Fiber Optics Sensing System (FOSS) at NASA Armstrong Flight Research Center (AFRC): Summary and Recent Deployments

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3rd Edwards Technical Symposium

Edwards AFS

September 10th, 2018

OUTLINE

- Motivation
- Traditional Strain Gauge vs Fiber Optics Sensors
- Technology overview of Fiber Optics Sensors
- FOSS technology review
- Development of FOSS at NASA
- Capabilities of FOSS
- Recent NASA projects involving FOSS

Sensors in a Human Body

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

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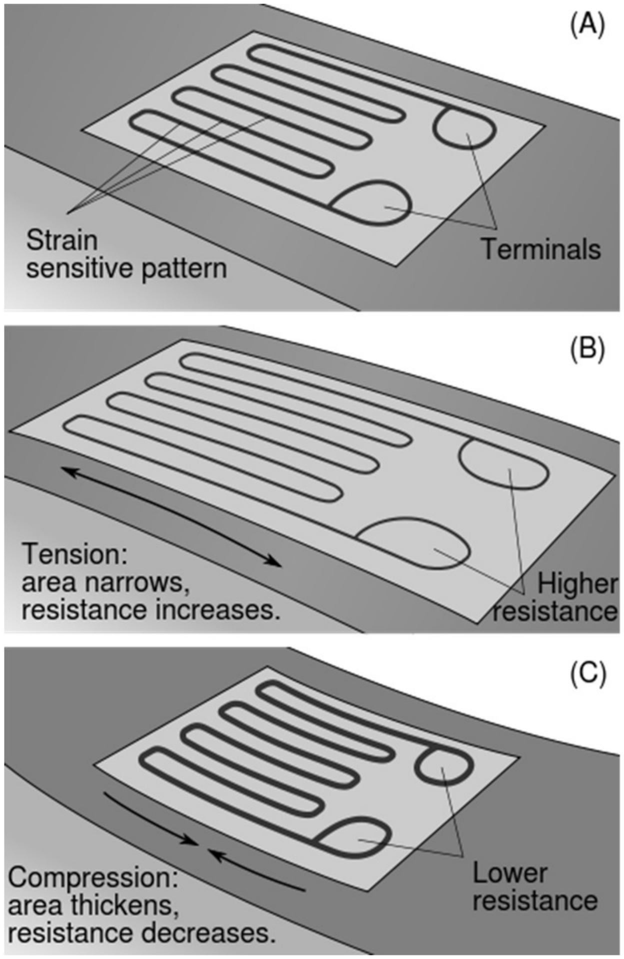
How Traditional Strain gauge works

- Invented by Edward E. Simmons and Arthur C. Ruge in 1938
- As the object is deformed, the foil is deformed, causing its electrical resistance to change
- Strain (ε) = $\frac{\Delta R}{\rho \cdot R_G}$
  - ΔR = change in resistance due to strain change
  - R_G = Initial resistance of gauge
  - ρ = gauge factor



Pros/Cons of Resistive Strain Gauge

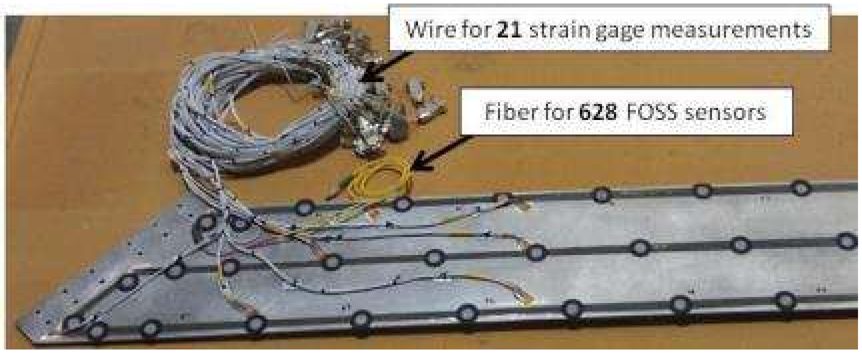
- Advantage
  - Industry Proven
  - High sample rate available (kHz to MHz) for dynamic response
- Disadvantage
  - Each gauge has unique gauge factor
  - No Multiplexing available
  - Susceptible to EMI (Electron-Magnetic Interference)
  - Lead Wire Resistance effect
  - Installation time
  - Temperature Compensation
  - 1 A/D card to interrogate 1 sensor → bulky

