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

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NASA Armstrong Flight Research Center
Edwards, CA

Information Updated

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National Aeronautics and Space Administration

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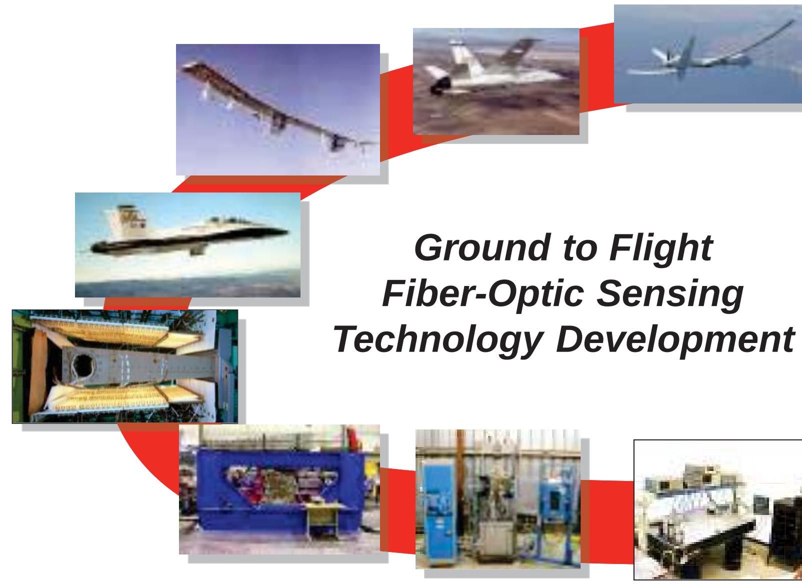
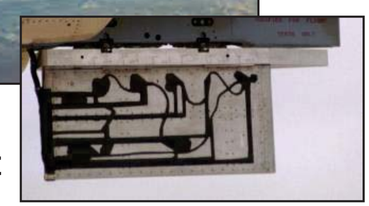
The FOSS Team

	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.**

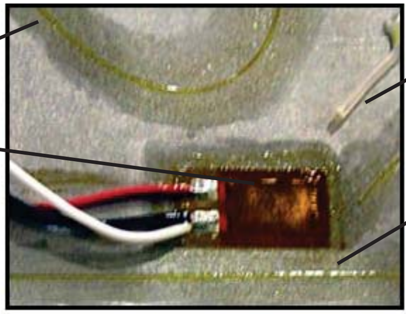




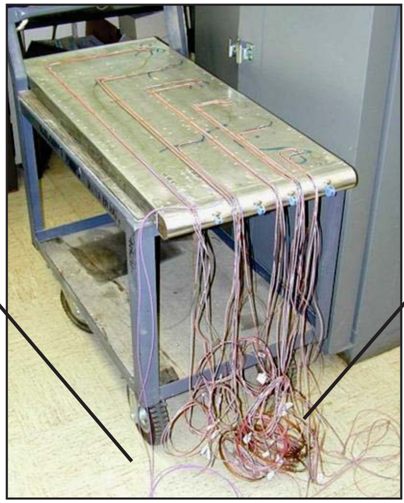
X-33 IVHM Risk Reduction Experiment

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

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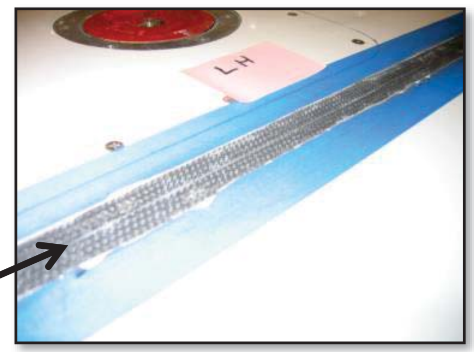
Installation Advantages and Limitations

Installation Advantages

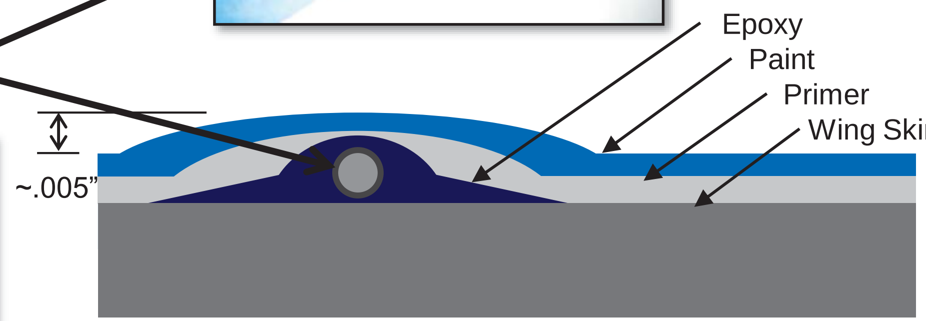
- Greatly reduced installation time compared to conventional strain gages
  - 2 man days for 40’ fiber (2000 strain sensors for a continuous surface run)
  - Multiple sensors installed simultaneously
  - Same surface preparation and adhesives as conventional strain gages
  - Minimal time spent working 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

