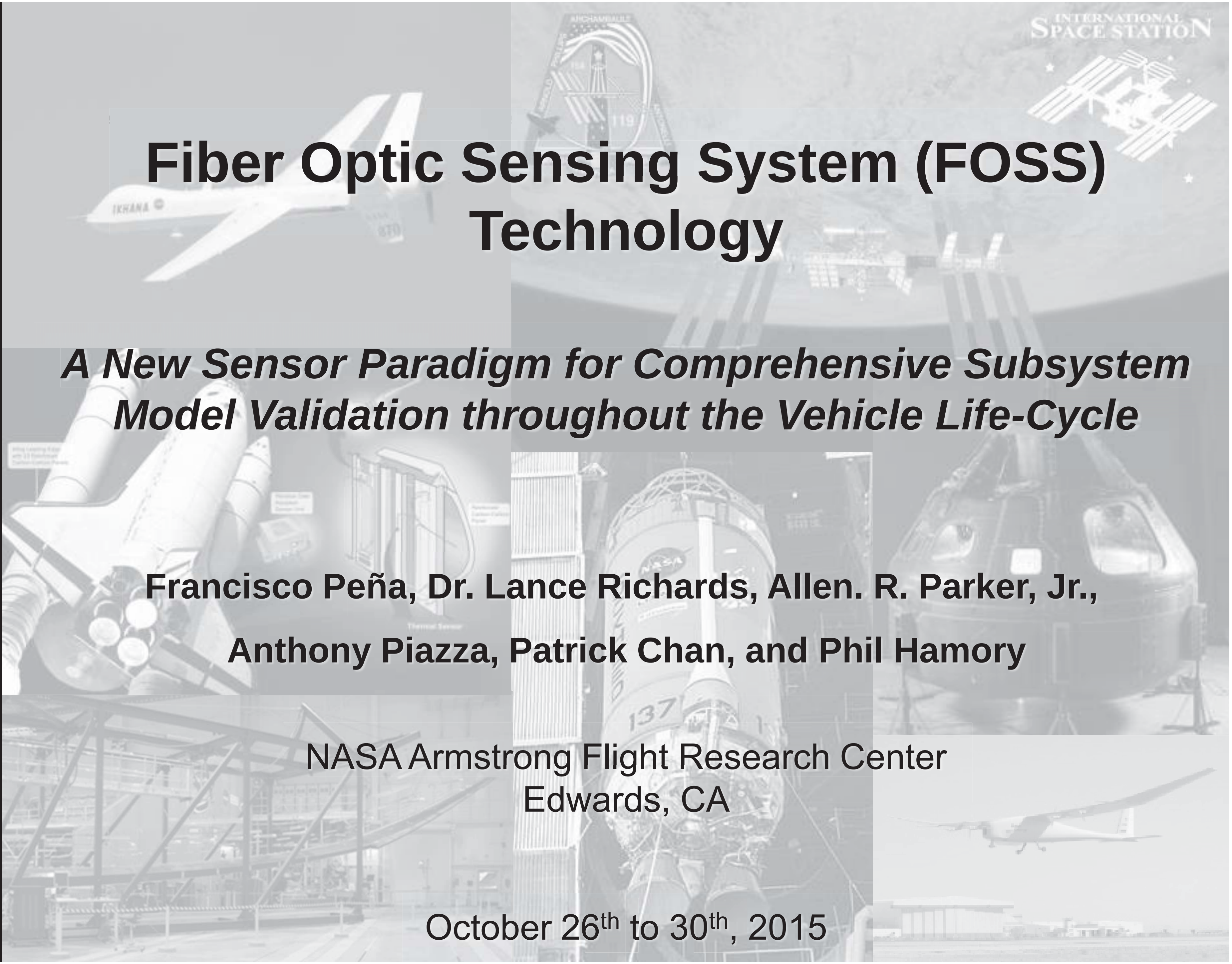
National Aeronautics and Space Administration



Fiber Optic Sensing System (FOSS) Technology

A New Sensor Paradigm for Comprehensive Subsystem 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

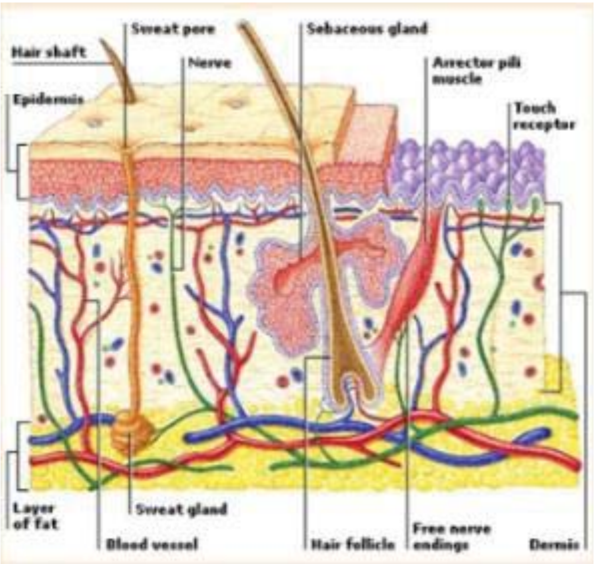
October 26th to 30th, 2015

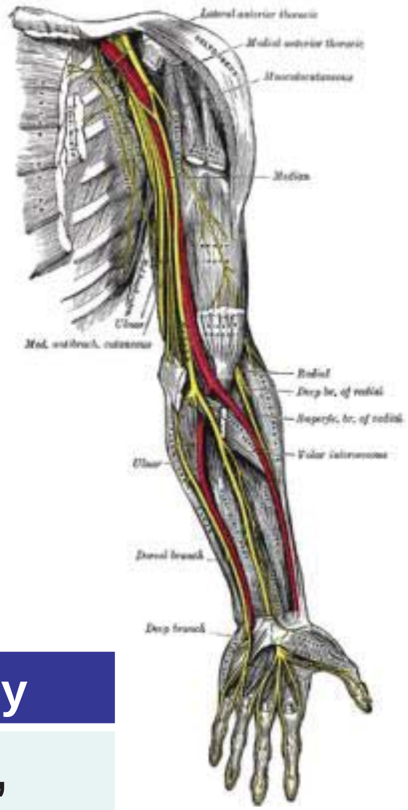
Background and Inspiration

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



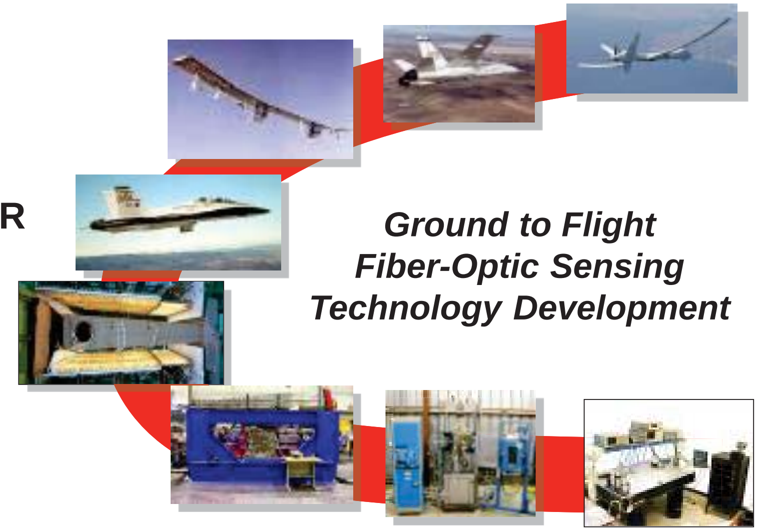


Courtesy: Airbus

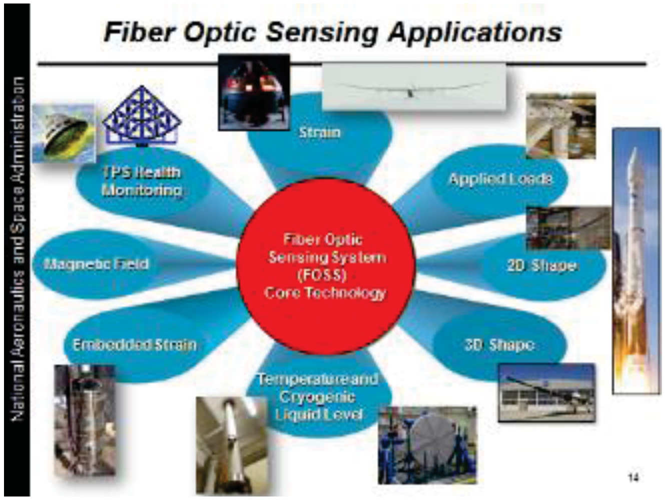
Smart Structure	Human Body
Fiber Optic Sensors	Pain, temp, pressure sensors
Piezo’s, SMAs	Muscles
IVHM, Smart Systems	Brain

Background

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



Ground to Flight Fiber-Optic Sensing Technology Development



National Aeronautics and Space Administration

Fiber Optic Sensing Applications

Fiber Optic Sensing System (FOSS) Core Technology

Strain

Applied Loads

2D Shape

3D Shape

Temperature and Cryogenic Liquid Level

Embedded Strain

Magnetic Field

TPS Health Monitoring

14

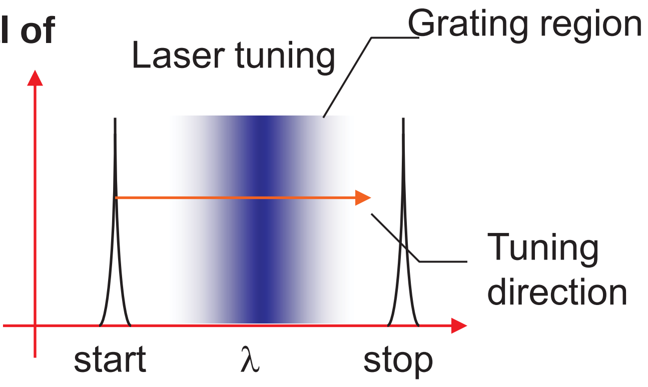
Background

- **The NASA Armstrong (formerly Dryden) Flight Research Center (AFRC) Fiber Optic Sensor System (FOSS) was originally developed for in-flight strain measurements of aircraft**
  - The system measures strain & temperature as changes in reflected wavelength from a laser source. The system has successfully flown on several aircraft at AFRC
- **LSP is sponsoring increased capability of FOSS technology to replace legacy flight instrumentation**
  - *Potential for light-weight, low-cost, reliable, easily installed system producing more data to replace strain gauges, accelerometers, rate gyros, thermocouples, propellant sensors for less $ than current systems*
  - LSP currently sponsoring testing of FOSS in in the CRYOTE 3 for further development of cryoFOSS for propellant mass gauging and propellant stratification measurements in LN_2 and LH_2. Results indicate promise for high accuracy mass gauging for increased propellant utilization
  - LSP currently sponsoring testing of FOSS development to increase sample rate with the goal of 40 kHz from the current 100 Hz with the goal of measuring acceleration
  - LSP is currently sponsoring an investigation the potential for FOSS to measure magnetic and RF fields.
  - LSP has sponsored design and development of FOSS for current ELVs on contract to NASA
    - Flight avionics FOSS box near completion (collaborative effort between LSP, AFRC, and MSFC
    - Currently in discussions with Commercial Space companies and NESC for potential flight opportunity
- **LSP is still seeking Agency-level funding to achieve greater agency integration ground testing, and flight applications**
  - Cross-Agency interest has been expressed by other governmental launch stakeholders

Fiber Optic System Operation Overview

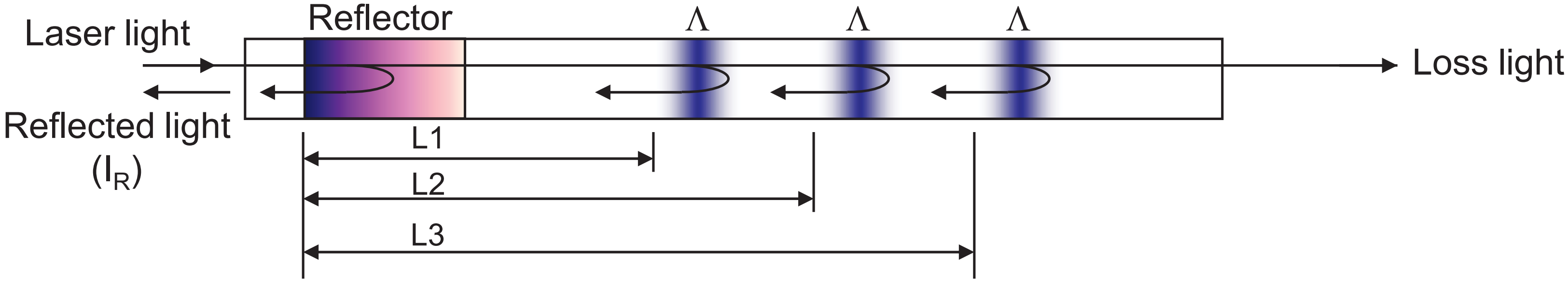
Fiber Optic Sensing with Fiber Bragg Gratings

- **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**

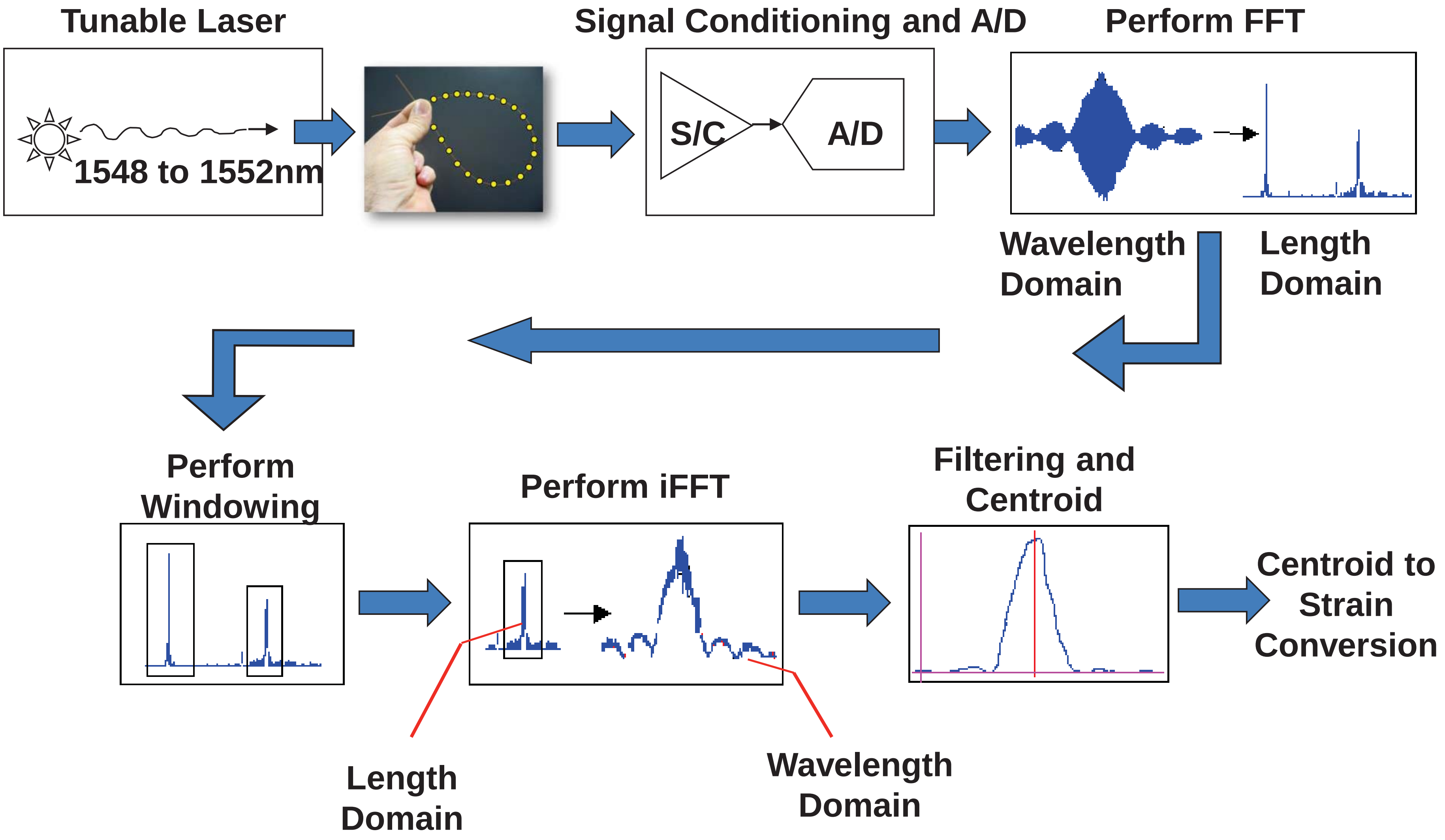


$$I_R = \sum_i R_i Cos(k2nL_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
n – effective index
L – path difference
k – wavenumber



