National Aeronautics and Space Administration

Fiber Optic Sensing System (FOSS) Technology

A New Sensor Paradigm for Comprehensive Structural Monitoring and Model Validation throughout the Vehicle Life-Cycle

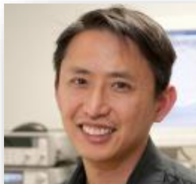
Francisco Peña, Dr. Lance Richards, Allen. R. Parker, Jr.,

Anthony Piazza, Patrick Chan, and Phil Hamory

NASA Armstrong Flight Research Center
Edwards, CA

January 20th, 2015

The FOSS Team

	Team member	Field	Contributions to FOSS
	**Patrick Chan**	Optics Engineer	Optics Development, laser research and development
	**Philip Hamory**	Electrical Engineer	Advanced System Algorithm Development
	**Francisco Pena**	Structures Engineer	Structural Test and Analysis
	**Allen Parker**	Electrical Engineer	Systems design & development, data processing and visualization
	**Anthony Piazza**	Instrumentation Specialist	Sensor characterization, application, & interpretation
	**Lance Richards**	Structures Engineer	Aircraft structures, strain measurement research

AFRC Structures Test and Analysis

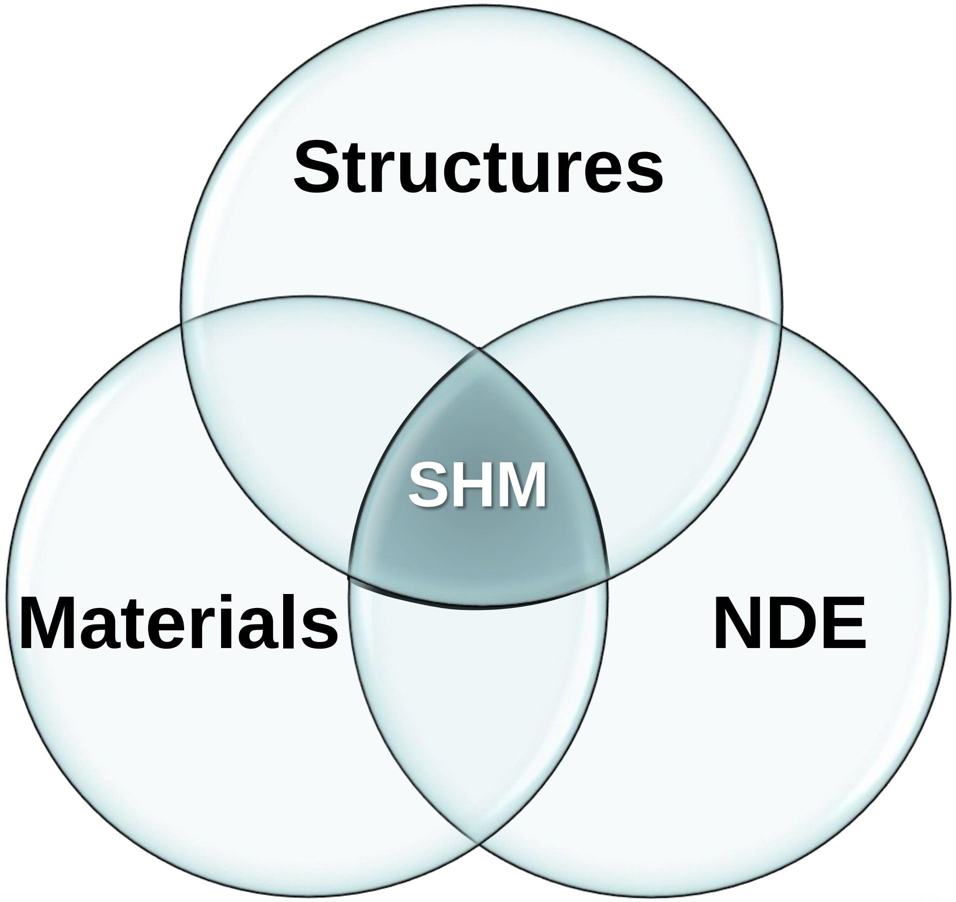
Structural Test and Analysis Products

- Experimental methods
  - Structural testing from coupon, subcomponent, component, qual-unit, flight component, full vehicle (for aircraft of all Mach no's, launch vehicles, spacecraft applications)
  - Ground testing (structural labs, wind tunnels, cryogenic labs)
  - Flight testing
  - Mechanical: Load frames, custom designed test setups, load introduction hardware, restraints,
  - Thermal: high & low temperature (radiant quartz lamps and cryogenic cooling, resp)
  - Aero
- Structural measurement methods
  - Strain (stress), temperature, displacement, load, heat flux, discrete, full-field
  - Strain gage technology, fiber optic sensors, load cells, LVDTs, potentiometers, TCs, digital image correlation, thermal imaging, Interferometry, Moire,
  - Experimental Stress Analysis, measurement uncertainty (temperature compensation methods)
  - Correlation of experimental / analytical results
  - Collaborate with analysts to correlate experimental results with analytical predictions
- Analytical, computational, empirical
  - Pre-test, pre-flight predictions
  - Validated structural analysis from coupon, subcomponent, component, qual-unit, flight component, full vehicle (for aircraft of all Mach no's, launch vehicles, spacecraft applications)
  - Collaborate with experimentalists to correlate real-time structural monitoring (comparison of structural performance vs analytical predictions)
  - Post-test, post flight, correlation of analytical/experimental results
    - Tuning of B/Cs, mat props, loads (mech/thermal, i.e applying measured data to analysis models)

NASA Focused Structural Health Monitoring

Key Drivers

Vehicle-focused
Real-time, decision-making
Online processing
Onboard systems
Lightweight, Small size, Low power,
System solutions



Enabling Technologies

Advanced Sensing
- Multi-parameter
- Sensor arrays

Advanced Systems and Processing
- Solid state
- Rugged
- High Speed

Ultra-Efficient Algorithms

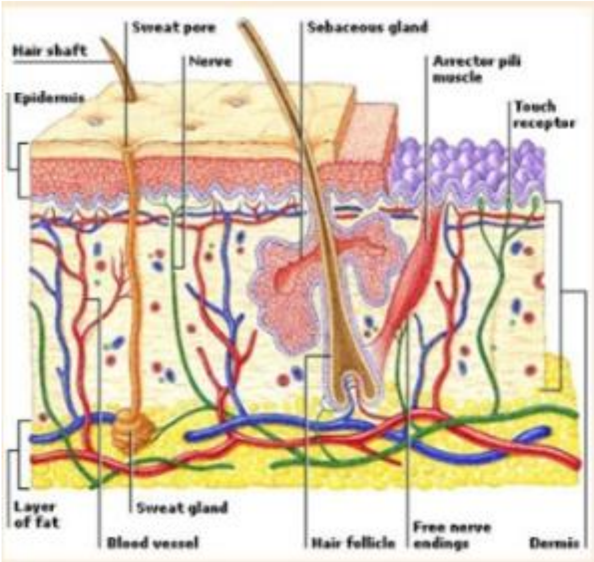


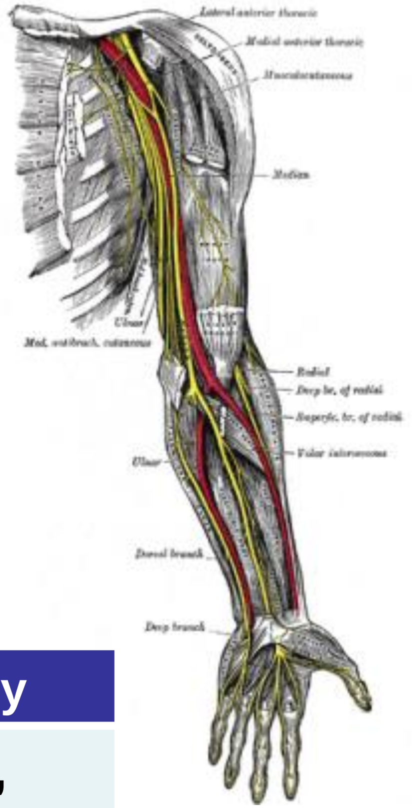

Background and Inspiration

Biological Inspiration of Fiber Optic Smart Structures

One Square-Inch of Human Skin

- Four yards of nerve fibers
- 600 pain sensors
- 1300 nerve cells
- 9000 nerve endings
- 36 heat sensors
- 75 pressure sensors
- 100 sweat glands
- 3 million cells
- 3 yards of blood vessels



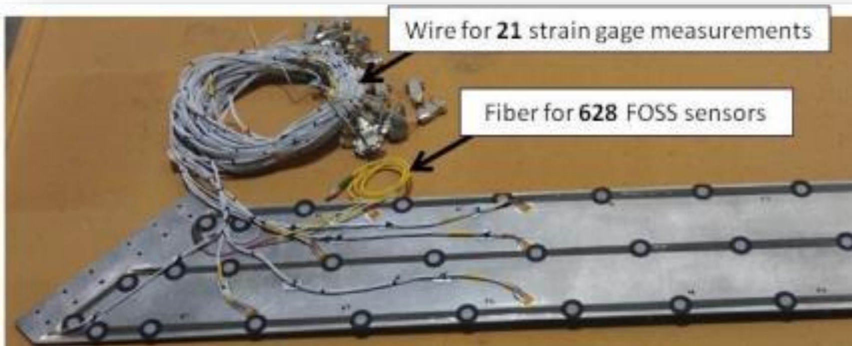


Smart Structure	Human Body
Fiber Optic Sensors	Pain, temp, pressure sensors
Piezo's, SMAs	Muscles
IVHM, Smart Systems	Brain

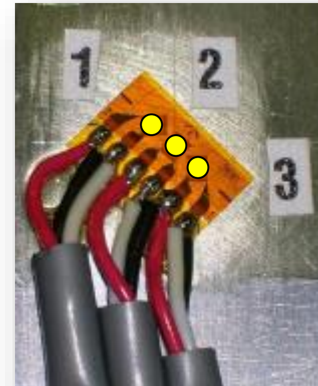
Courtesy: Airbus

Why Fiber Optic Sensors?

One Of These Things (is Not Like The Others)

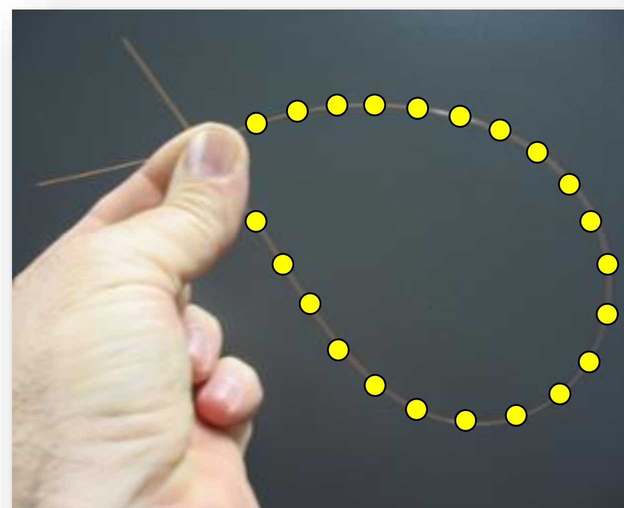


(Heavy)



(Big)

(Complex)

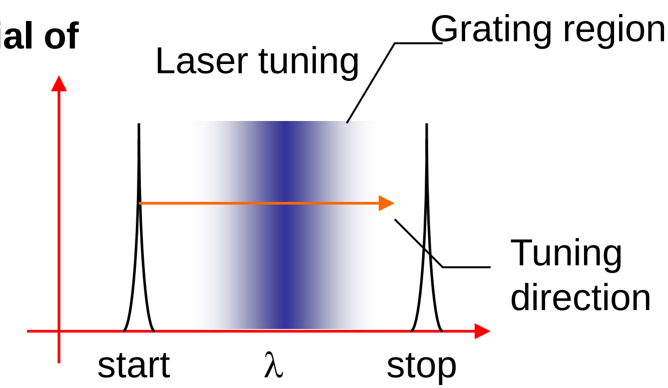


(Light, small, easy)

Fiber Optic System Operation Overview

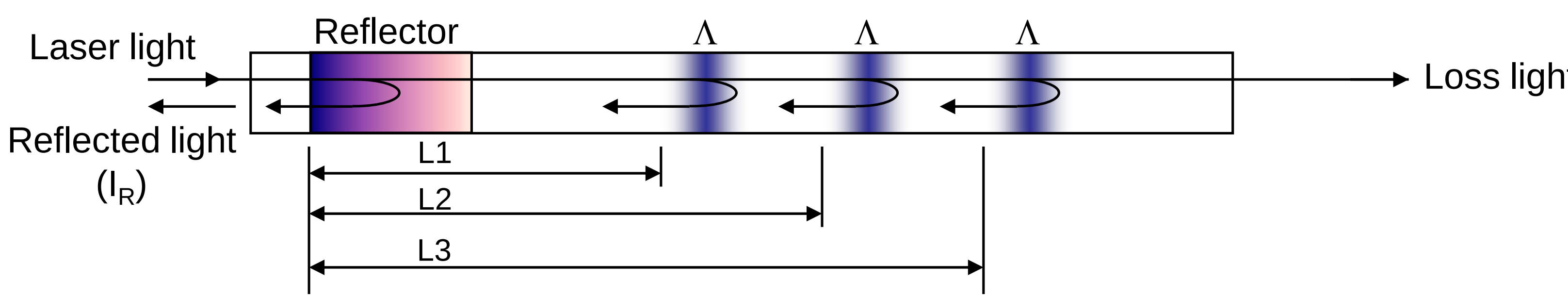
Fiber Optic Sensing with Fiber Bragg Gratings

- **Immune to electromagnetic / radio-frequency interference and radiation**
- **Lightweight fiber-optic sensing approach having the potential of embedment into structures**
- **Multiplex 100s of sensors onto one optical fiber**
- **Fiber gratings are written at the same wavelength**
- **Uses a narrowband wavelength tunable laser source to interrogate sensors**
- **Typically easier to install than conventional strain sensors**
- **In addition to measuring strain and temperature these sensors can be use to determine shape**

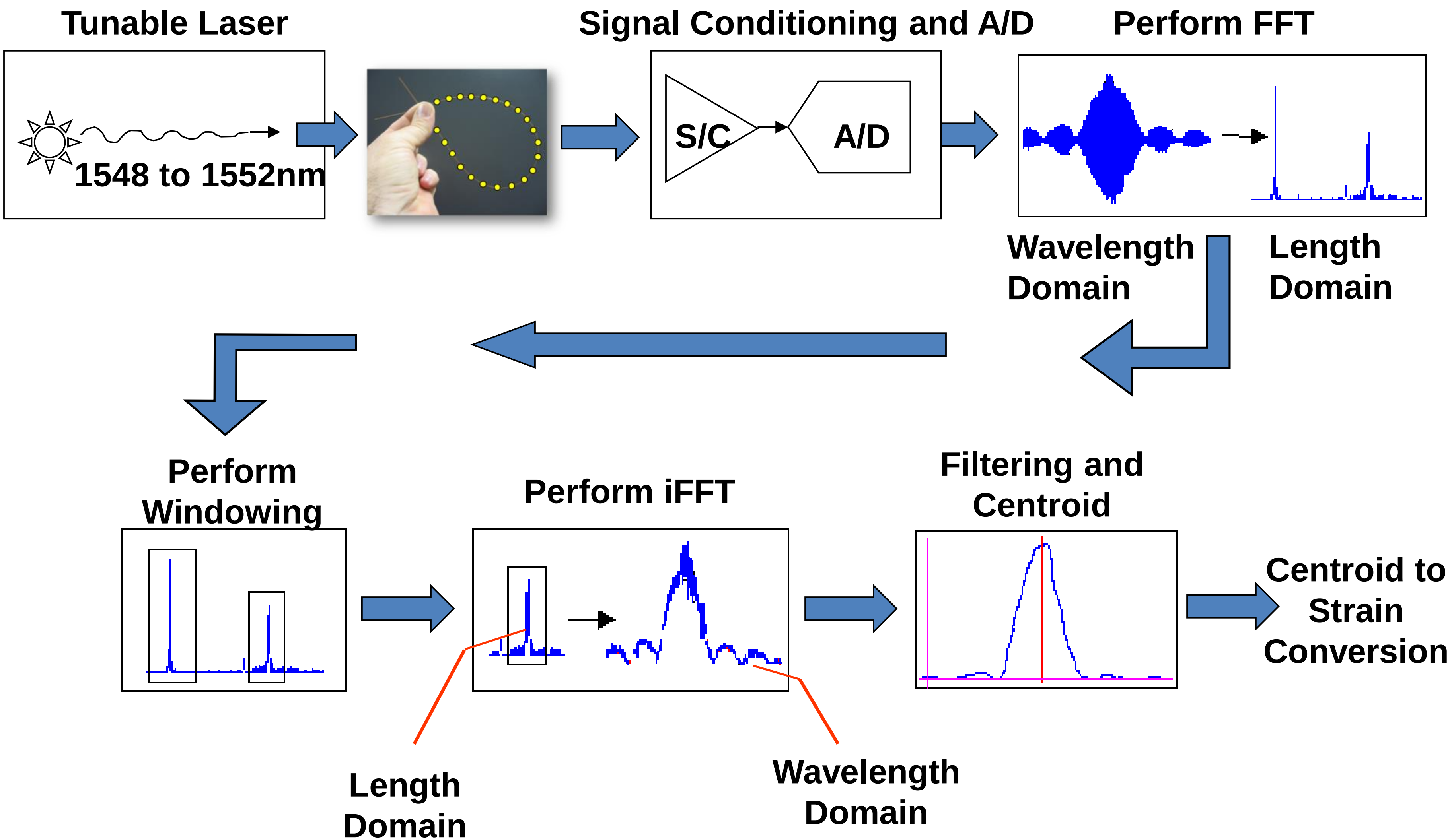


$$I_R = \sum_i R_i Cos(k2nL_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i[th] grating
n – effective index
L – path difference
k – wavenumber



How it Works: FBG OFDR Overview



Armstrong's FOSS Technology Current Capabilities

Current system specifications

- Fiber count 16
- Max sensing length / fiber 40 ft
- Max sensors / fiber 2000
- Total sensors / system 32000
- Max sample rate (flight) 100 sps
- Max sample rate (ground) 60 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

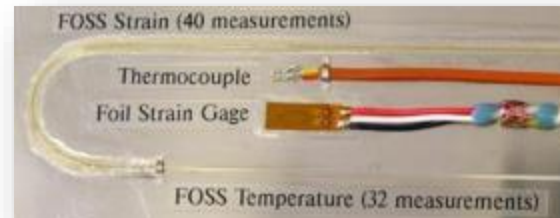
Ground System

Predator -B in Flight

Fiber Bragg Grating (FBG) Optical Frequency Domain Reflectometry (OFDR)

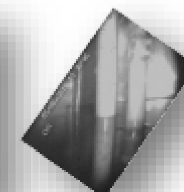
FBG-OFDR can dramatically improve structural and system efficiency for space vehicle applications by improving both affordability and capability by …

- Providing >100x the number measurements at 1/100 the total sensor weight
- Providing validated structural design data that enables future launch systems to be lighter and more structurally efficient
- Reducing data system integration time and cost by utilizing a single small system for space / launch vehicles
- Increasing capability of measuring multiple parameters in real time (strain, temp., accel, liquid level, shape, applied loads, stress, mode shapes, natural frequencies, buckling modes, etc.)
- Providing an unprecedented understanding about system/structural performance throughout space craft and mission life cycle



Metallic Coupon


Pressure monitoring

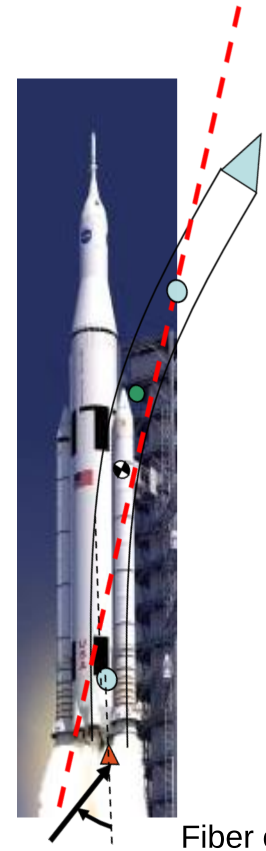

Liquid level sensing

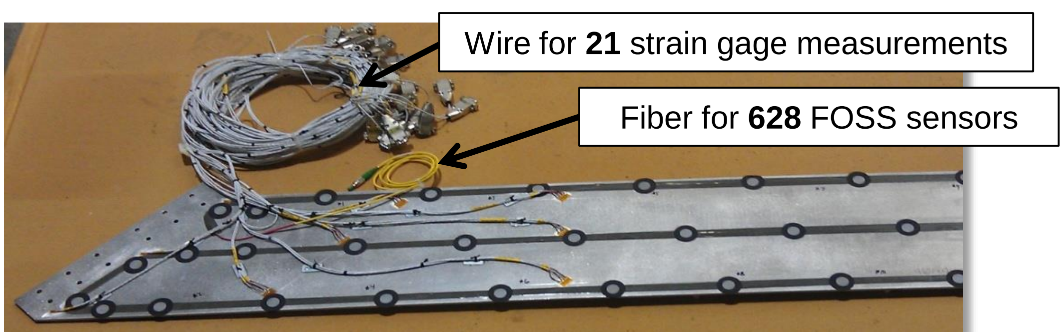

ISS COPV strain & temp monitoring

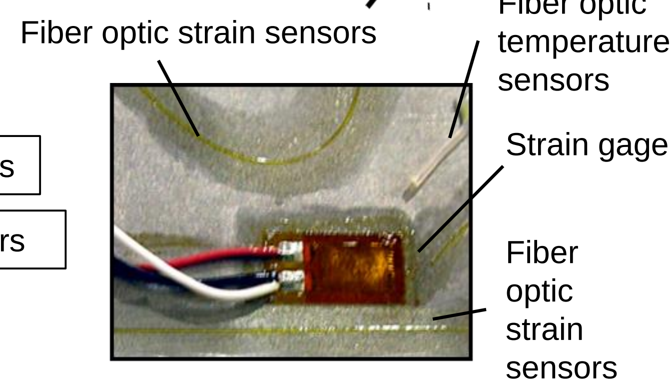

Shape sensing for vehicle control

FOSS Advantages to Conventional Strain Measurements

- Unrivaled spatial density of sensors for full-field measurements
- Measurements immune to EMI, RFI and radiation
- Lightweight sensors
  - Typical installation is 0.1 - 1% the weight of conventional gage installations (based on past trade studies)
  - 1000’s of sensors on a single fiber (up to 80 feet per fiber)
  - No copper wires
- With uniquely developed algorithms, these sensors can determine deformed shape and loads at points along the fiber for *real-time* feedback
- Great in high strain and fatigue environments
- Small fiber diameter
  - Approximately the diameter of a human hair
  - Unobtrusive installation
  - Fibers can be bonded externally or applied as a ‘Smart Layer’ top ply
- Single calibration value for an entire lot of fiber
- Wide temperature range
  - Cryogenic up to 500°F
  - Very linear thermal compensation

