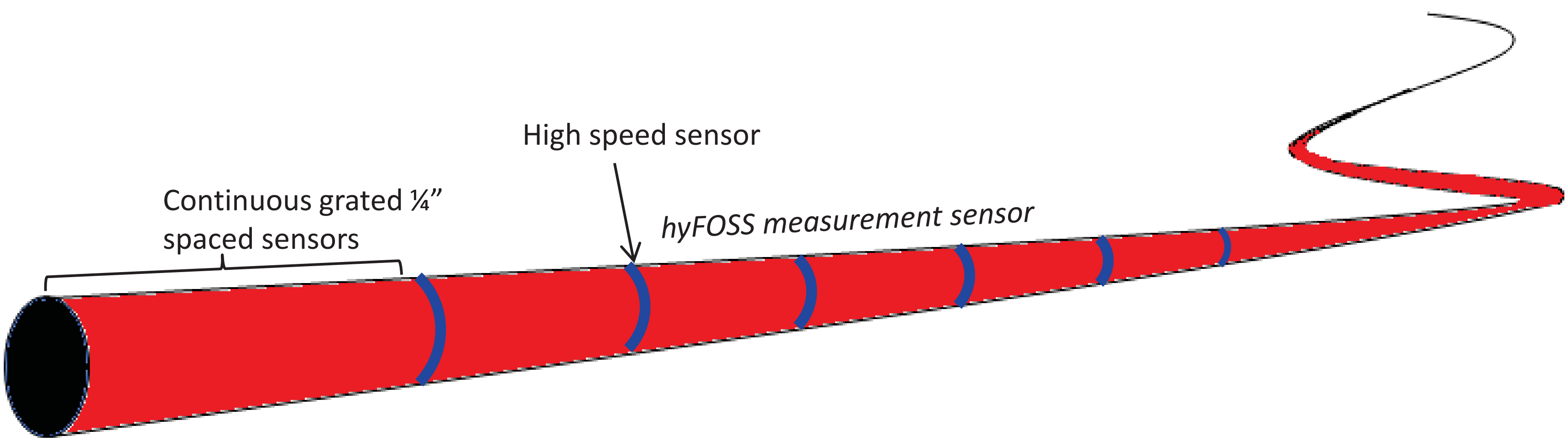
CryoFOSS compared to Boroscope

hyFOSS

Current Capabilities

Current system specifications

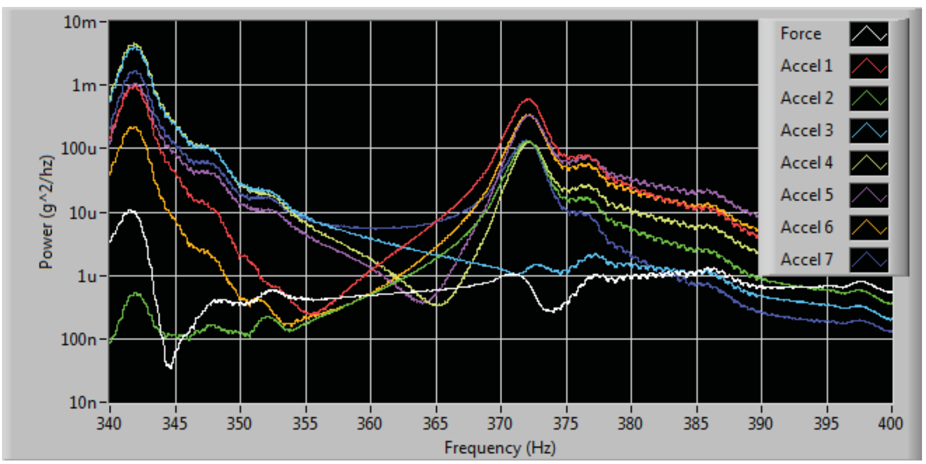
Sensor Range	+/- 12,000 micro Strain
Resolution	2 micro Strain
Accuracy	5%
Fiber count	8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Total sensors / system	16000
Max sample rate	100 sps
Power	110 VAC
User Interface	Ethernet
Weight	~20 lbs
Size	7 x 12 x 11 in