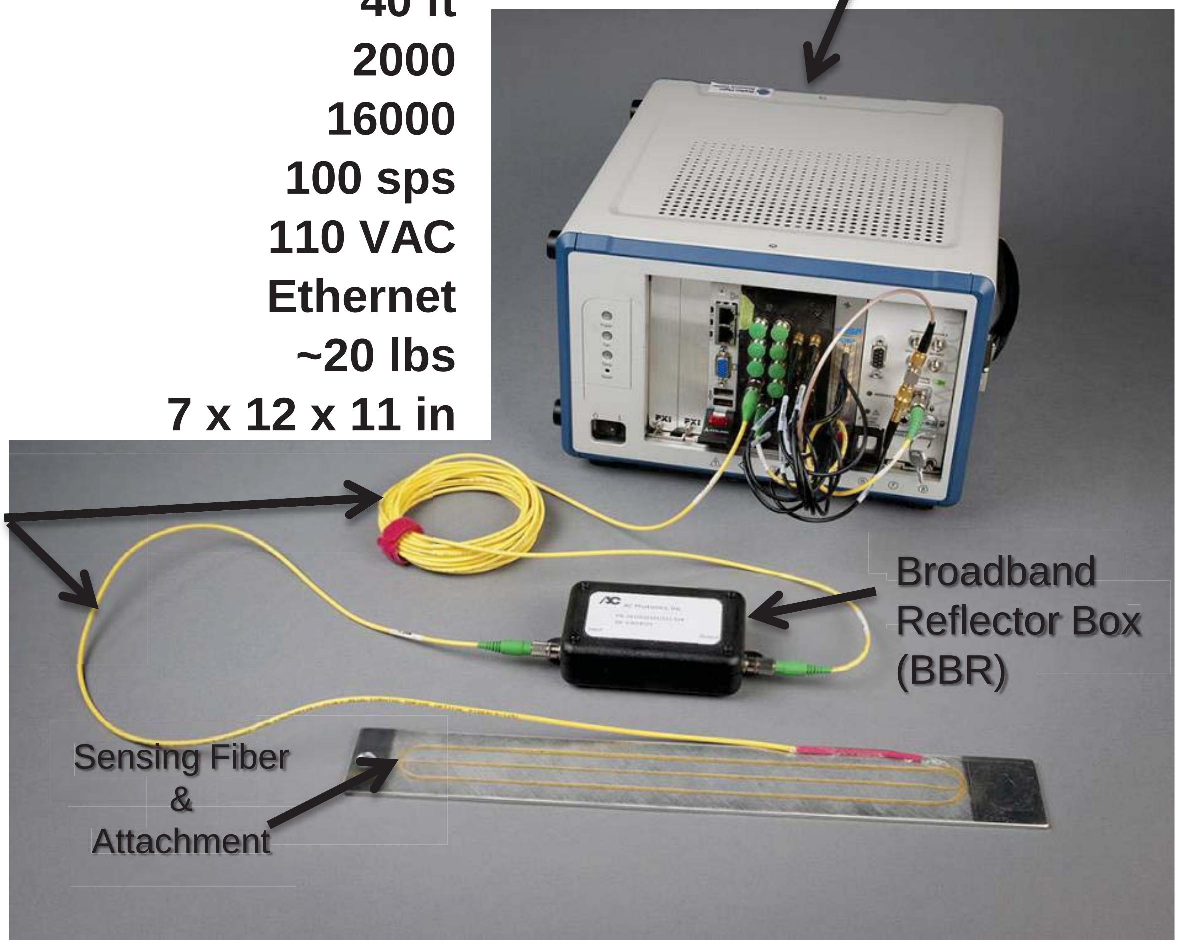


Strain Sensing – Ground System

Current Capabilities

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

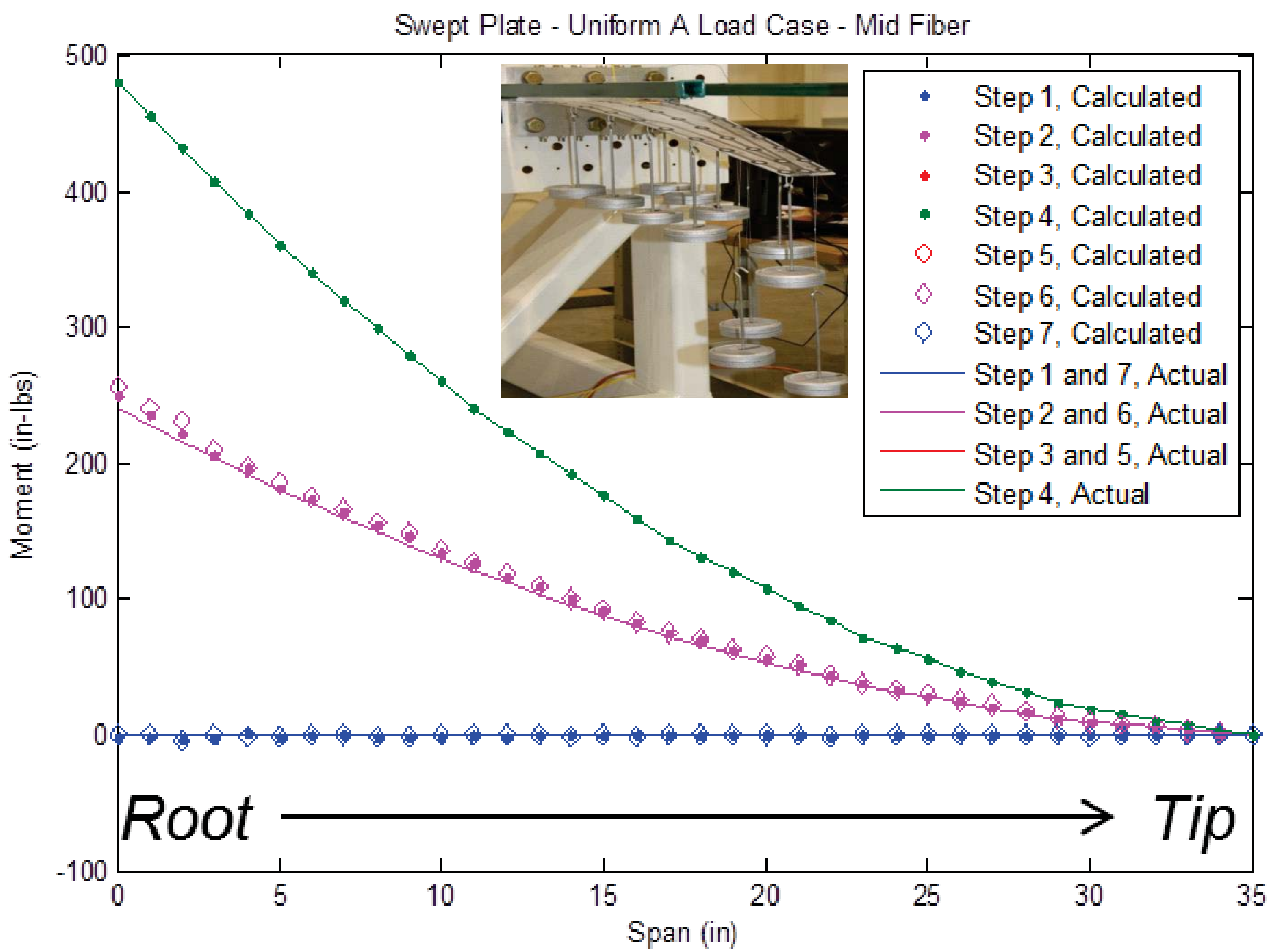
• Shock	8g
• Vibration	1.1 g-peak sinusoidal curve
• Altitude	60kft at -56C for 60 min
• Temperature	-56 < T < 40C

Predator -B in Flight

Strain and Applied Loads

Aluminum Flat Plate Validation Testing

Applied Loads Results

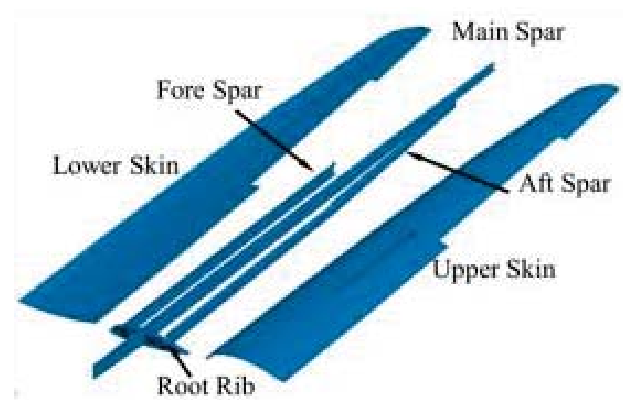


Strain and Applied Loads

Large-Scale Composite Wings - Mississippi State Univ

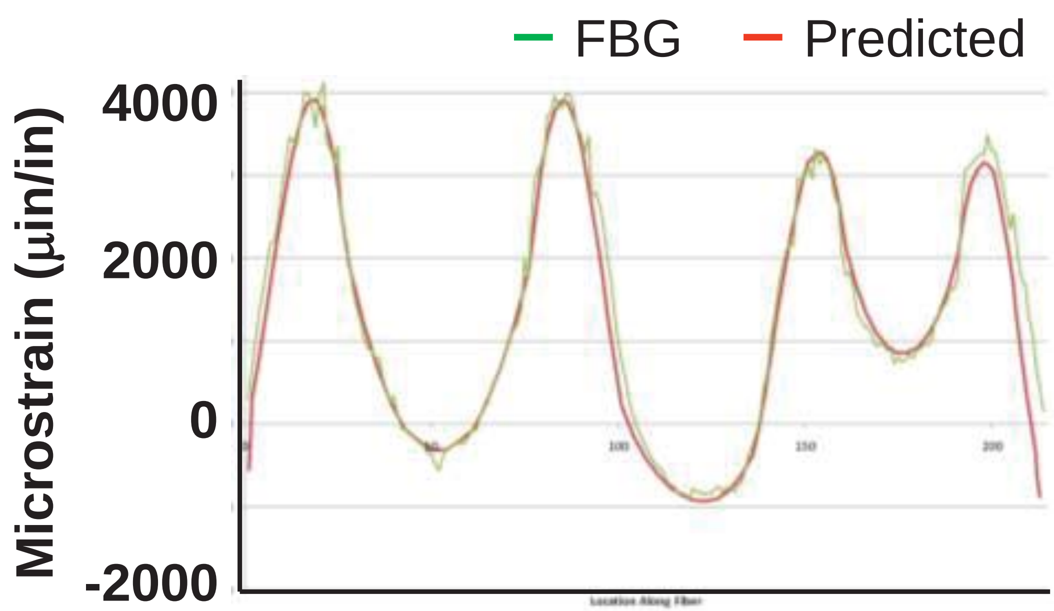
ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

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."