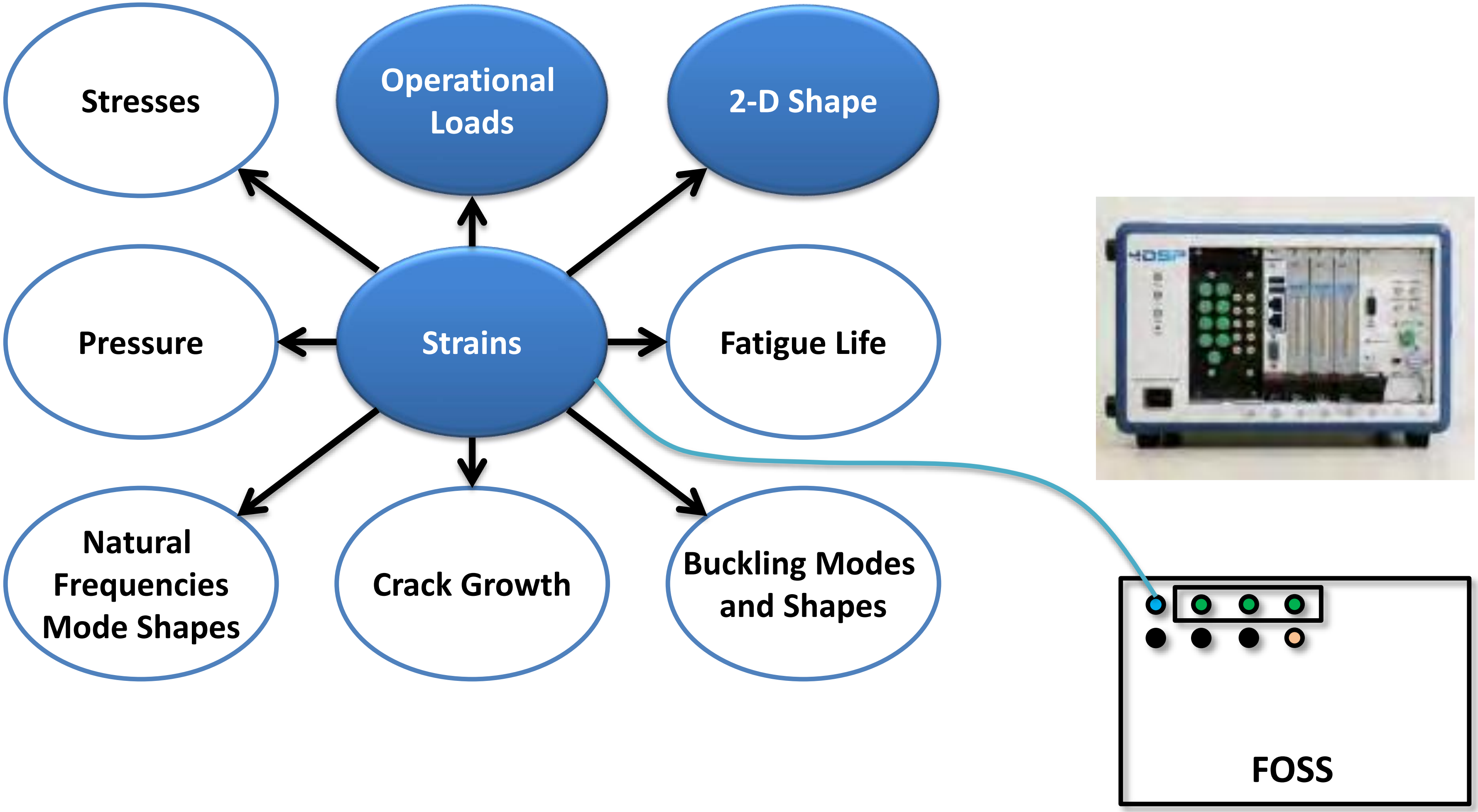




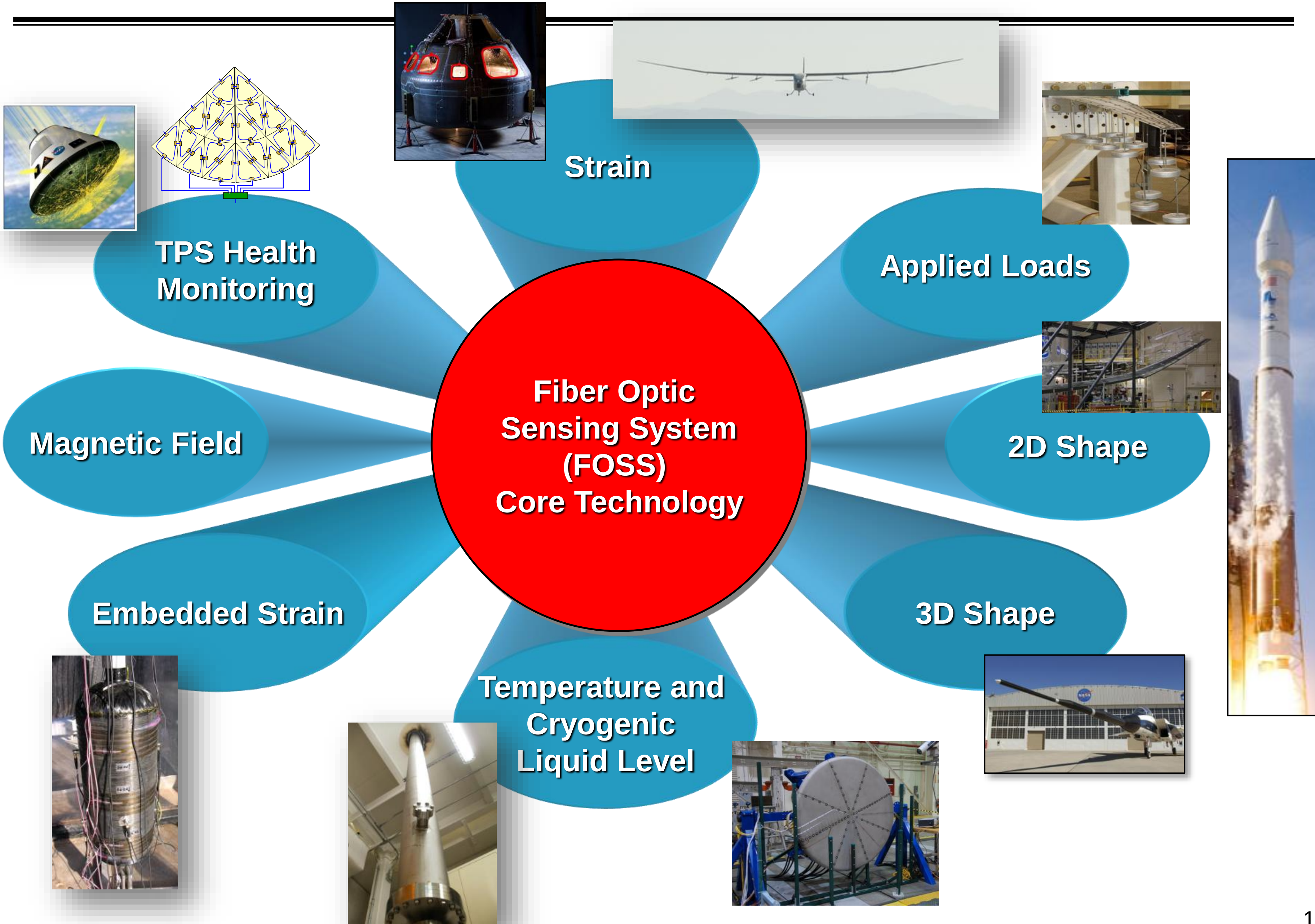


Strain sensor comparison

FOSS Sensor Technology Comparison



Fiber Optic Sensing Applications

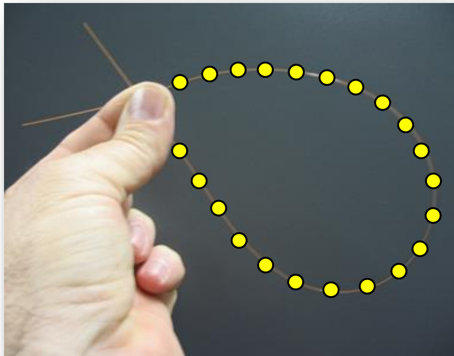


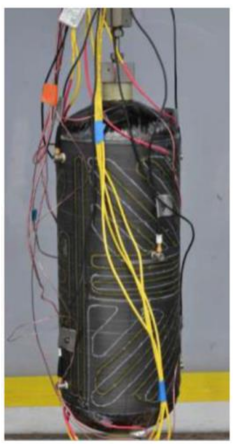
Strain Sensing Applications

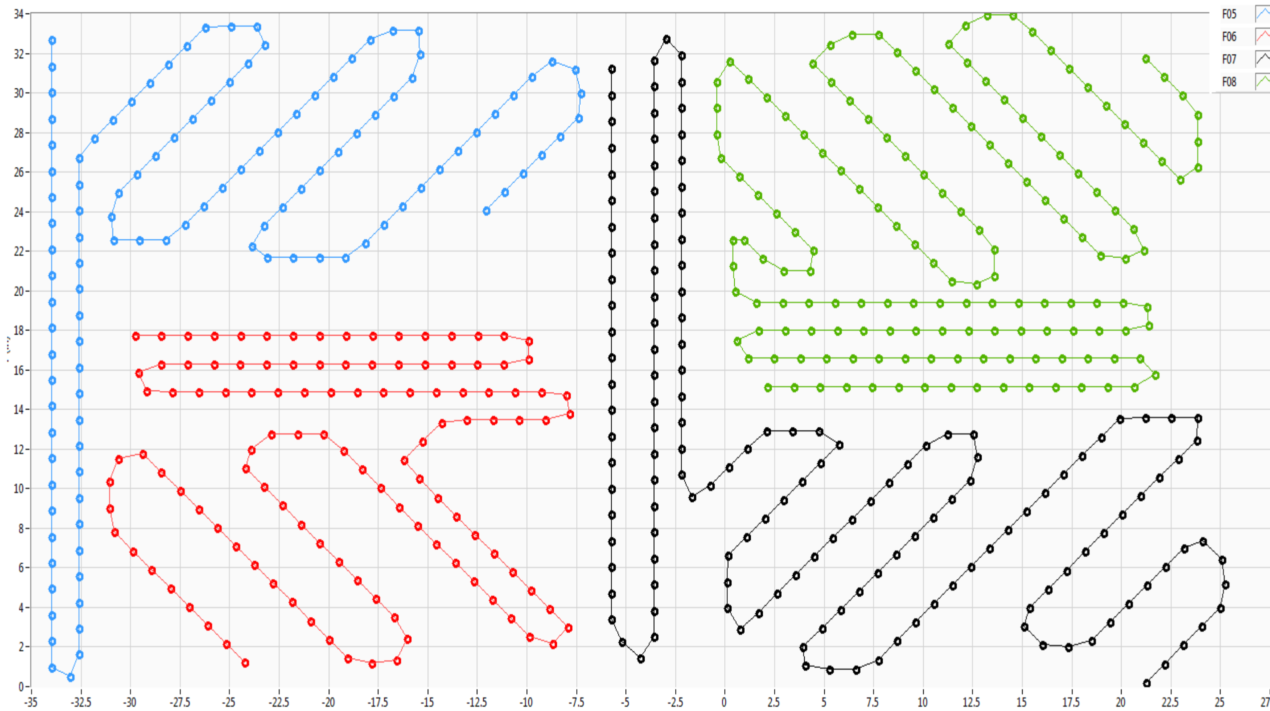
National Aeronautics and Space Administration

Composite Overwrapped Pressure Vessel (COPV)

Sensor Mapping – Surface Mounted Fiber

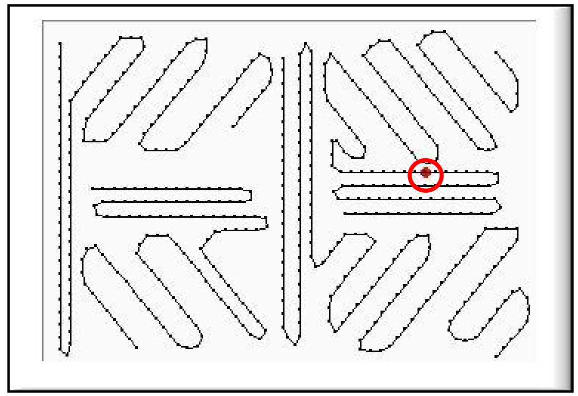






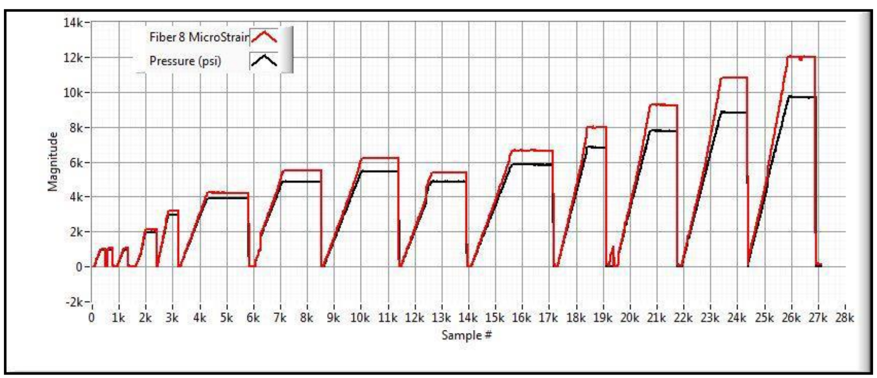
530 Surface strain measurements

COPV Stiffness / Pressure Monitoring, Individual Sensor

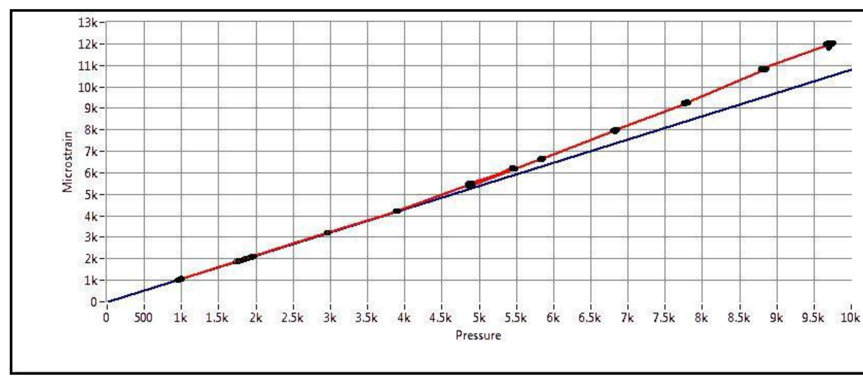


$$\frac{\varepsilon_i}{P} = \left(\frac{D}{n_i t}\right) \cdot \left(\frac{1}{E_i}\right)$$

Fiber line #8, FBG #97,
Micro-strain & Pressure (psi) Vs. Time



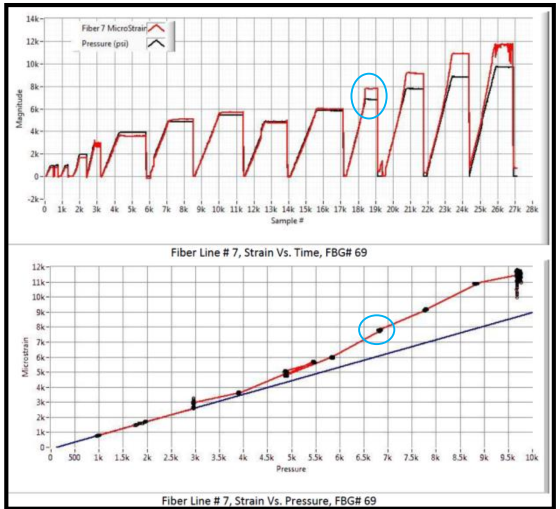
Fiber line #8, FBG #97,
Micro-strain Vs. Pressure (psi)

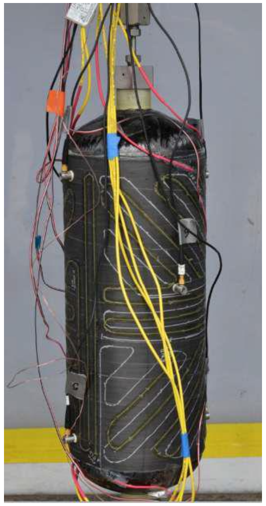


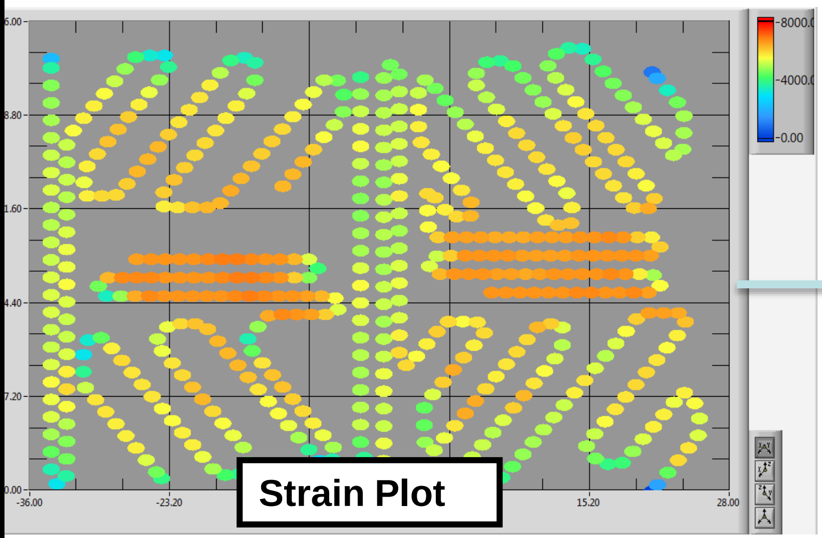
Pena, F., Strutner, S., Richards, W. L., Piazza, A., Parker, A. R. “Evaluatin of Embedded FBGs in Composite Overwrapped Pressure Vessels for Strain Based Structural Health Monitoring”, Proc. SPIE 2014-9059

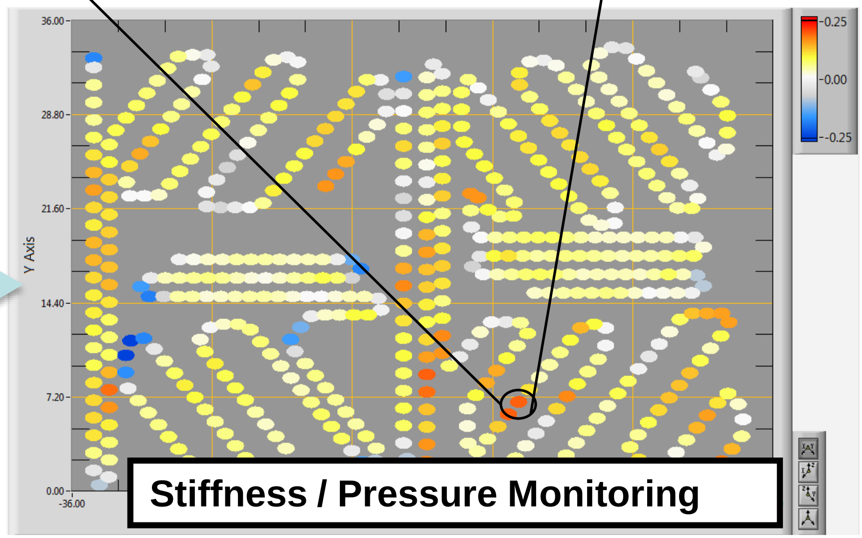
COPV Stiffness / Pressure Monitoring

- **Expands previous studies performed by the Armstrong NNWG on the structural health monitoring techniques**
  - **Implementation of real-time finite-element-like fringe plots**
  - **Further studies into stiffness/pressure monitoring as SHM parameter**









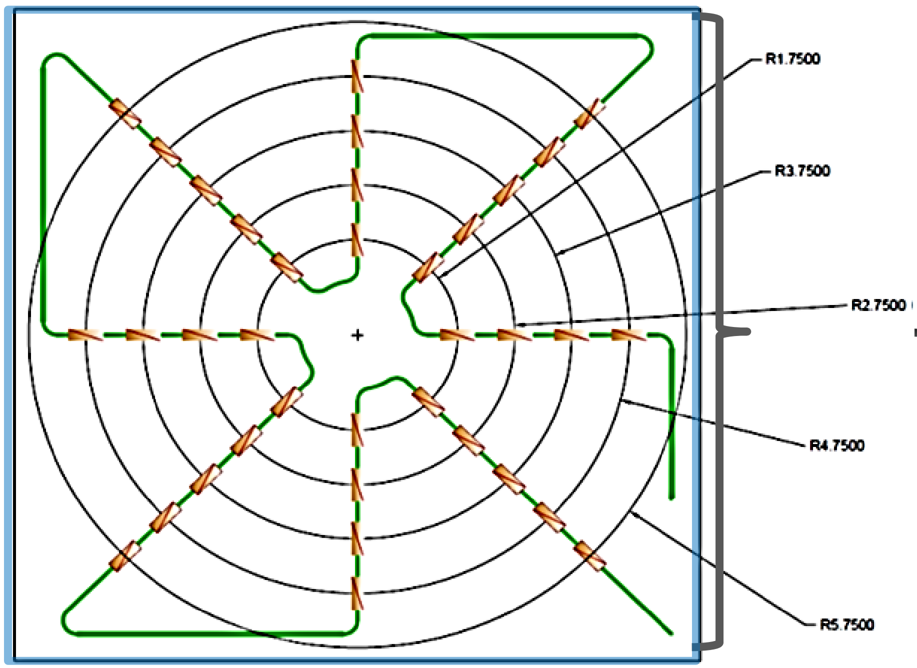
Pena, F., Strutner, S., Richards, W. L., Piazza, A., Parker, A. R. “Evaluatin of Embedded FBGs in Composite Overwrapped Pressure Vessels for Strain Based Structural Health Monitoring”, Proc. SPIE 2014-9059

Simulated Shield MMOD Testing with Fiber Optic Sensors

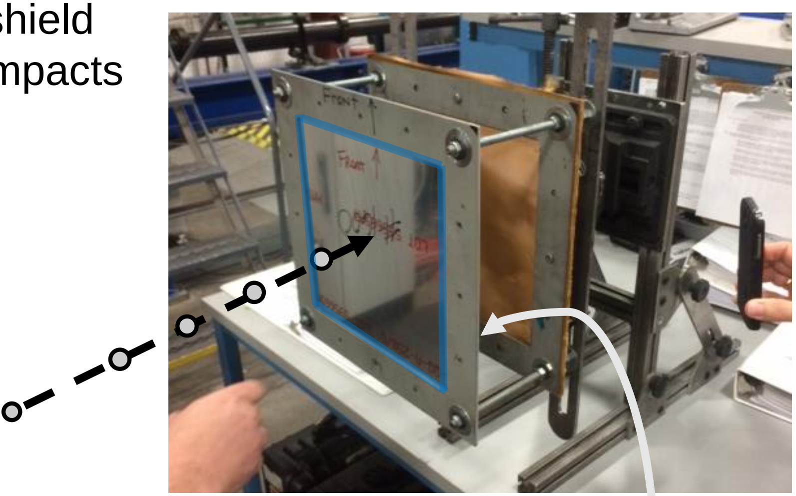
Utilize Fiber Optic Sensors on a simulated MMOD shield structure to monitor the response to hypervelocity impacts

Use Fiber Optic Sensors to determine:

1. If an impact occurred
2. When did the event occur
3. Where did the impact occur
4. Quantify Damage



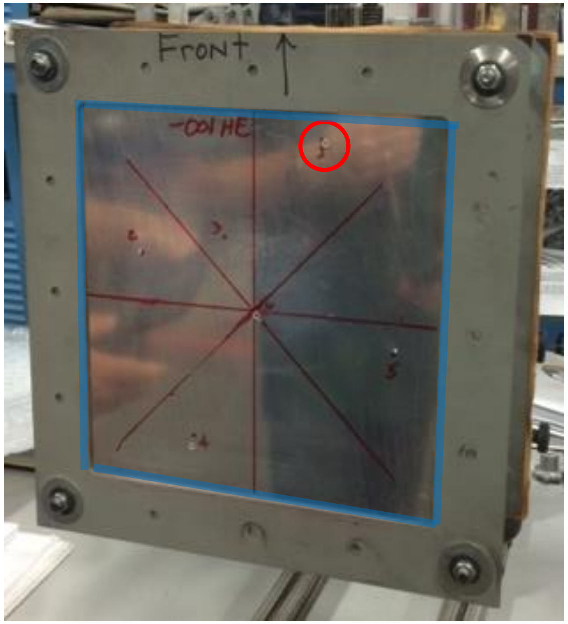
Fiber Optic Routing and Location of Sensors (as seen from back of plate)

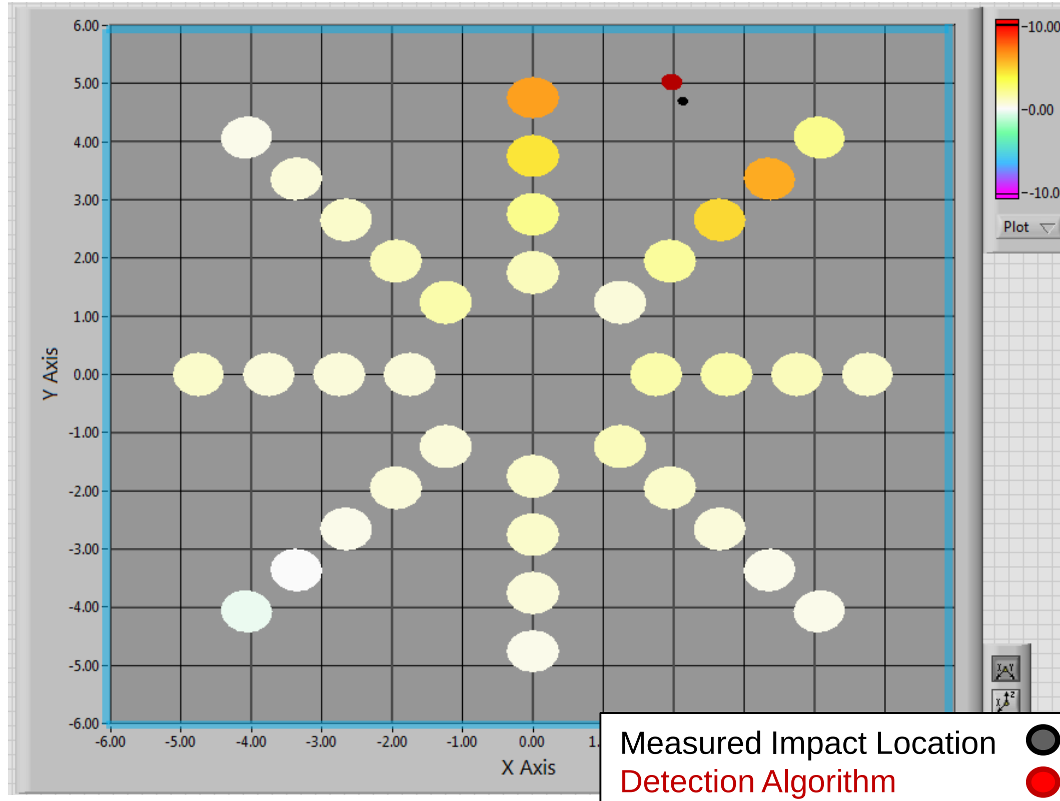


A NASA New Technology Report (NTR) has been filed for the MMOD detection method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Fiber Optic Sensing System Subject Matter Experts for more information

National Aeronautics and Space Administration

MMOD Impact Detection (Target 1)





Target 1

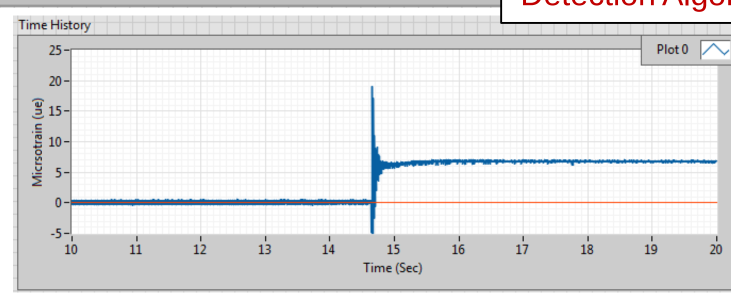
Projectile Diameter: 0.99mm

Projectile mass: 0.0014g

Projectile Velocity: 7,100 m/s

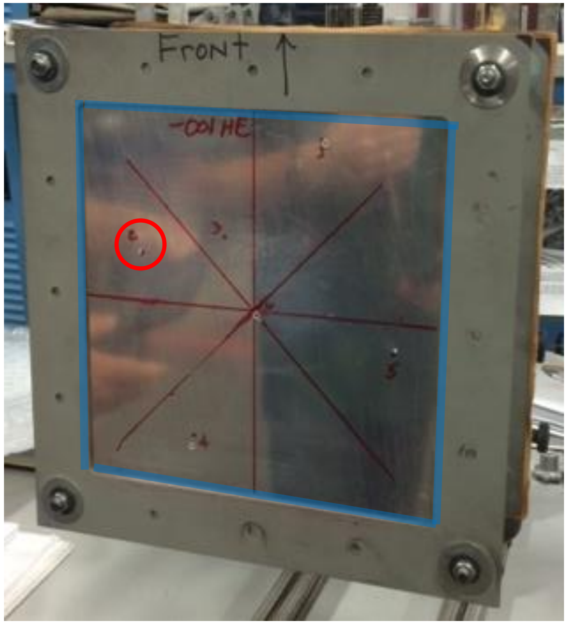
Use Fiber Optic Sensors to determine:

1. If an impact occurred ☑
2. When did the event occur ☑
3. Where did the impact occur ☑
4. Quantify Damage ☐

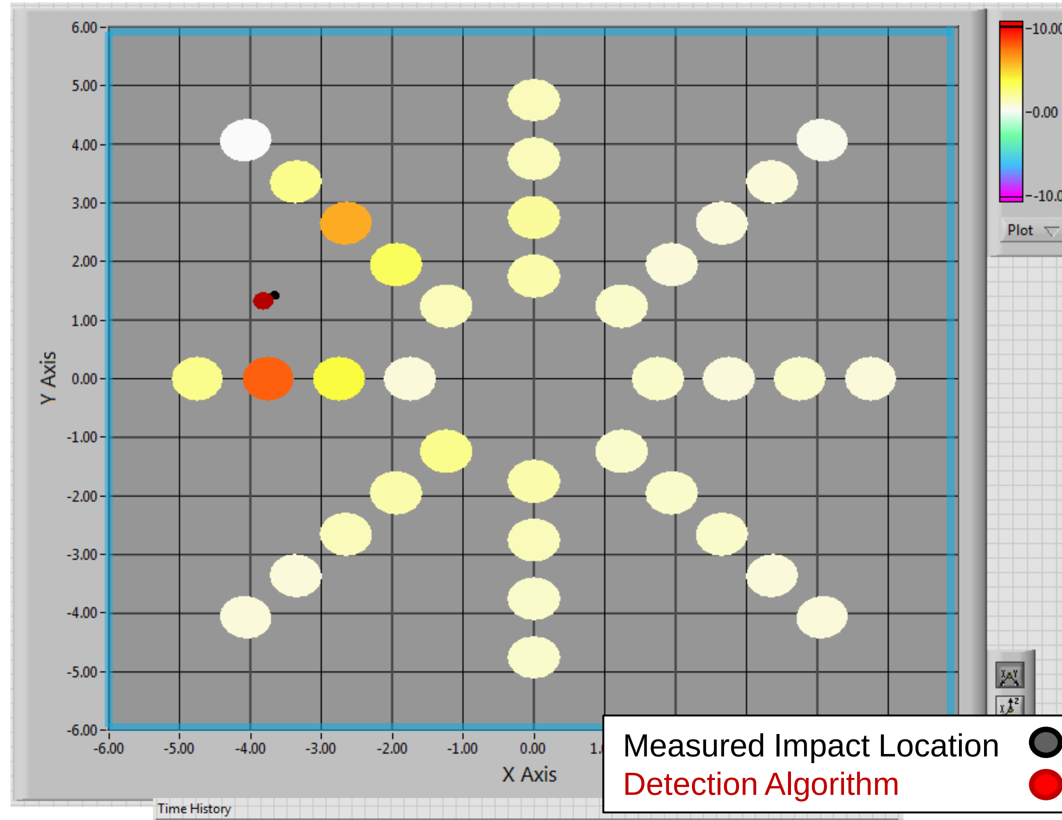


A NASA New Technology Report (NTR) has been filed for the MMOD detection method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Fiber Optic Sensing System Subject Matter Experts for more information

MMOD Impact Detection (Target 2)

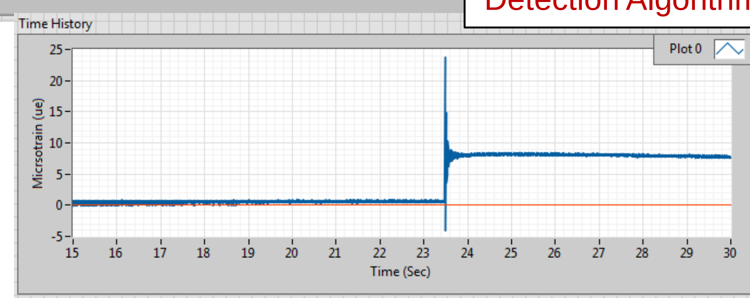


Target 2
Projectile Diameter: 0.49mm
Projectile mass: 0.00017g
Projectile Velocity: 6,980 m/s



Use Fiber Optic Sensors to determine:

1. If an impact occurred ☑
2. When did the event occur ☑
3. Where did the impact occur ☑
4. Quantify Damage ☐



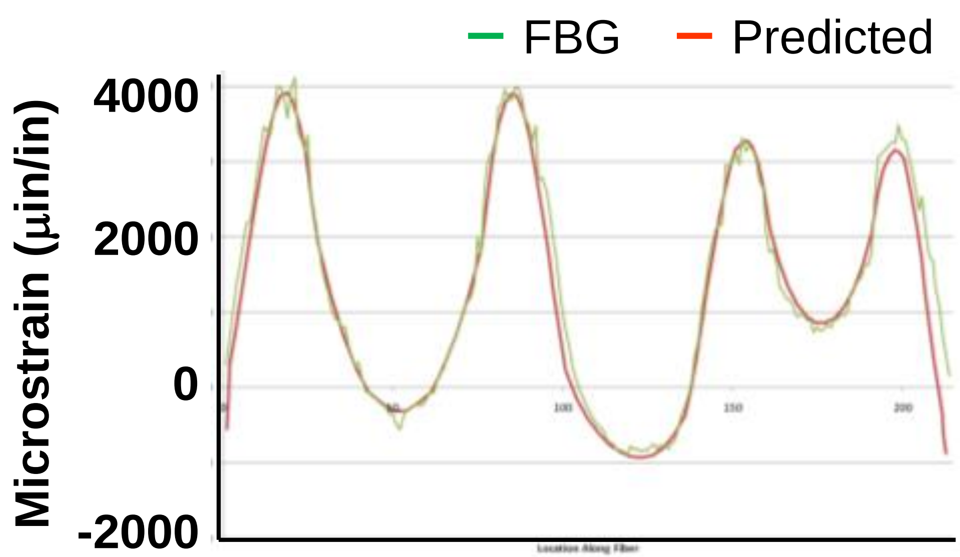
A NASA New Technology Report (NTR) has been filed for the MMOD detection method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Fiber Optic Sensing System Subject Matter Experts for more information

National Aeronautics and Space Administration

Strain Sensing

NESC Composite Crew Module

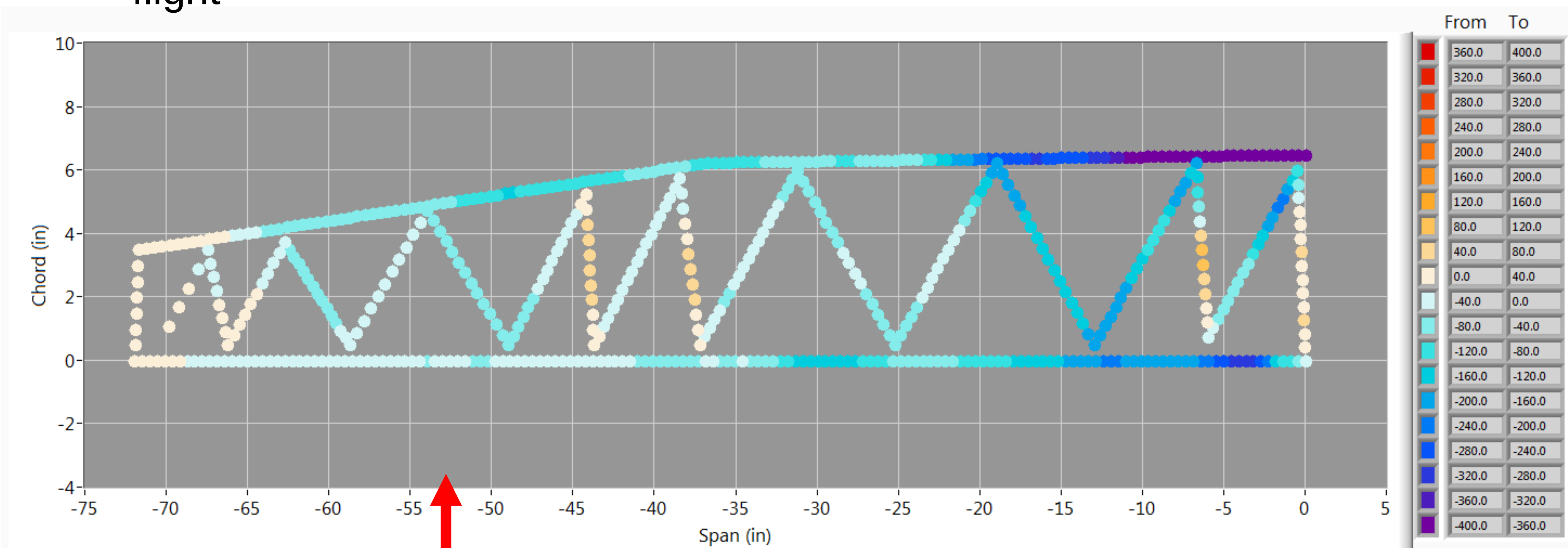
- **Four fibers were installed around the module's three windows and one hatch**
- **3300 real-time strain measurements were collected at 30Hz as the module underwent 200%DLL pressurization testing**
- **Measured strains were compared and matched well to predicted model results**
- **Project concluded:**
  - **"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

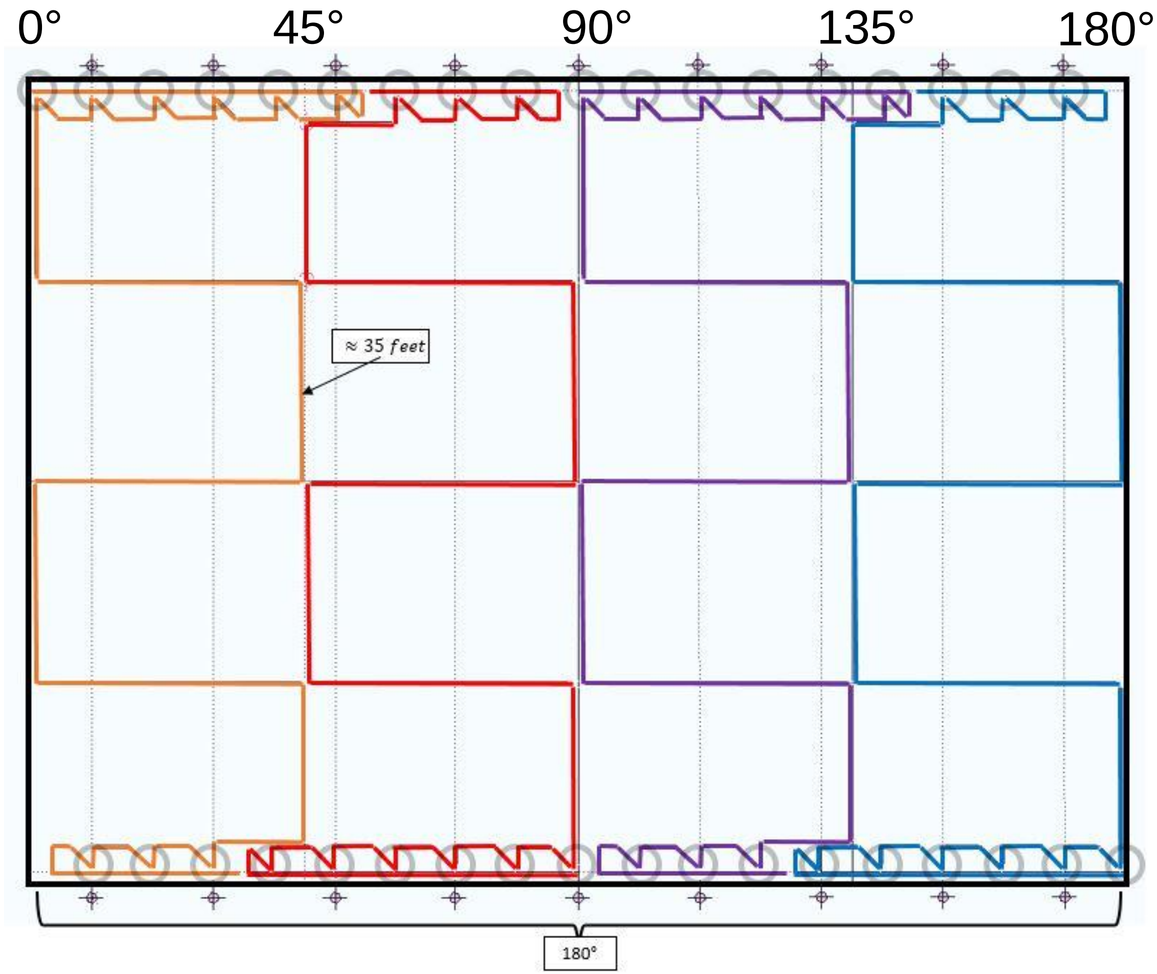
In-Flight Strain Sensing
Small Scaled UAV

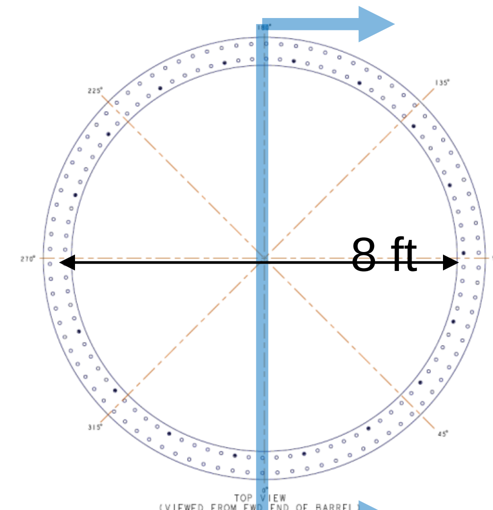
- Four Fibers were installed on the aircraft wings on top and bottom of the Left and Right wing
- 2000 time strain measurements were collected at 20Hz during flight



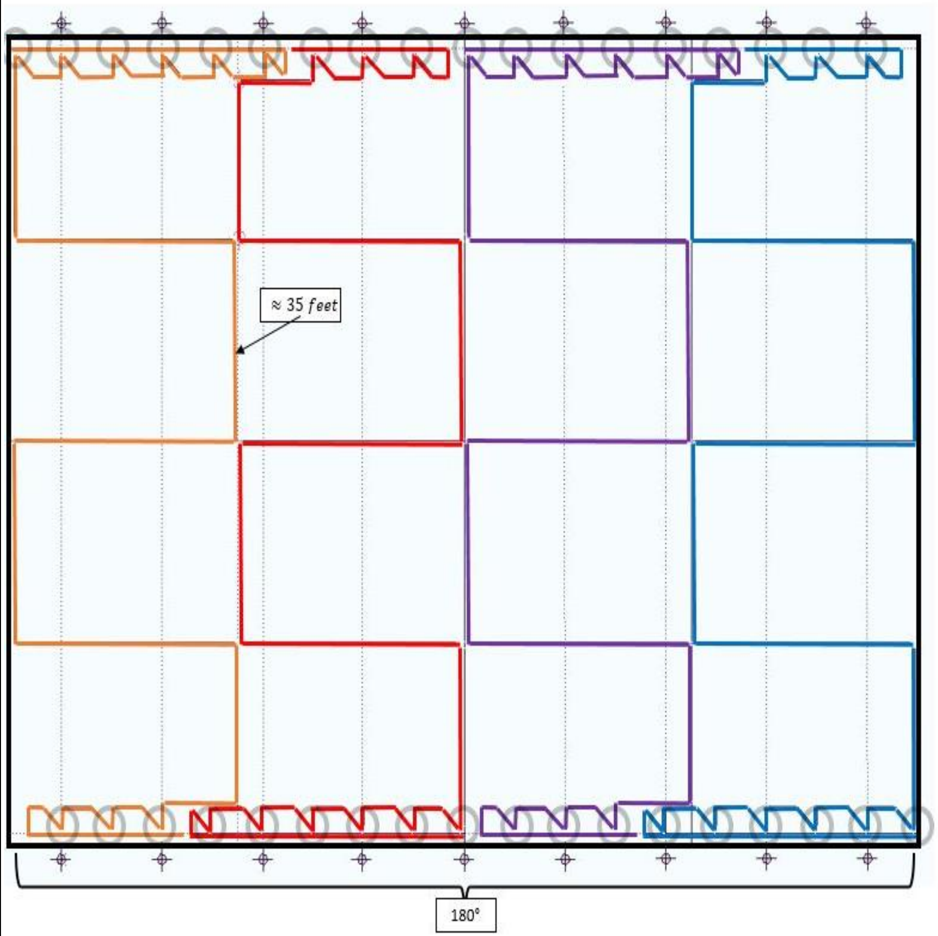
Current Project:

NESC Shell Buckling Knockdown Factor (SBKF)



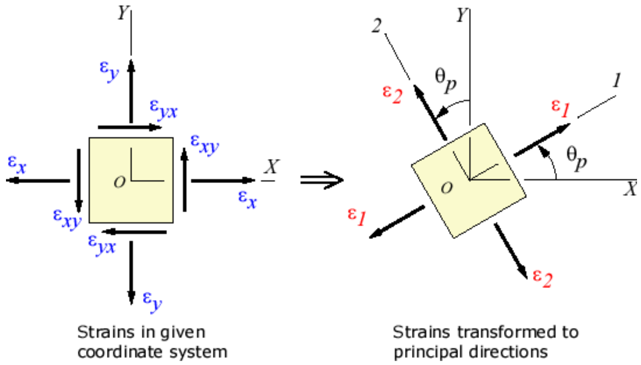


Current Project:
Shell Buckling Knockdown Factor (SBKF)