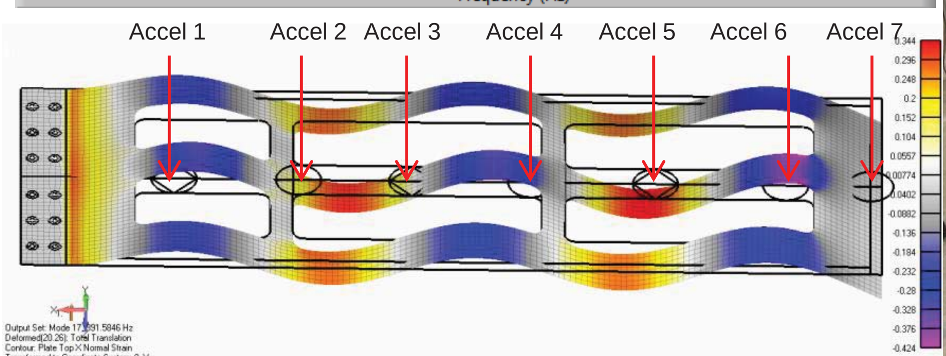


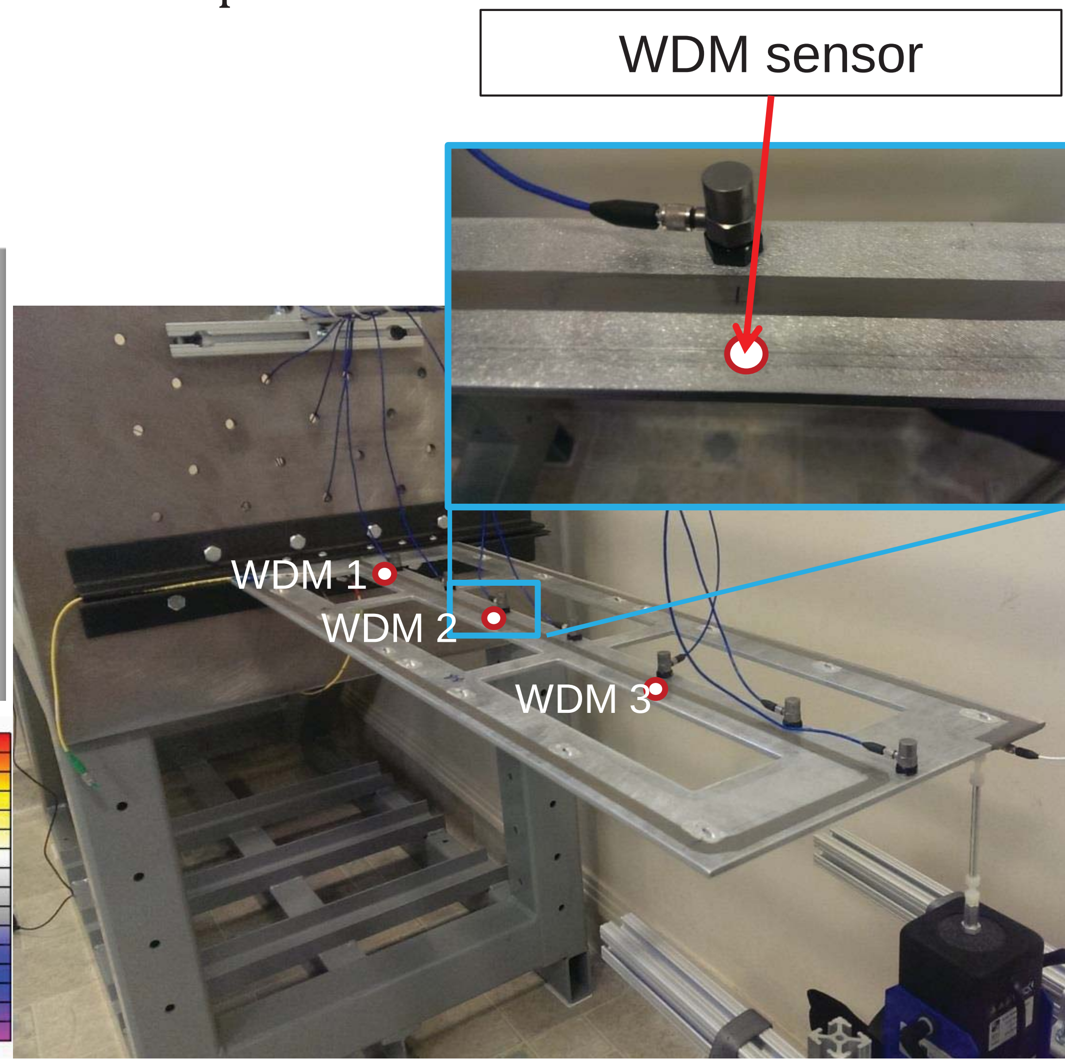
HyFOSS Open Plate test article

Experimental setup

- 7 Accelerometers are mounted to the structure to monitor structure mode shapes