How Does it Work: FBG OFDR Overview



Tunable Laser

Signal Conditioning and A/D

Perform FFT

Wavelength Domain

Length Domain

Perform Windowing

Perform iFFT

Filtering and Centroid

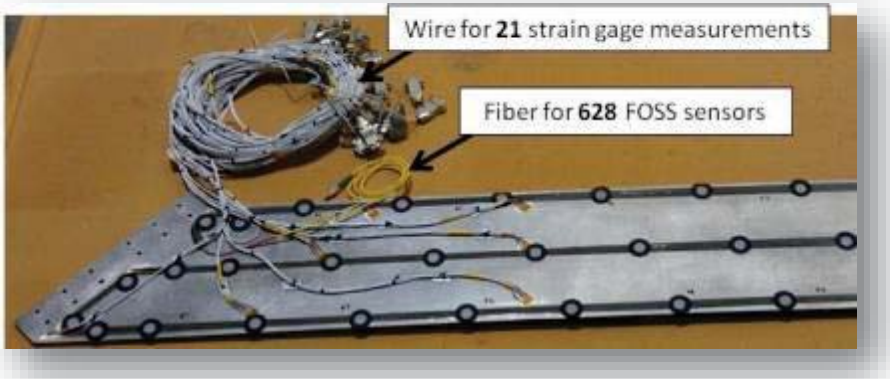
Centroid to Strain Conversion

Length Domain

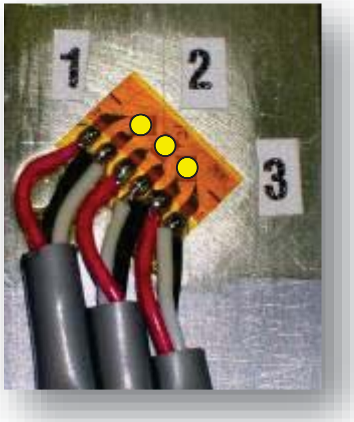
Wavelength Domain

Why Fiber Optic Sensors?

One Of These Things (is Not Like The Others)

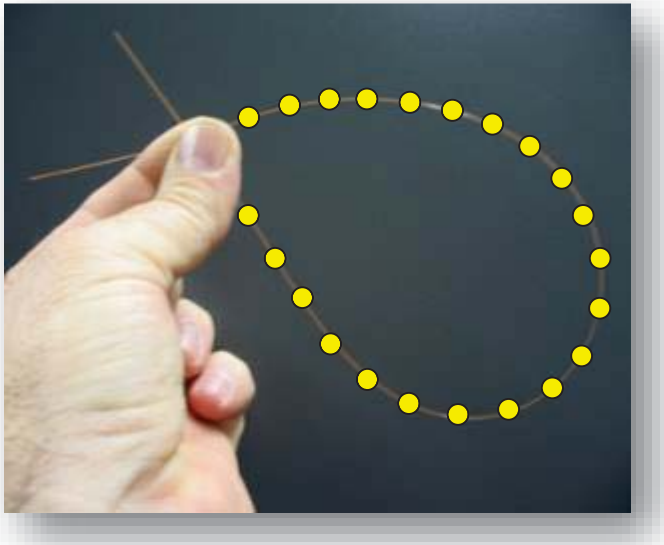


(Heavy)



(Big)

(Complex)



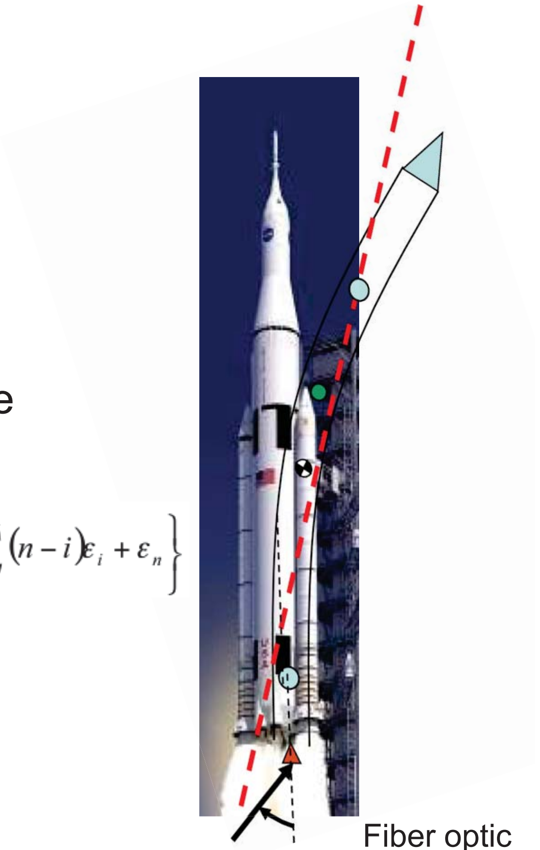
(Light, small, easy)

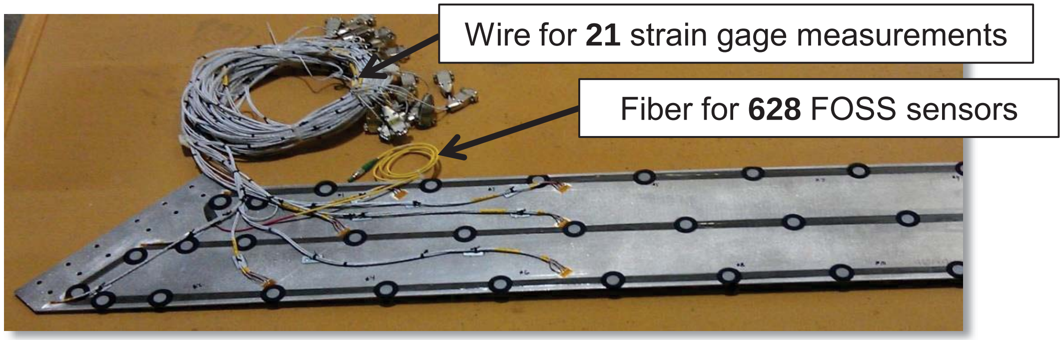
FOSS Advantages to Conventional Strain Measurements

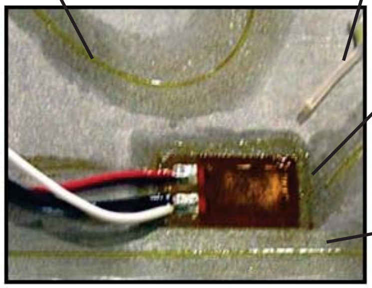
- Unrivaled spatial density of sensors for full-field measurements
- Measurements immune to EMI, RFI and radiation
- Lightweight sensors
    - Typical installation is 0.1 - 1% the weight of conventional gage installations (based on past trade studies)
    - 1000’s of sensors on a single fiber (up to 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

$$y_n = \frac{\Delta l^2}{6c}\left\{(3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1}(n-i)\varepsilon_i + \varepsilon_n\right\}$$

- 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





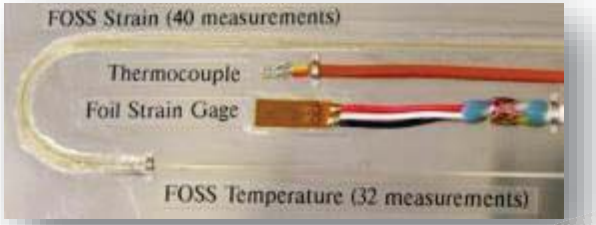


Strain sensor comparison

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

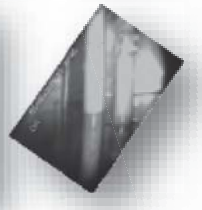
FBG-OFDR can dramatically improve structural and system efficiency for space vehicle applications by improving both affordability and capability by …

- 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



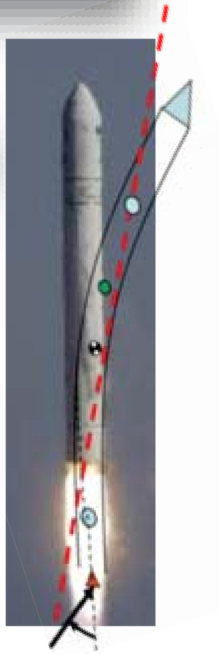
Metallic Coupon

Pressure monitoring



Liquid level sensing

ISS COPV strain & temp monitoring



Shape sensing for vehicle control

FOSS Rationale for Loads / Dynamics

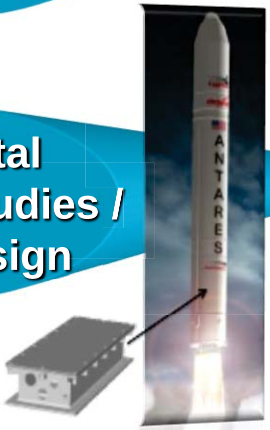
Excerpts from Larsen et. al. NESC 2015

- ***"For complex space systems, historical data indicates that unless a model is tuned/adjusted to its mode survey test data, it will contain significant errors."***
- ***"Accurate loads analysis models (from element-level to full-scale) can only be achieved with test validation."***
- ***"The ultimate goal is a validated and verified model of the vehicle during future launch operations that can be used to reliably predict response with different payloads, wind profiles, etc."***
- ***"Developmental Flight Instrumentation (DFI) provides the data to reduce the uncertainty in the predicted loads and dynamic responses, update the model, and identify excess/insufficient margins before future flights."***
- ***"DFI is essential to identifying behaviors that cannot be measured during ground tests, or cannot be easily excited or replicated."***
- ***"To date, in every first flight and <u>in many subsequent flights</u> of NASA man-rated space launch vehicles, DFI has helped reveal important vehicle responses that were not initially predicted in ground-based testing and analysis and in prior flights."***
  - **For manned space exploration missions, there is no such thing as "<u>Operational</u> Flight Instrumentation" CAIB**
- ***"Because of flight-to-flight variability, data must be collected from numerous flights to properly/conservatively establish behavior of the system."***
- **FOSS has potential to "break the rules" for DFI; it can be used throughout loads / dynamics modeling efforts (from ground to flight) by providing an unprecedented understanding about LV/SC performance <u>throughout vehicle life cycle</u>**
  - **Unlike conventional DFI philosophy, more trouble to remove FOSS due to low weight, small size**

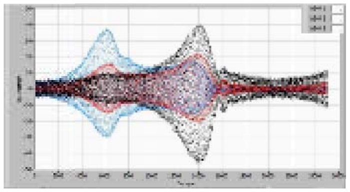
LSP Funded FOSS R&D Activities

Magnetic Field

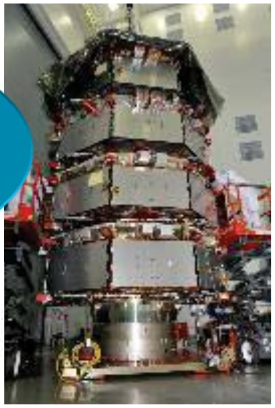
ULA, Orbital Feasibility Studies / Prelim. Design



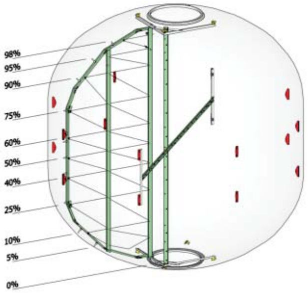
Dynamic Strain & Accelerometer Measurements



MMS Clamp Band Testing



***Cryogenic* Liquid Level**



Bridging the Gap Between Aeronautics and Space

Implementation of FOSS on ELVs

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

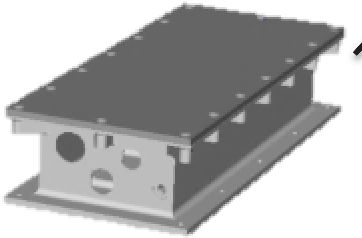

Predator -B in Flight

Compact FOSS v2.0 Launch System Specs.

- **Targeted Specifications:**

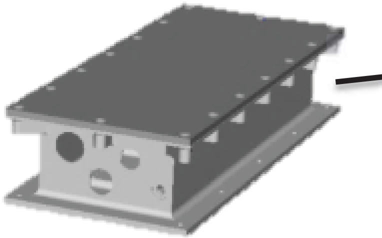
– Fiber count:	8
– Max sensing fiber length:	80 ft
– Max fiber length from system:	~300 ft
– Fiber type:	SMF-28
– Max # sensors/system:	32,000
– Max Sample rate:	100 Hz
– Interface:	Ethernet
– User Interface Protocol:	TCP/IP
– Operational Communication Protocol:	UDP
– Power:	68W @ 28Vdc
– Weight (including enclosure):	<20 lbs
– Size (application specific):	17.7 x 7.5 x 3.5 in

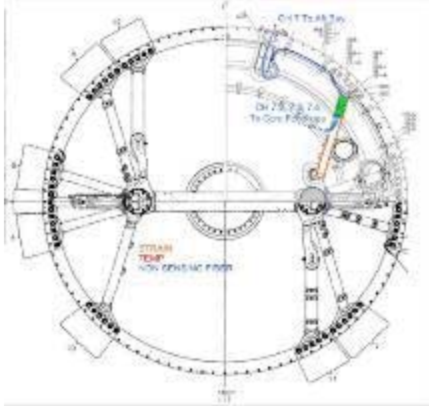
- **Applications:**
  - Launch vehicles
  - Aircrafts
  - UAVs



Implementation of FOSS on ELVs

- **NASA LSP is sponsoring design and development of FOSS for current ELVs on contract to NASA**
  - Desired goal is an FY17 flight demonstration of FOSS technology on two different ELVs, each on a different LV stage
  - Initial flight to produce flight data to prove utility, justify use on other vehicles
- **NASA LSP is seeking cross-Agency and commercial advocacy to finalize flight demonstration funding**
  - Cross Agency interest has been expressed by other governmental launch stakeholders
  - Space Act Agreements with commercial launch providers are either in place or currently in work





Bridging the Gap Between Aeronautics and Space

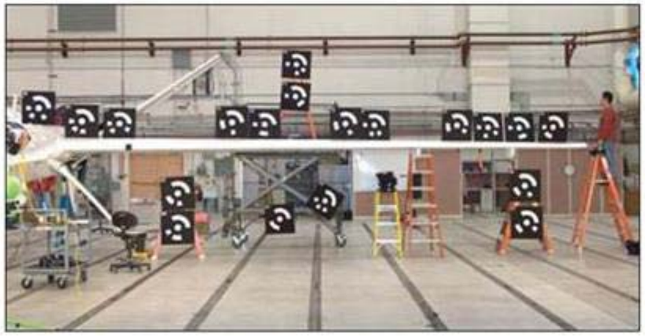
Comprehensive Real-time Operational Loads Monitoring and Vehicle Control with FOSS