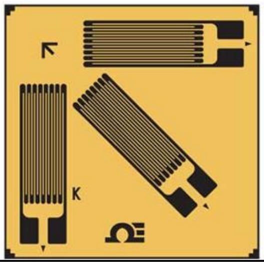


- **FOSS Install goals**
- **Fibers installed on OML and IML surface**
- **Each fiber near 40 foot long**
- **FOSS rosette near each bolt interface plus a second rosette halfway between two bolts**
- **Nearly continuous axial measurements every 45° from top to bottom**
- **Five nearly continuous hoop measurements around the circumference of the cylinder**
- **No interference with existing conventional strain gage locations**

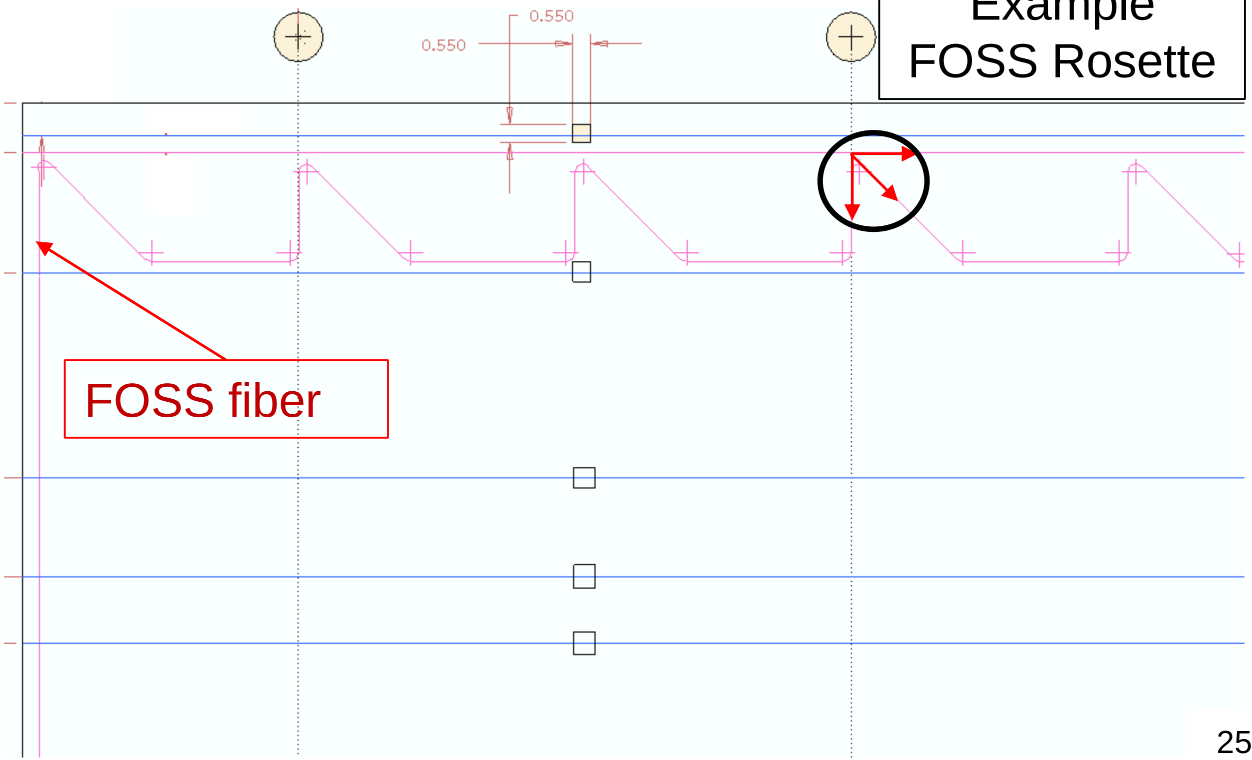
Current Project:
Shell Buckling Knockdown Factor (SBKF)



- Rosettes are installed in critically loaded areas
- Principle strain orientation and magnitude can be determined
- Distributed strain measurements could be used to verify proper load introduction into the test article



Example Conventional Rosette



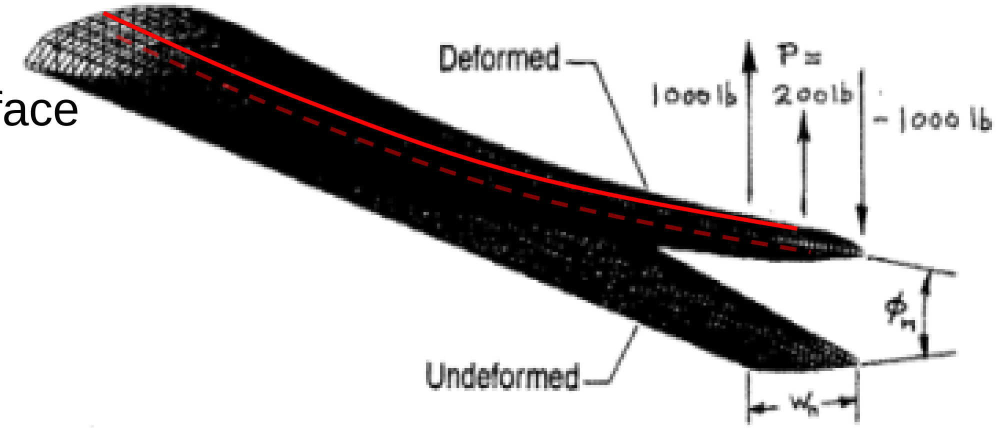
Example FOSS Rosette

Shape Sensing Applications

Two Strain-Based Deflection Methods

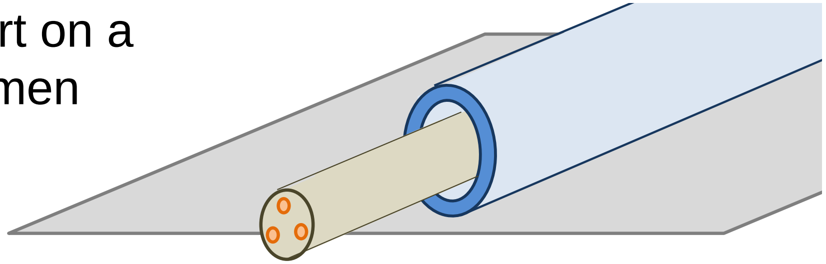
2D Shape Sensing Method

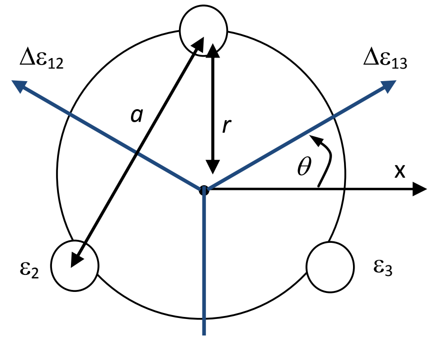
- Uses structural strains to get deflection in one direction
- Fibers on top and bottom surface of a structure (e.g. wing)



3D Shape Sensing Method

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

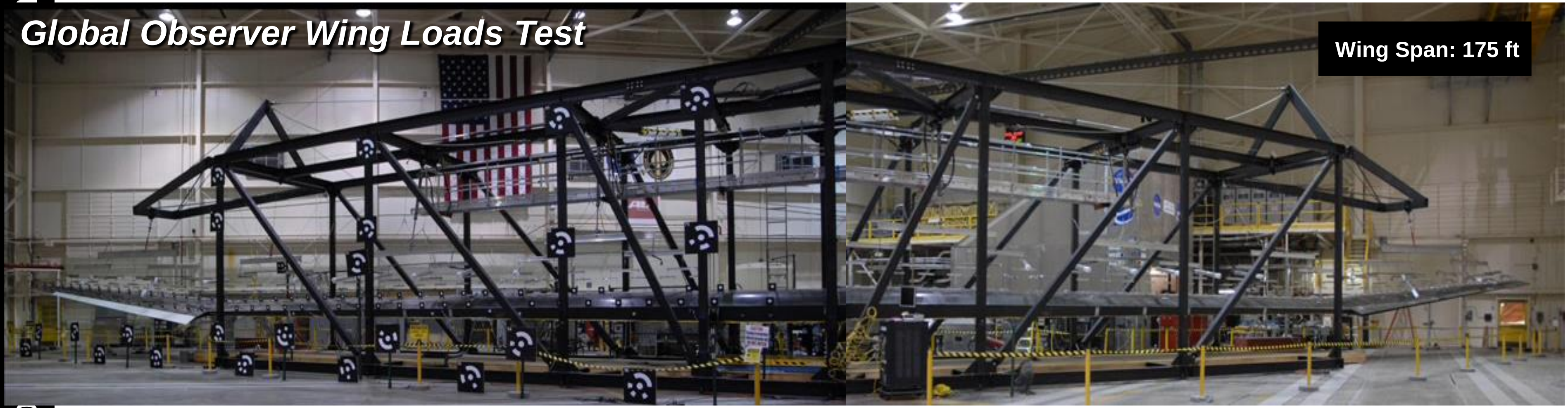




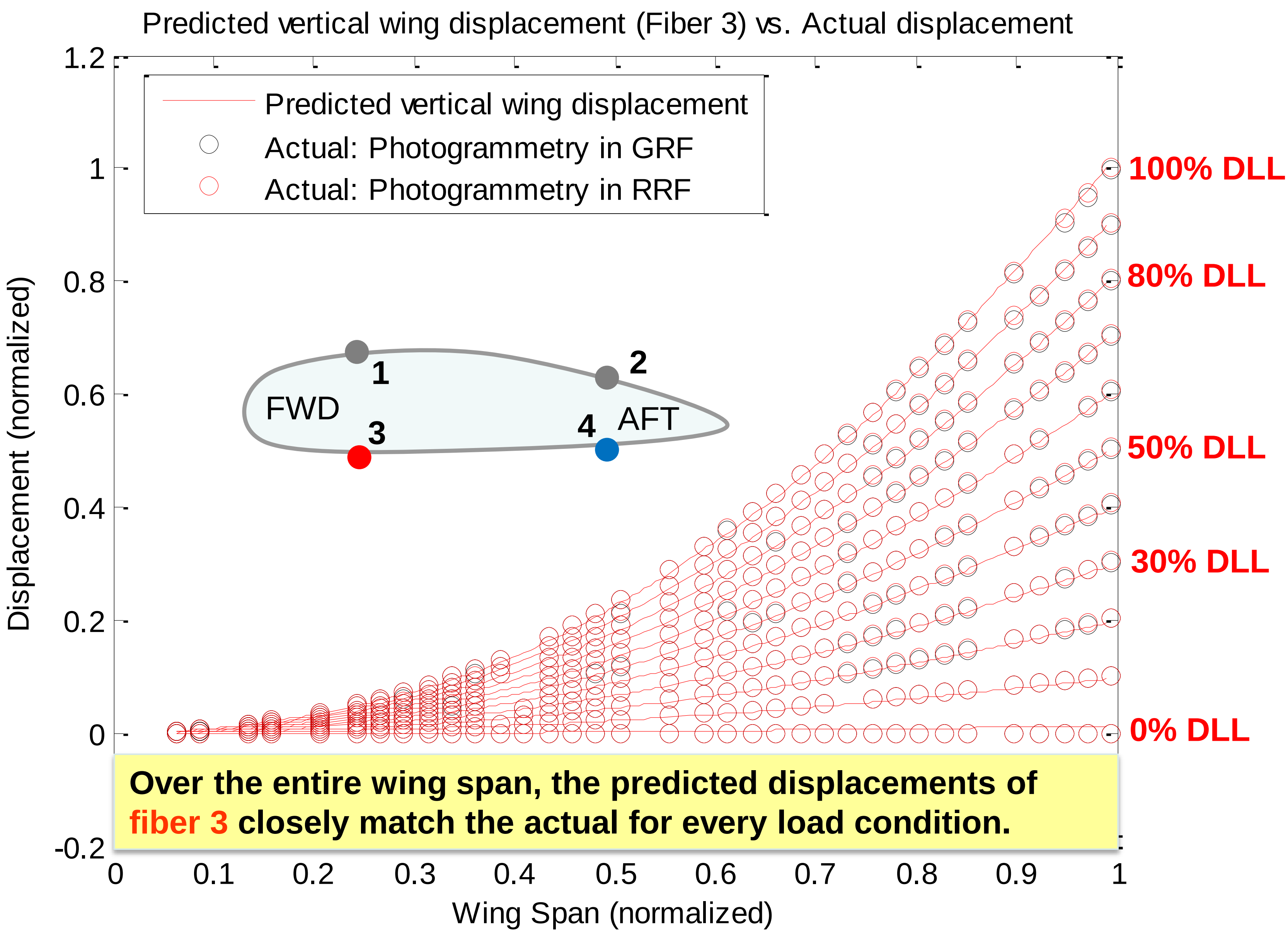
Uninhabited Aerial Vehicles

Global Observer UAS - Aerovironment

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



2D Shape Sensing Results
Global Observer UAS



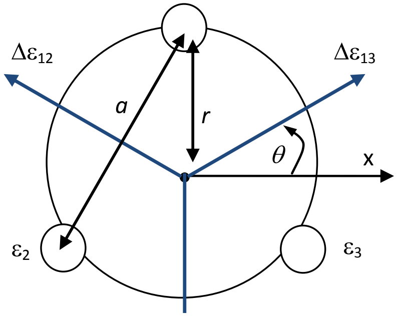
Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

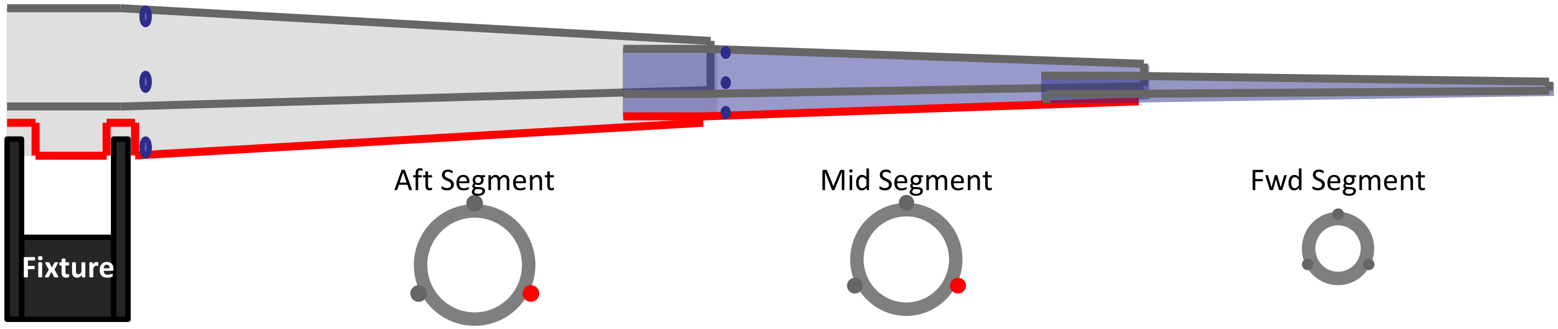
National Aeronautics and Space Administration

3D Shape Sensing

Prototype Quiet Spike Testing

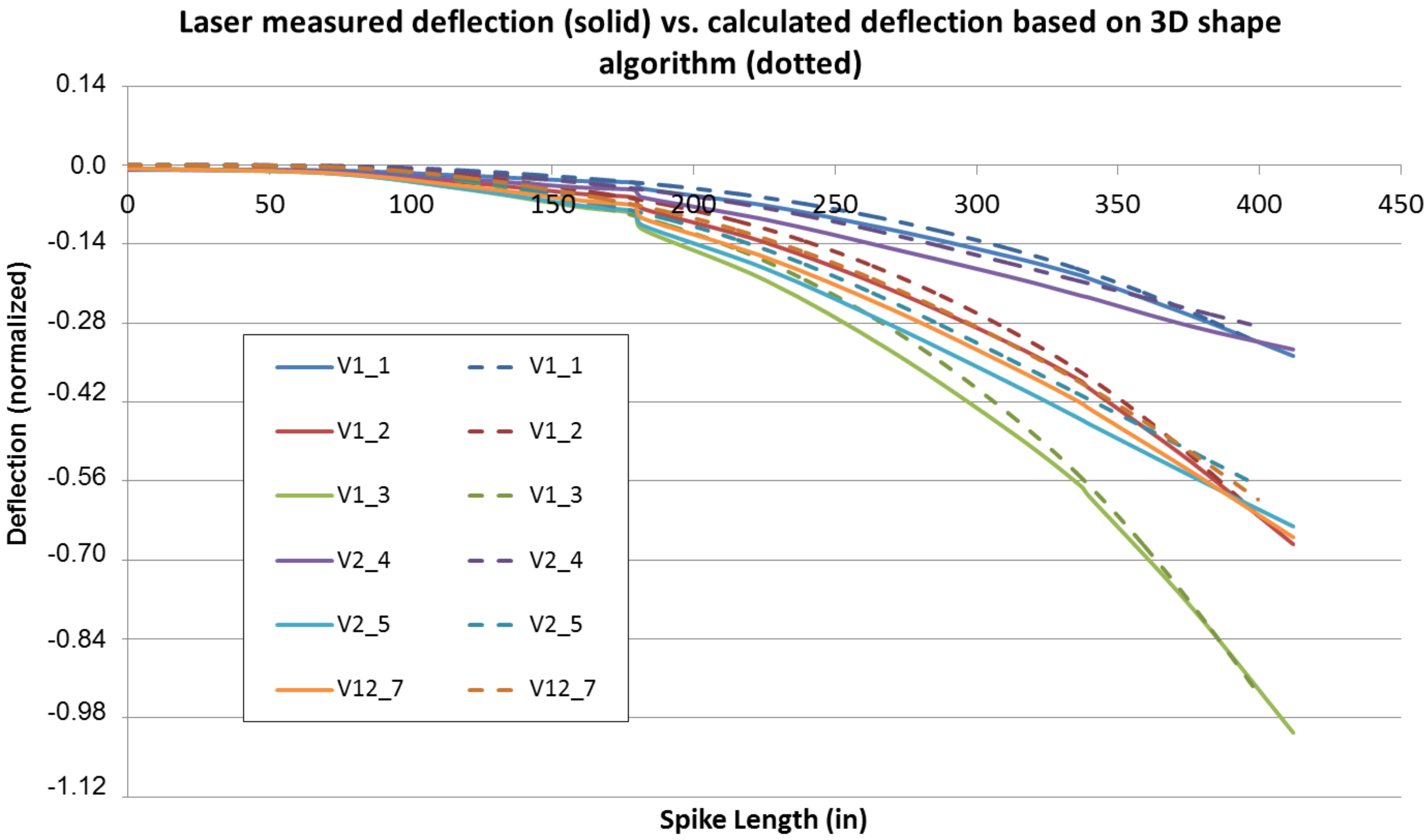
- **Fibers are installed on the prototype of 35ft quiet spike at Gulfstream in Savannah GA**
- **Performed tests to determined benefits of deploying FOSS on Low Boom Experimental Vehicle**
- **Installed a total of 5 fibers measuring strain at ½" increments (2,570 strain sensors)**
- **Deflection shape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





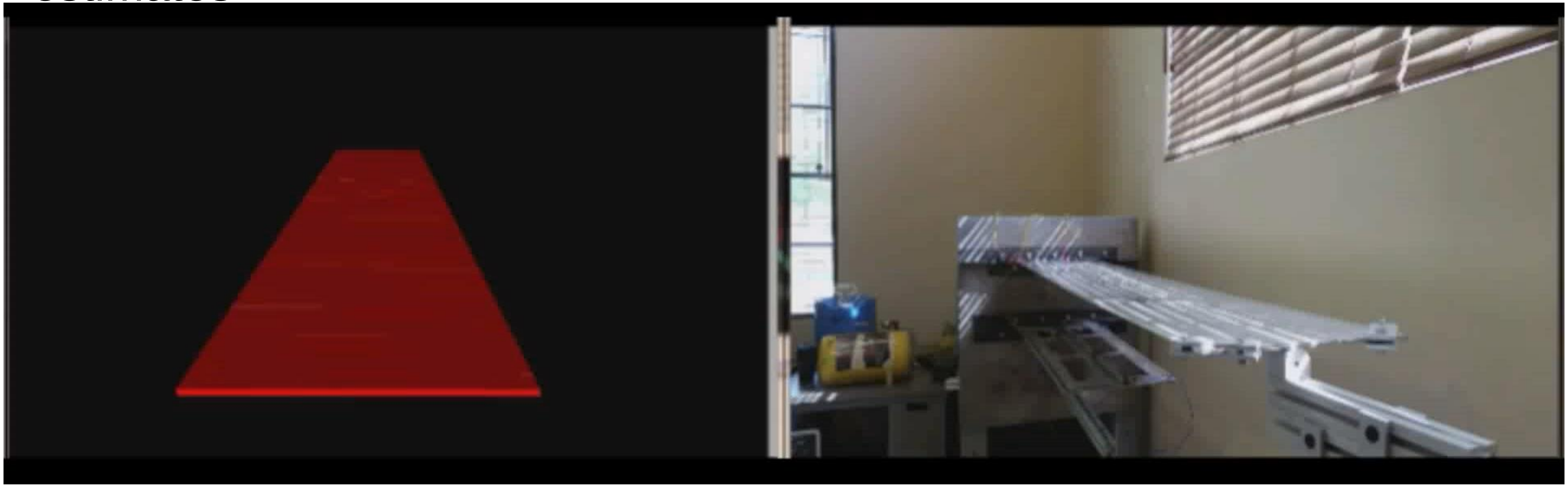
3D Shape Sensing

Quiet Spike Testing Results – lateral deflection



2D Shape + Twist Sensing

- Real-time algorithms enable vertical deflection and twist to be obtained from distributed strain measurements
- LabVIEW user interface allows the user to visualize an estimate of the full filed deformation
- A digital inclinometer is used to verify twist estimates



A NASA New Technology Report (NTR) has been filed for the Twist Sensing Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

Load Sensing

Loads Calibration with conventional strain gage technology

Loads calibrations on A/C wings with conventional strain gages have been successfully performed for over 50 years

- Skopinsky and Aiken Loads Calibration Method allows engineers to obtain:
  - Lift or Shear Force
  - Bending Moment
  - Pitching Moment or Torque

Conventional Loads Calibration Setup

<u>Typical Conventional Loads Calibration requires:</u>

- Dozens of metallic strain gages
  - One sensor per channel
  - Installed on interior load bearing structure of wing
  - Wing skins need to be removed
  - Installation time of approx. 4 to 8 hours per sensor
  - Finite point measurements
- Removal of ground-test-specific instrumentation prior to flight
  - Bulky sensor size restricts the use in high lift regions
- 16 channels of load actuators
  - Application of an array of mechanical loads to determine bending and torsional stiffness properties
- Limited Span-wise load sensing capabilities

Simplified Approach with FOSS

Investigations of Fiber Optic Sensing System (FOSS) for Distributed Load Calibration Methodology

Technical Challenge:

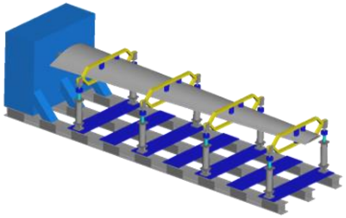
- Future projects require a method for monitoring the load distribution within aerospace structures
- Instrumentation weight and installation time of conventional strain gages limit the ability to monitor and control distributed loads within aerospace structures