NI 9235, NI 9236

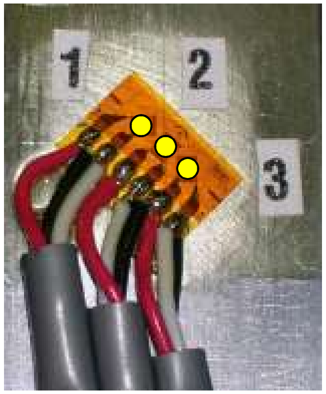
±29.4 mV/V, Quarter-Bridge Strain Gage, 10 kS/s/ch, 8 Ch Mod

Why Fiber Optic Sensors?

One Of These Things (is Not Like The Others)

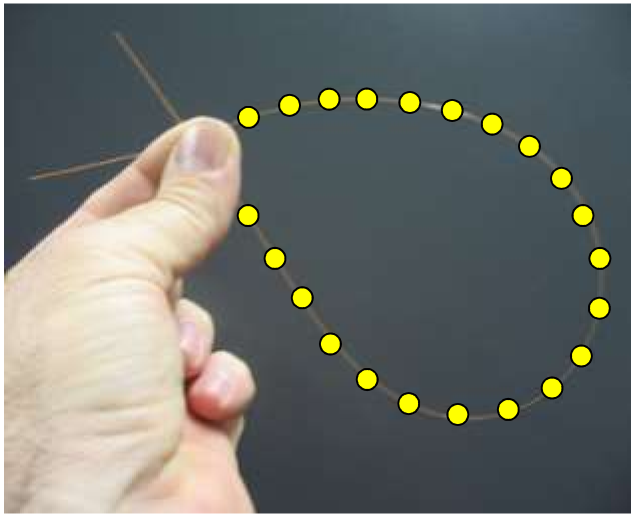


(Heavy)



(Big)

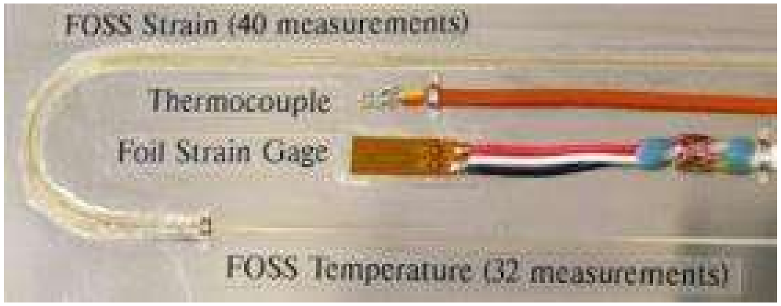
(Hard)



(Light, small, easy)

PROS/CONS OF FIBER OPTICS SENSORS

- Advantage
  - No unique gauge factor
  - Multiplexing available
  - Not Susceptible to EMI
  - No Lead Wire Resistance effect
  - Installation time
  - 1 A/D channel can interrogate hundreds of sensors
- Disadvantage
  - New technology
  - Temperature Compensation also required