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



Simplified Approach with FOSS

Typical Conventional Loads Calibration requires:

- 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

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

Current State-of-the-Art:

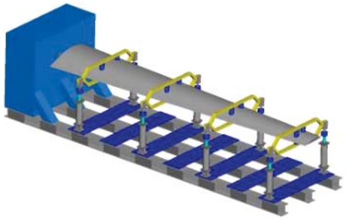
- Fiber optic strain sensing (FOSS) technology is transitioning to an airworthy alternative to conventional strain gages and will change the approach to aircraft loads calibrations
- FOSS will open up new opportunities to monitor and facilitate control of future launch vehicles

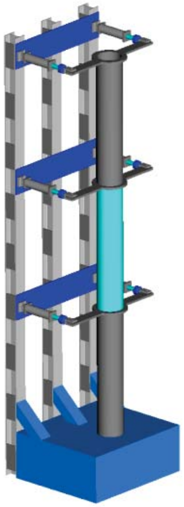
Potential Applications:

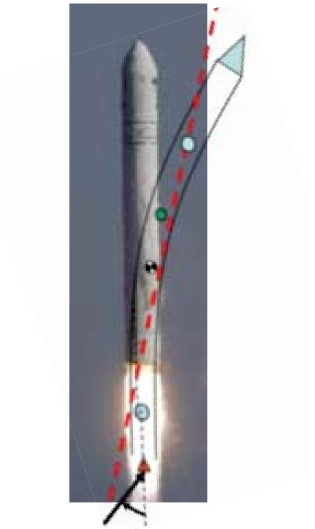
- Improved understanding of distributed aerodynamic loading
- Optimized process for aircraft structural loads calibrations for monitoring and controlling flexible, high aspect ratio wings and rocket bodies
- A detailed understanding of the span-wise load distribution will be required for optimizing the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

Helios Wing

In-flight breakup







Shape sensing for vehicle control

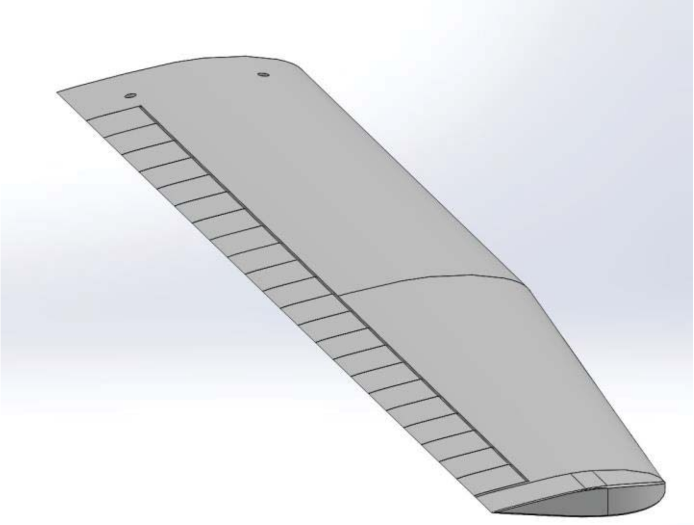
Aircraft Vehicle Load Control

- **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

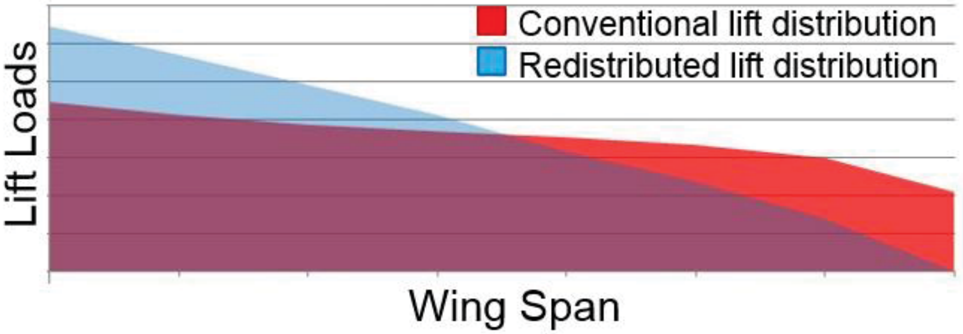
- **Autonomously Piloted Vehicle 3 (APV3)**
  - Span: 12 ft
  - Max Takeoff Weight: 55 lbs
  - 22 control surfaces per wing
  - 2,000 fiber optic strain sensors on wings (top and bottom surfaces)

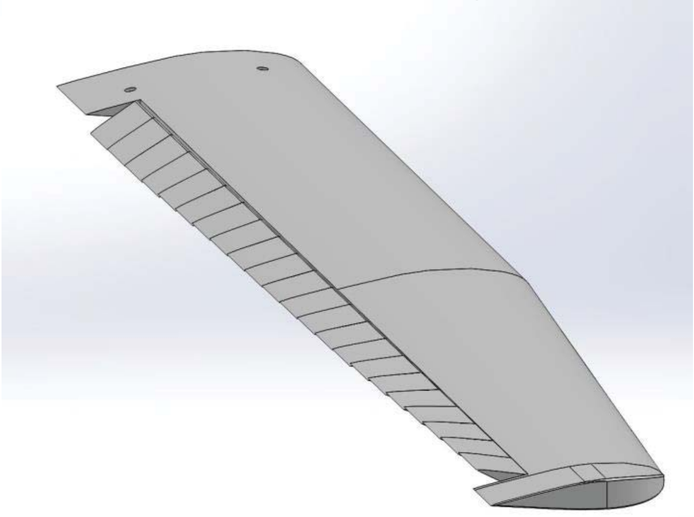
APV3 Segmented Control Surfaces

- 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

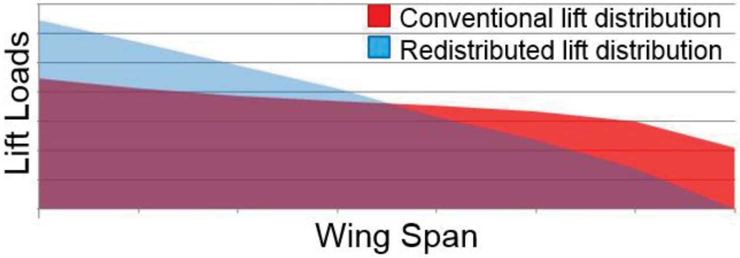


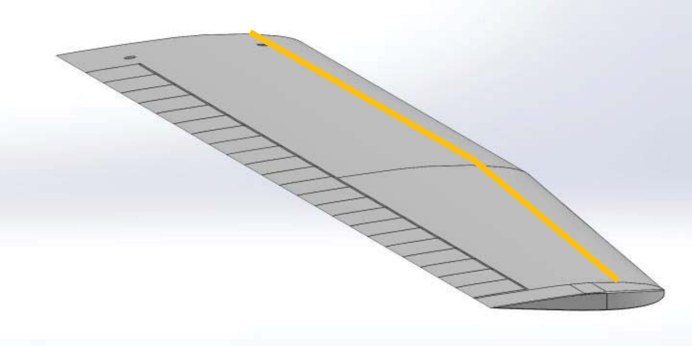


load alleviation configuration

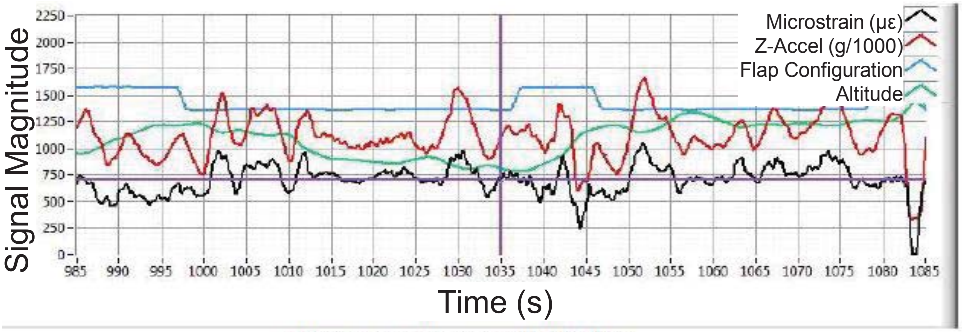
Operational Load Estimation Method Applied Results With Flight Data

APV3 in flight

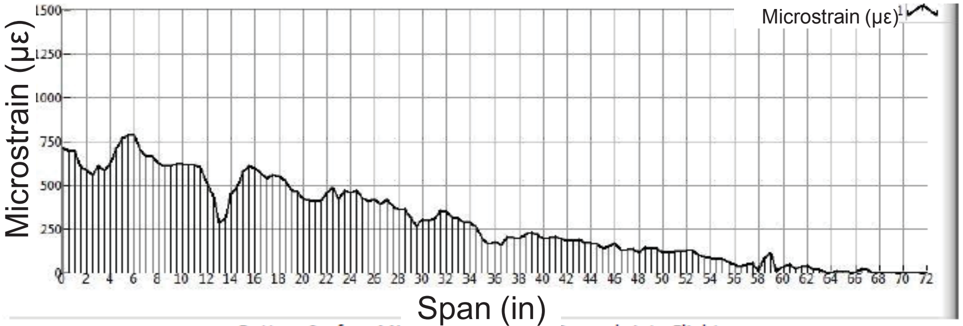




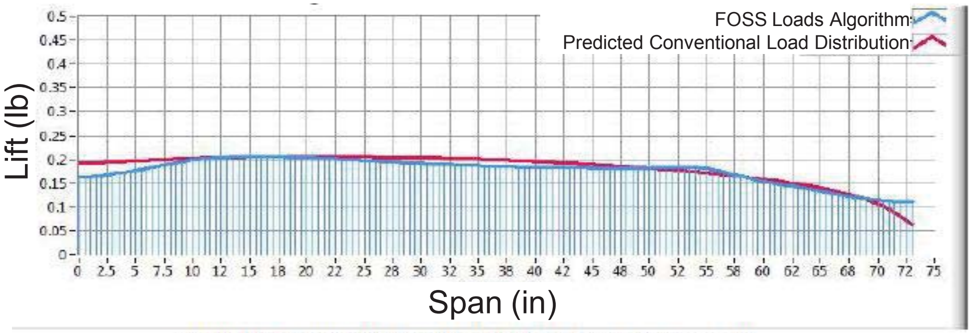
Conventional configuration



Flight Data at 1035 Seconds into Flight



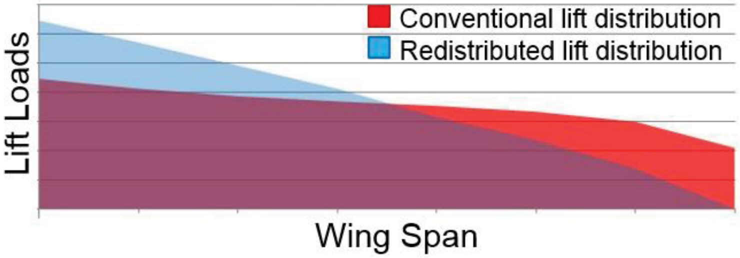
Bottom Surface Microstrain at 1035 Seconds into Flight

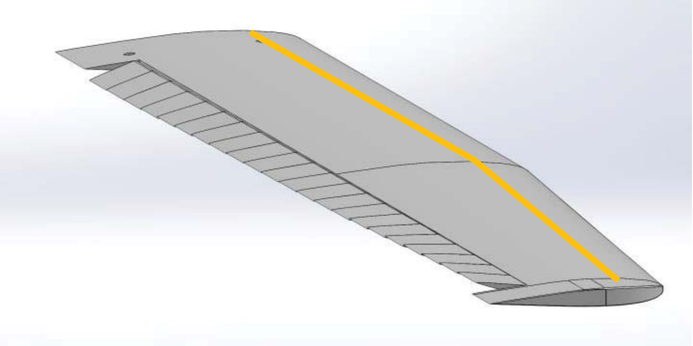


Lift Distribution at 1035 Seconds into Flight, Total Lift Force = 26

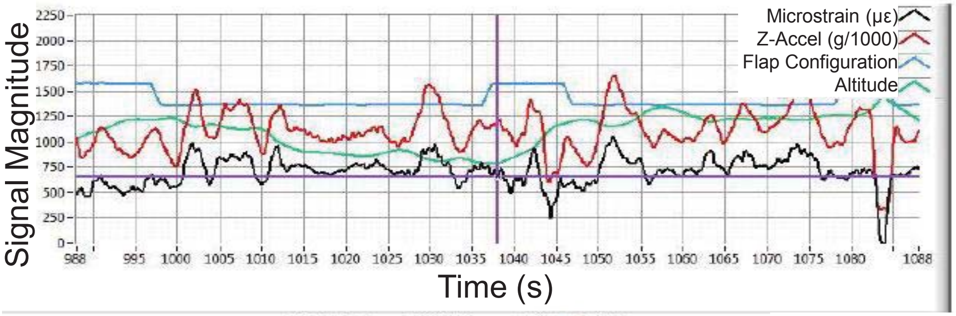
Operational Load Estimation Method Applied Results With Flight Data

APV3 in flight

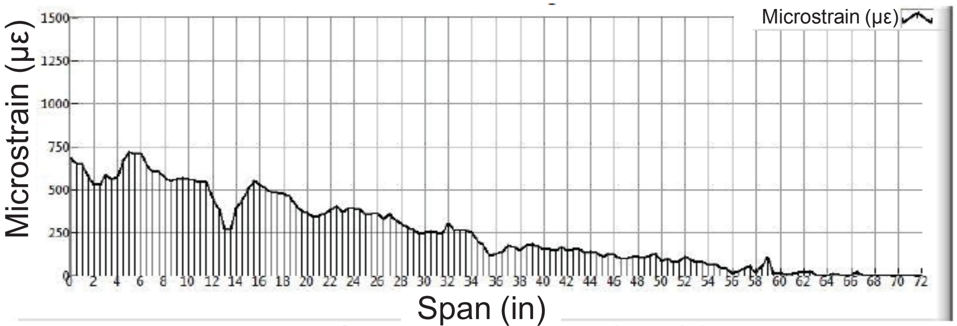




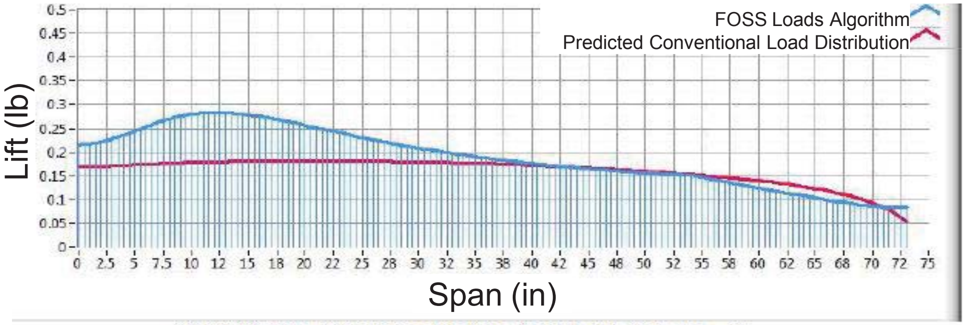
Redistributed lift configuration



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

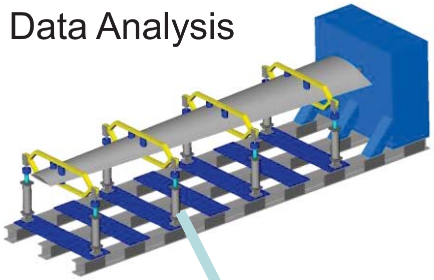
Distributed Loads Technology Roadmap

Aviation

CIF FY16

Autonomously Piloted Vehicle 3 (APV3)