- OFDR and WDM sensors (3) are bonded to the plate







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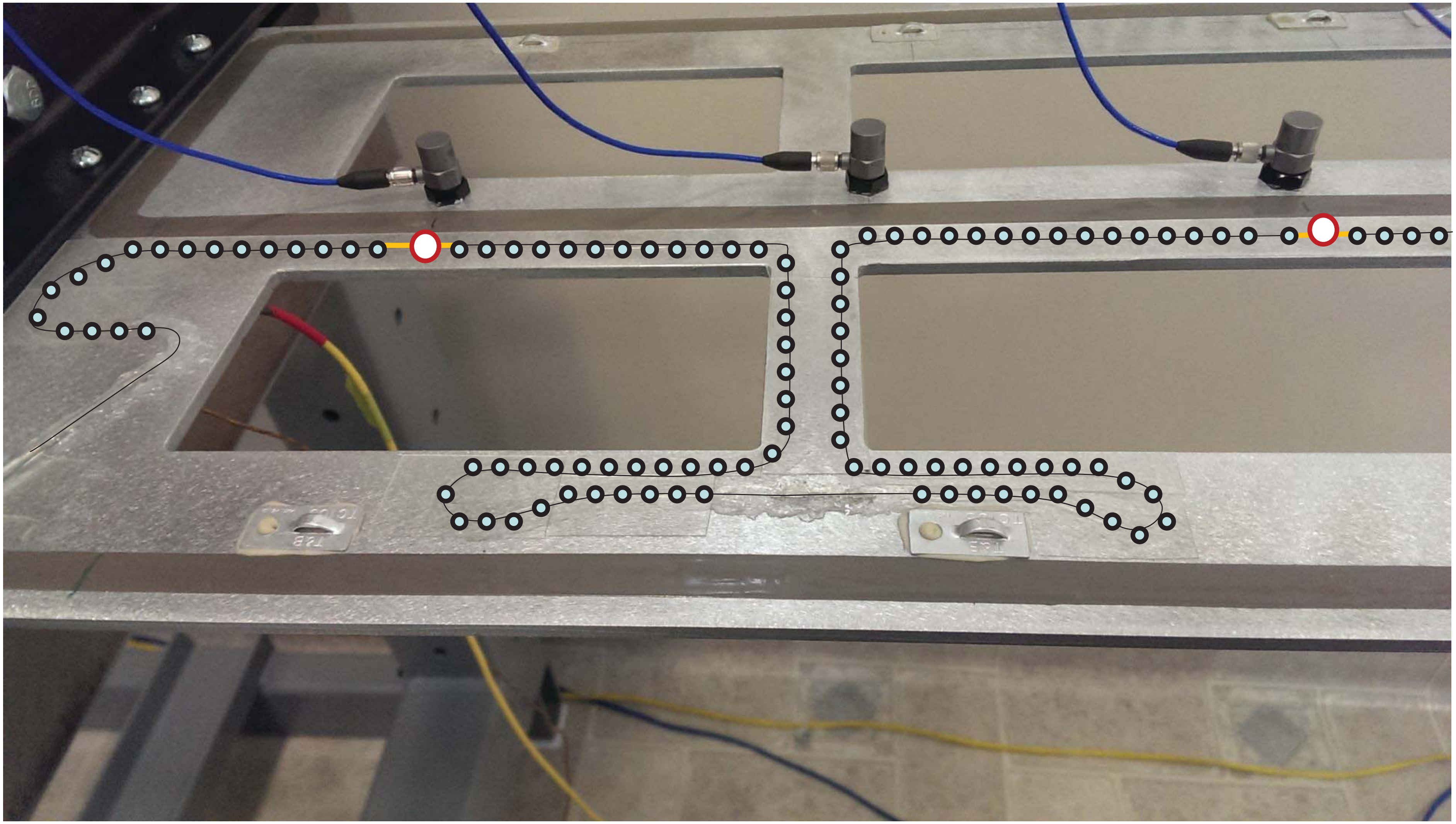
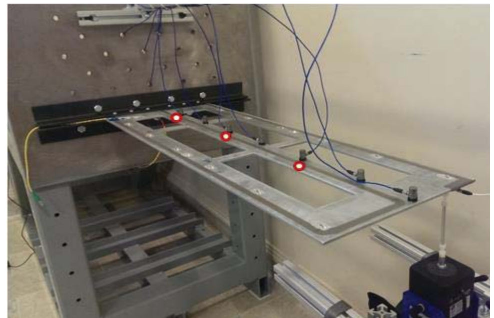
HyFOSS Sensor Installation