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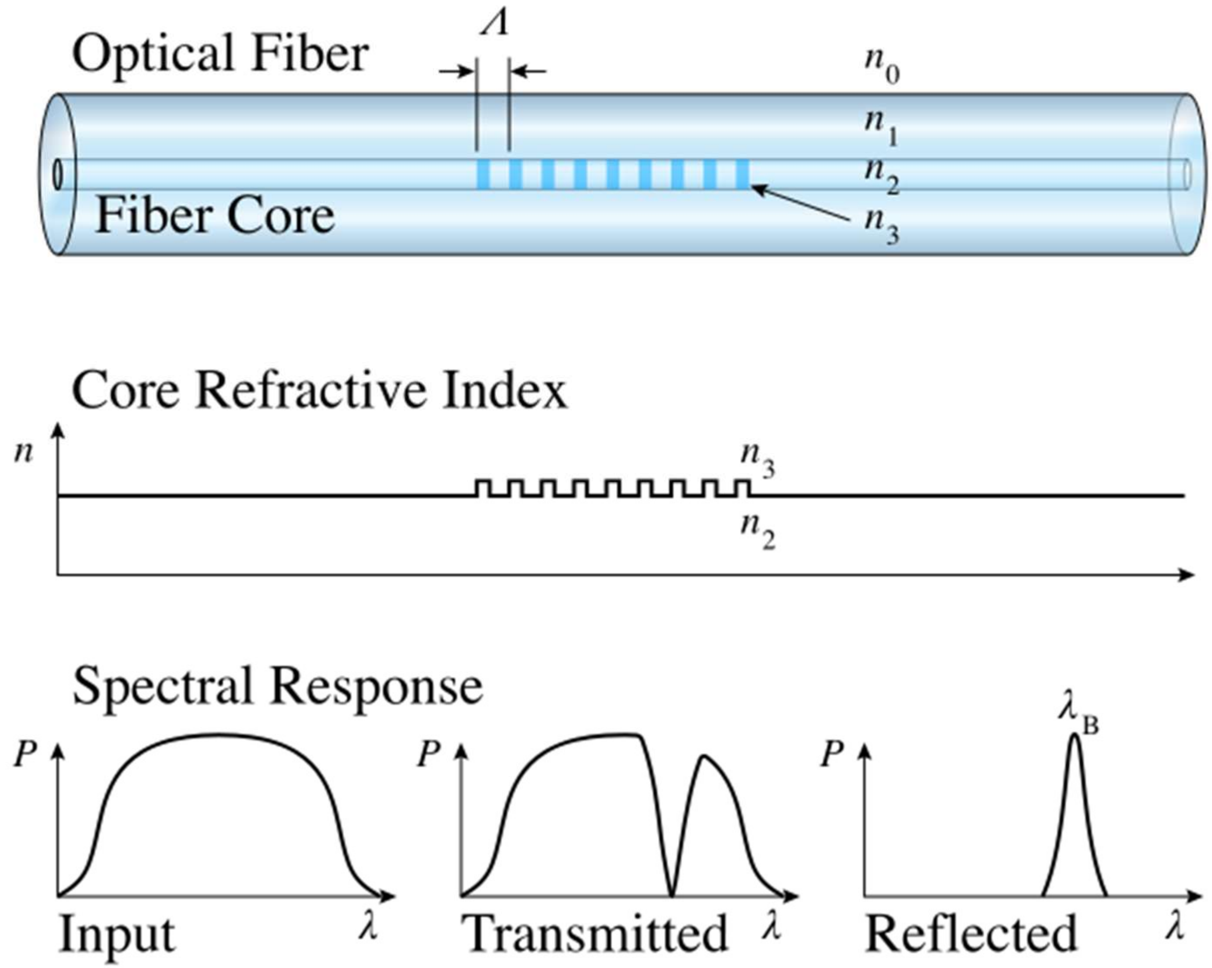