AFRC FLL Test Execution and Data Analysis



IKHANA Flight Demonstration

High Aspect Ratio Wing FLL Ground Test

FY 2015

FY 2016

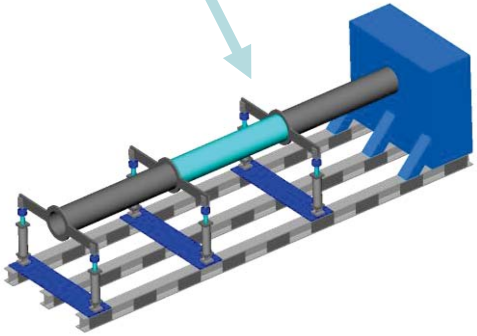
FY 2017

FY 2018

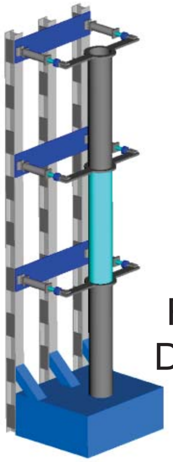
FY 2019

Space

CIF FY17



Sounding Rocket FLL Loads and Modal Test



Sounding Rocket Flight Demonstration

Bridging the Gap Between Aeronautics and Space

FOSS for High Frequency Launch Vehicle Applications

HyFOSS for High Frequency Launch Vehicle Applications

Purpose

- **Evaluate, identify, and demonstrate enhancements to AFRC's FOSS System to gather high frequency loads & dynamics data**
- **Determine feasibility of replacing accelerometers with FOSS sensors**

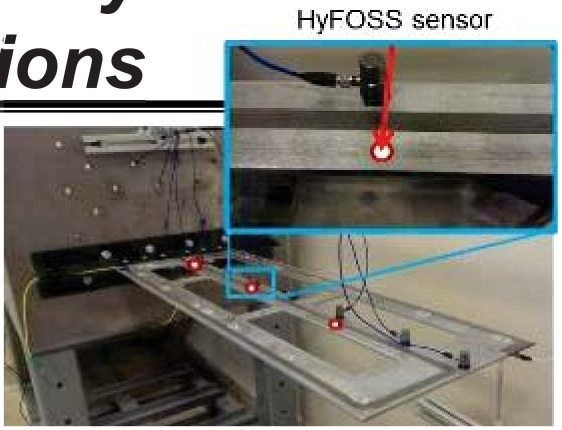
Innovation

- **Developed novel single hybrid interrogation scheme that gleans the benefits of two different FBG sensing technologies, WDM and OFDR, in one small system:**
    - WDM acquires FBG measurements at higher speed (35kHz) and lower density (~80/fiber)
    - OFDR acquires higher density FBG measurements (2000/fiber) and lower speed (100Hz)
- **A single small system can be used to sample a large number (16000) measurements at 0.25 in spatial resolution at 100 Hz and sample a small number (80) of high dynamic strains at 5 Khz**

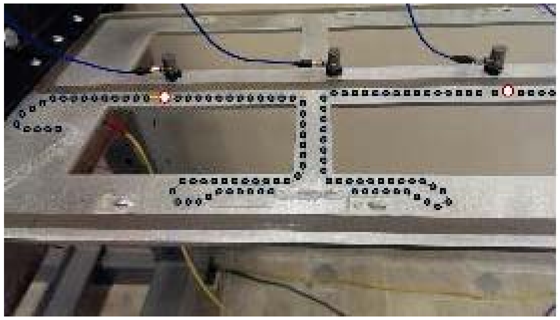
Results

- **Conducted impact testing / modal surveys to 525 Hz; obtained good correlation between FOSS derived accels and accelerometers, thus demonstrating feasibility**
- **Patent pending**

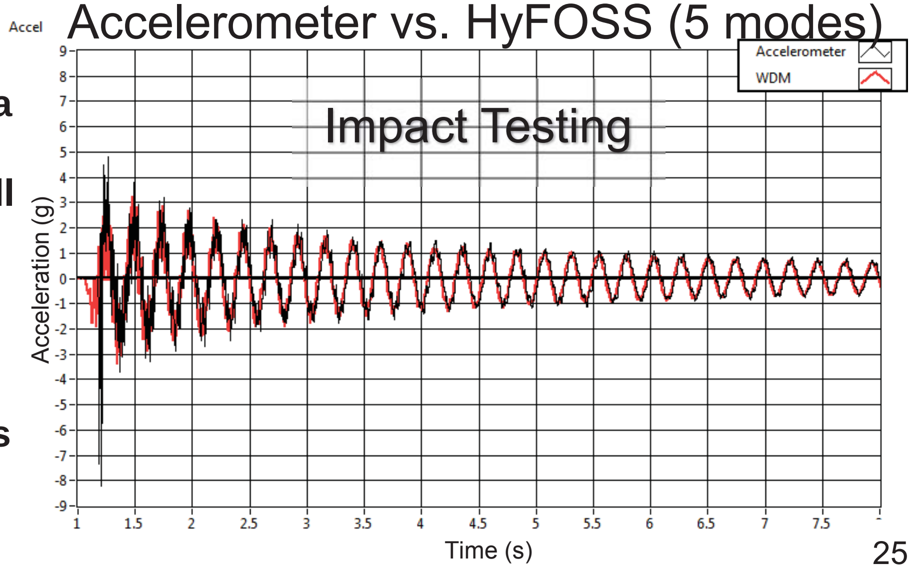
Test Set-up



HyFOSS Sensor Installation



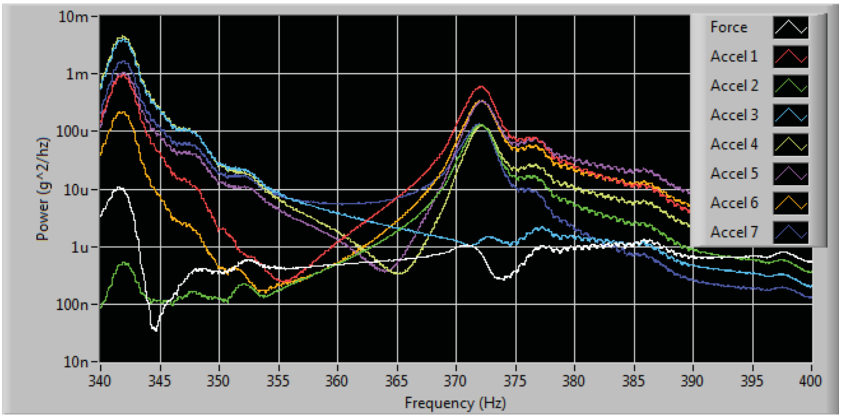
Accelerometer vs. HyFOSS (5 modes)

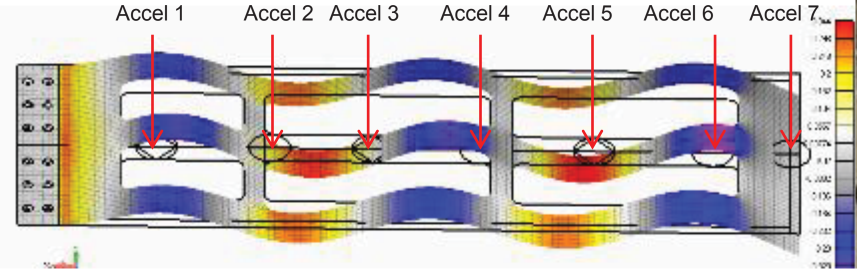


HyFOSS, Frequency Sweep Vibration Testing

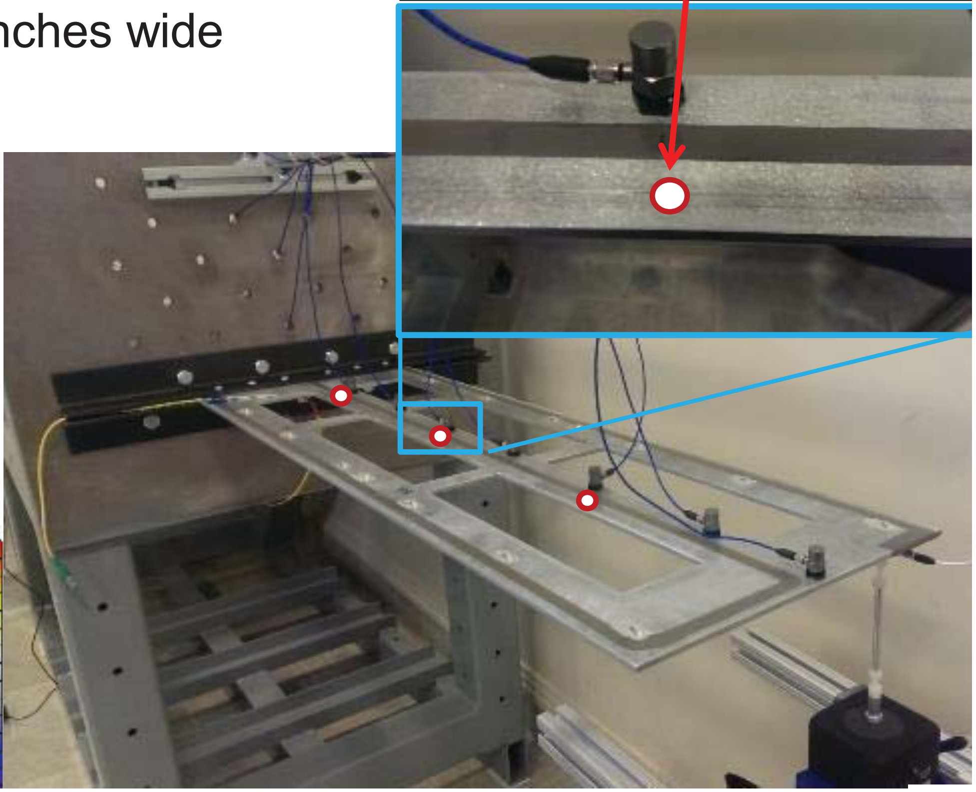
Experimental setup

- 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

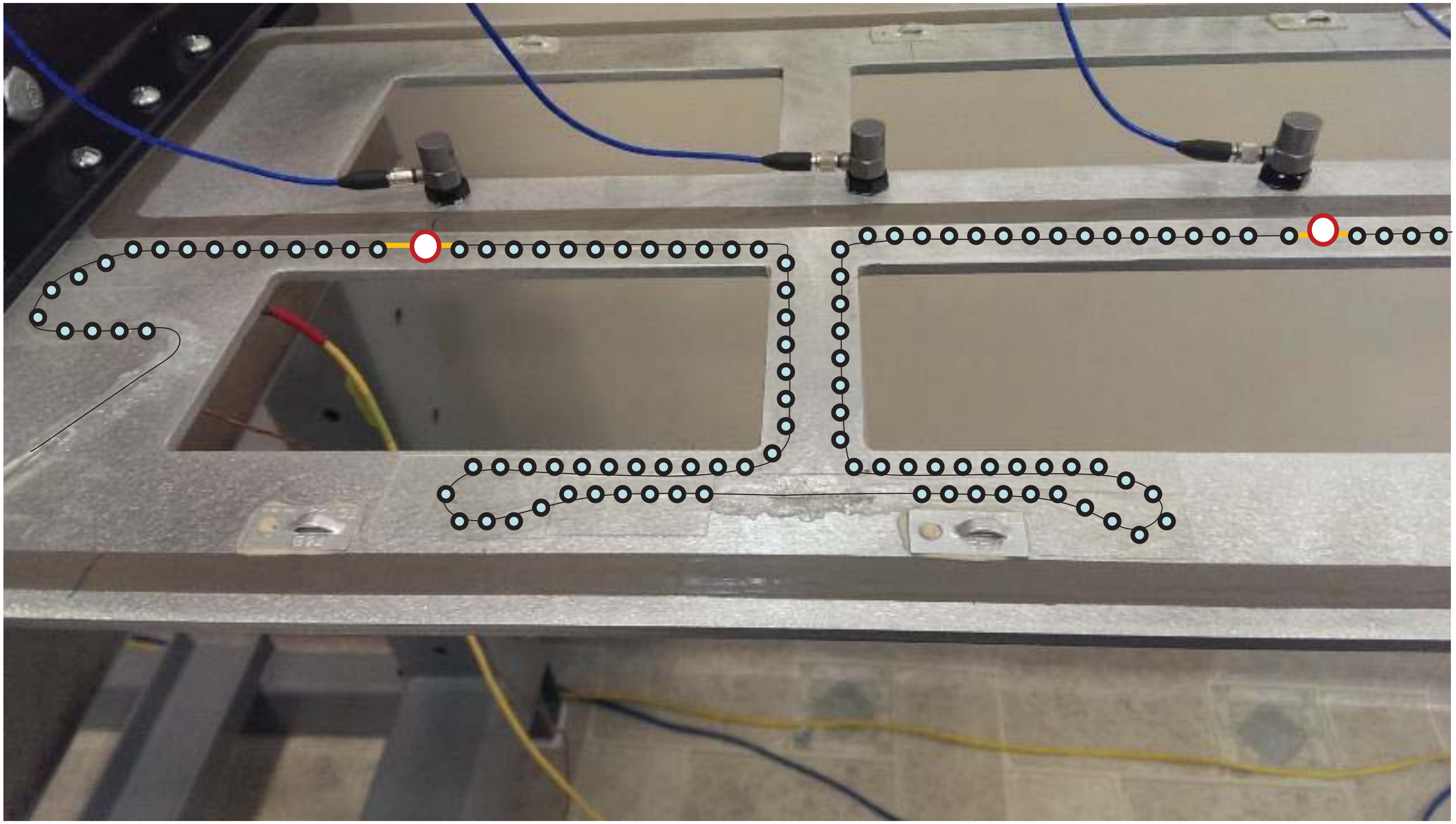




WDM / High Speed Fiber Optic Sensor



HyFOSS Sensor Installation

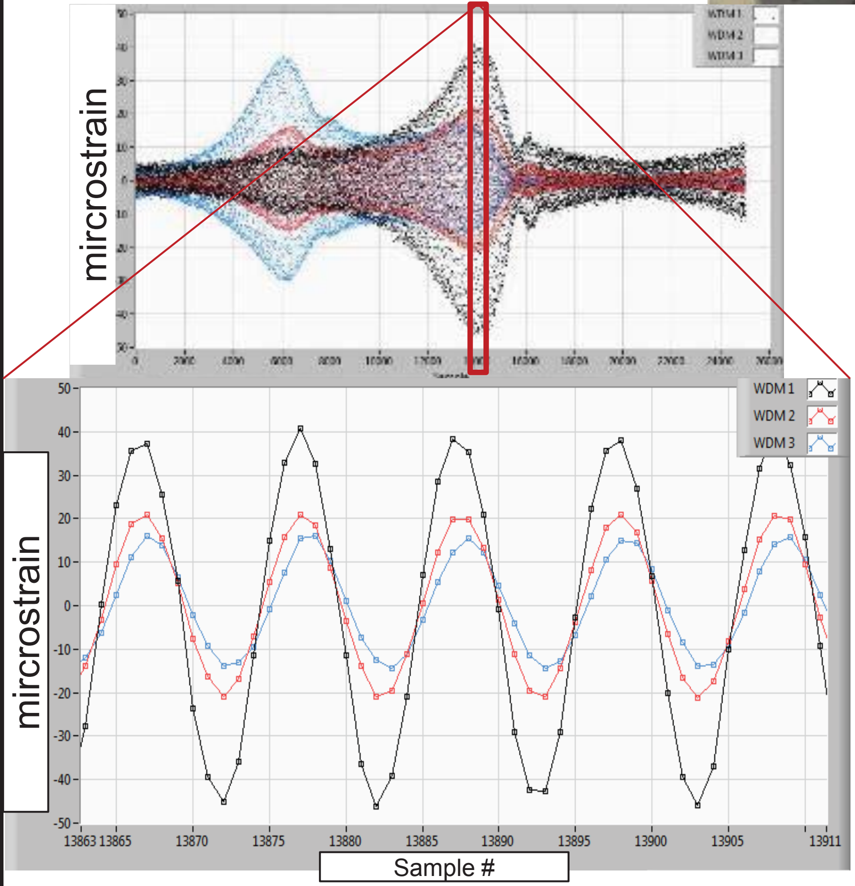


● - 100 Hz (OFDR)