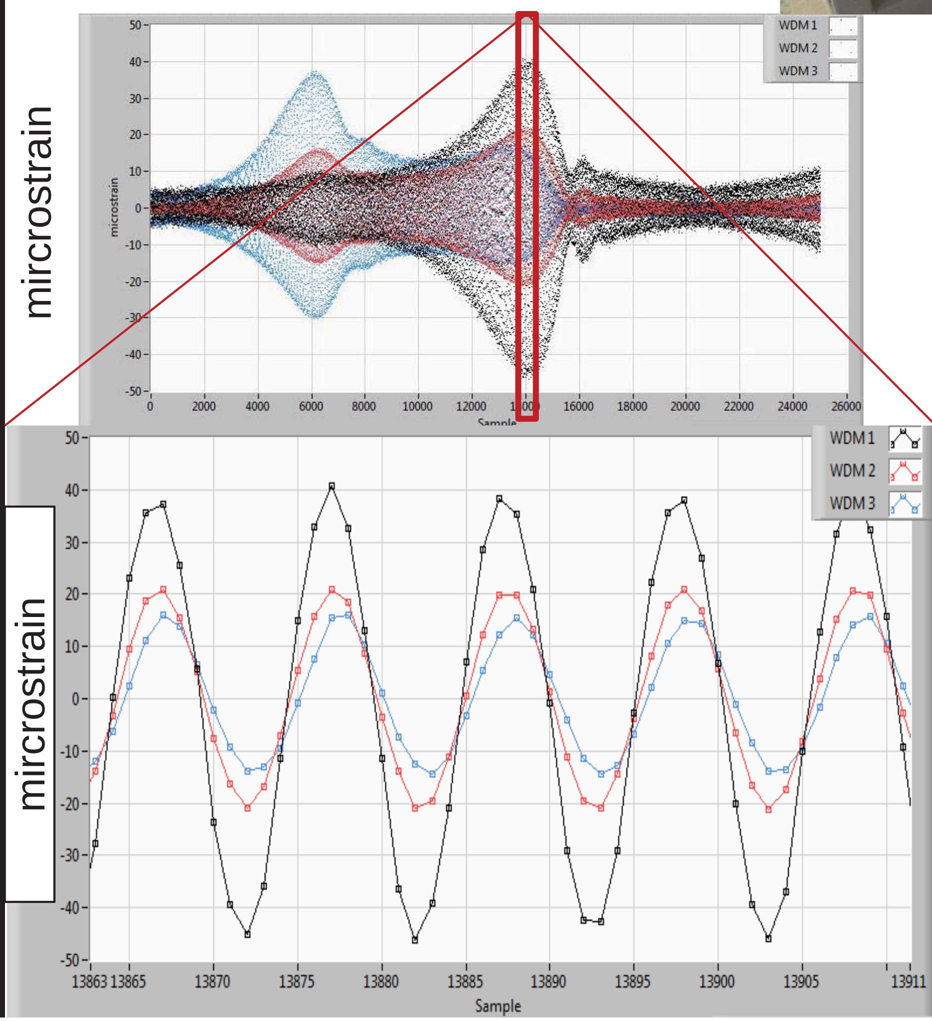
- 100 Hz (OFDR)
- 5,000 Hz (WDM)