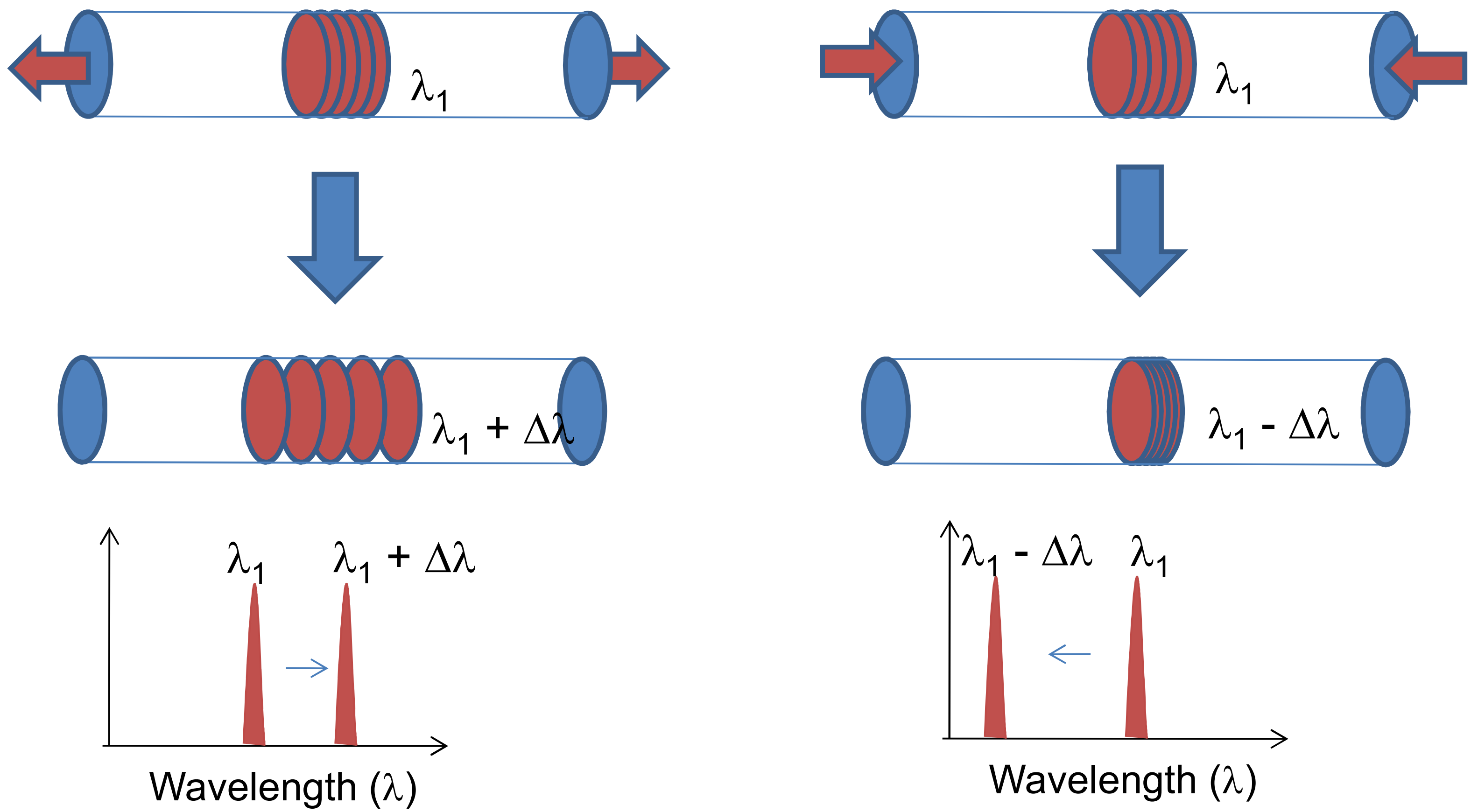
Fiber Sensor – Fiber Bragg Grating (FBG)