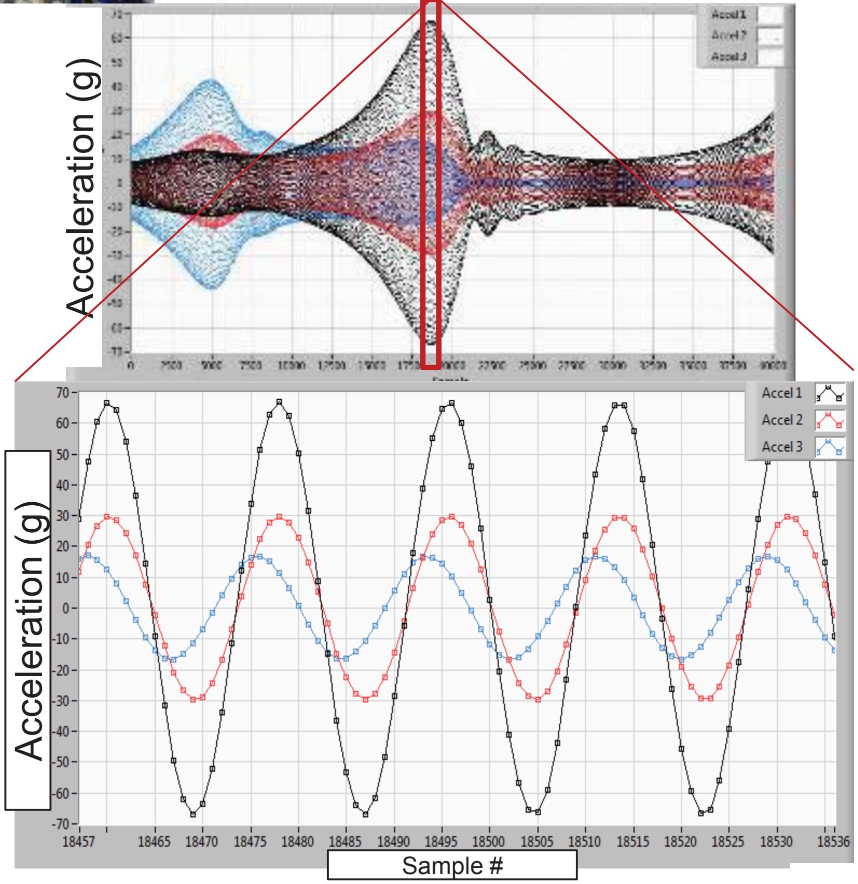
○ - 5,000 Hz (WDM)

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

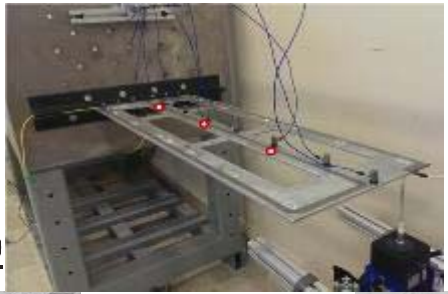
High Speed Fiber Optics (5 kHz)



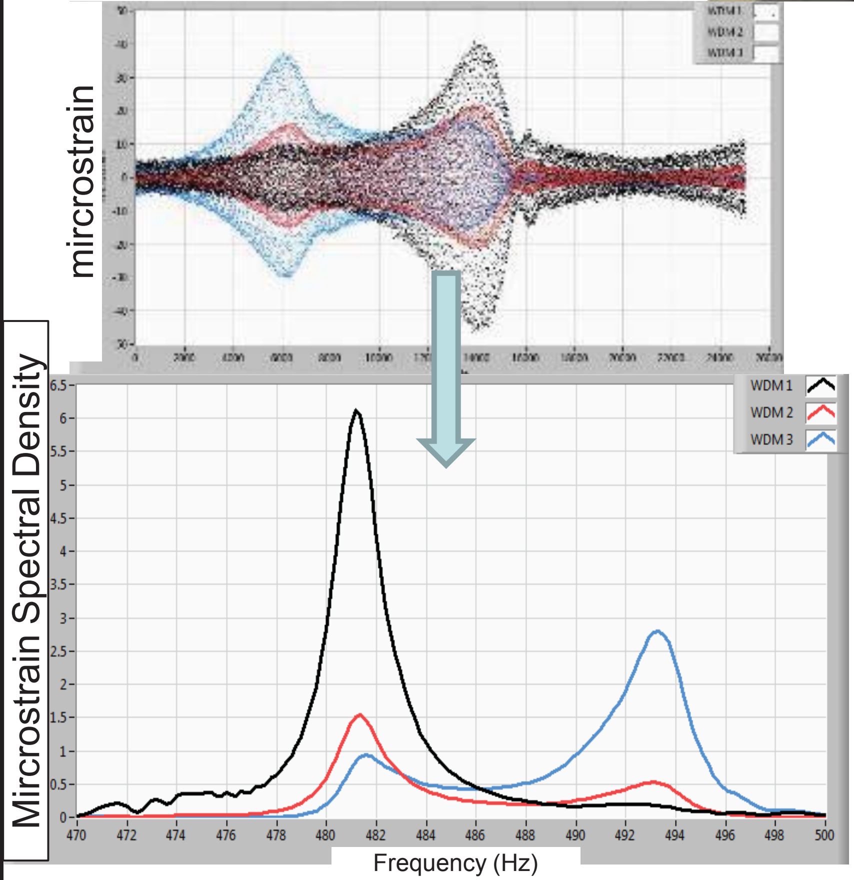
Accelerometers (8 kHz)



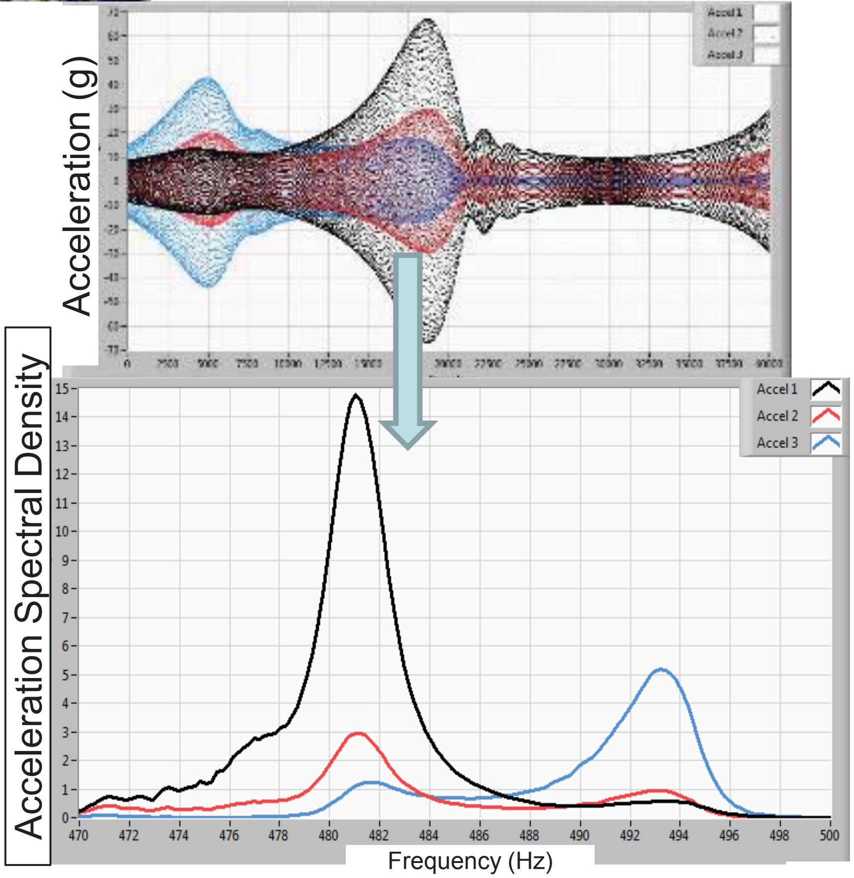
HyFOSS Plate – Fiber Optics & Accelerometer Power Spectral Density (475 Hz to 525 Hz)



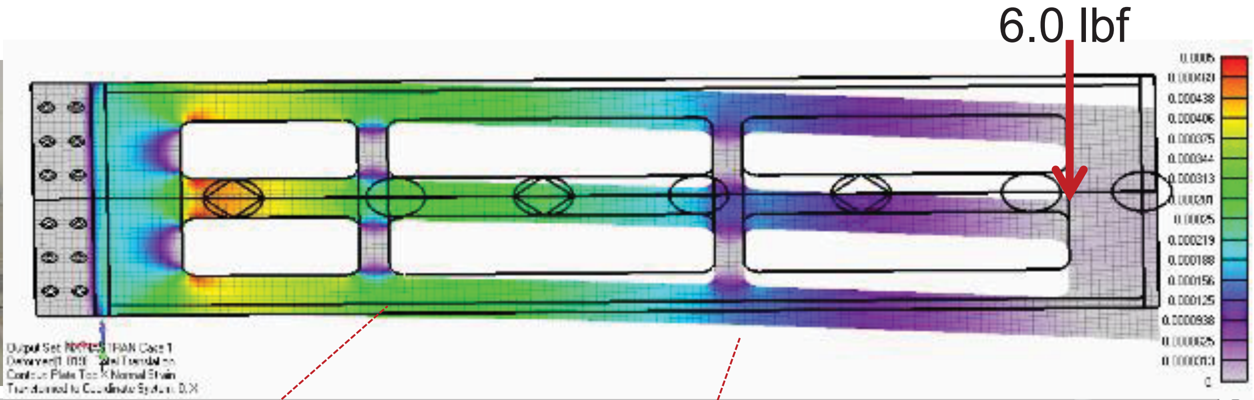
High Speed Fiber Optics (5 kHz)

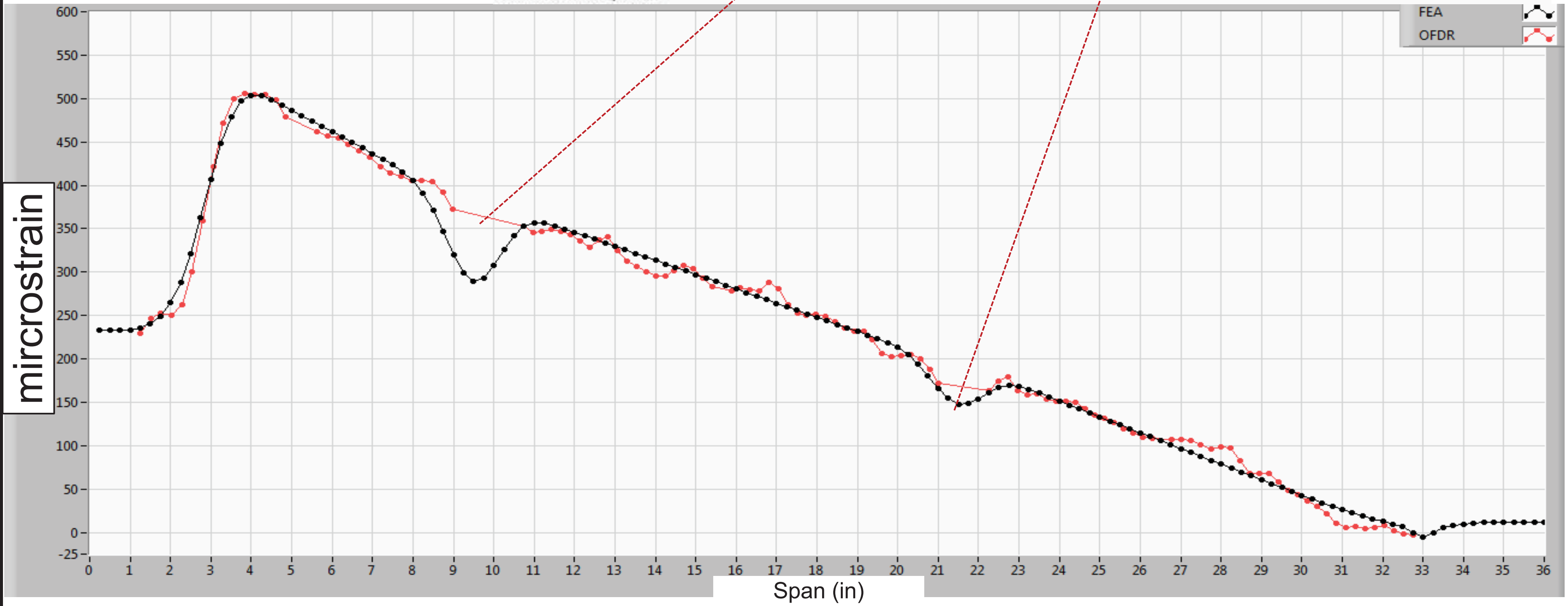


Accelerometers (8 kHz)