Helios Wing

In-flight breakup

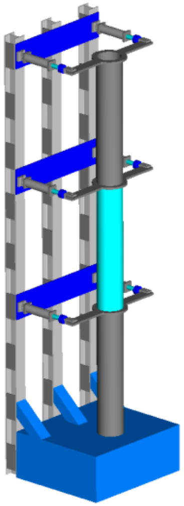
Current State-of-the-Art:

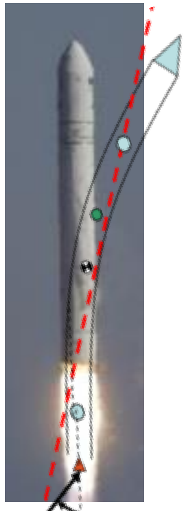
- Fiber optic strain sensing (FOSS) technology is transitioning to an airworthy alternative to conventional strain gages and will change the approach to aircraft loads calibrations
- FOSS will open up new opportunities to monitor and facilitate control of future launch vehicles



Potential Applications:

- Improved understanding of distributed aerodynamic loading
- Optimized process for aircraft structural loads calibrations for monitoring and controlling flexible, high aspect ratio wings and rocket bodies
- A detailed understanding of the span-wise load distribution will be required for optimizing the aerodynamic performance of future aerospace structures



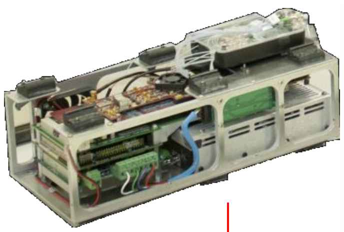


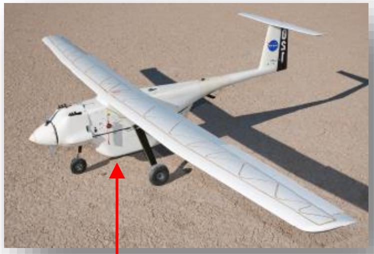
Shape sensing for vehicle control

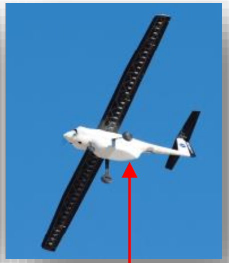
National Aeronautics and Space Administration

Aircraft Vehicle Load Control

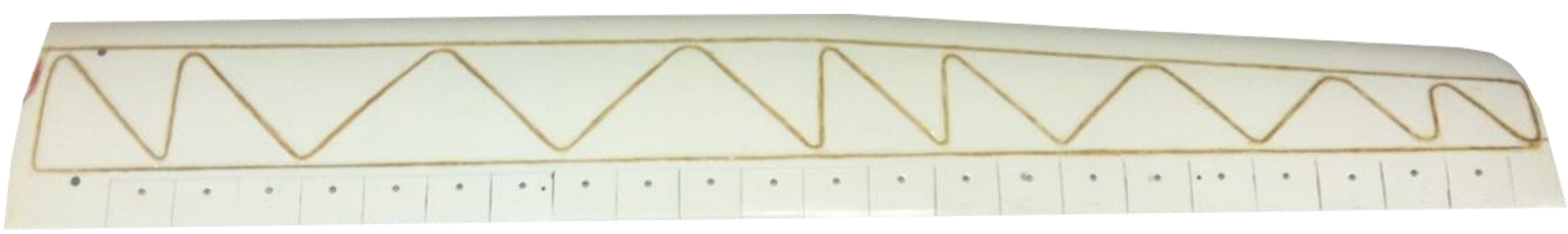
- **cFOSS 1.0 sUAS Flight system specifications (Convection)**
  - 4 Fiber system
  - Total sensors: 4000
  - Sample rate (max) 100 sps
  - Weight 5 lbs
  - Size 3 x 5 x 11in





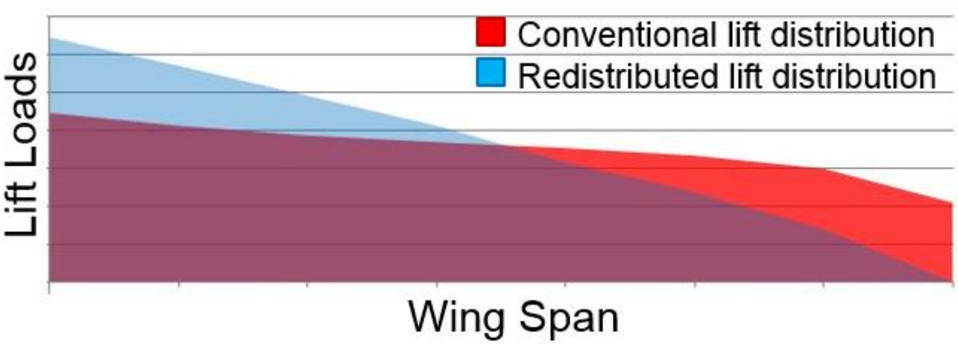


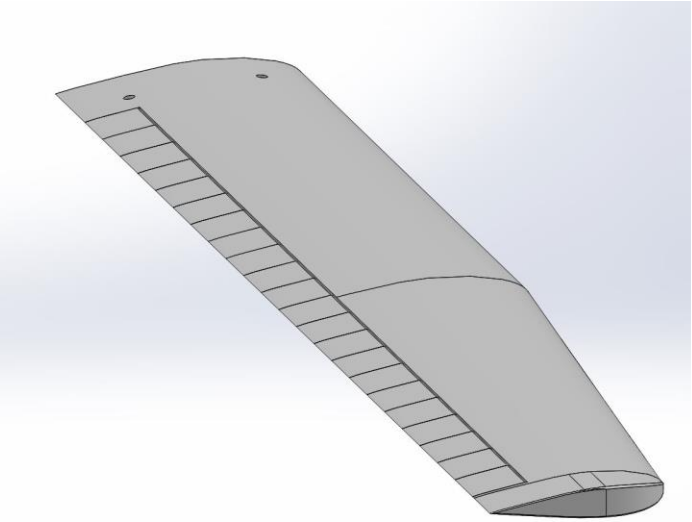
- **Autonomously Piloted Vehicle 3 (APV3)**
  - Span: 12 ft
  - Max Takeoff Weight: 55 lbs
  - 22 control surfaces per wing
  - 2,000 fiber optic strain sensors on wings (top and bottom surfaces)



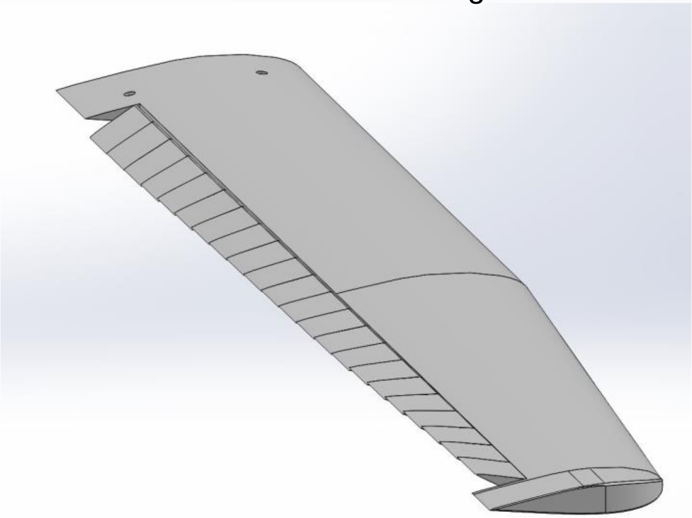
APV3 Segmented Control Surfaces

- Segmented Control Surfaces (SCS) can be utilized to redistribute load in-board to reduce loads during high-g maneuvers
- FOSS strain and/or deflection measurements could be used with a flight controller to provide load alleviation control





conventional configuration

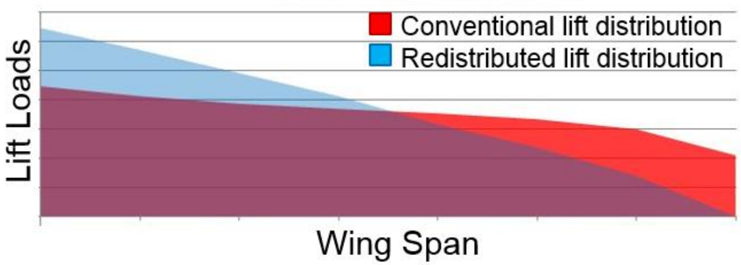


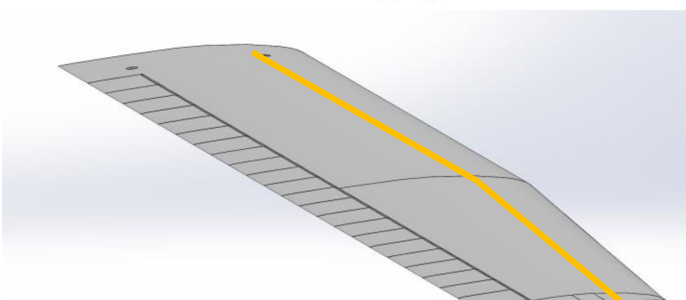
load alleviation configuration

National Aeronautics and Space Administration

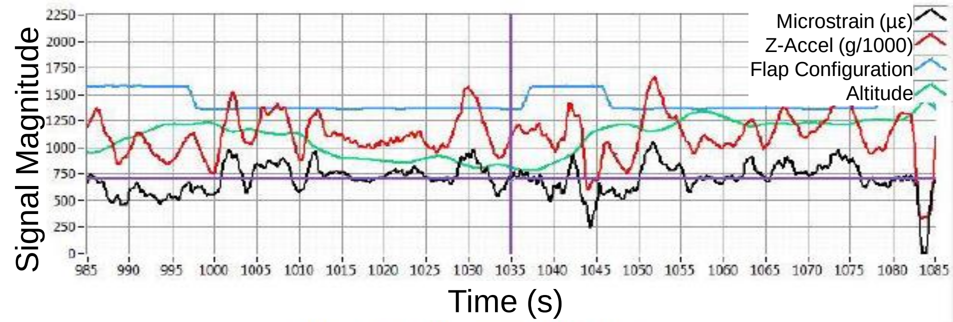
Operational Load Estimation Method Applied Results With Flight Data

APV3 in flight

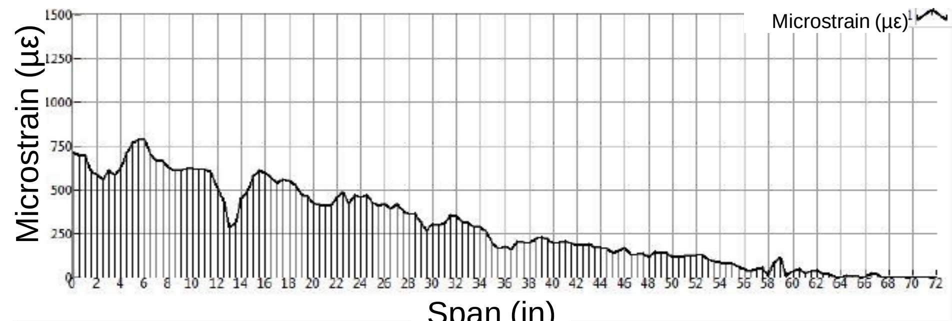




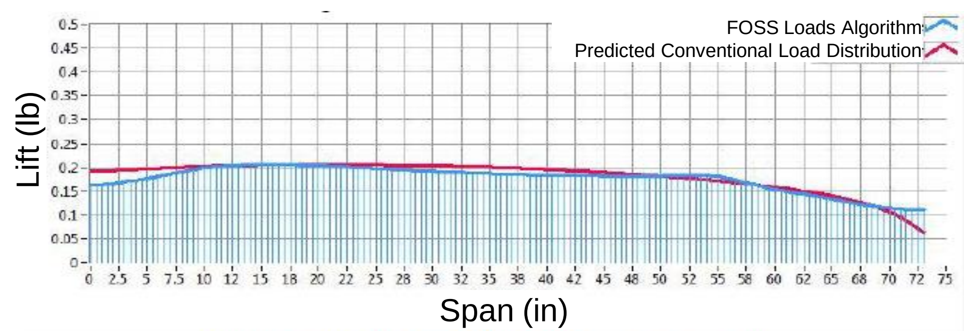
Conventional configuration



Flight Data at 1035 Seconds into Flight



Bottom Surface Microstrain at 1035 Seconds into Flight

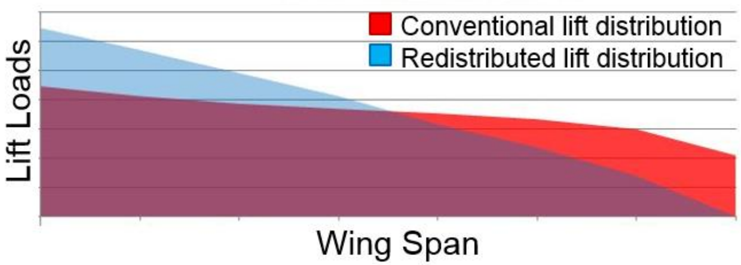


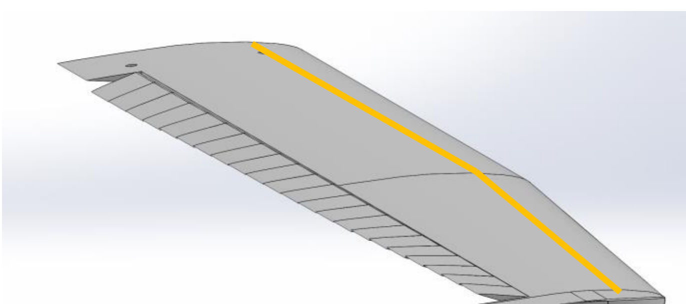
Lift Distribution at 1035 Seconds into Flight, Total Lift Force = 26

A NASA New Technology Report (NTR) has been filed for the Load Sensing Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

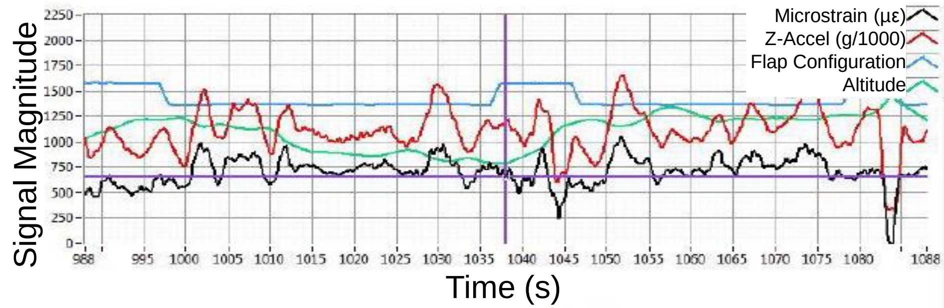
Operational Load Estimation Method Applied Results With Flight Data

APV3 in flight

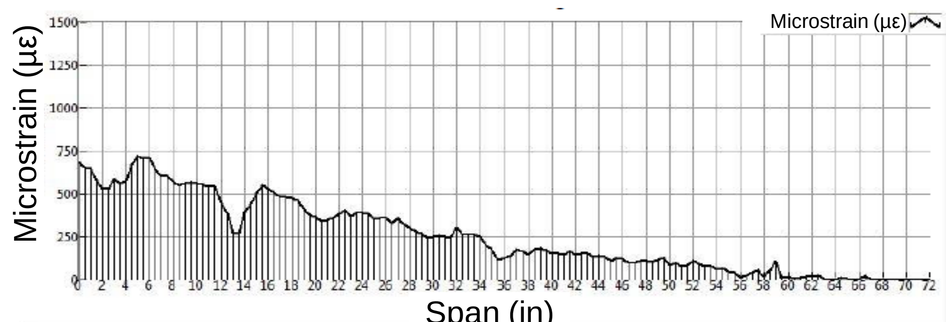




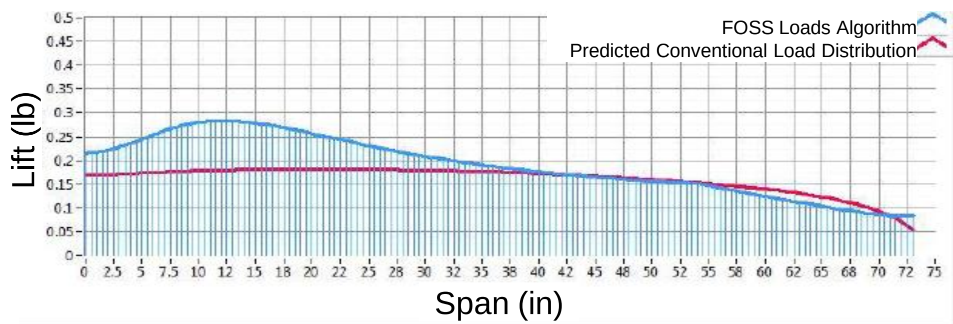
Redistributed configuration



Flight Data at 1038 Seconds into Flight



Bottom Surface Microstrain at 1038 Seconds into Flight



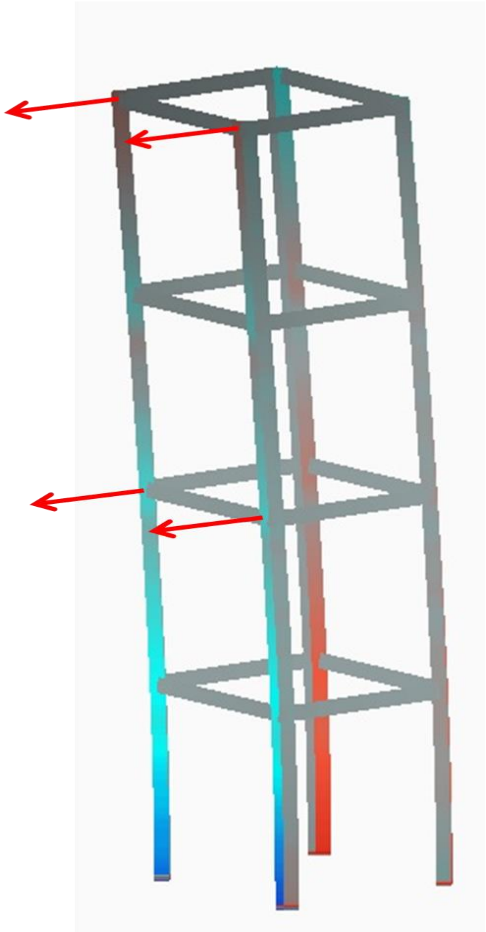
Lift Distribution at 1038 Seconds into Flight, Total Lift Force = 28

A NASA New Technology Report (NTR) has been filed for the Load Sensing Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

Operational Load Estimation Method

Trusses and Moment Frames

Moment Frame Test Article with FOSS

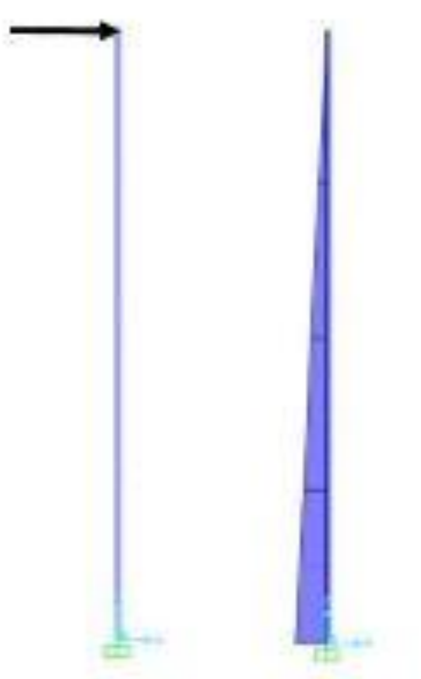


Real-time display of FOSS data

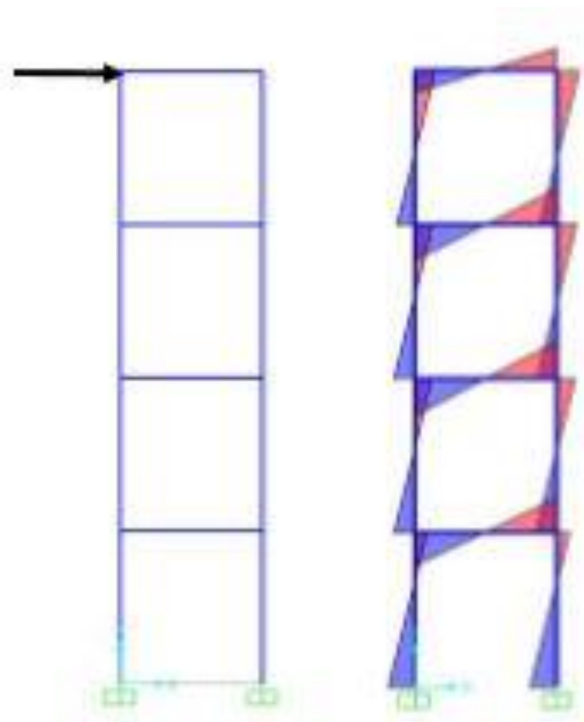
Solar Array and truss structure

Operational Load Estimation Method

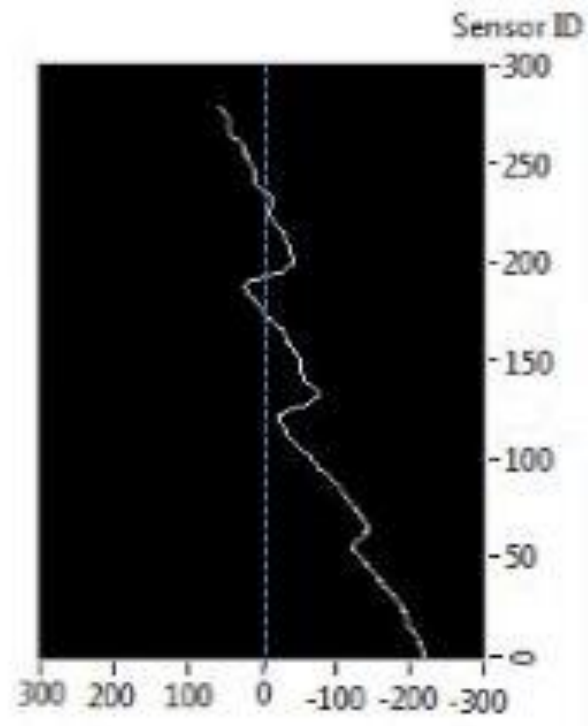
Truss and Moment Frames



Cantilever Moment Diagram



Frame Moment Diagram



Measured Moment Diagram on Column *(Showing Semi-Frame Behavior)*

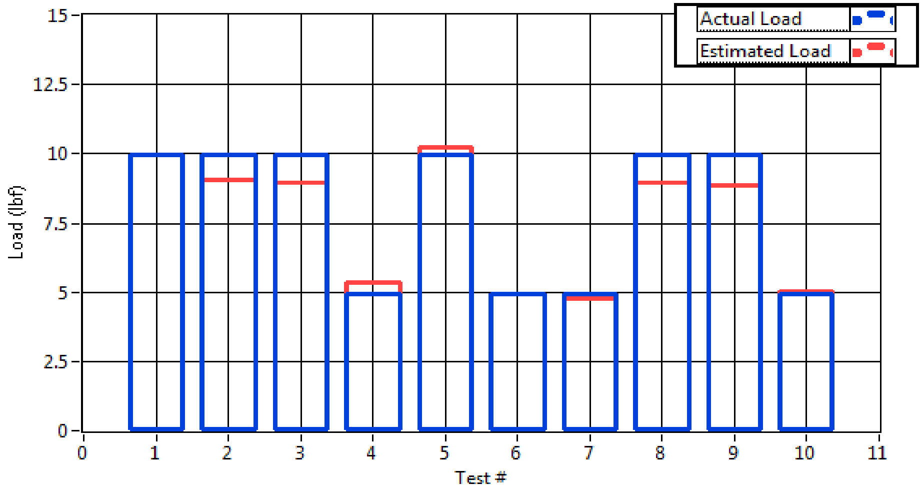
Operational Load Estimation Method

Truss and Moment Frames

Moment Frame Test Article with FOSS

Preliminary OLEM Test Results on Moment Frame Test Article

Test (#)	Actual Force (lbf)	Estimated Force (lbf)	Difference (%)	Actual Location (in)	Calculated Location (in)	Difference (%)
1	10.0	10.0	0.0%	67.5	67.5	0.0%
2	10.0	9.1	-9.0%	60.5	61	0.8%
3	10.0	9.0	-10.0%	50.5	50.6	0.2%
4	5.0	5.4	8.0%	50.5	50.6	0.2%
5	10.0	10.3	3.0%	43	43.9	2.1%
6	5.0	5.0	0.0%	43	42.9	-0.2%
7	5.0	4.8	-4.0%	32.75	33.8	3.2%
8	10.0	9.0	-10.0%	32.75	33.8	3.2%
9	10.0	8.9	-11.0%	25.5	25.9	1.6%
10	5.0	5.1	2.0%	25.5	25.7	0.8%