- Fiber Reflector that reflects a particular wavelength and transmit all others
- Bragg Wavelength: $\lambda_B = 2 n_e \Lambda$

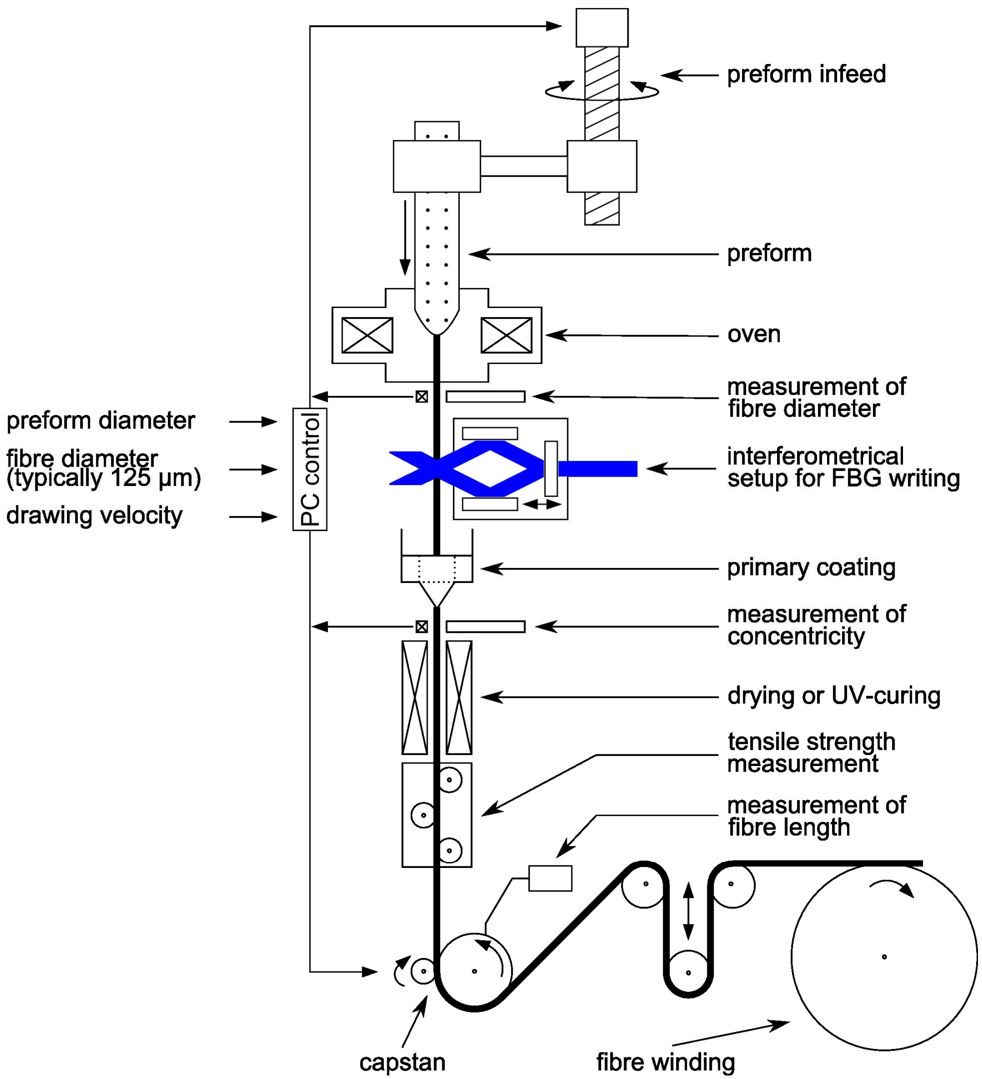


How do FBG sensors works?

- Like an accordion → change in Bragg Wavelength



FBG FABRICATION (DRAW TOWER GRATING)

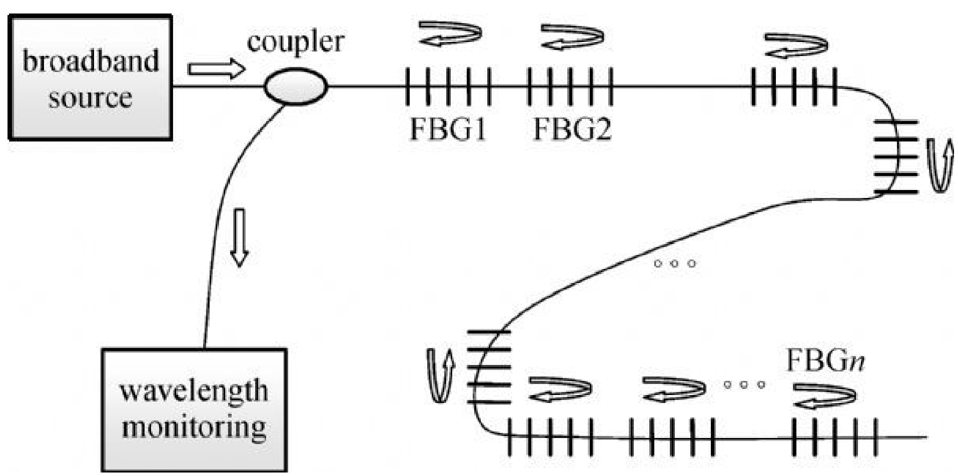


How is Strain/Temperature calculated?

- Similar to Strain Gauge
- Strain (ε) = $\frac{\Delta\lambda_B}{\rho \cdot \lambda_B}$
  - $\Delta\lambda_B$= change in Bragg wavelength due to environmental change
  - λ_B= Initial Bragg wavelength of FBG
  - ρ = strain-optics coefficient

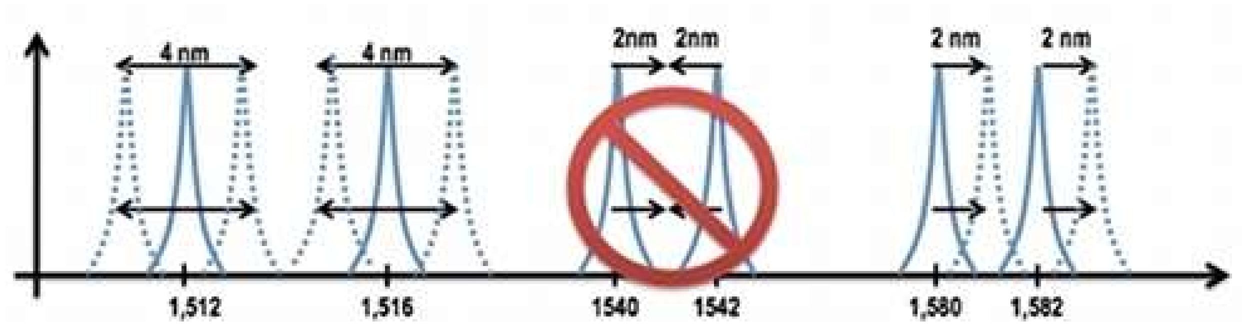
TYPICAL FBG SENSING VIA WAVELENGTH DIVISION MULTIPLEXING (WDM)