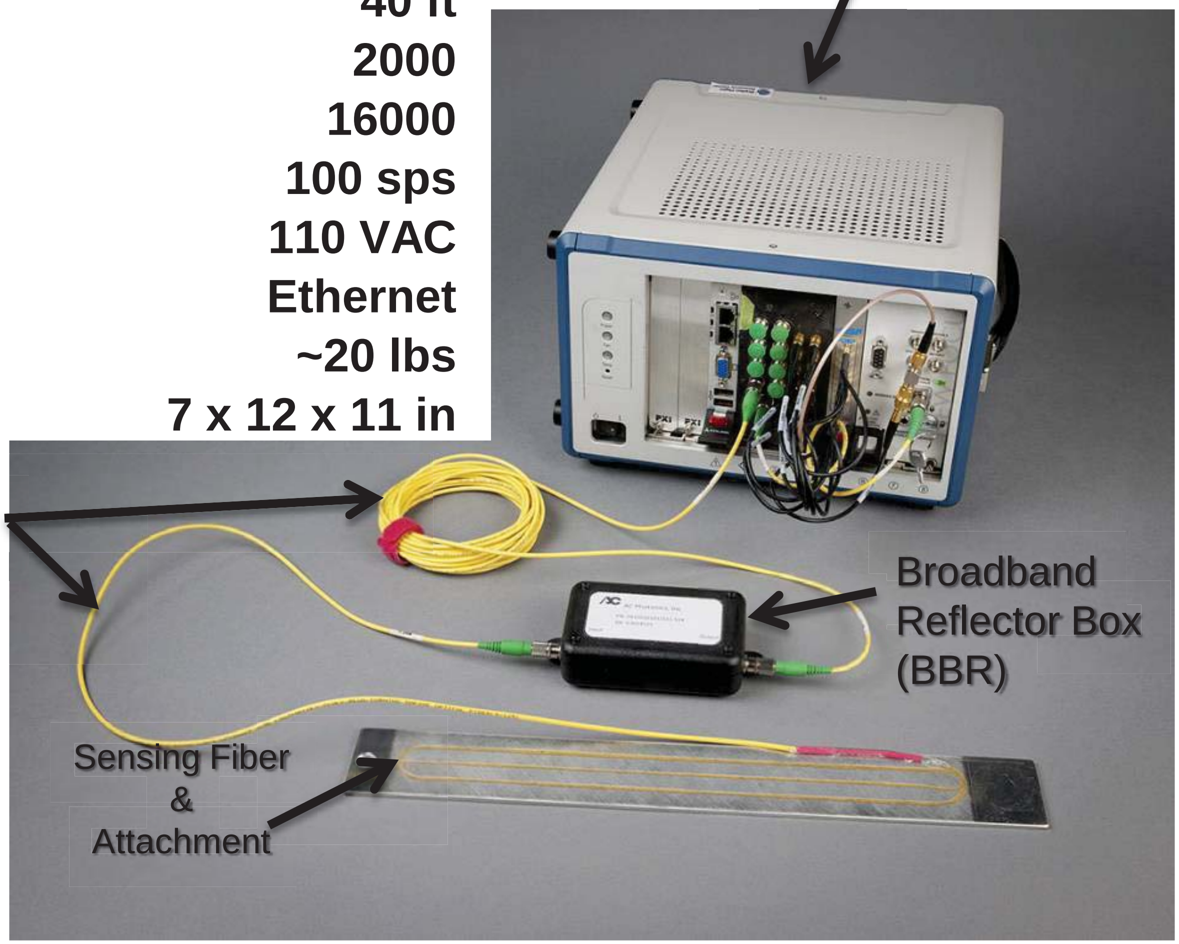
Inner Hatch FBG Strains, Max Pressure

Temperature Sensing

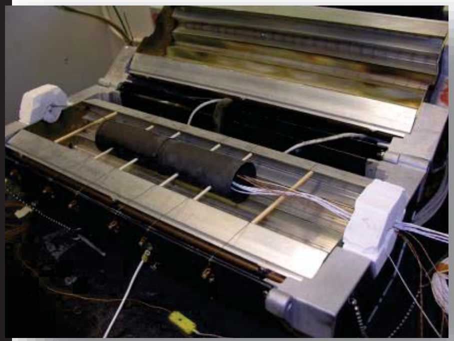
Current Capabilities

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

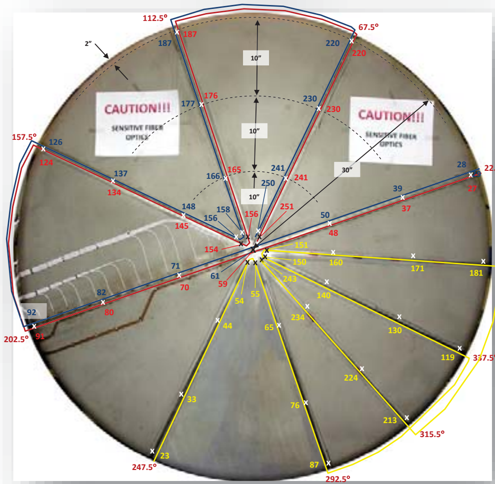


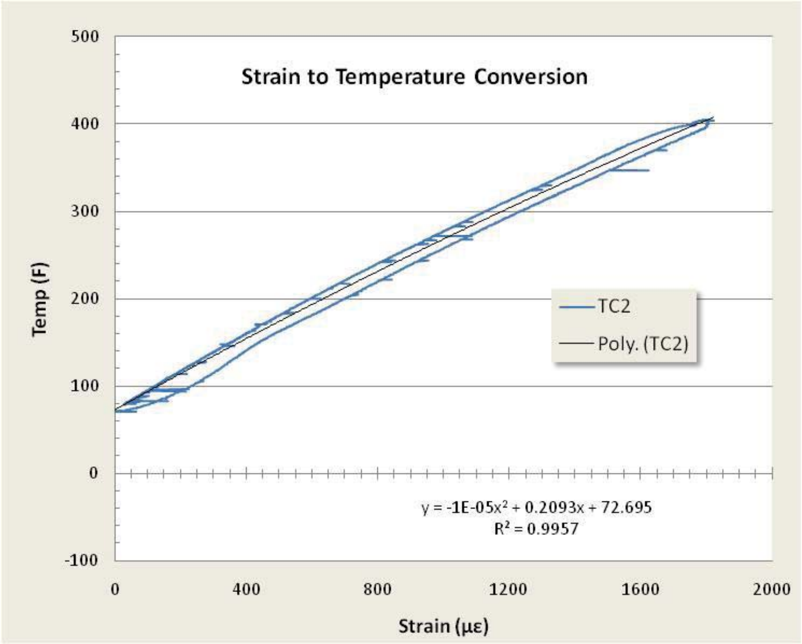
Temperature Conversion

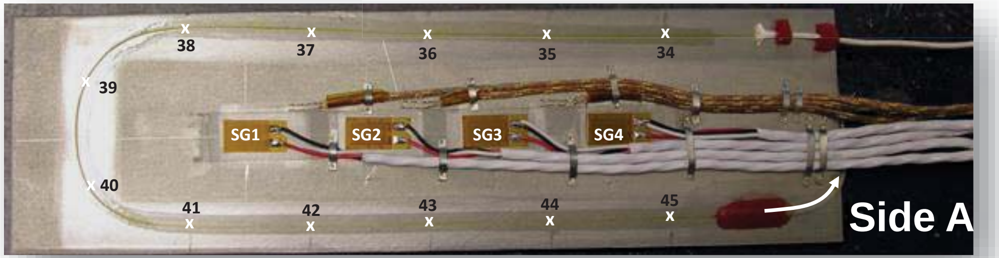


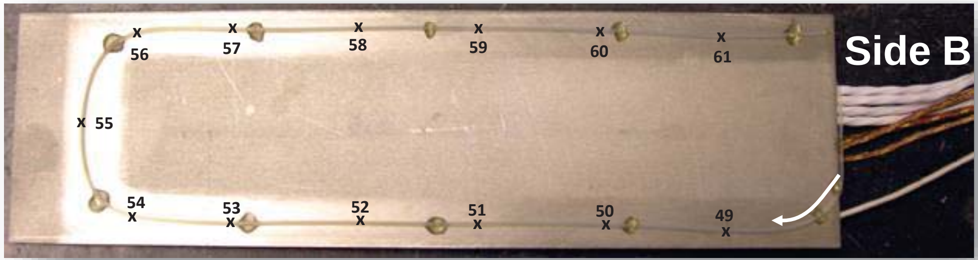
Test Notes

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









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

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

Requires knowledge of the structures centroid

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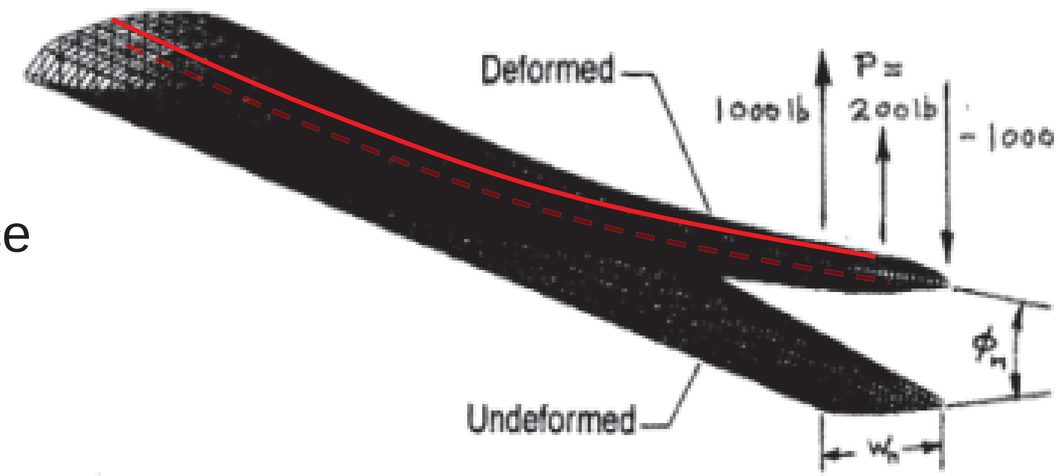
2D Strain-Based Deflection Methods