A NASA New Technology Report (NTR) has been filed for the Load Sensing Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

HyFOSS

HyFOSS: What The Technology Does

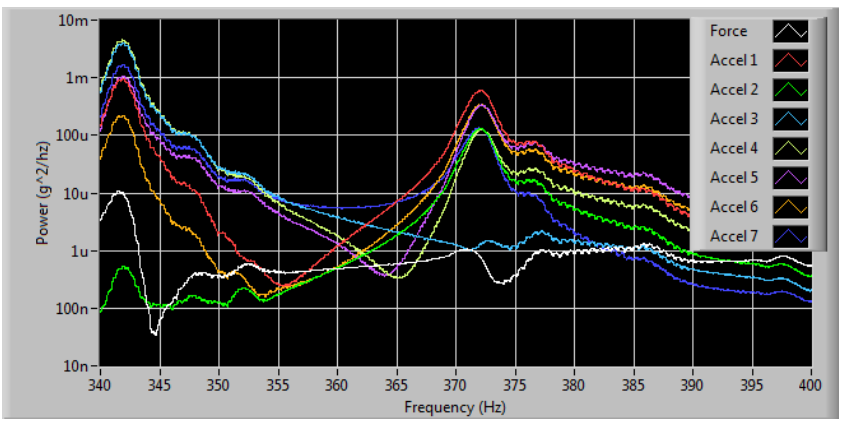
- Hybrid fiber optic sensing system (HyFOSS) is a combination of two existing technologies both based on fiber Bragg gratings
- Technology #1: Wavelength Division Multiplexing (WDM) allows for high speed (kHz) acquisition speed but low number of gratings per fiber
- Technology #2: Optical Frequency Domain Reflectometry (OFDR) allows for high spatial resolution (1000s of grating) but inherently low sample rates(<100Hz)
- To combine the best of both technologies coupled on to the **same fiber** allows for high spatial resolution (lower sample rates) along the entire length of the fiber using OFDR as well as high sample rates at strategic points along the fiber using WDM

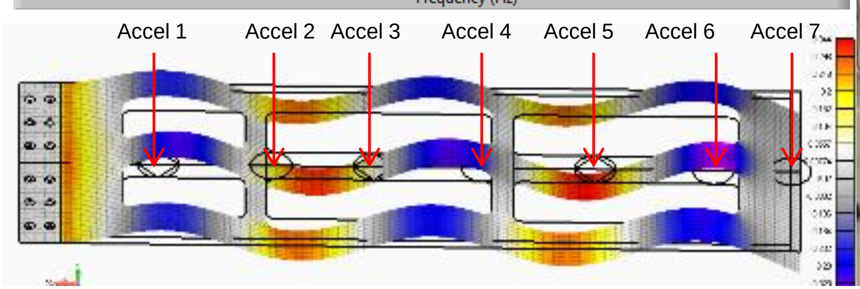
Example hyFOSS fiber layout

HyFOSS, Frequency Sweep Vibration Testing

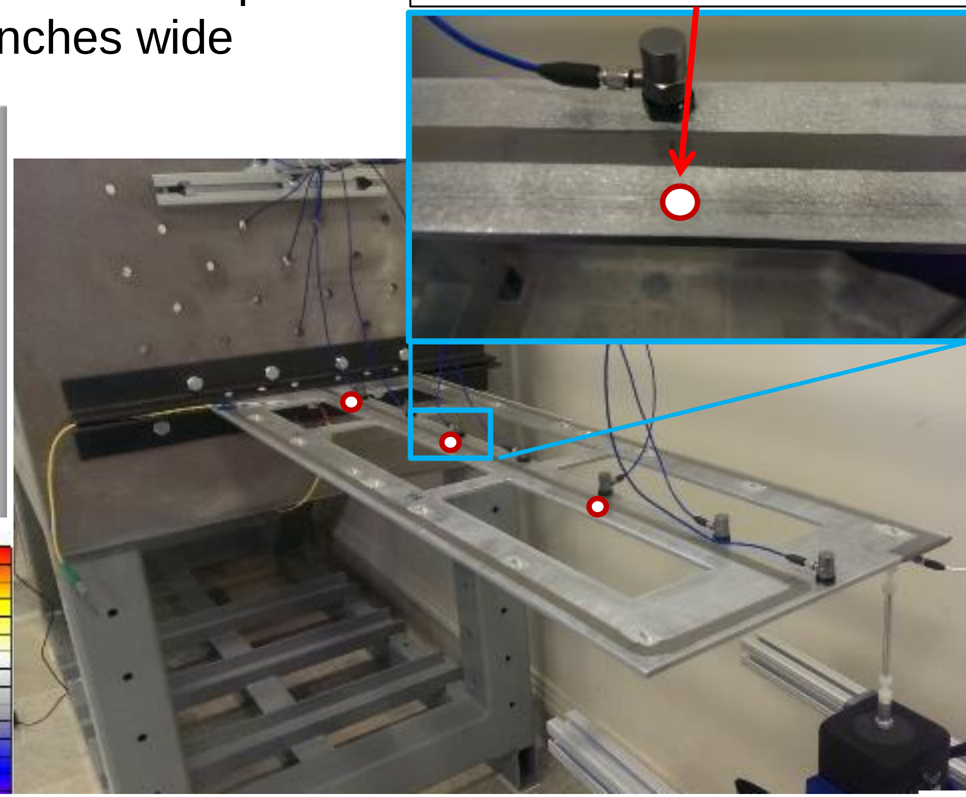
Experimental setup

- Cantilever test article with discontinuous section properties.
- A Finite Element Model has been created to determine strain gage locations
- Aluminum wing plate structure is excited by an electrodyanamic shaker
- 7 Accelerometers are mounted to the structure to monitor structure mode shapes
- OFDR and WDM sensors (3) are bonded to the plate
- Test article is 36 inches long and 12 inches wide

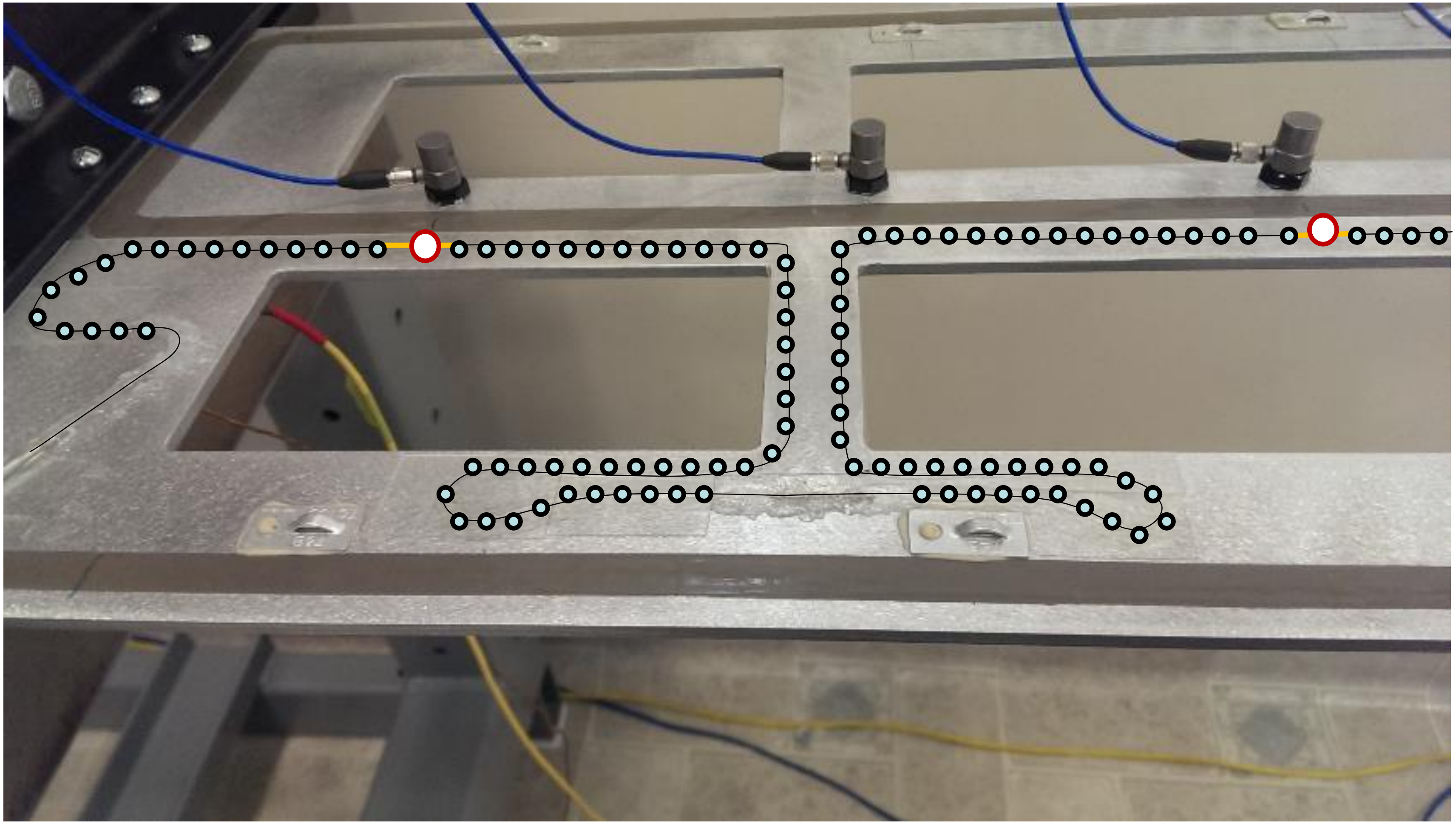




WDM / High Speed Fiber Optic Sensor



HyFOSS Sensor Installation



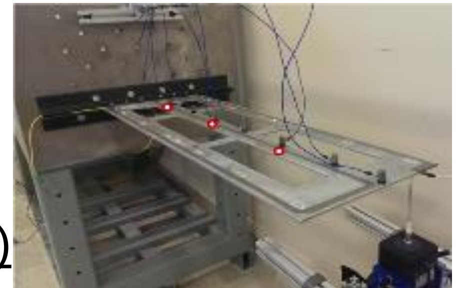
• - 100 Hz (OFDR)

○ - 5,000 Hz (WDM)

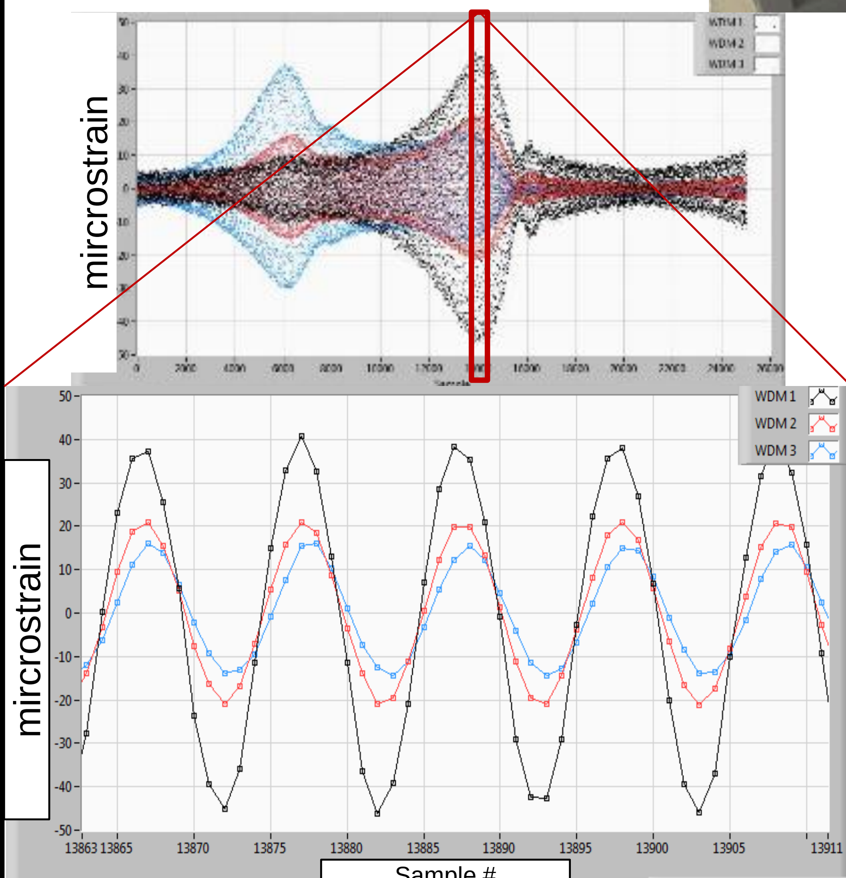
National Aeronautics and Space Administration

National Aeronautics and Space Administration

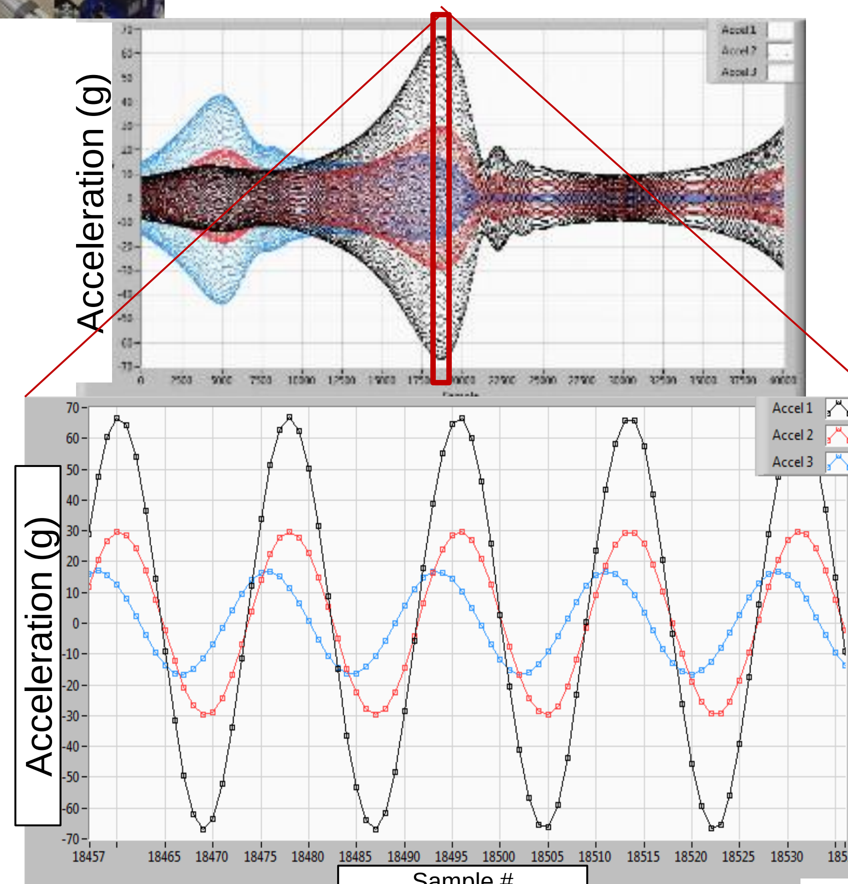
HyFOSS test – Fiber Optics & Accelerometer Frequency Sweep 475 Hz to 525 Hz



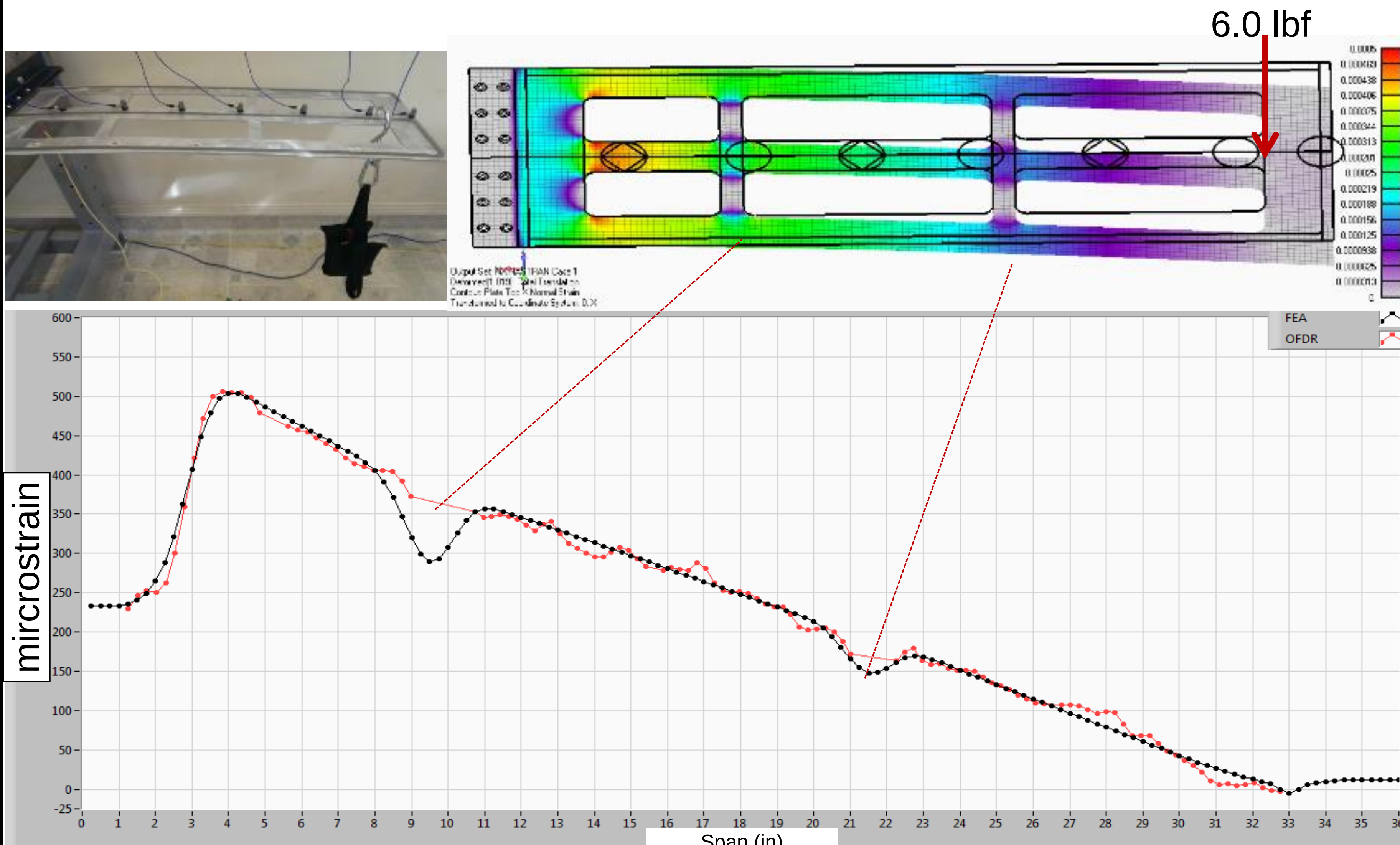
High Speed Fiber Optics (5 kHz)



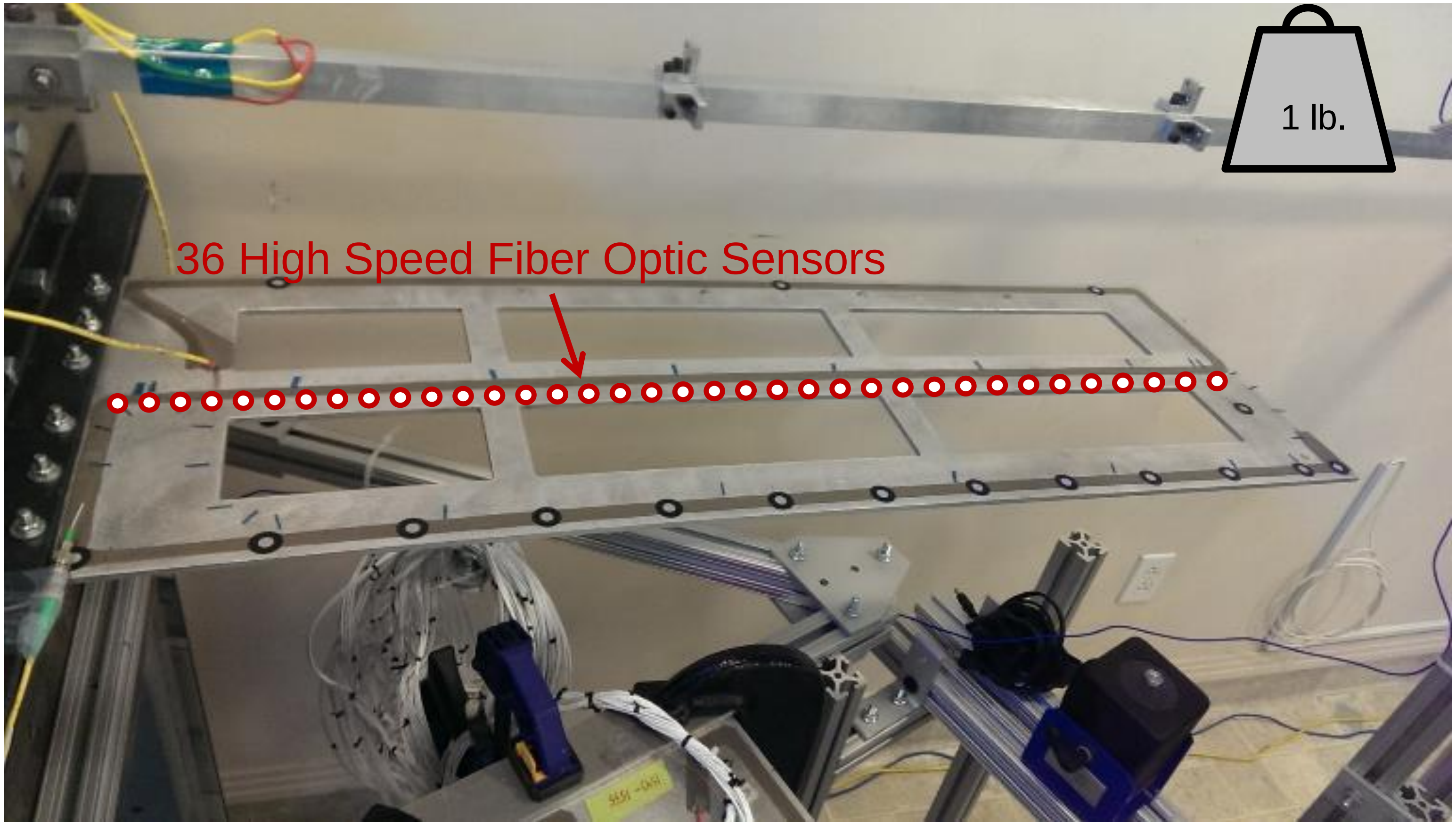
Accelerometers (8 kHz)