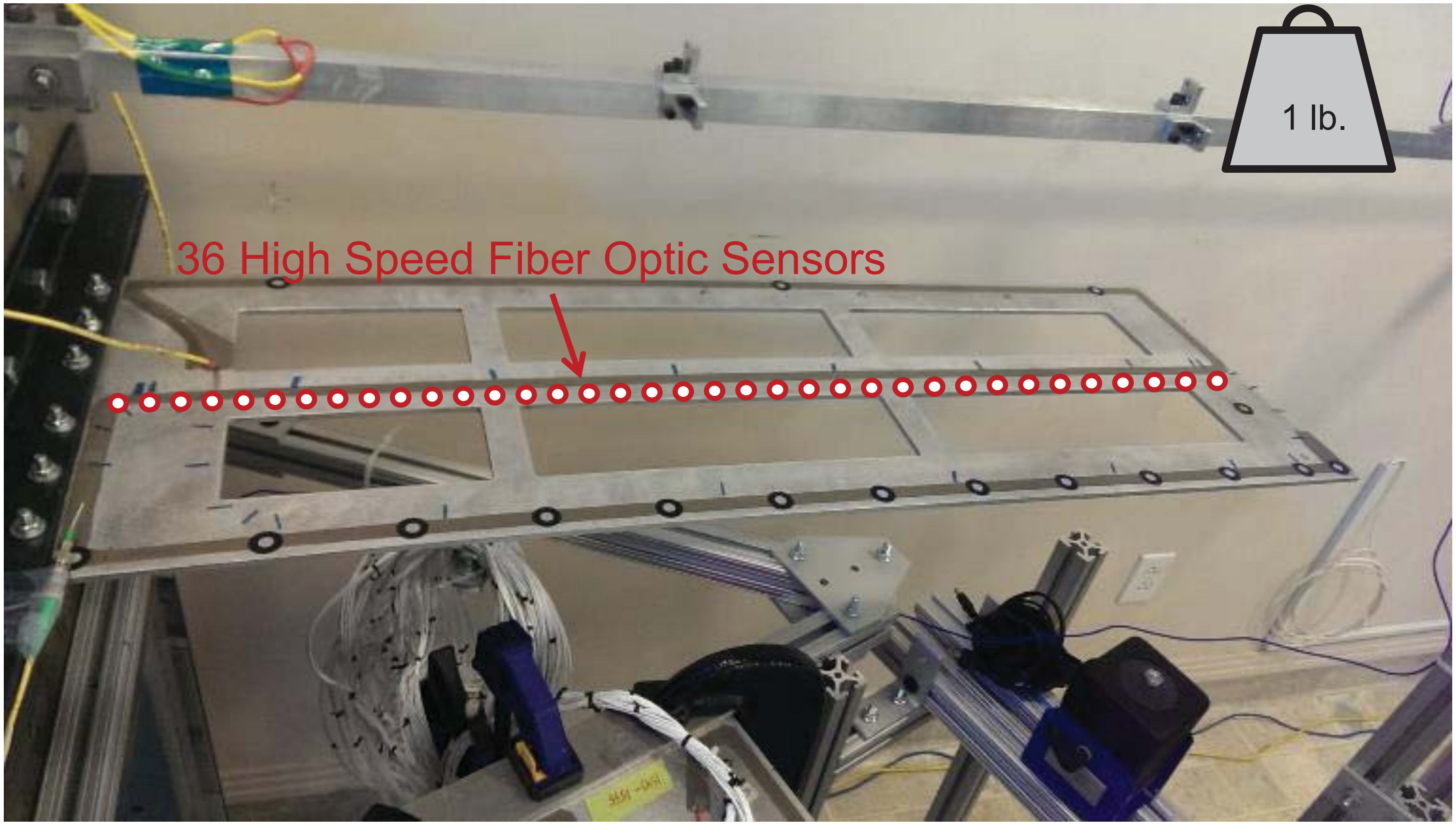


Finite Element Output & 100 Hz Fiber Optic Sensors



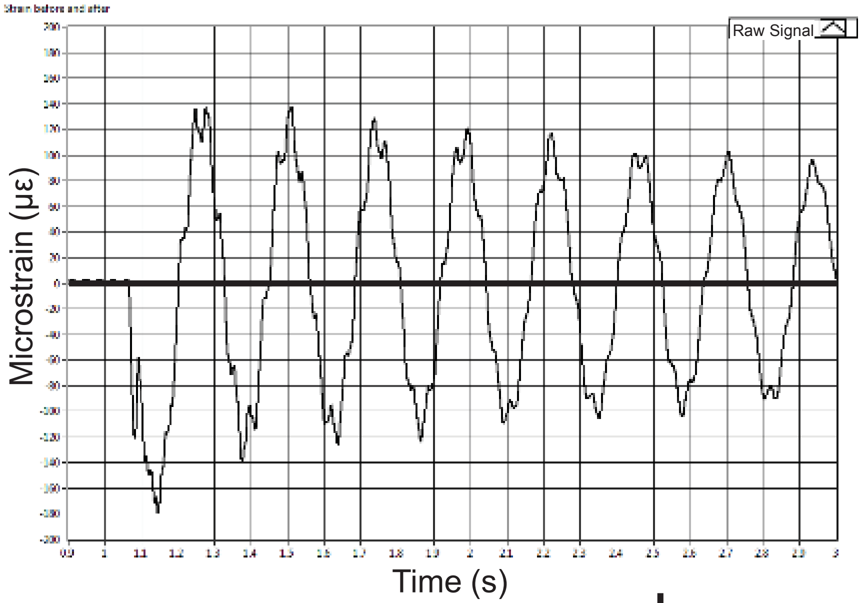


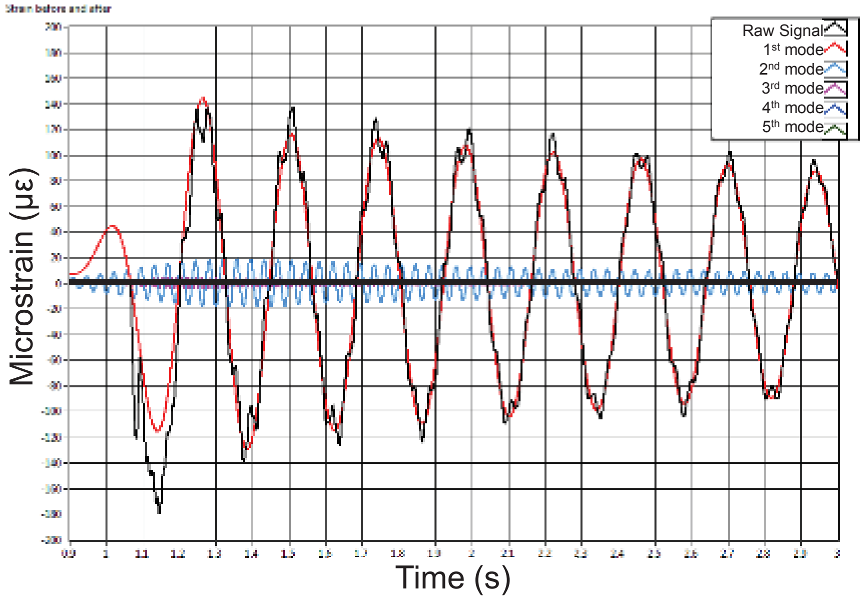
Dedicated High Speed Testing, Impact Test

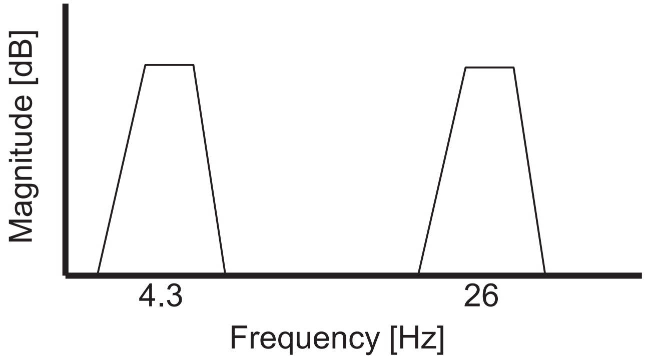


Impact test, Strain Data time history

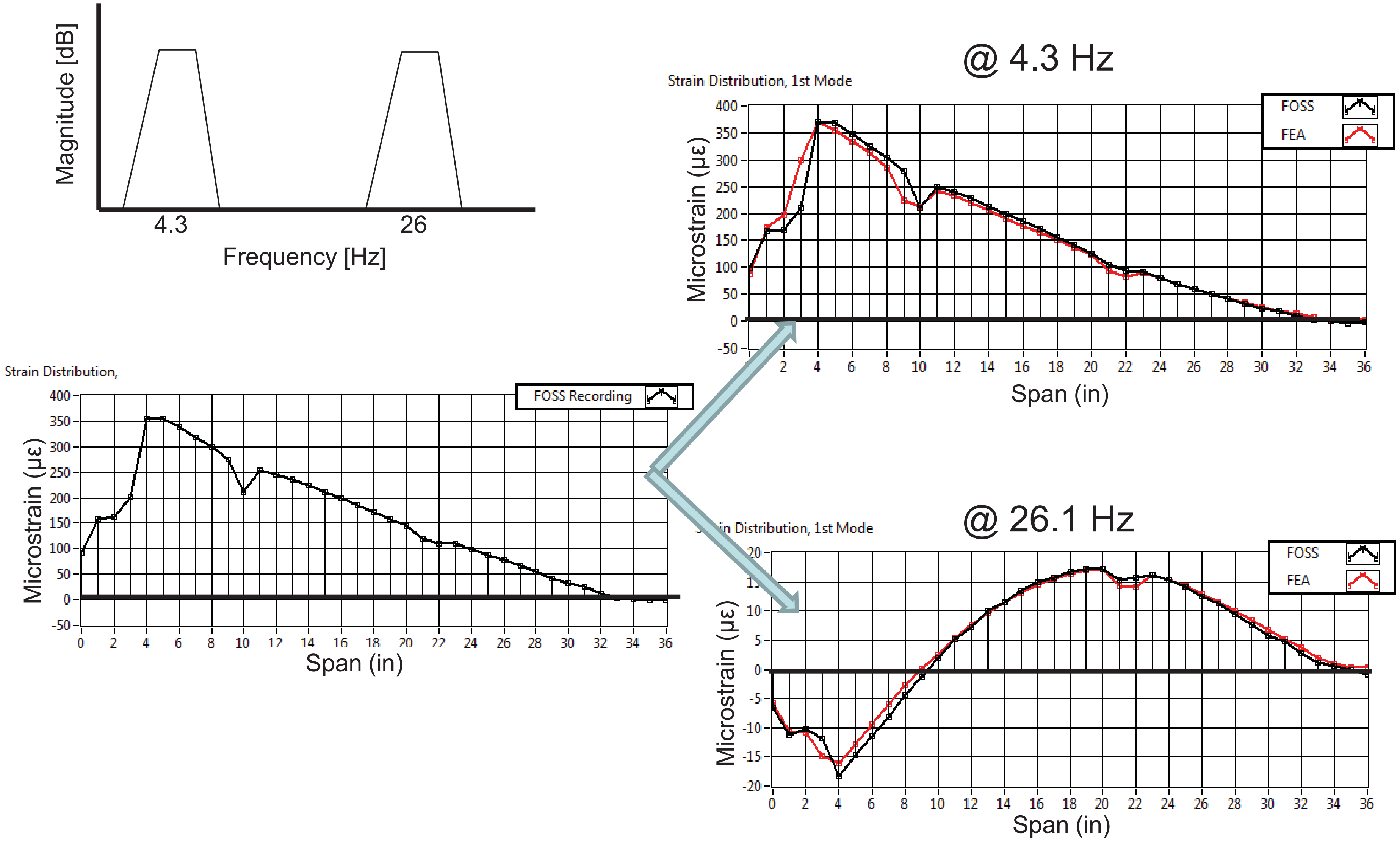
Raw → Filtered







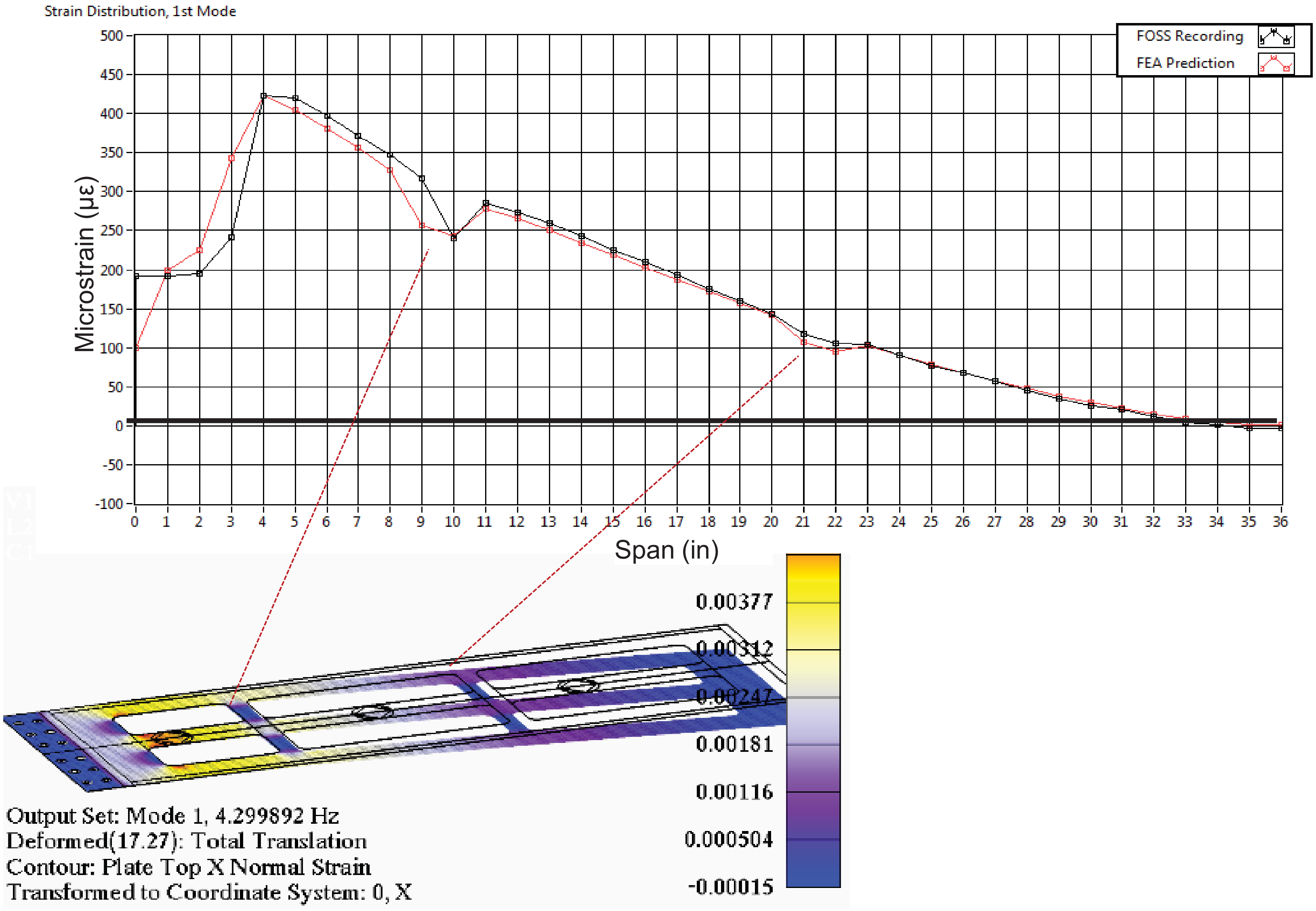
Isolating Mode Shapes



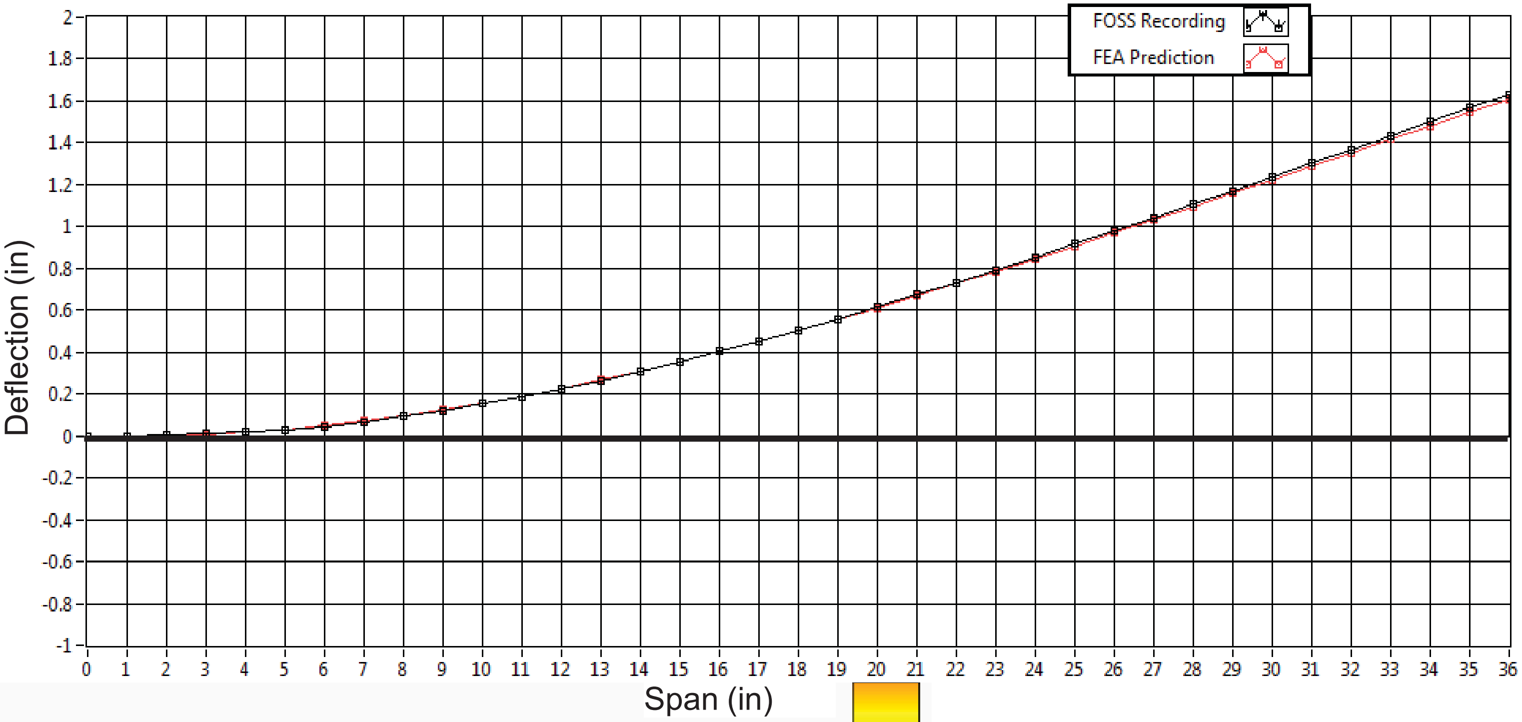
@ 4.3 Hz

@ 26.1 Hz

1st mode strain distribution (4 Hz)