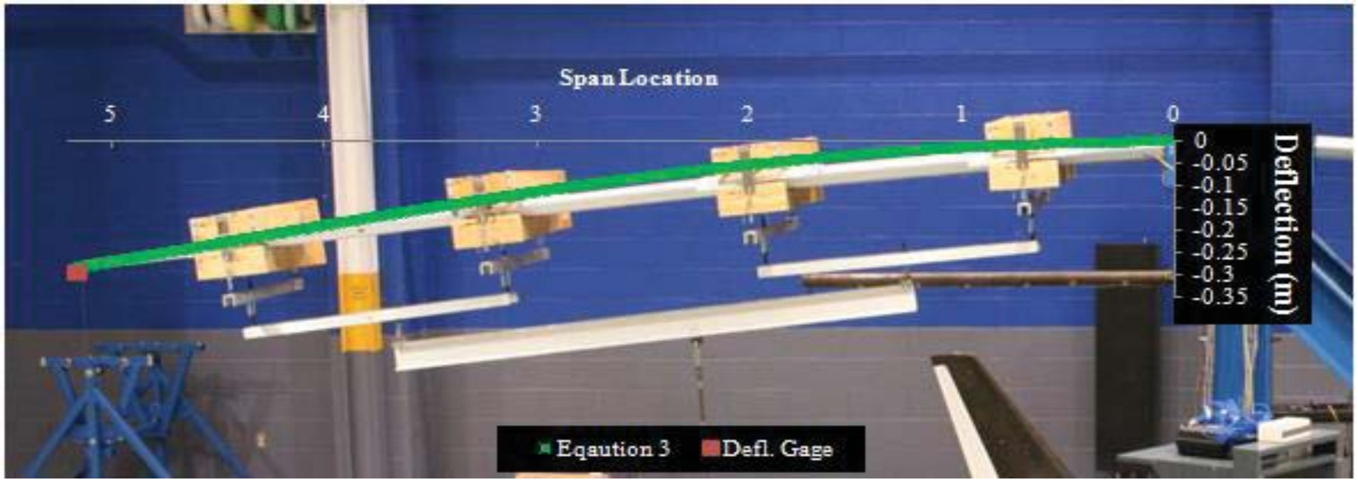
2D Shape Sensing Method

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



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

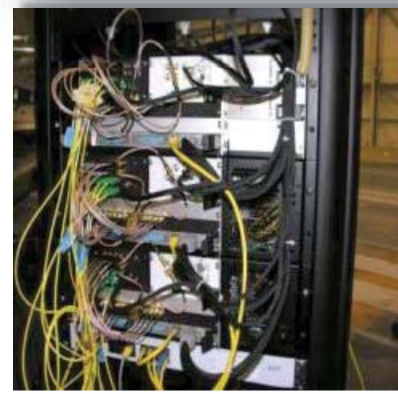
OUT-OF-PLANE APPLIED LOAD

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

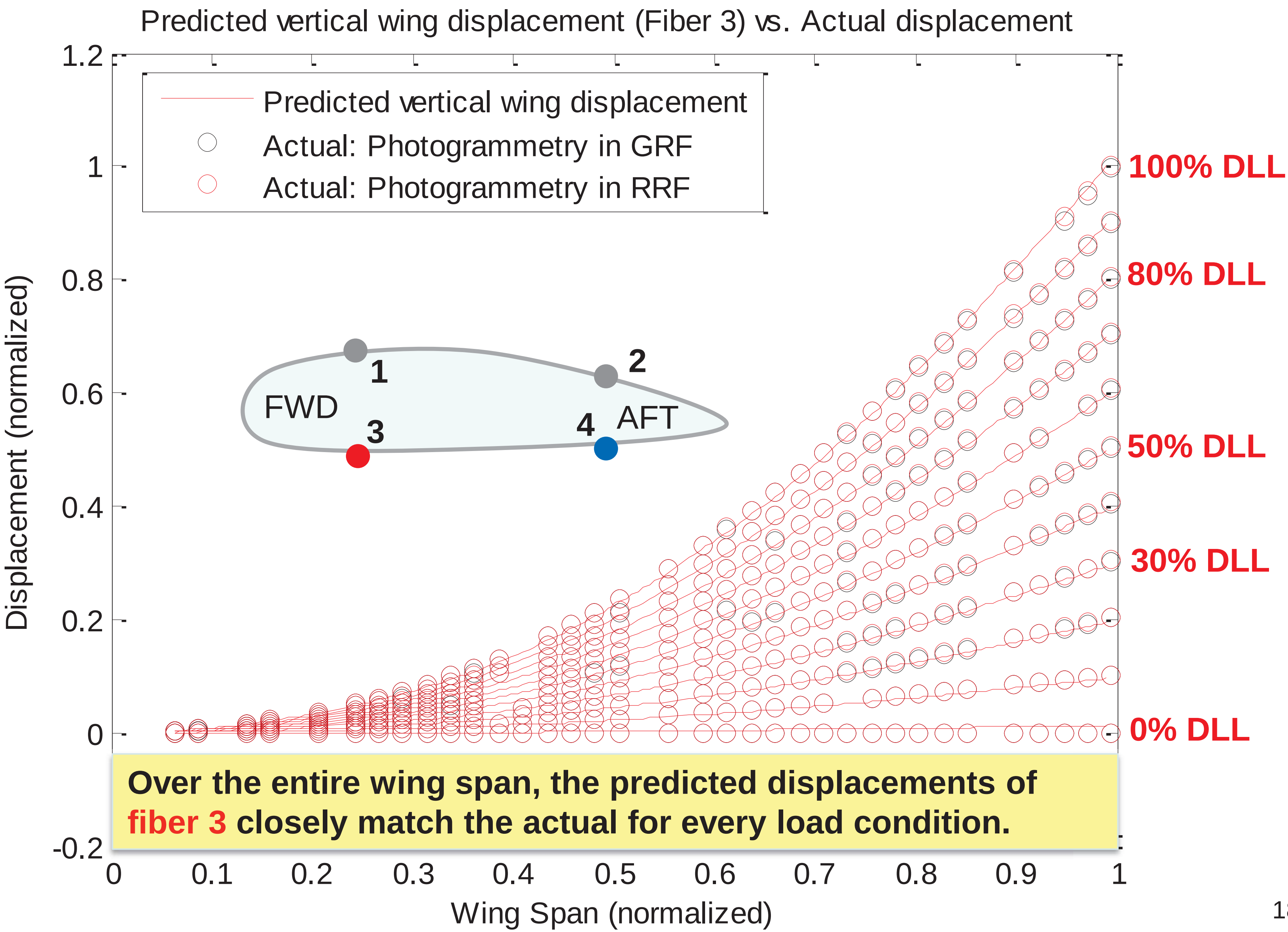


- **Validate strain predictions along the wingspan**
- **Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.**
- **FO Strain distribution measurements are being used to interpret shape using AFRC's 2D shape algorithm**
- **A 24-fiber system 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

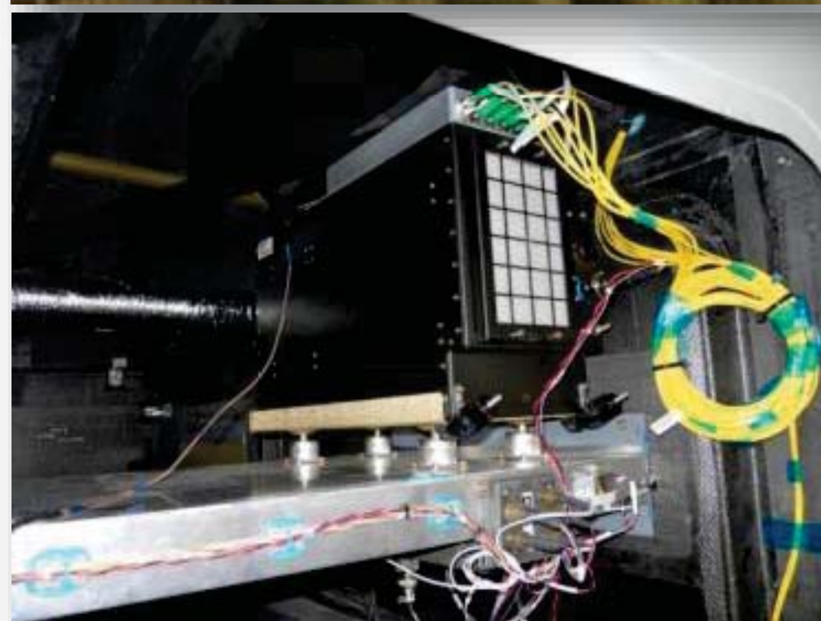


Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

Strain and 2D Shape Sensing

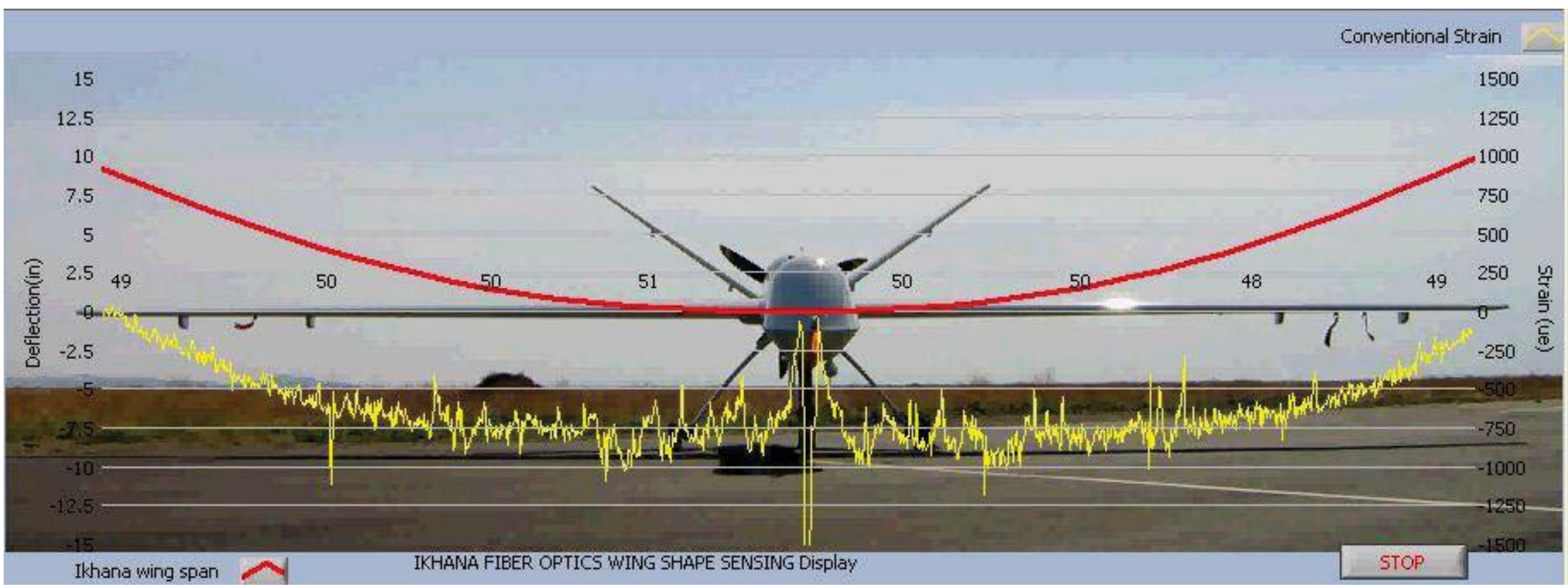
Global Observer UAS - Flight Testing

- **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

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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

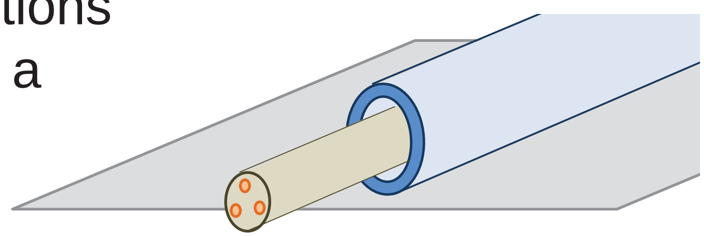
Environmental qualification specifications for flight system

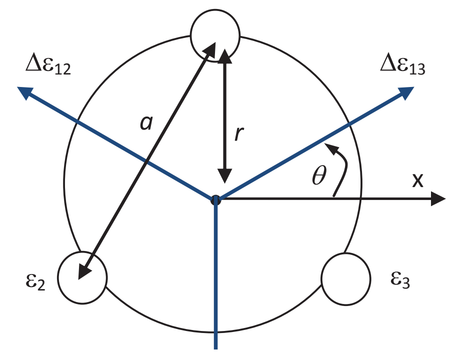
Shock	8g
Vibration	1.1 g-peak sinusoidal curve
Altitude	60kft at -56C for 60 min
Temperature	-56 < T < 40C