National Aeronautics and Space Administration

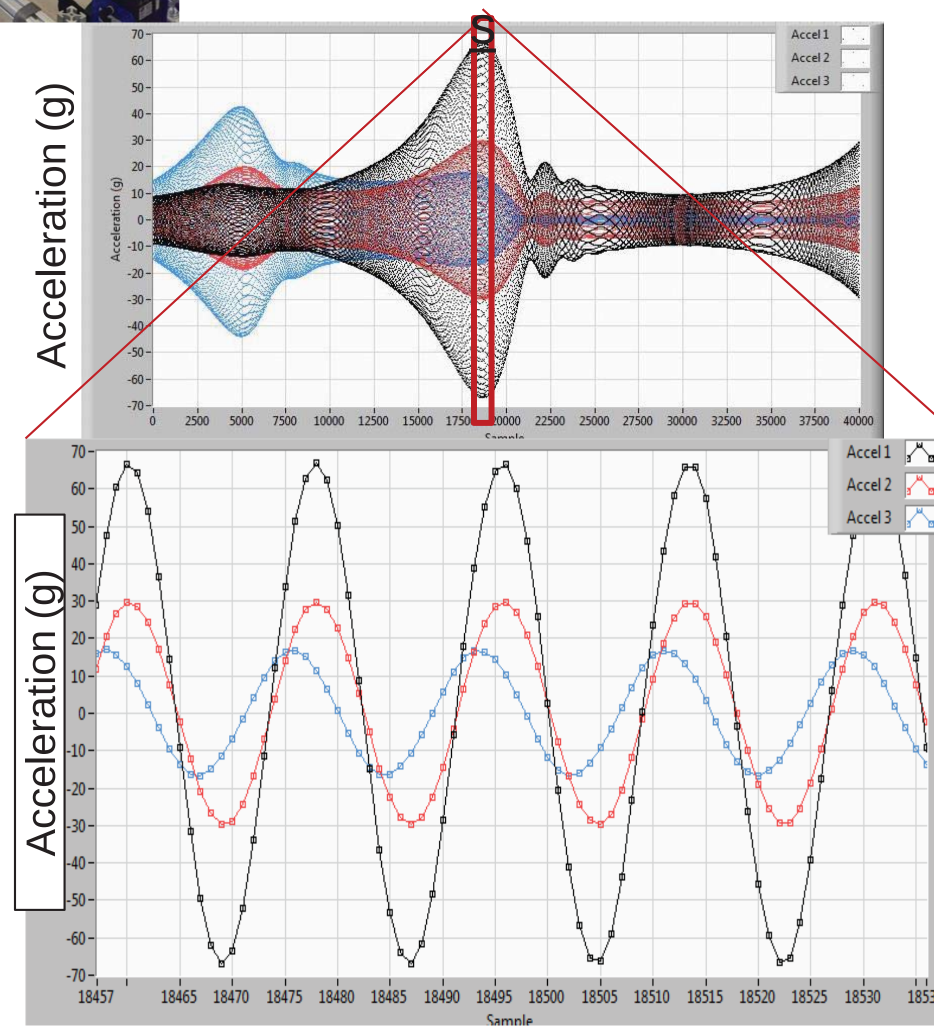
HyFOSS Plate – WDM & Accelerometer Frequency Sweep 475 Hz to 525 Hz