- Excitation Source (light source)
  - LED
  - Laser
- Fiber Sensors (FBG)
- Photodetector (A/D)
- Detection Scheme (Optical Spectrum Analyzer)



PRO/CON OF WDM

- Advantage
  - Sensors can be ~km away from interrogator
  - Relative Simple Measurement
  - Commercially Available
  - High Sampling Speed Available (~MHz)
- Disadvantage
  - Location of each sensor matters
  - Each sensors has to have unique wavelength
  - Only ~10 sensor can occupied 1 data channel
    - Aliasing effect
      - When 2 sensors intersects one another

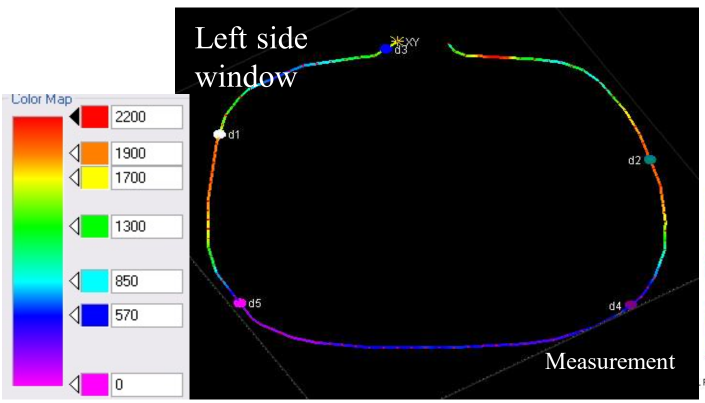


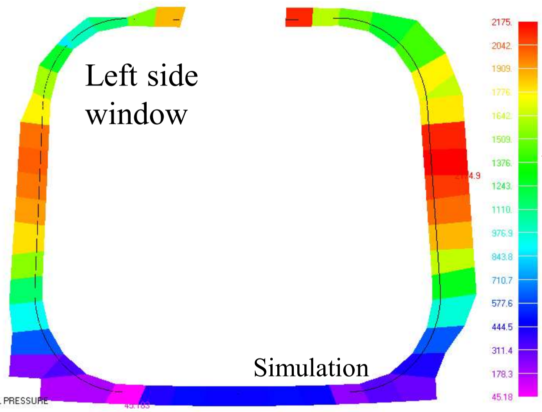
NASA's Unique FBG Interrogation Technique: OFDR

- Optical Frequency Domain Reflectometry (OFDR):
  - Based on laser interferometry
    - Single Longitudinal mode laser needed
  - Involves signal processing
    - Fourier Transform/inverse Fourier Transform
  - Use weak reflectivity FBG
    - Typical WDM FBG's R=80%
    - Typical OFDR FBG's R=0.05%
  - So why use OFDR for sensing instead?
    - Many advantages that WDM can't match

Advantage of OFDR over WDM

- High Spatial Density over WDM-based sensing
  - Up to 1000 FBGs can be multiplexed onto single fiber
  - FEM type of data can be achieved through real-time testing





NASA Composite Crew Module Testing (2011)

- Cost per sensor length is reduce vs WDM-based sensors
  - $60/meter of draw tower made FBG (1/2" per FBG) vs $200 per WDM FBG