Finite Element Output & 100 Hz Fiber Optic Sensors

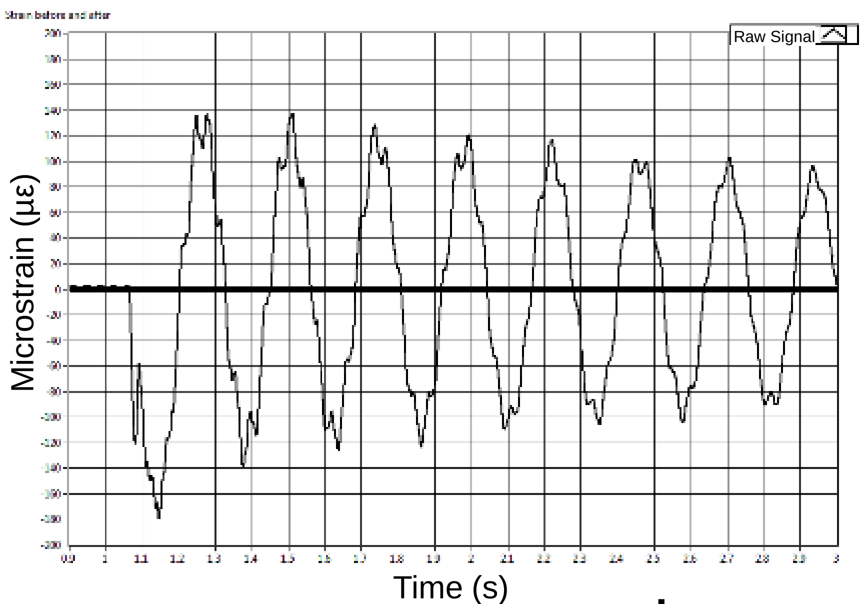


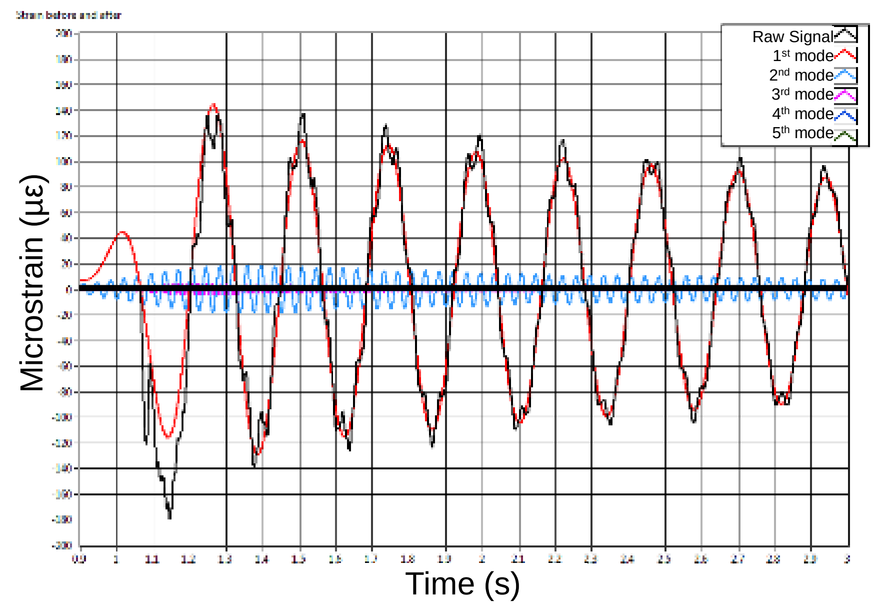
Dedicated High Speed Testing, Impact Test

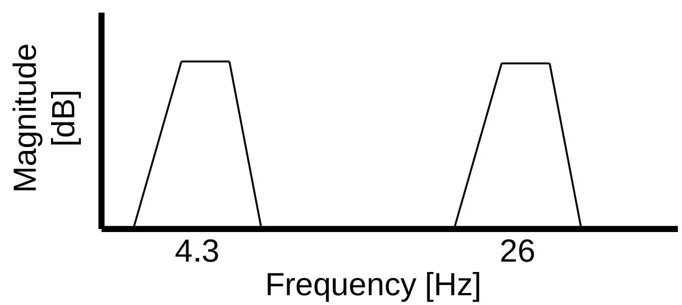


Impact test, Strain Data time history

Raw → Filtered

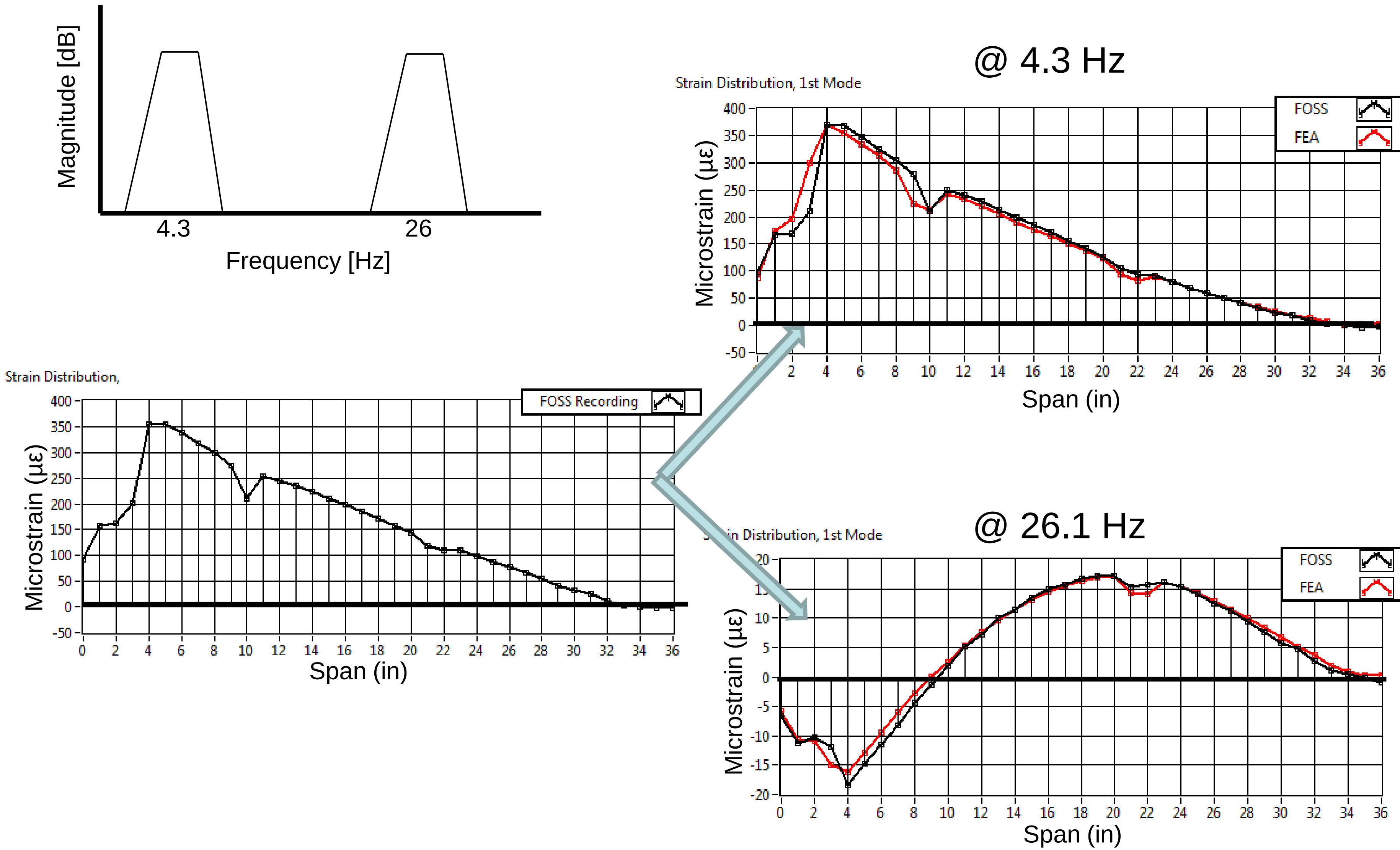






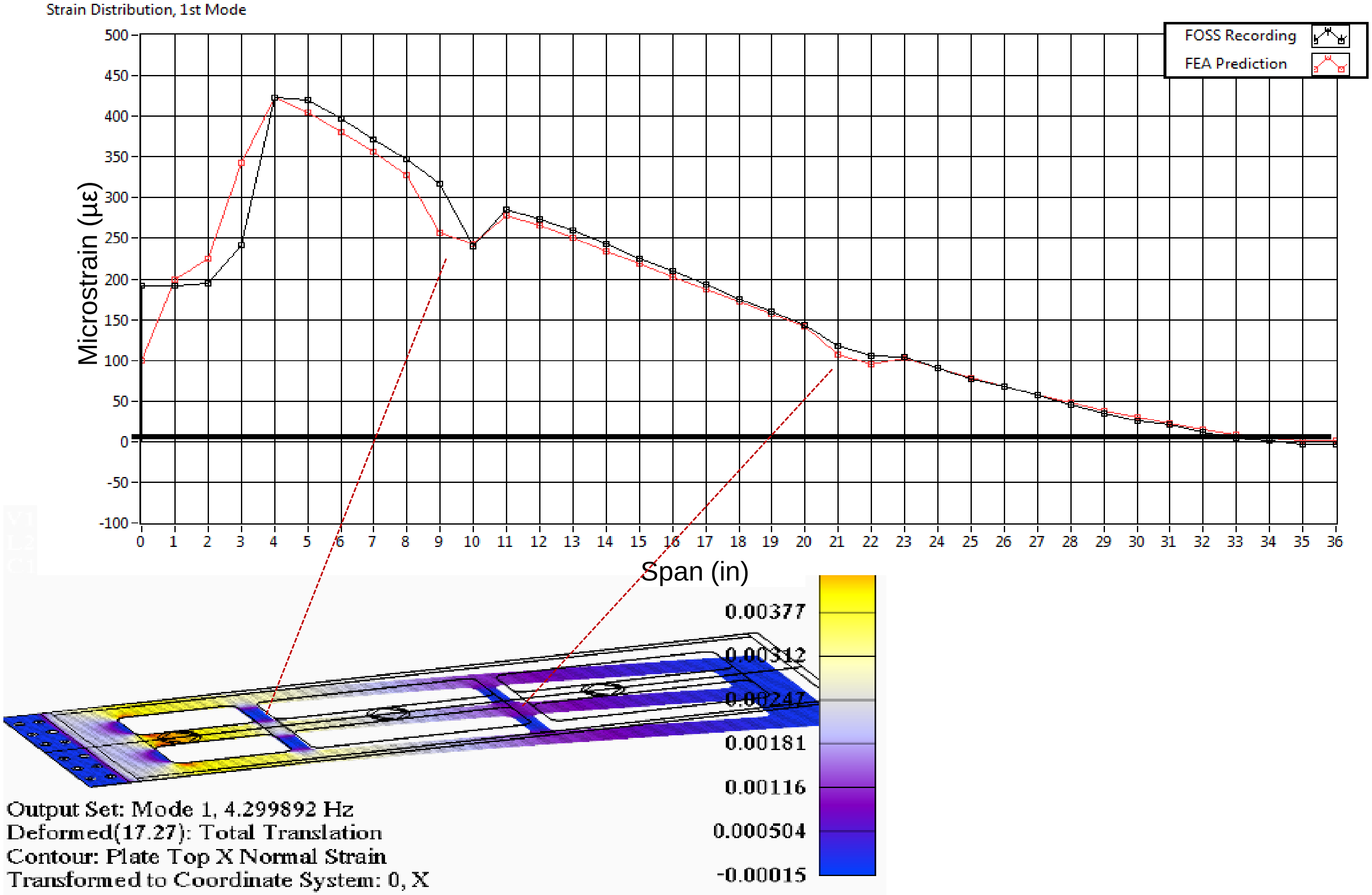
A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

Isolating Mode Shapes



A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

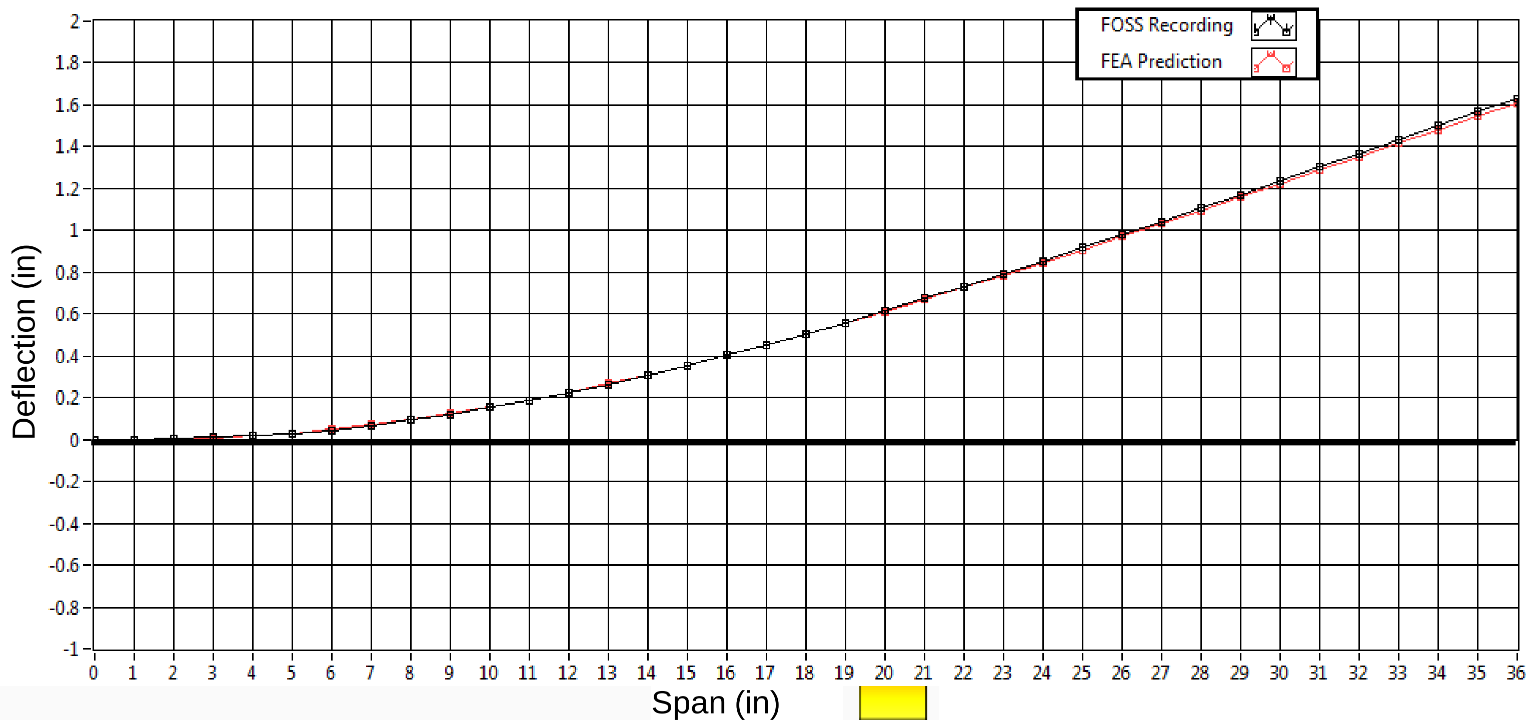
1st mode strain distribution (4 Hz)



A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

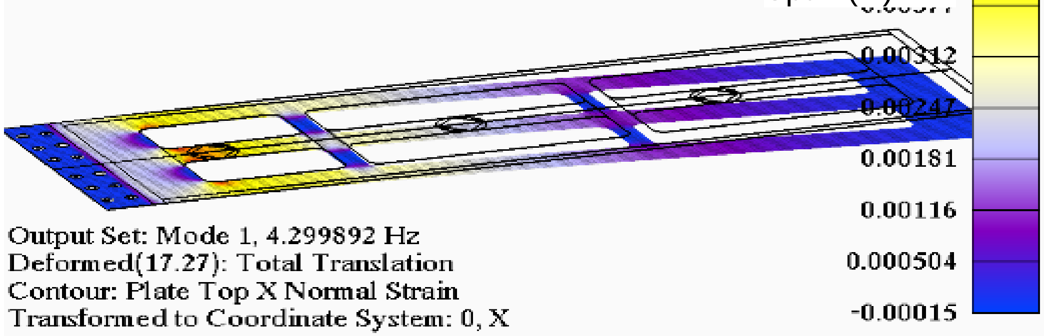
National Aeronautics and Space Administration

1st mode deflection comparisons (4 Hz)



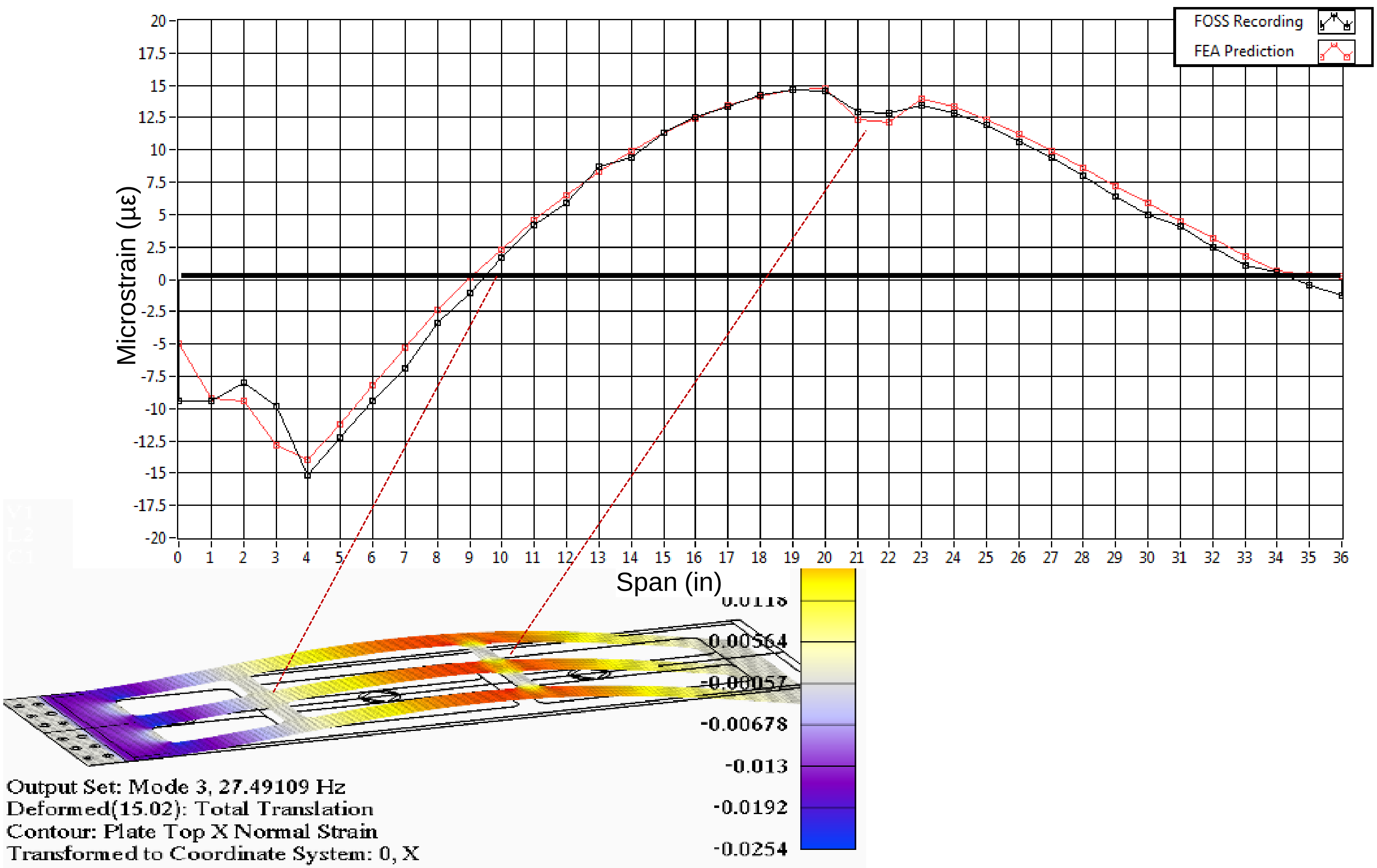
$\approx 2.62g$

$\approx 2.62g$



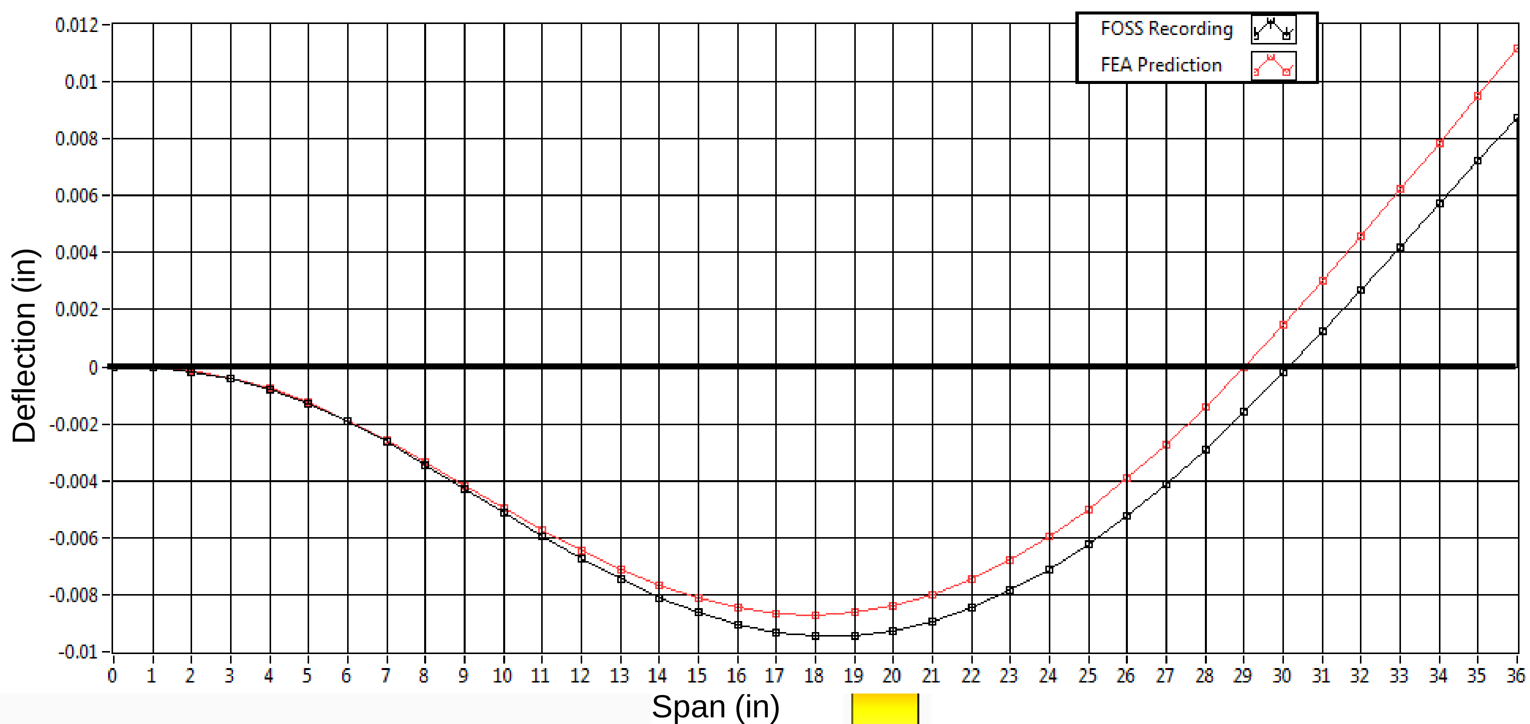
A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