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

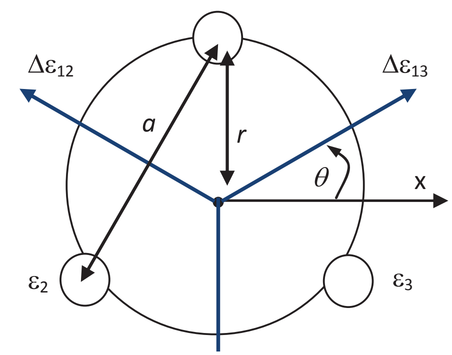


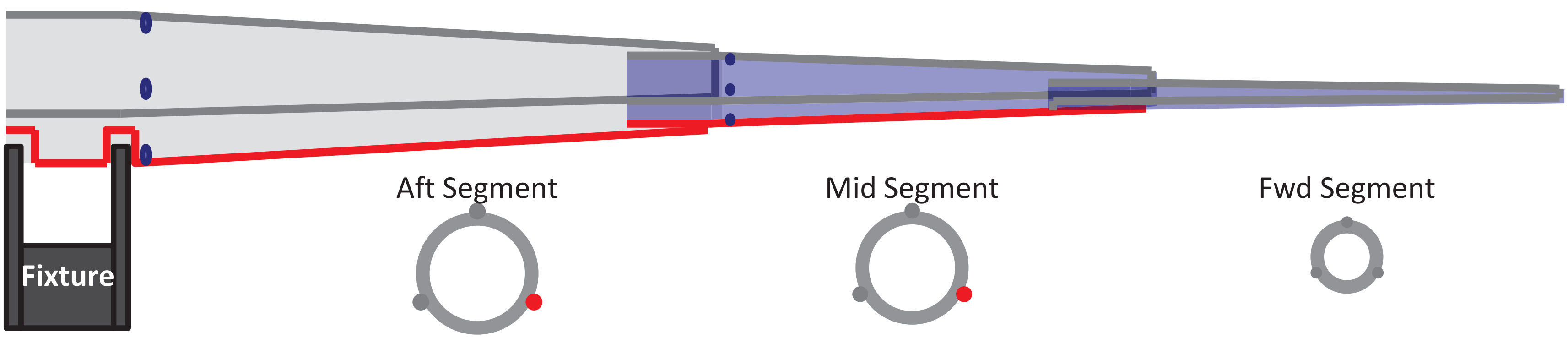


3D Shape Sensing

Prototype Quiet Spike Testing

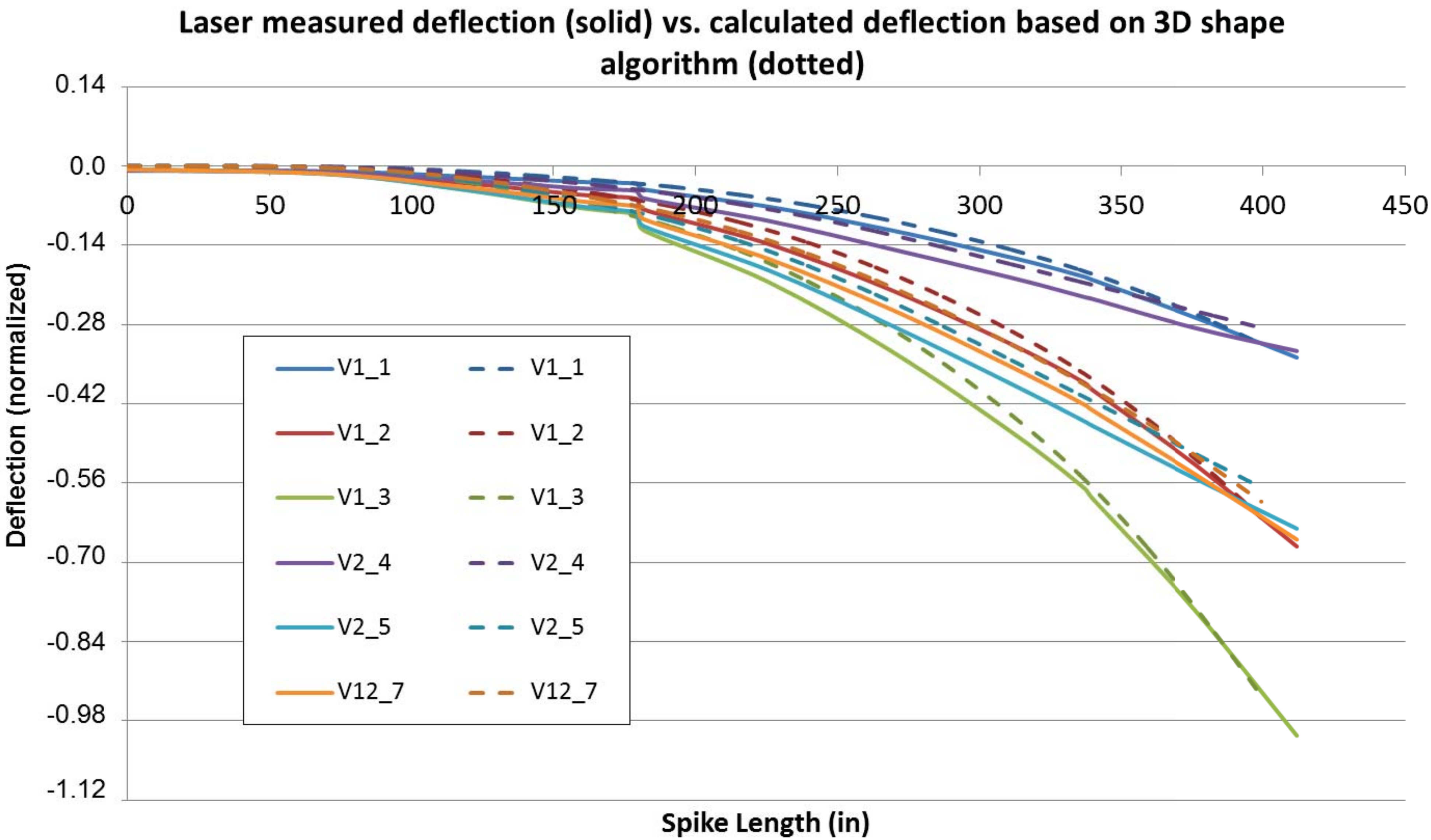
- Fibers are installed on the prototype of 35ft quiet spike at Gulfstream in Savannah GA
- Performed tests to determined benefits of deploying FOSS on Low Boom Experimental Vehicle
- Installed a total of 5 fibers measuring strain at ½" increments (2,570 strain sensors)
- Deflection shape of the Quiet Spike evaluated through the 3D shape algorithm





3D Shape Sensing

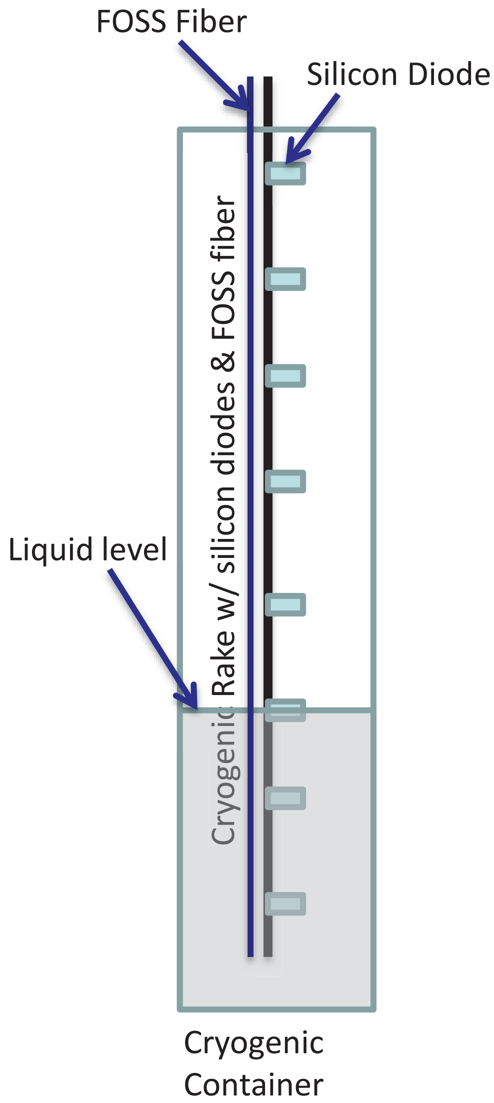
Quiet Spike Testing Results – lateral deflection



Liquid Level & Cryogenic Liquid Level Sensing
Current Capabilities

Current system specifications

• 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



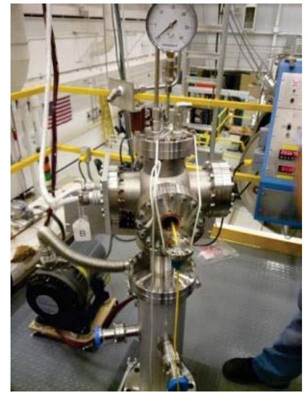
Cryogenic Liquid Level-Sensing

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

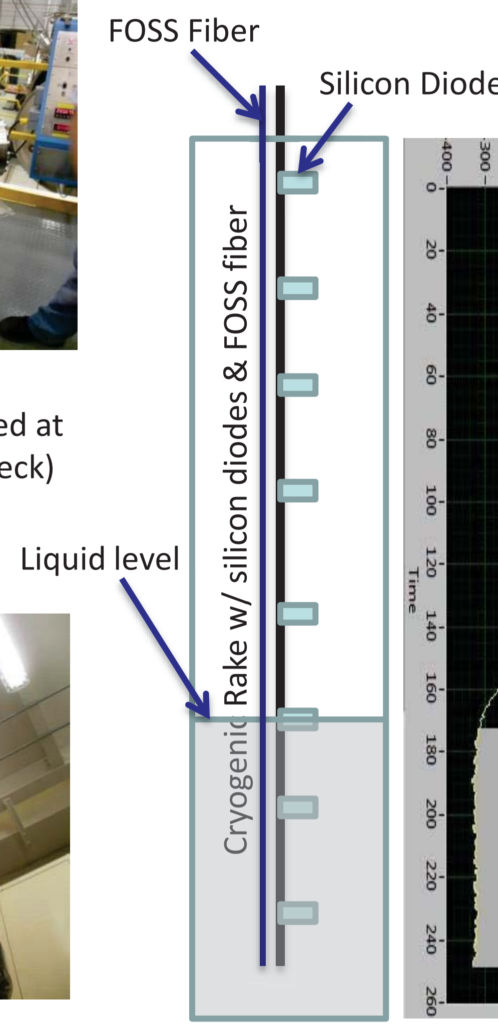
FOSS Approach

- 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”

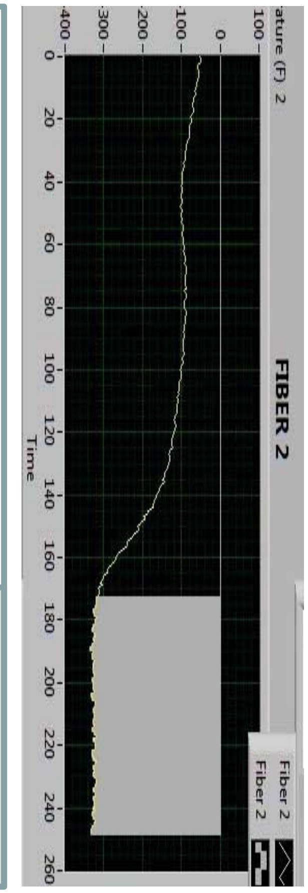


Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)