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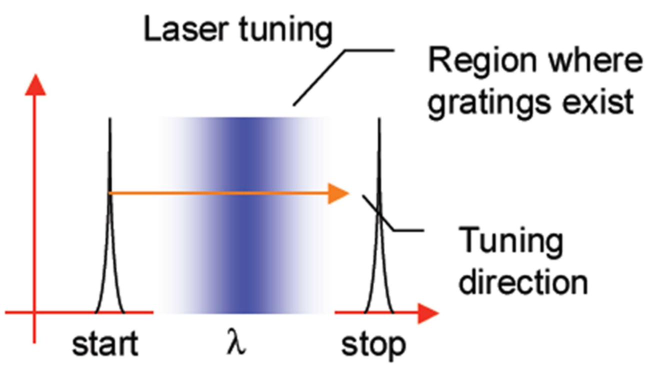
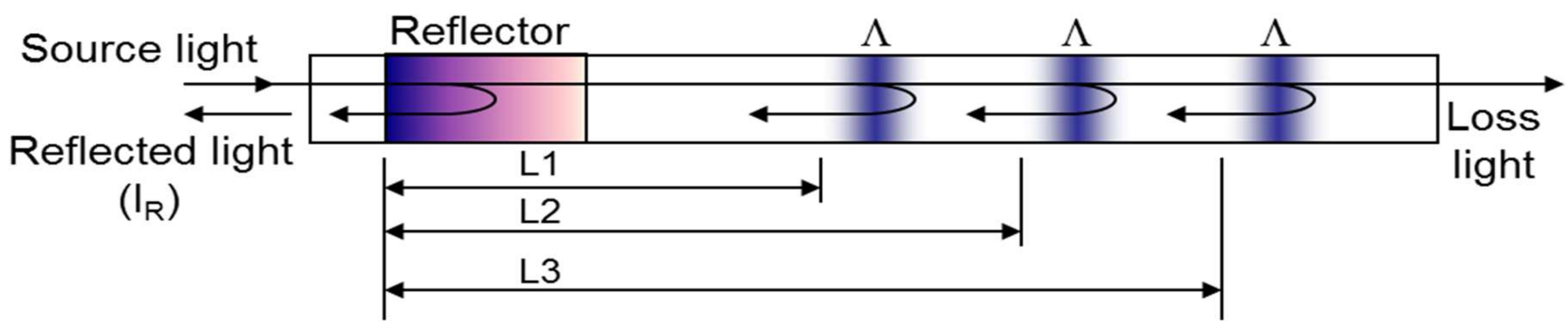
FOSS Grating Modulation Multiplexing Method (Optical Frequency Domain Reflectometry)

- All FBGs are written at the same wavelength (λ_B), instead of each having a unique wavelength (WDM)
  - Multiplexing of hundreds of sensor is possible.
- A narrowband wavelength tunable laser source is used to interrogate sensors.
- Each FBG sensor is only ½ inch long