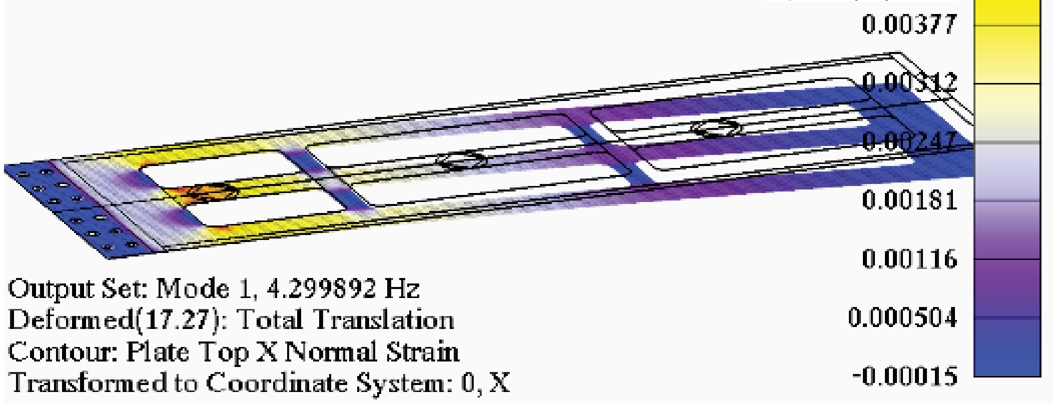


1^{st} mode deflection comparisons (4 Hz)



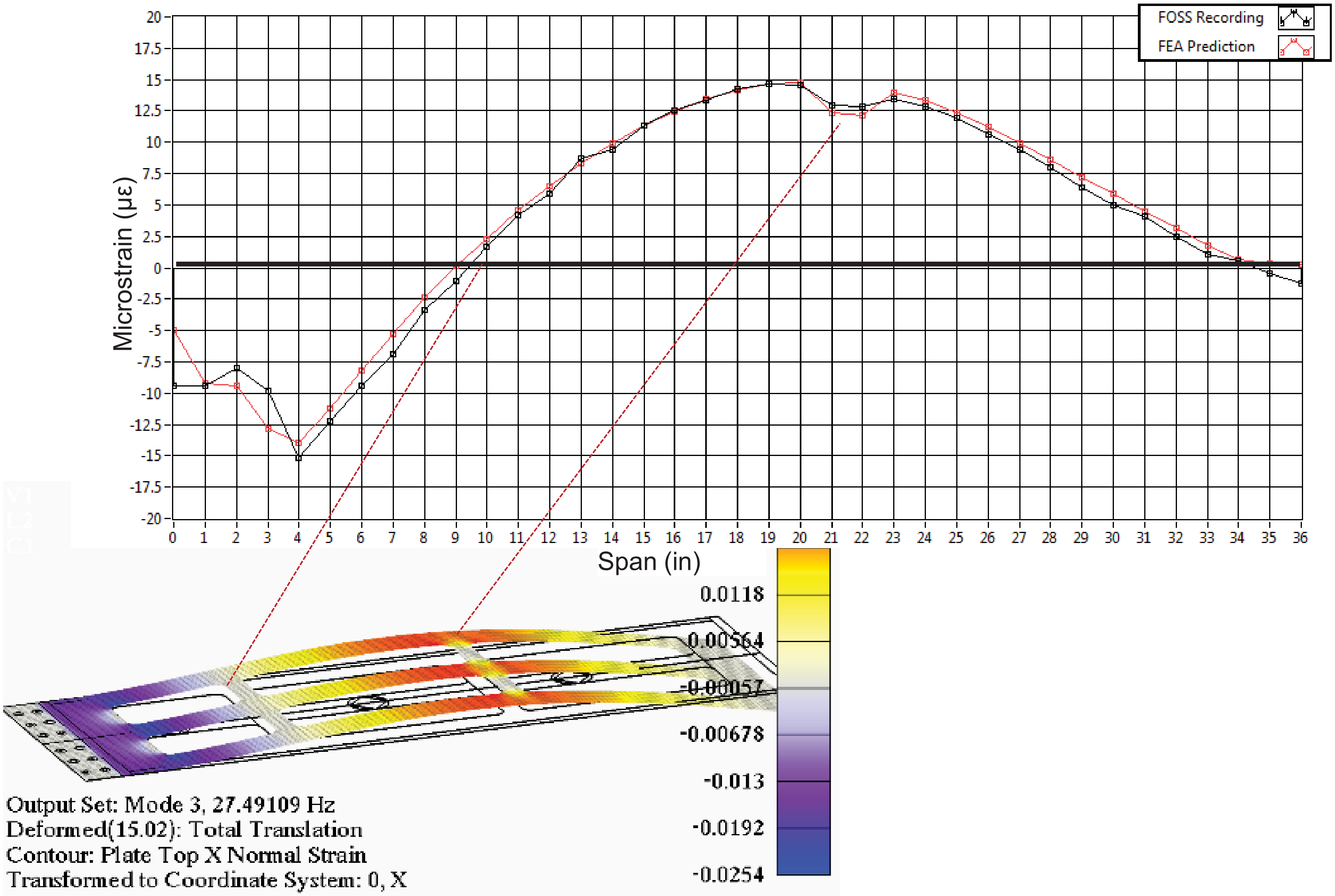
$\approx 2.62g$

$\approx 2.62g$



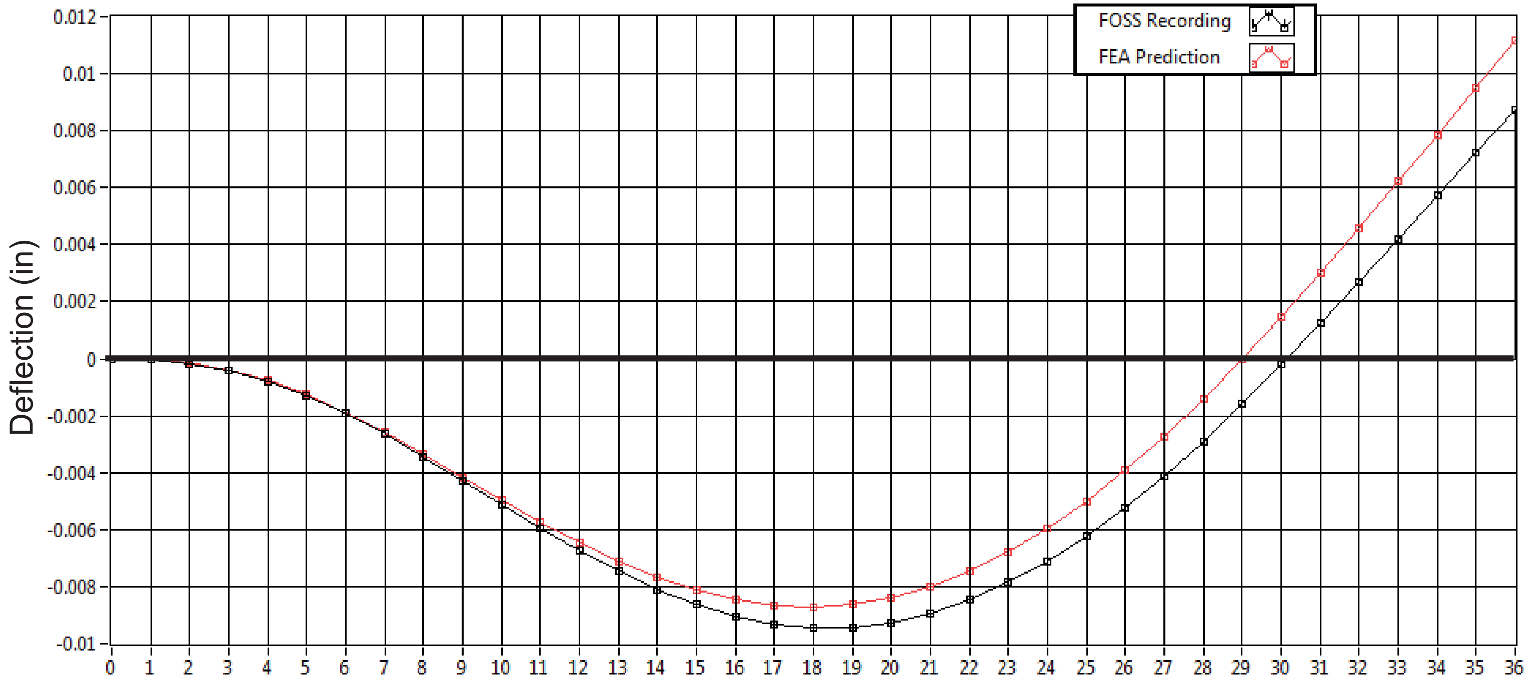
Output Set: Mode 1, 4.299892 Hz
Deformed(17.27): Total Translation
Contour: Plate Top X Normal Strain
Transformed to Coordinate System: 0, X

2nd mode strain distribution (26.5 Hz)



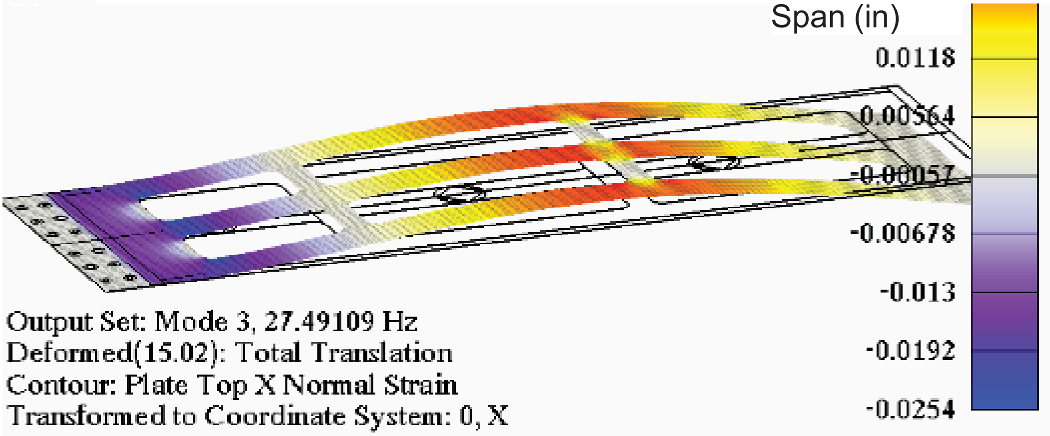
Output Set: Mode 3, 27.49109 Hz
Deformed(15.02): Total Translation
Contour: Plate Top X Normal Strain
Transformed to Coordinate System: 0, X

2nd mode deflection comparisons (26.5 Hz)



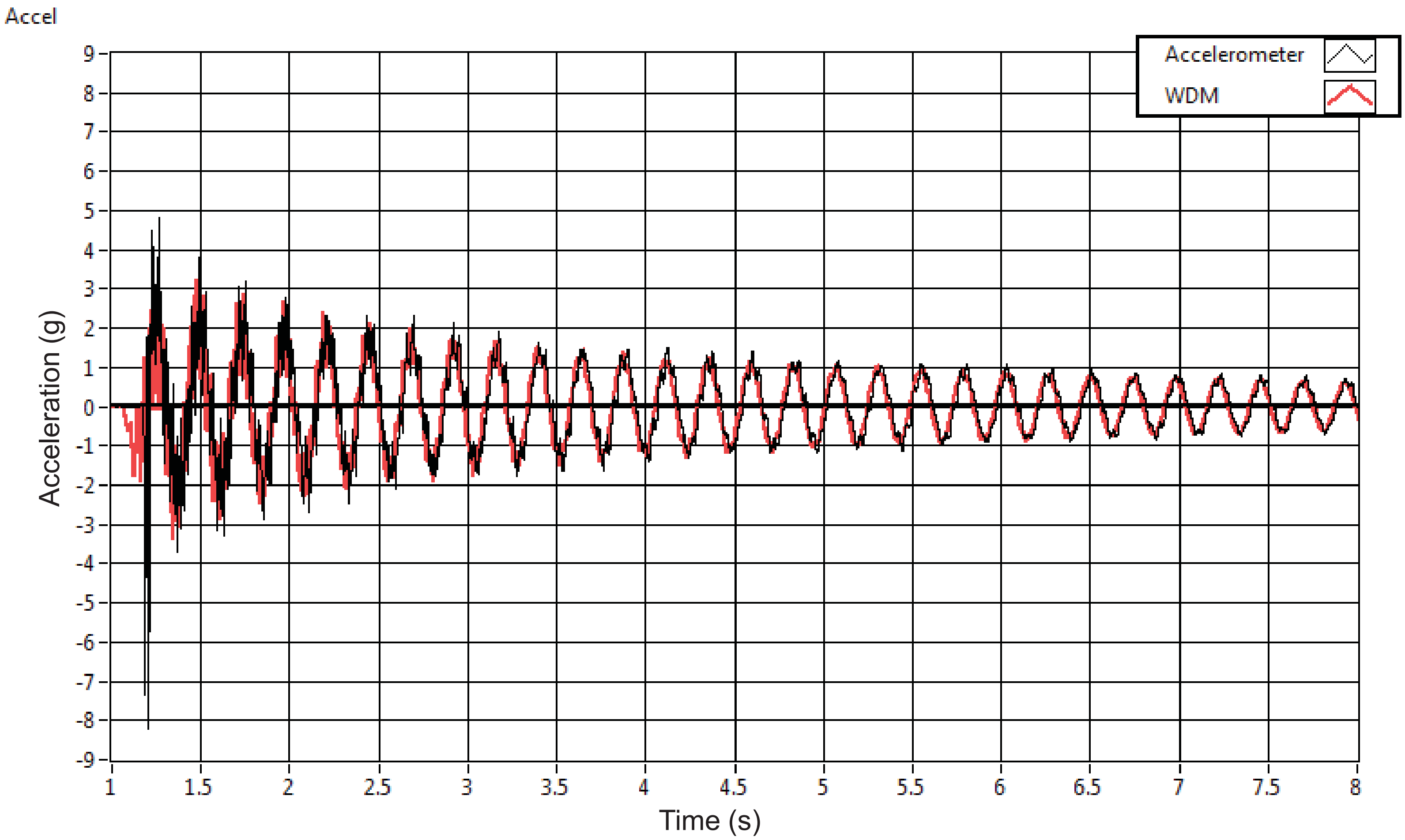
$\approx 0.79g$

$\approx 0.64g$



Output Set: Mode 3, 27.49109 Hz
Deformed(15.02): Total Translation
Contour: Plate Top X Normal Strain
Transformed to Coordinate System: 0, X