Cryogenic Container



1st Gen CryoFOSS Test Results

LH_2 Testing of CryoFOSS at MSFC

Objective

- Experimentally validate CryoFOSS using AFRC's FOSS technology

Test Details

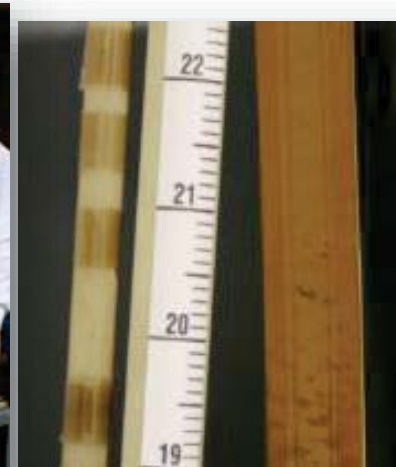
- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of 20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope with a ruler (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH_2 liquid level sensor(CryoFOSS)

Results

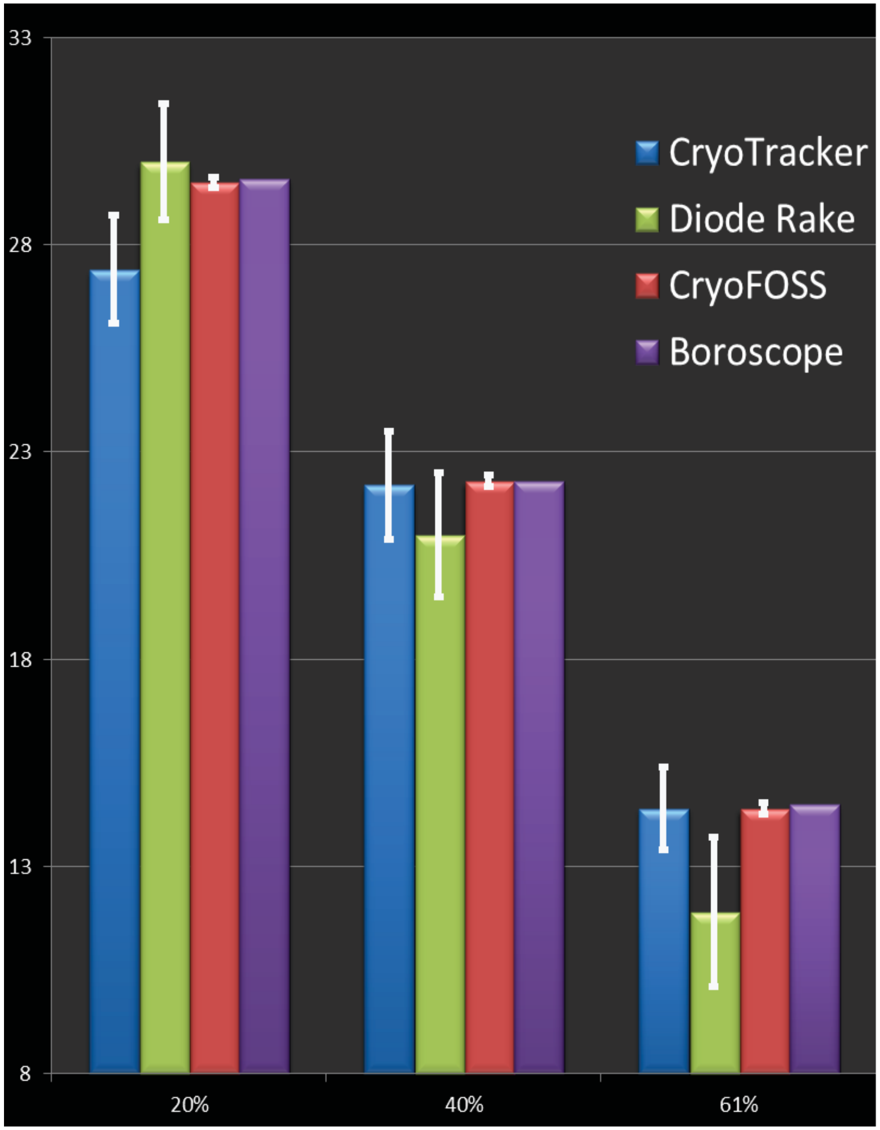
- CryoFOSS sensor discerned LH_2 level to ¼" in every case
- Excellent agreement achieved between CryoFOSS, boroscope, and silicon diode Cryotracker

Bottom line

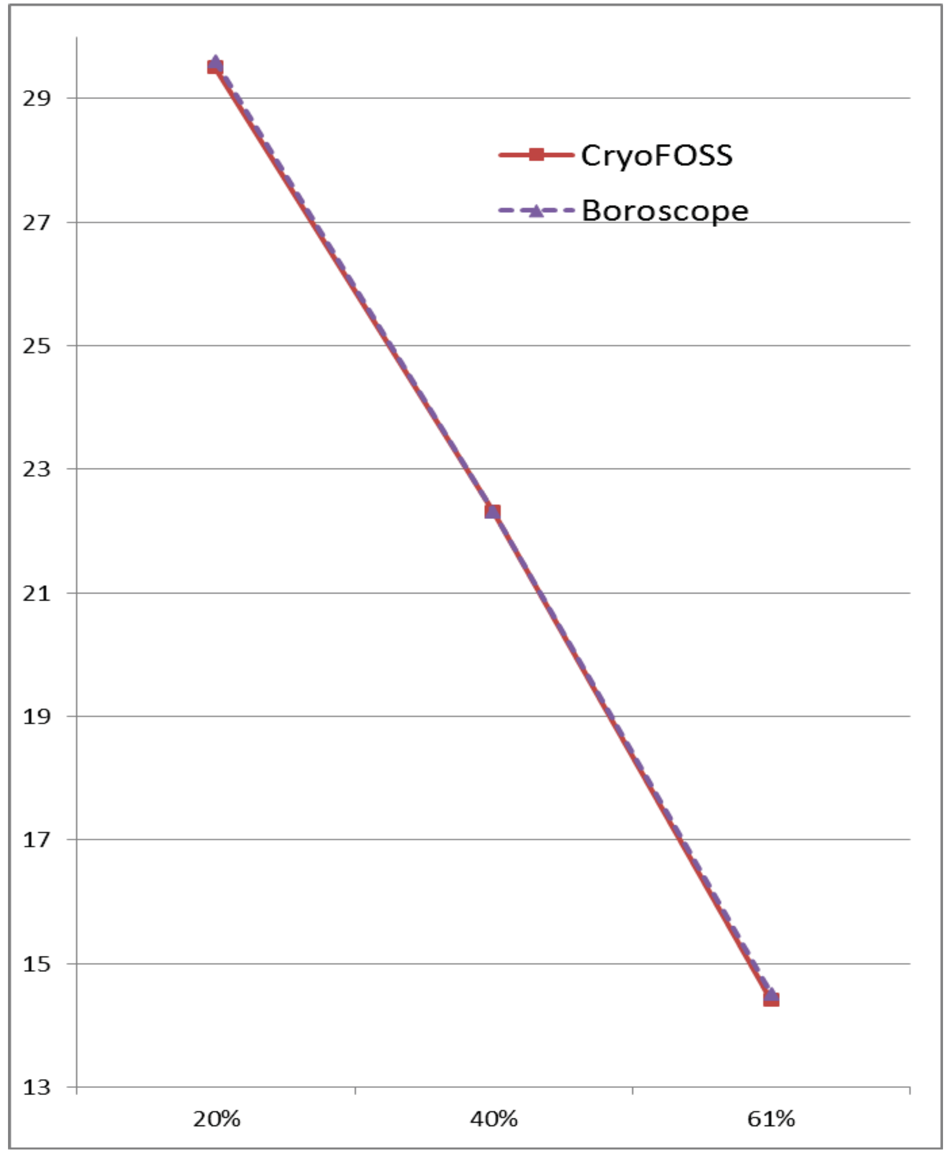
- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for ground and in-flight cryogenic fluid management systems



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
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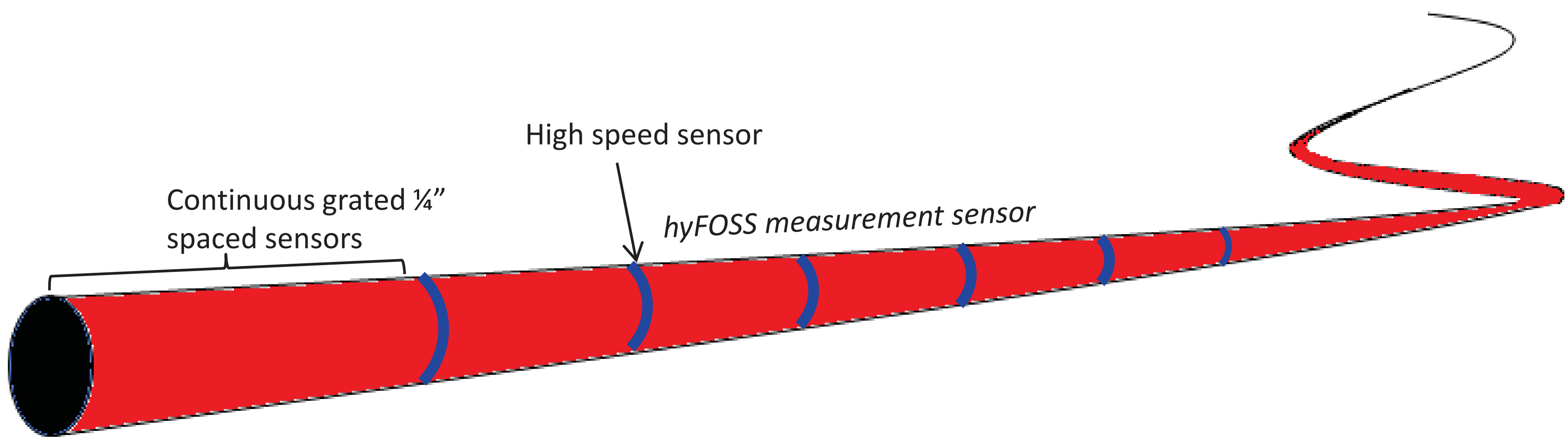