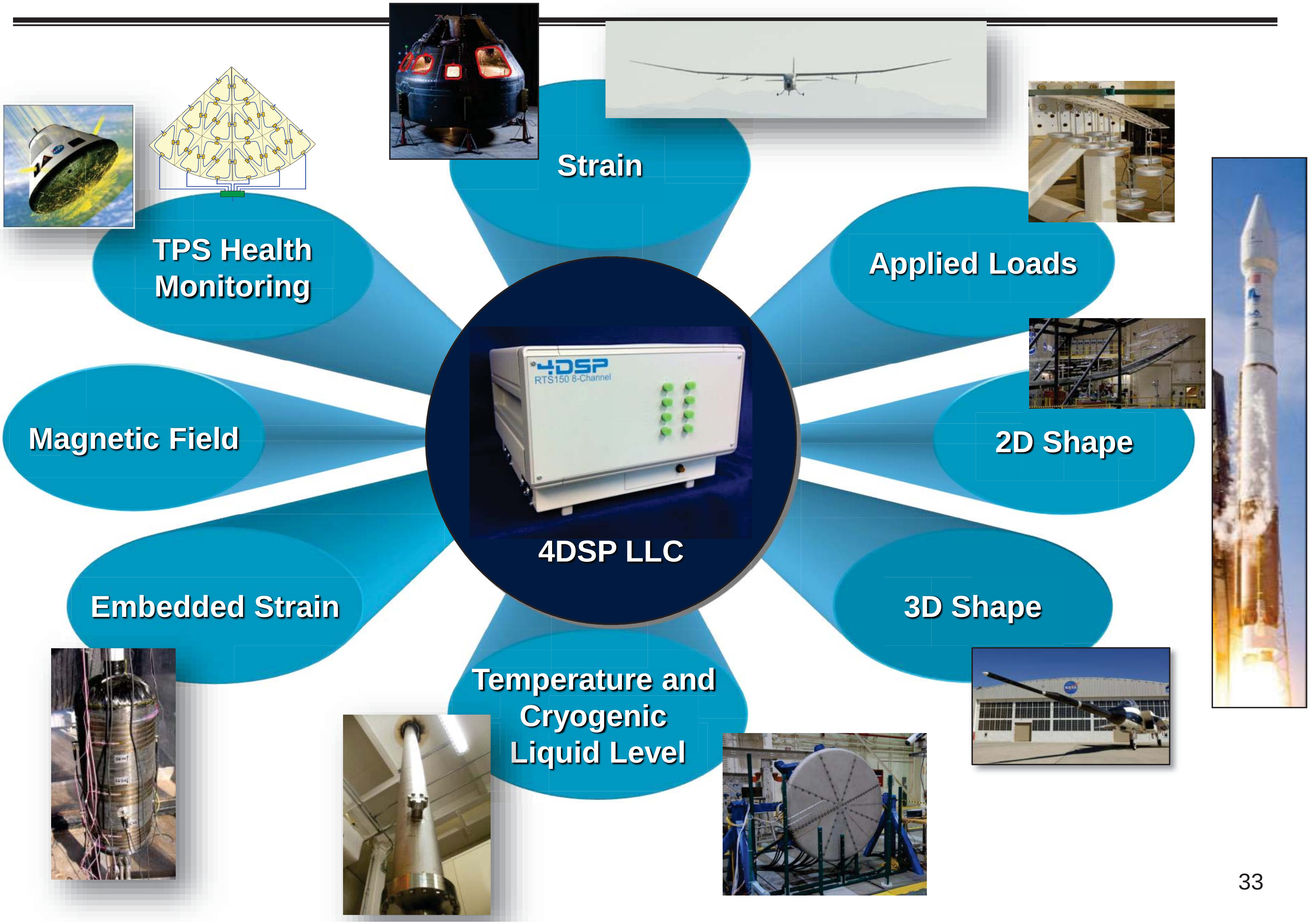
WDM



Accelerometer



Evaluation & Licensing Opportunities



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