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



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

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

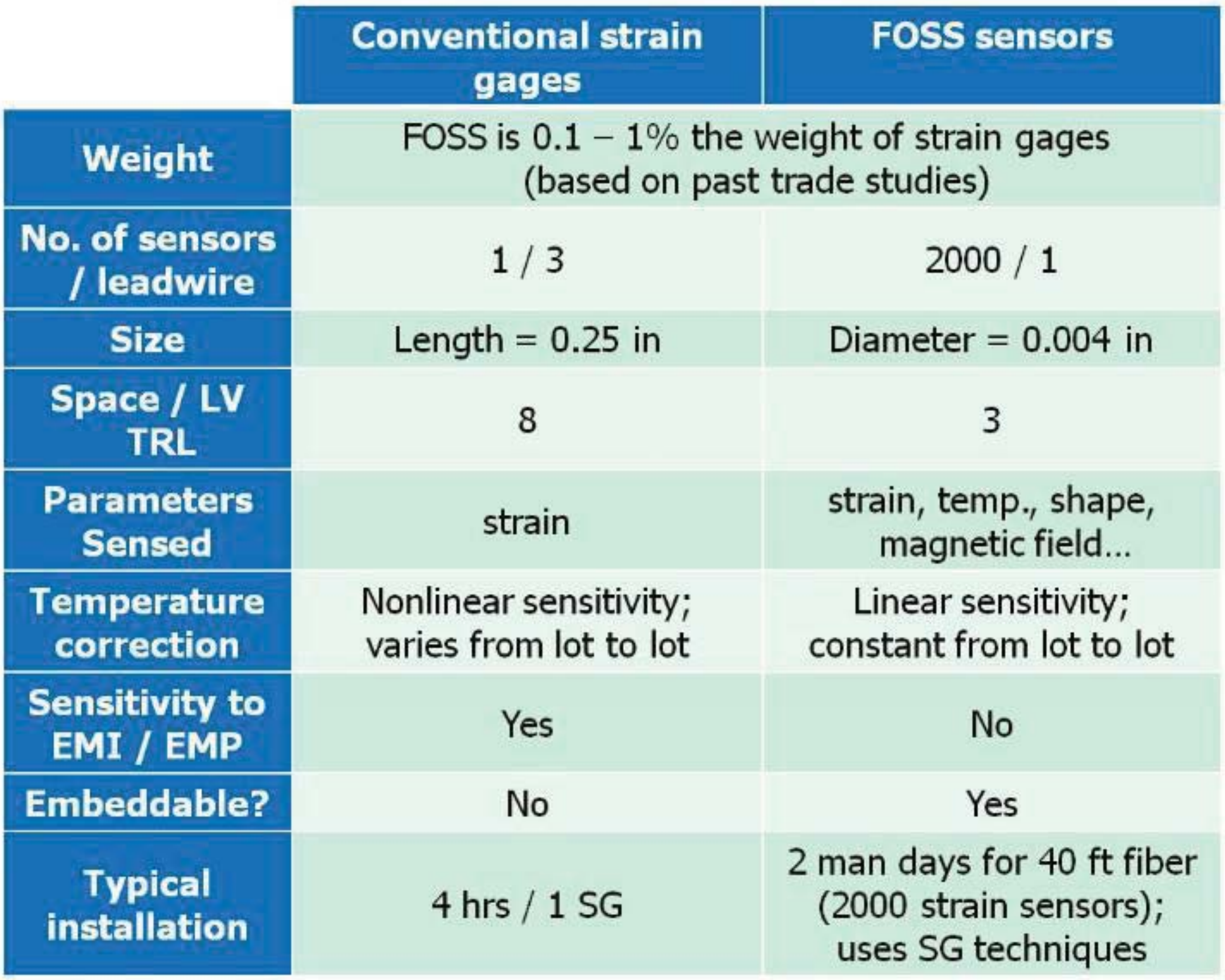
$$\ddot{x} = -\omega_{n1}^2 \cdot A_1 \cdot sin(\omega_{n1}t + \phi_1) - \omega_{n2}^2 \cdot A_2 \cdot sin(\omega_{n2}t + \phi_2)\ldots$$

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***
- ***LSP has funded studies to explore FOSS potential for high frequency launch vehicle applications***
- ***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)
- ***Conducted impact testing / modal surveys to 525 Hz***
- ***Obtained good correlation between FOSS derived accels and accelerometer measurements, thus demonstrating feasibility***
- ***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***

Backup Charts

FOSS State of the Art (SOA) Comparison

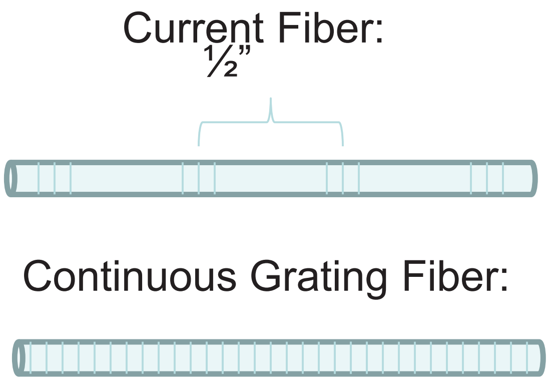


	Conventional strain gages	FOSS sensors
Weight	FOSS is 0.1 – 1% the weight of strain gages (based on past trade studies)	
No. of sensors / leadwire	1 / 3	2000 / 1
Size	Length = 0.25 in	Diameter = 0.004 in
Space / LV TRL	8	3
Parameters Sensed	strain	strain, temp., shape, magnetic field…
Temperature correction	Nonlinear sensitivity; varies from lot to lot	Linear sensitivity; constant from lot to lot
Sensitivity to EMI / EMP	Yes	No
Embeddable?	No	Yes
Typical installation	4 hrs / 1 SG	2 man days for 40 ft fiber (2000 strain sensors); uses SG techniques

Continuous Grating Fiber

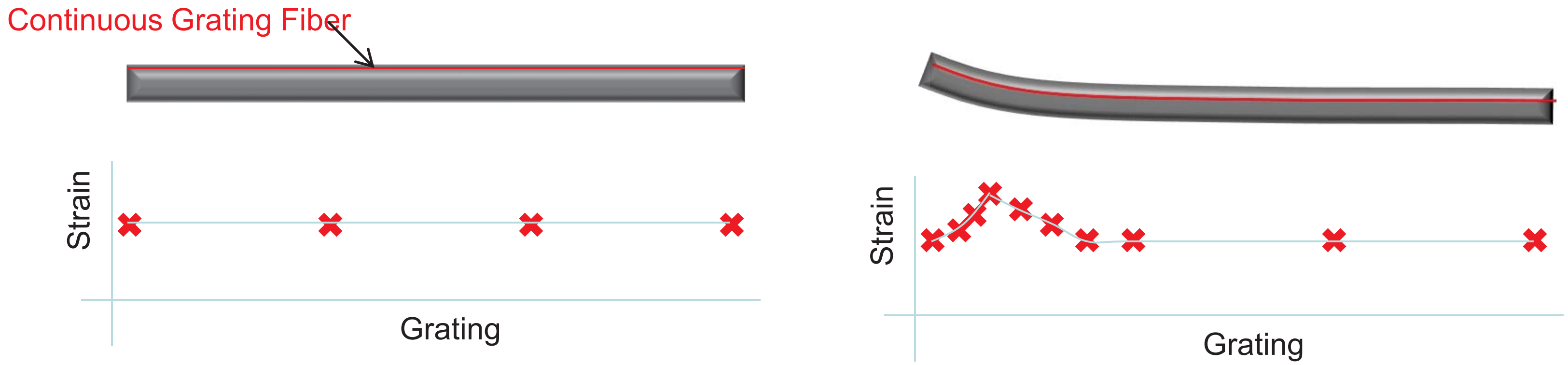
Technical Advantages

- No separation between measurements
- Allows measurement density as fine as 1/32”
- Laboratory demonstrated
- Fiber Cost: Approx $150/meter



Adaptive Spatial Density Algorithm

- If collected at full capability, data sets would become extremely large
- Algorithm collects only the data necessary to characterize the structure at each instant
  - Measurement density increases at high strain gradients
  - Sensitivity and minimum measurement spacing can be adjusted
- Reduces data analysis and investigation time
- Algorithm has already been developed and demonstrated



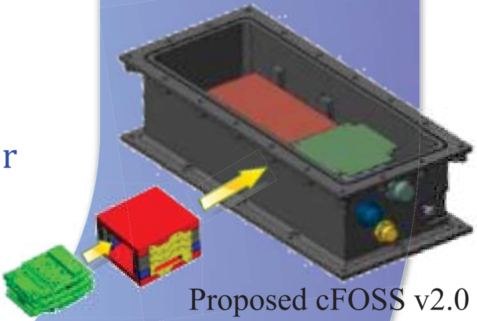
Compact Fiber Optic Sensing System (cFOSS)

- cFOSS designed to meet the demanding requirements of next generation advanced unmanned as well as manned vehicles
- With increased sample rate, decrease power, volume and weight cFOSS will be capable of meeting small to large scale vehicle health monitoring requirements
- cFOSS capable of sampling multiple fibers simultaneously up to 100Hz, producing 1000's of measurements at ¼" intervals.
- A lighter weight convection cooled version(cFOSS v1.0@5.8lbs) and a conduction cooled version(cFOSS v2.0) has been developed to meet the needs of a wide range of operating environments.

Accomplishments

- Flight demonstrated cFOSS v1.0 onboard UAV
- Completed design and fabrication of components for cFOSS v2.0 ready for system integration
- Collaborating with KSC and Orbital to fly cFOSS v2.0 on an ELV in FY16
- The previous generation FOSS was a 2013 R&D 100 Winner

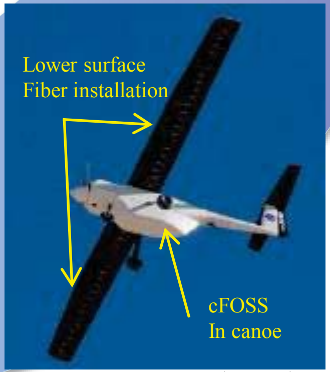

Proposed cFOSS v2.0 on
Antares (KSC,DFRC,Orbital FY13-15)


Proposed cFOSS v2.0
Design (FY13-14)


Original Flight FOSS System
Onboard Global Observer


Proposed cFOSS v1.0
Design


cFOSS v1.0



cFOSS v1.0 onboard
APV-3

cFOSS v1.0 System Specs.

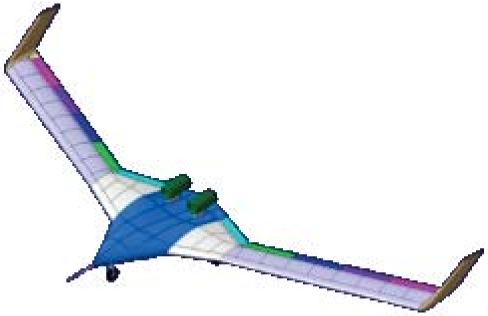
- **Targeted specifications:**

Fiber count:	4
Max Fiber length:	80 ft
Max # sensors/system:	8,000
Max Sample rate:	100 Hz
Power:	50W @ 28Vdc
Weight(w/o enclosure):	~6lbs
Size (w/o enclosure):	3.5 x 5.7 x 12 in
Vibration and Shock(**targeted**):NASA Curve A (DCP-O-018)	
Altitude (w/o enclosure):	15kFt

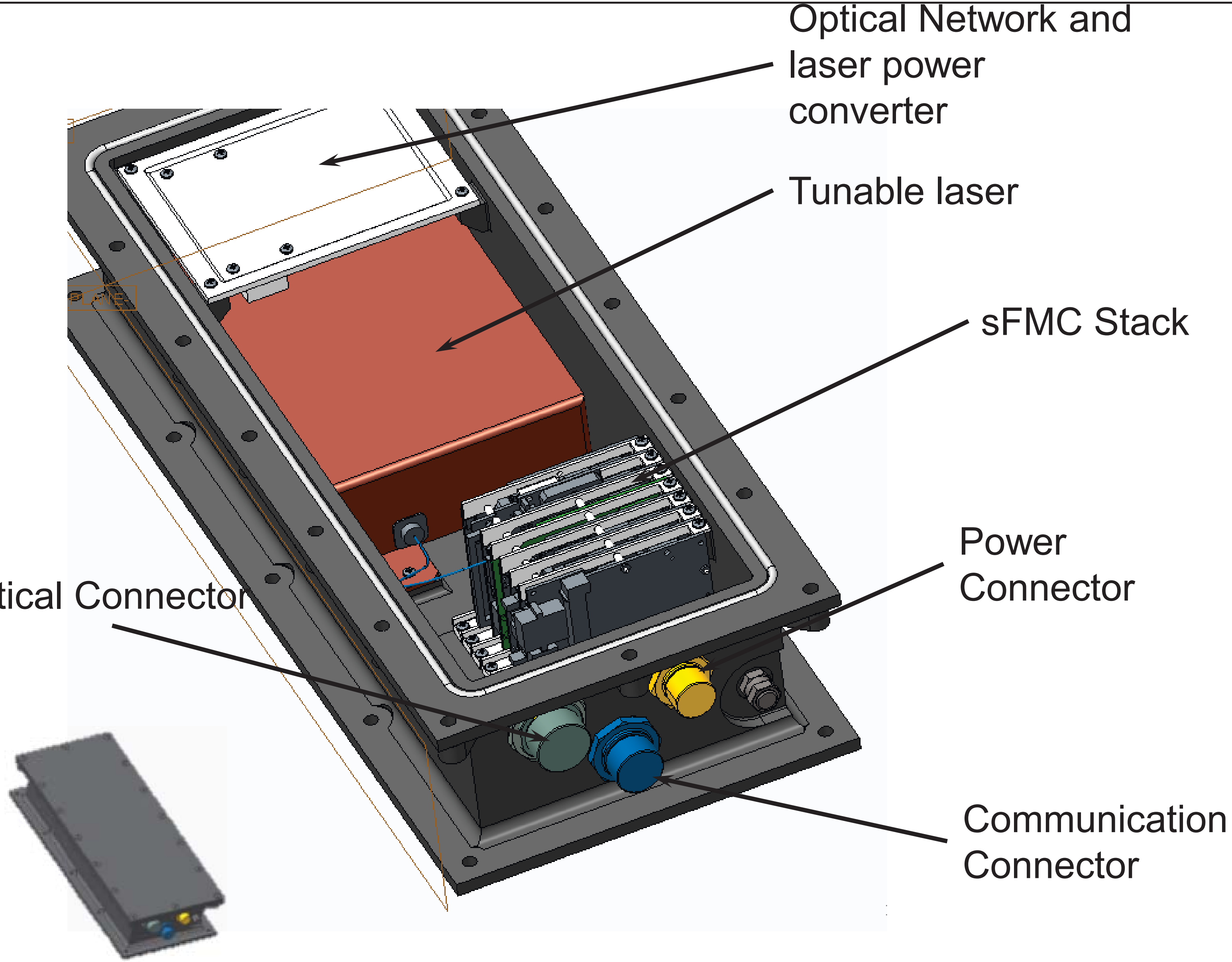
- **Applications:**
  - UAVs
- **Target system cost: $35K**
- **Convection cooled model**

cFOSS v1.0

cFOSS v1.0 onboard APV-3



cFOSS Preliminary Box Design



Optical Network and laser power converter

Tunable laser

sFMC Stack

Power Connector

Optical Connector

Communication Connector