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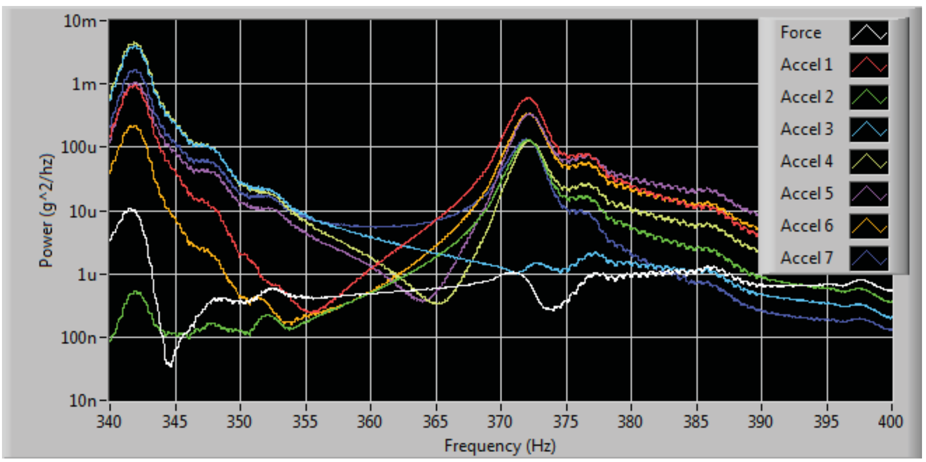
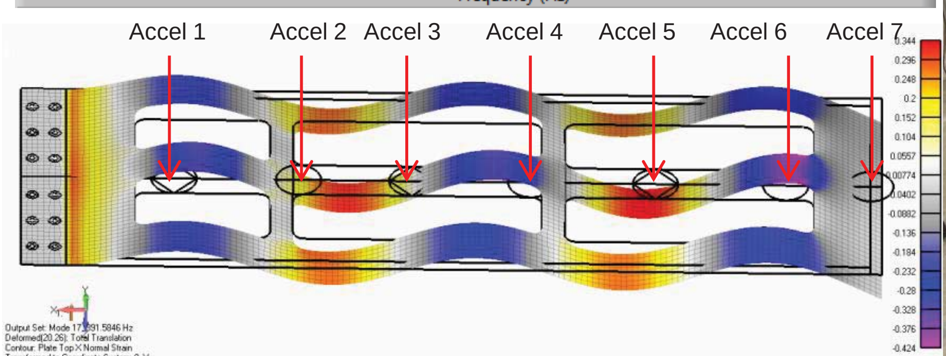
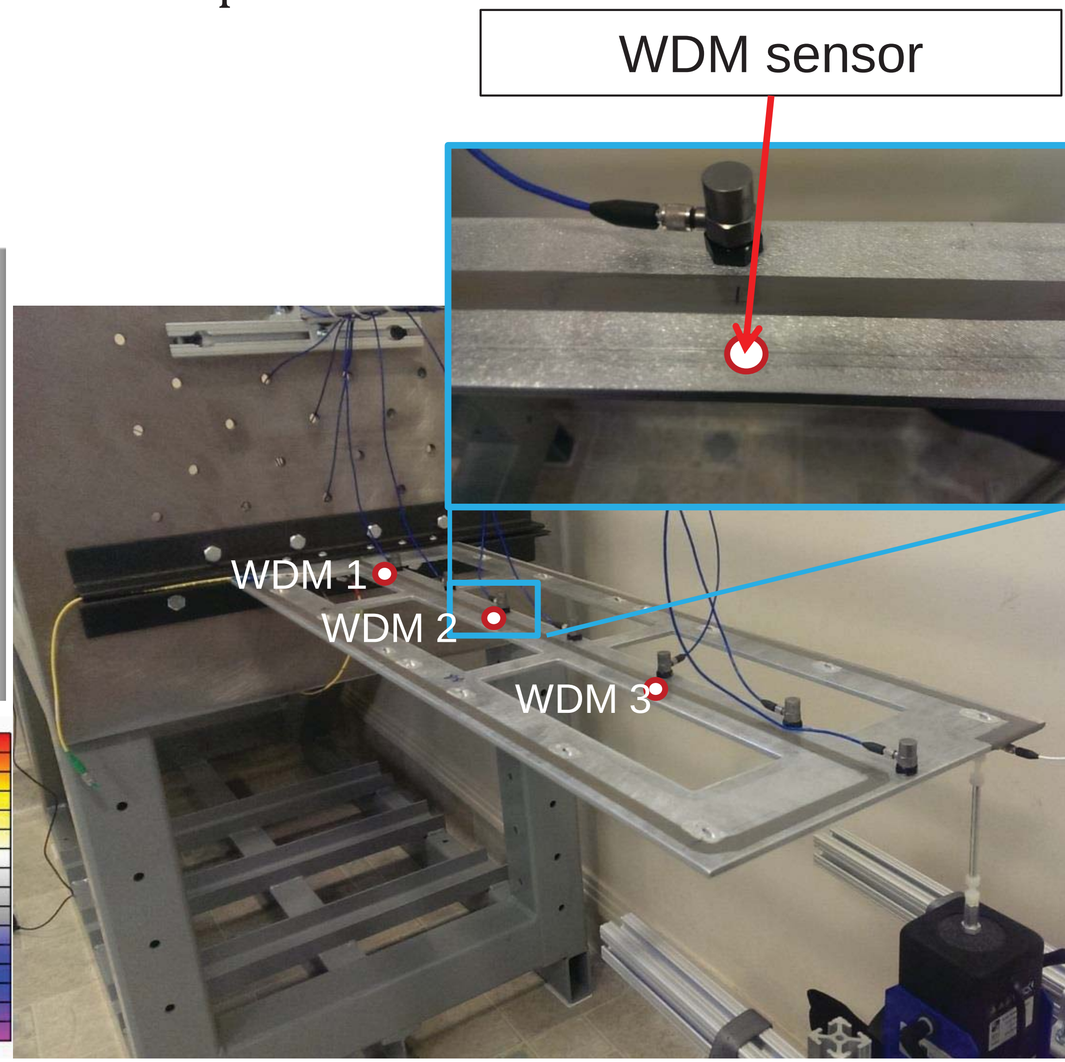
HyFOSS Open Plate test article

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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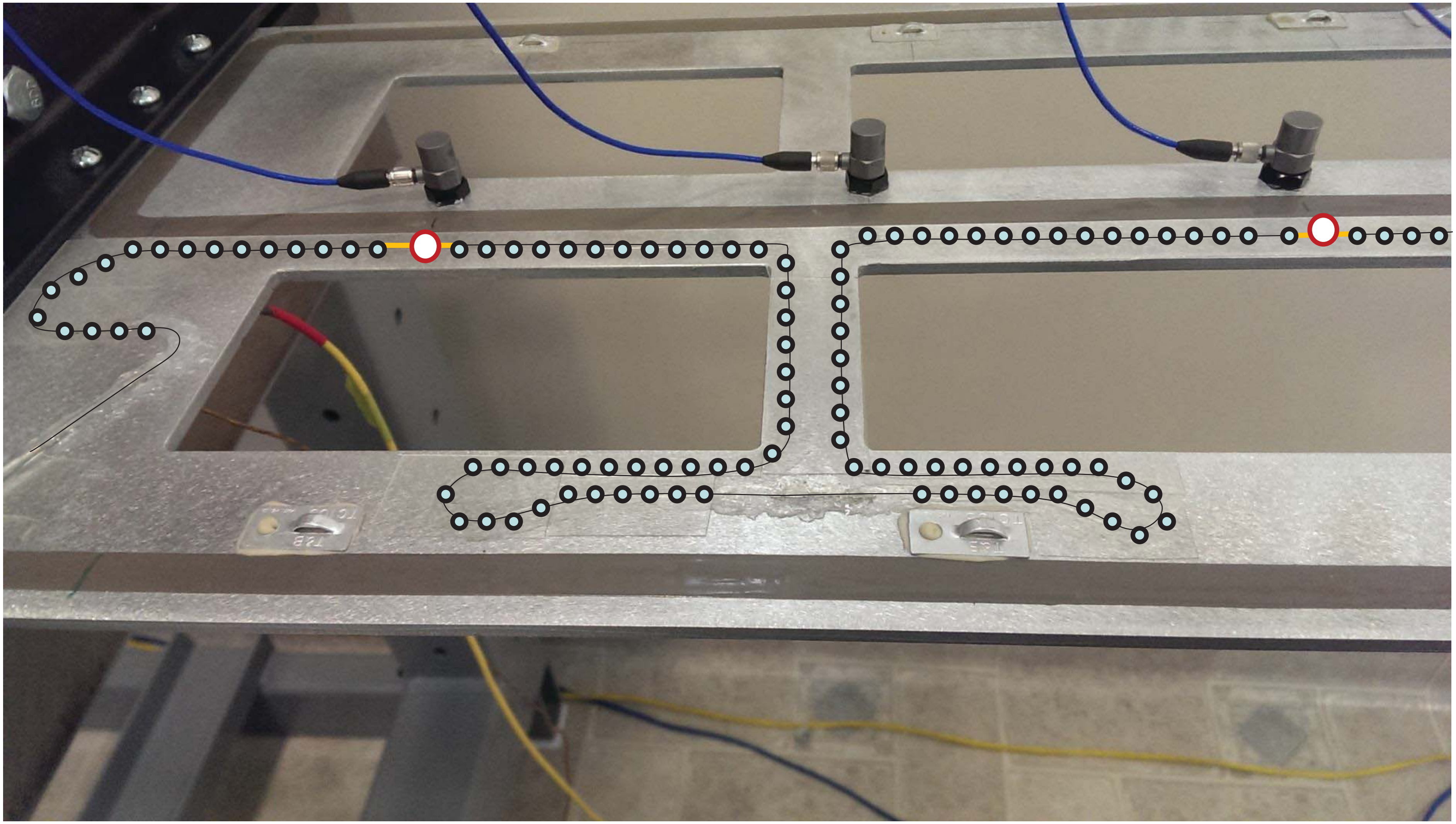
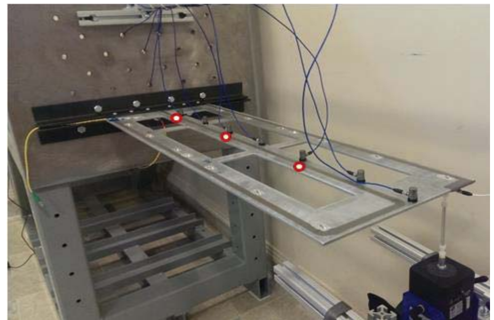
HyFOSS Sensor Installation