2nd mode strain distribution (26.5 Hz)



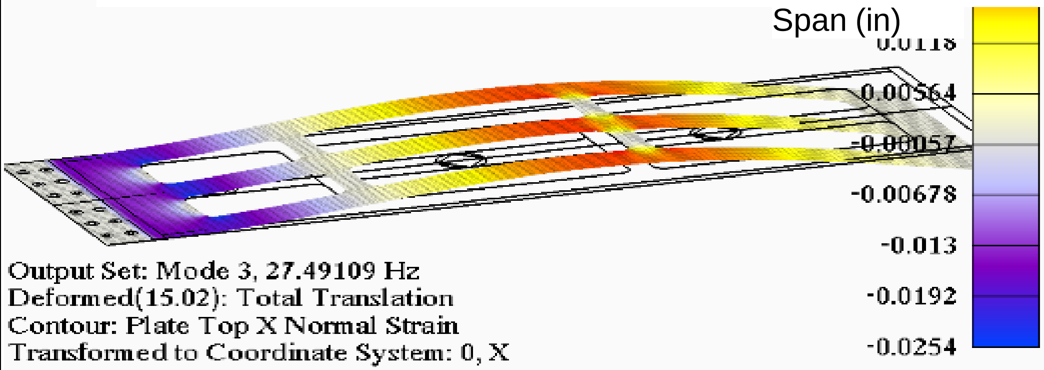
A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

2nd mode deflection comparisons (26.5 Hz)



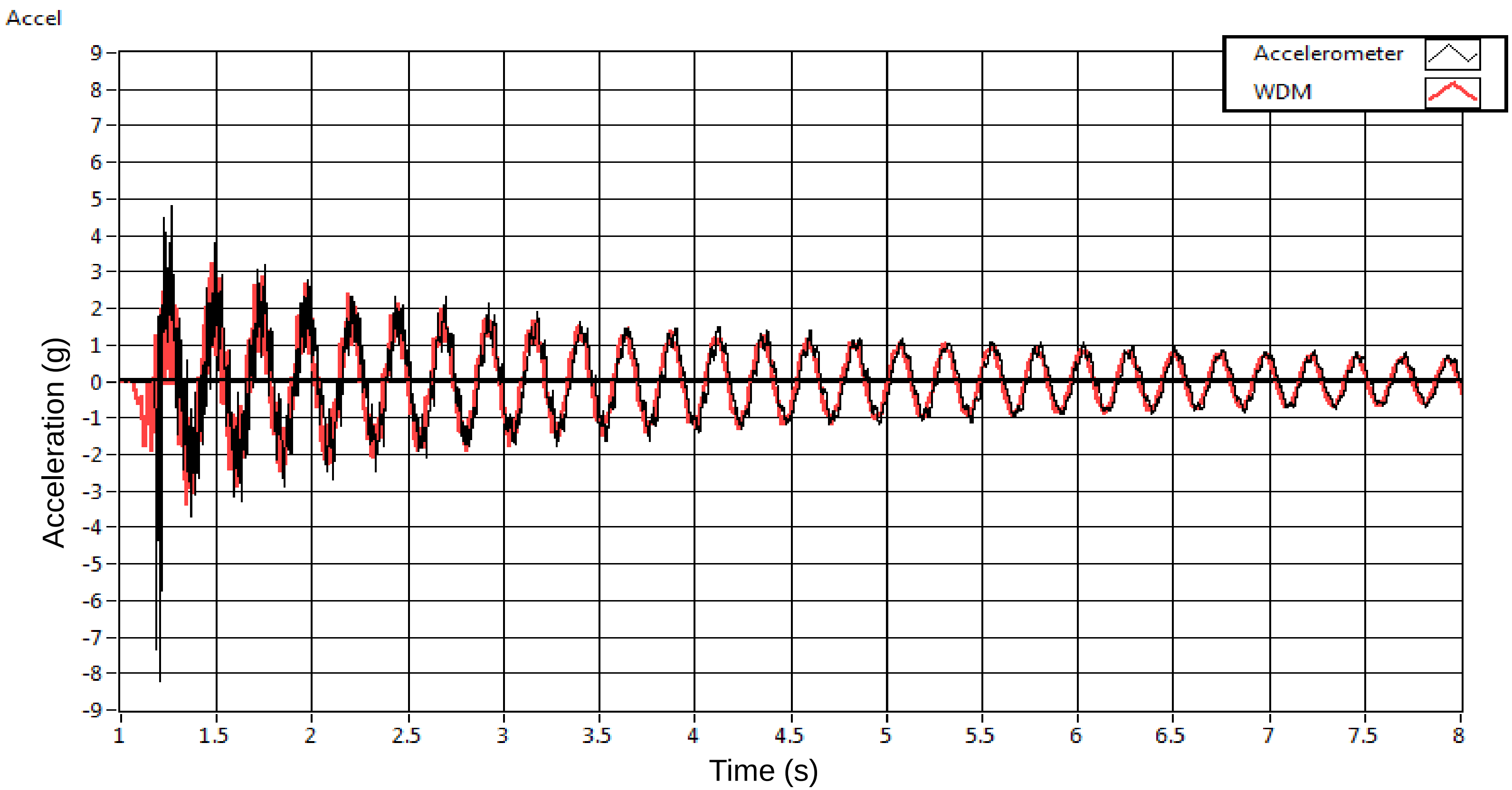
$\approx 0.79g$

$\approx 0.64g$



A NASA New Technology Report (NTR) has been filed for the Mode Shape and Acceleration Monitoring Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information

Impact test, Accelerometer vs. High Speed Fiber Optics (5 modes) Test



$$x = A_1 \cdot sin(\omega_{n1}t + \phi_1) + A_2 \cdot sin(\omega_{n2}t + \phi_2)\ldots$$

$$\dot{x} = \omega_{n1} \cdot A_1 \cdot cos(\omega_{n1}t + \phi_1) + \omega_{n2} \cdot A_2 \cdot cos(\omega_{n2}t + \phi_2)\ldots$$

$$\ddot{x} = -\omega_{n1}^2 \cdot A_1 \cdot sin(\omega_{n1}t + \phi_1) - \omega_{n2}^2 \cdot A_2 \cdot sin(\omega_{n2}t + \phi_2)\ldots$$

Anticipated Impact of Fiber Optic based SHM

National Aeronautics and Space Administration

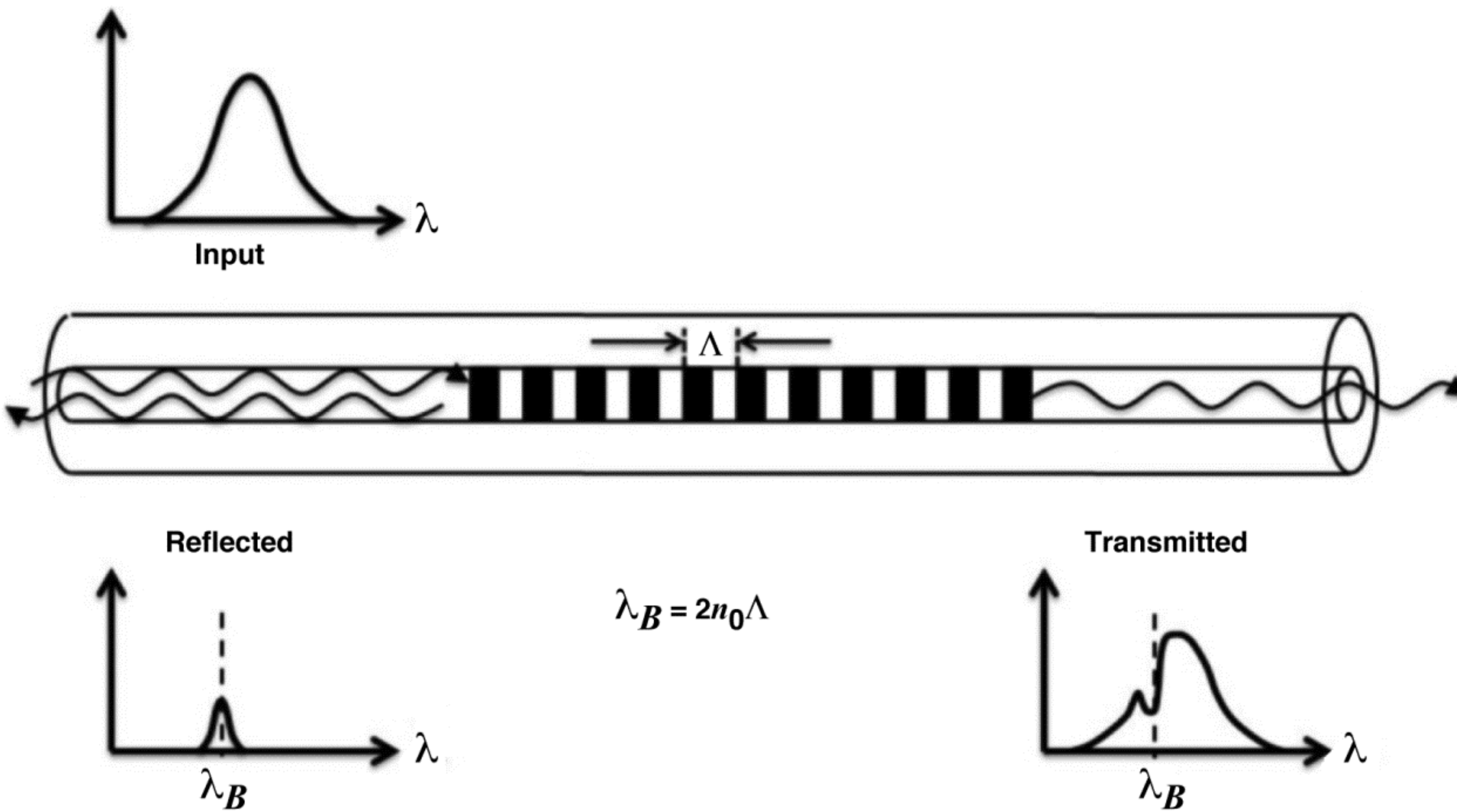
- **Potential to revolutionize aerospace design and performance throughout the vehicle life-cycle**
  - Design and development
  - Fabrication
  - Test and Evaluation
  - In-flight operation
  - Off-nominal flight
  - End of life-cycle decisions

Concluding Remarks

- ***FOSS Benefits***
  - Provides >100x the number measurements at 1/100 the total sensor weight
  - Increases capability of measuring multiple parameters in real time (strain, temp., accel, liquid level, shape, applied loads, stress, mode shapes, natural frequencies, buckling modes, etc.)
  - Provides comprehensive datasets to validate loads / dynamics models
- ***For most full-scale structural dynamics applications, FOSS sample rates (16,000 sensors at 100sps) are sufficient***
- ***A single hybrid interrogation scheme that gleans the benefits of two different FBG sensing technologies, WDM and OFDR, has been developed and demonstrated***
  - OFDR acquires higher density FOSS measurements (16,000) and lower speed (100Hz)
  - WDM acquires FOSS measurements at higher speed (35kHz) and lower density (~80/fiber)
- ***FOSS has the potential to "break the rules" for DFI; it can be used throughout loads/dynamics modeling effort (from ground to flight) by providing an unprecedented understanding about system/structural performance of LV/SC throughout the vehicle life cycle***

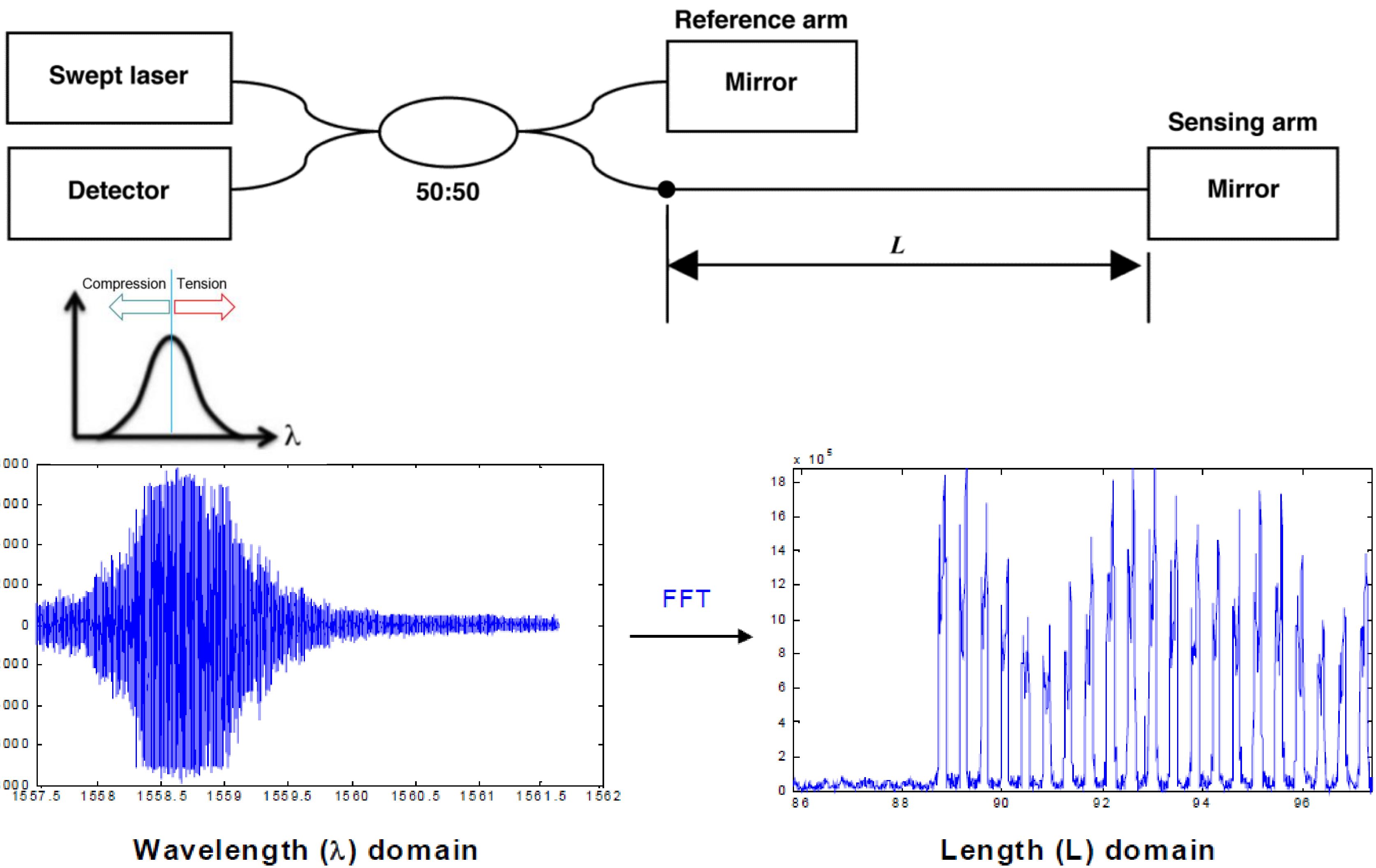
Extra Slides

Fiber Bragg Gratings (FBGs)

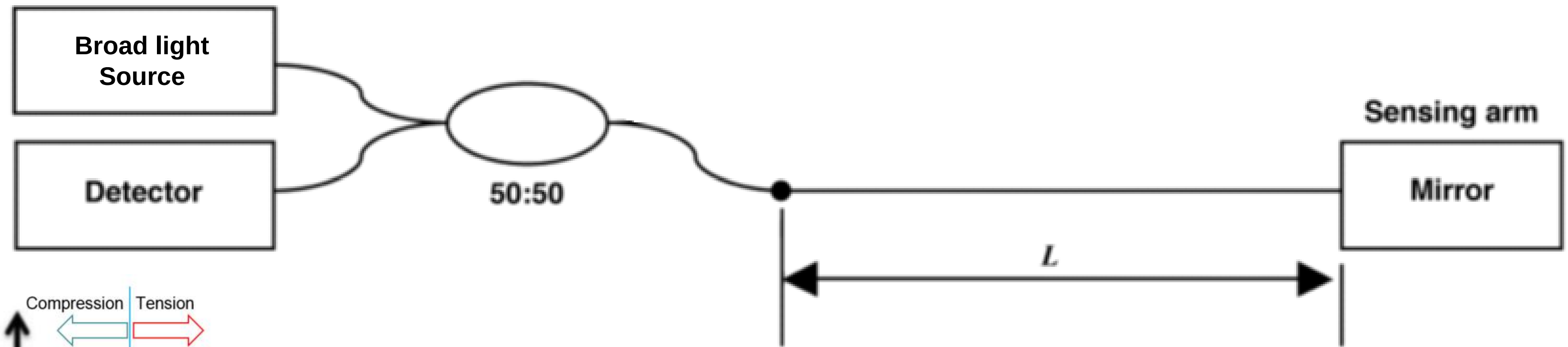


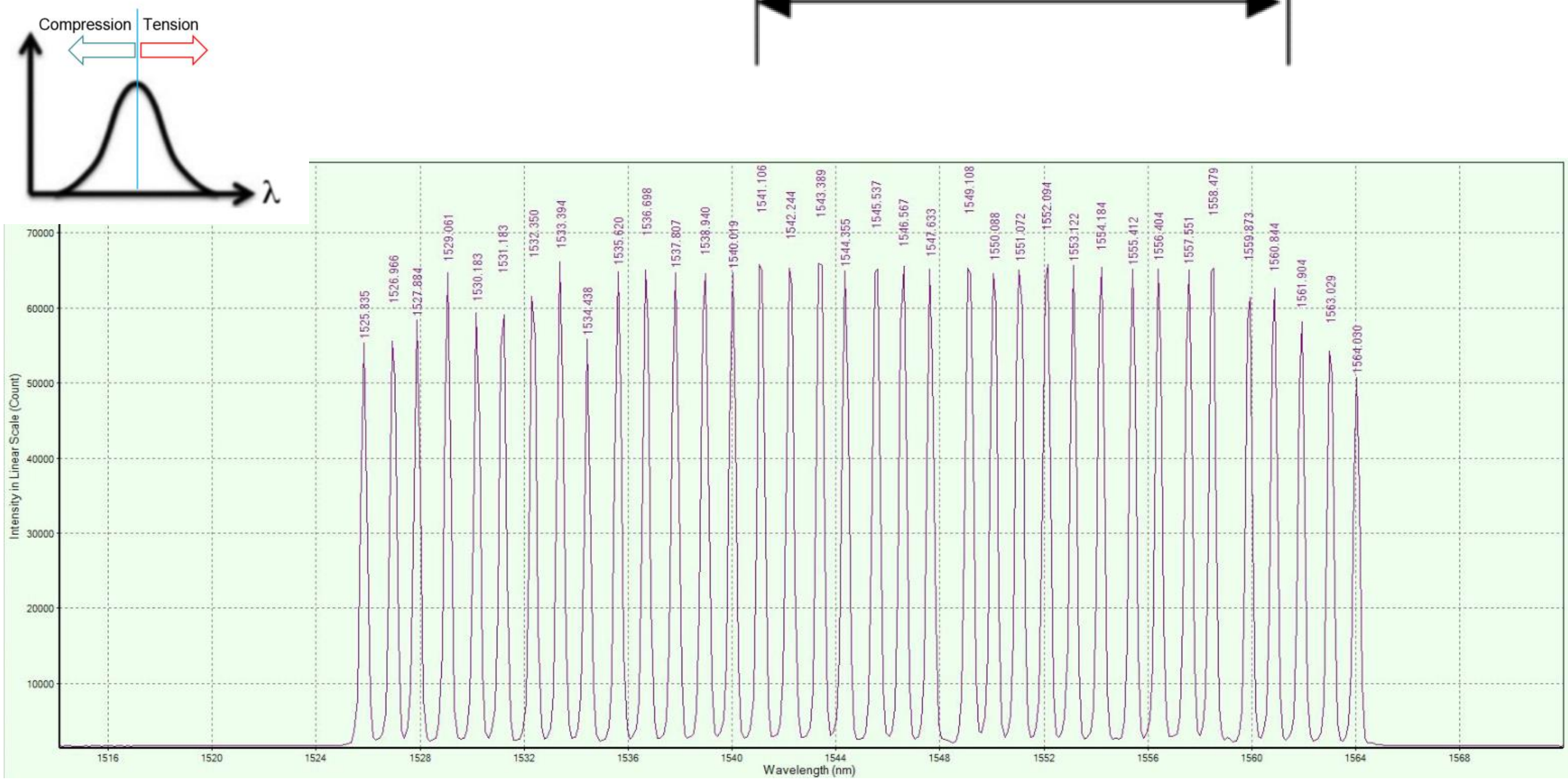
$$\lambda_B = 2n_0\Lambda$$

OFDR


Reference arm
Swept laser
Mirror
Sensing arm
Detector
50:50
Mirror
L
Compression
Tension
λ
FFT
x 10^5
Wavelength (λ) domain
Length (L) domain

WDM


Broad light Source
Detector
50:50
Sensing arm
Mirror
L


Compression
Tension
λ
Intensity in Linear Scale (Count)
70000
60000
50000
40000
30000
20000
10000
1516
1520
1524
1528
1532
1536
1540
1544
1548
1552
1556
1560
1564
1568
Wavelength (nm)
1525.835
1526.966
1527.884
1529.061
1530.183
1531.183
1532.350
1533.394
1534.438
1535.620
1536.698
1537.807
1538.940
1540.019
1541.106
1542.244
1543.389
1544.355
1545.537
1546.567
1547.633
1549.108
1550.088
1551.072
1552.094
1553.122
1554.184
1555.412
1556.404
1557.551
1558.479
1559.873
1560.844
1561.904
1563.029
1564.030