- 100 Hz (OFDR)

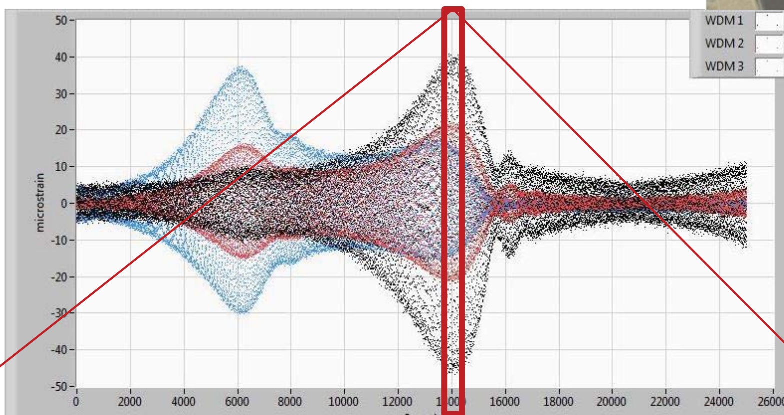
- 5,000 Hz (WDM)

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



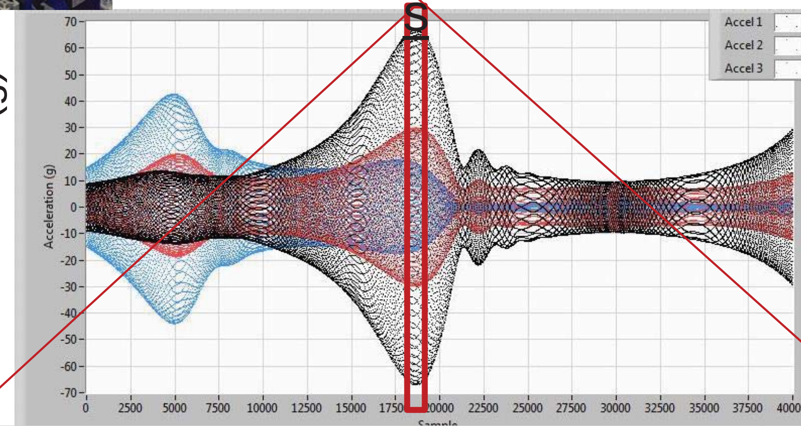
WDM

mircrostrain

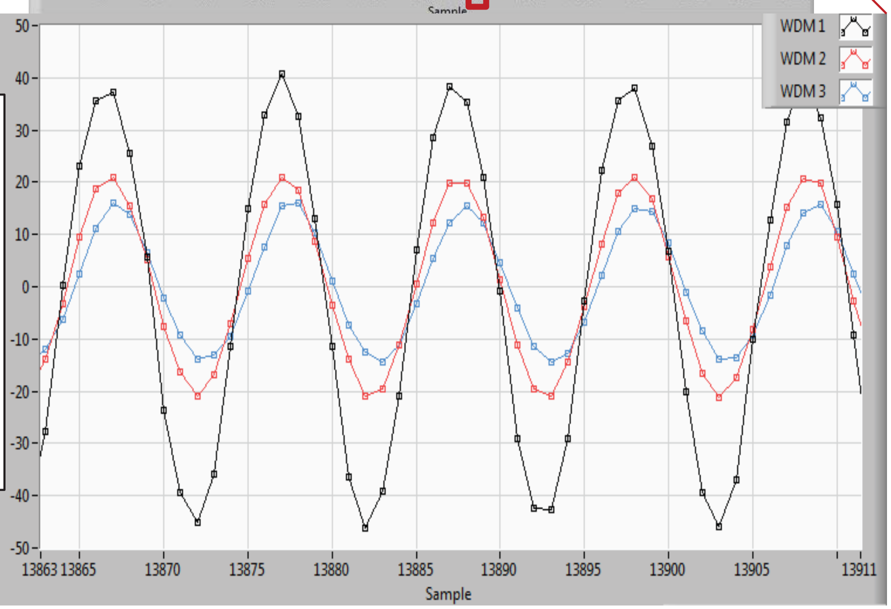


Accelerometer

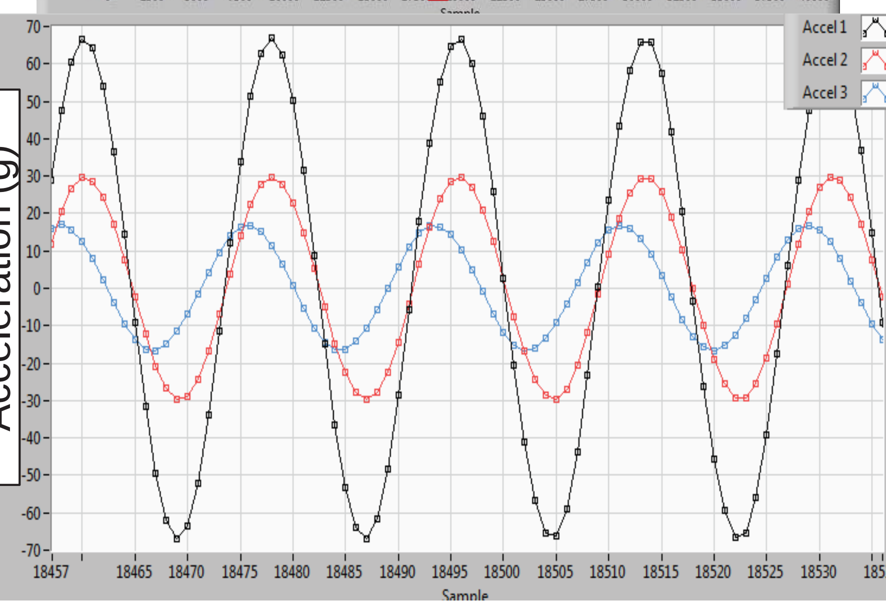
Acceleration (g)



mircrostrain



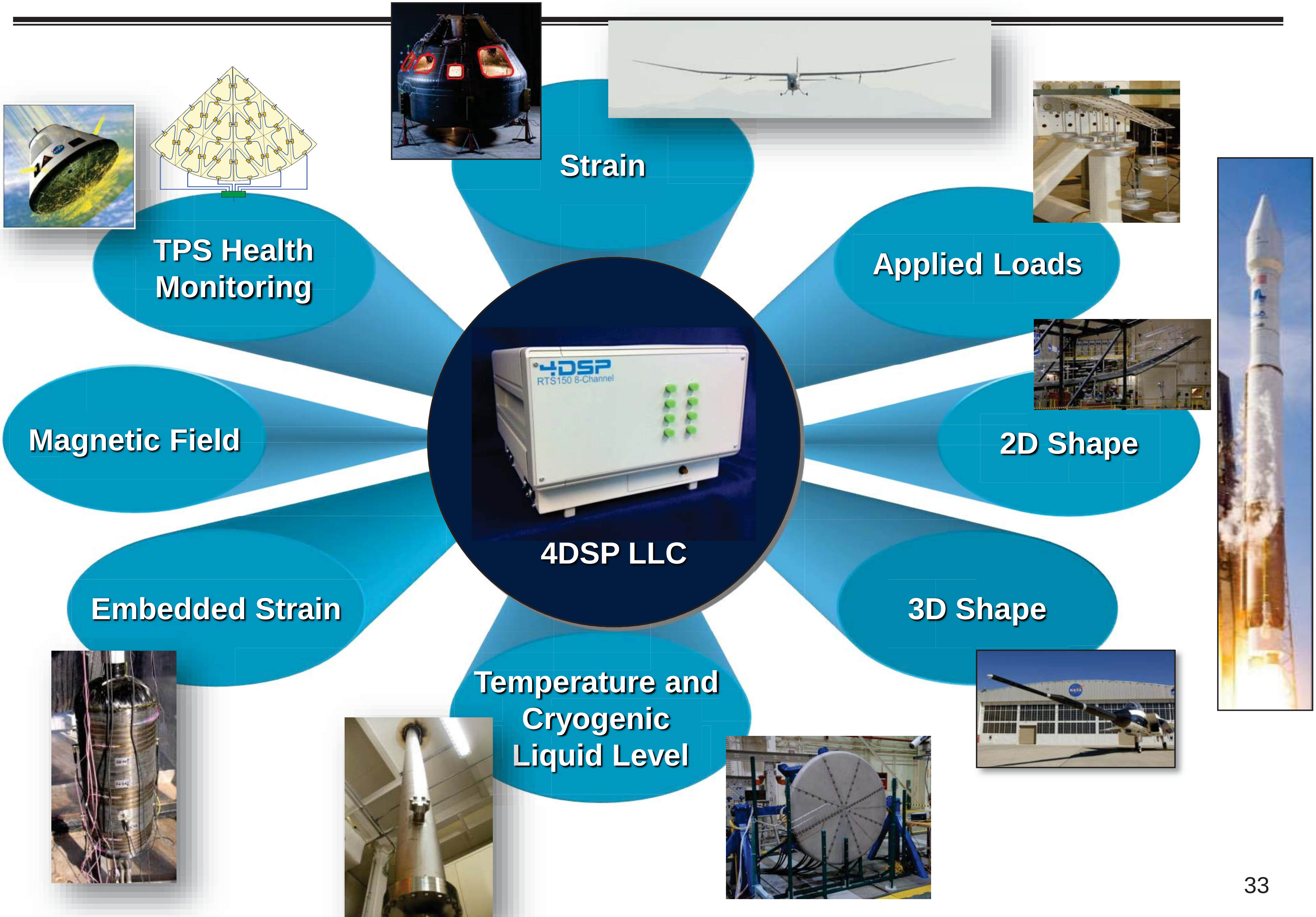
Acceleration (g)



National Aeronautics and Space Administration

Evaluation & Licensing Opportunities

National Aeronautics and Space Administration



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