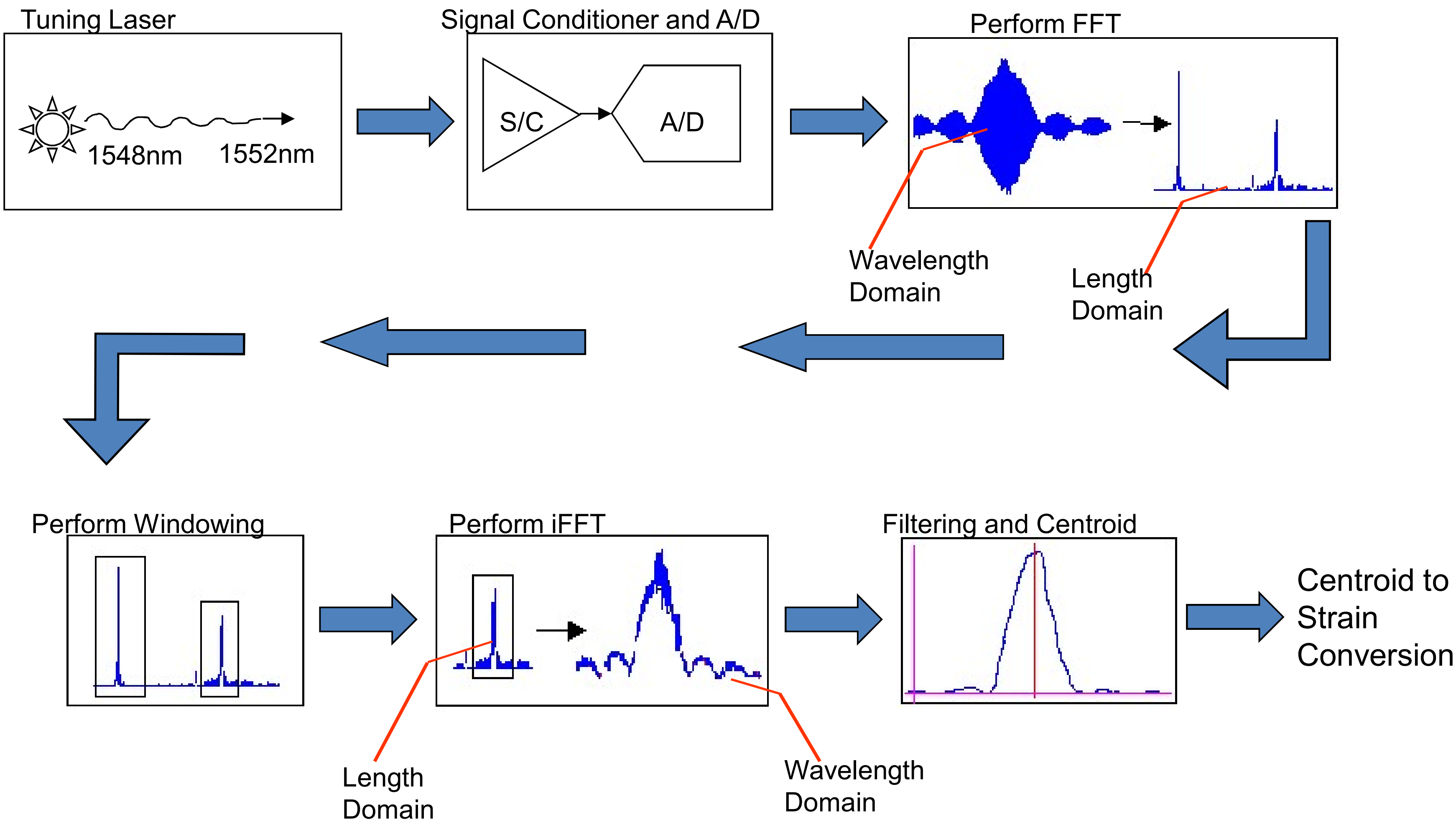


$$I_R = \sum_i R_i Cos(k2n_0L_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
n_0 – effective index
L – path difference
k – wavenumber



PROCESSING PROCEDURE (COMPLETE PICTURE)



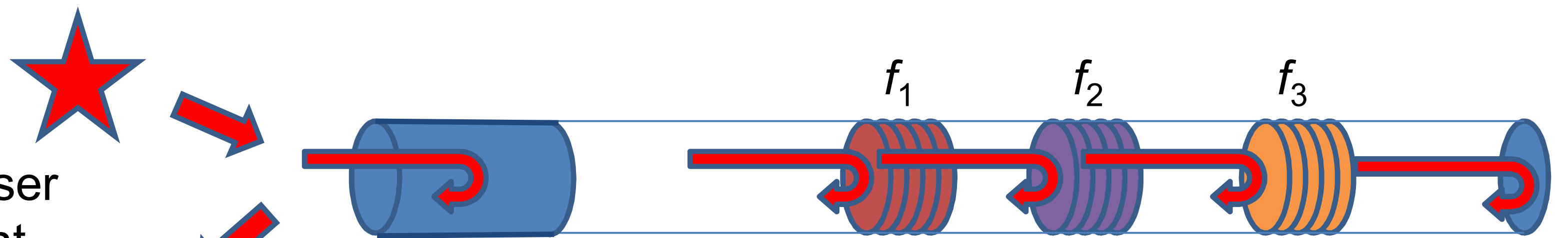
LAYMAN'S TERM: TUNING YOUR FAVORITE RADIO STATION!

Radio receives ALL frequencies

Radio tuner accepts ONE frequency

Multiple frequencies
are broadcasted on airwave

Radio analogy to Optical Frequency Domain Reflectometry

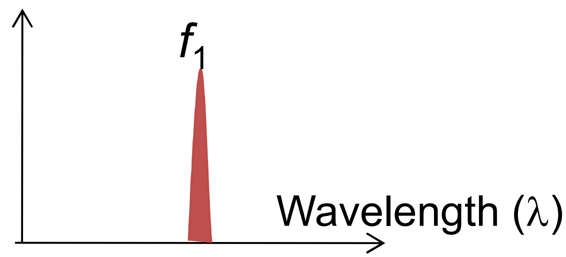


Laser light

Photo-detector
(Receive ALL sensor signal)

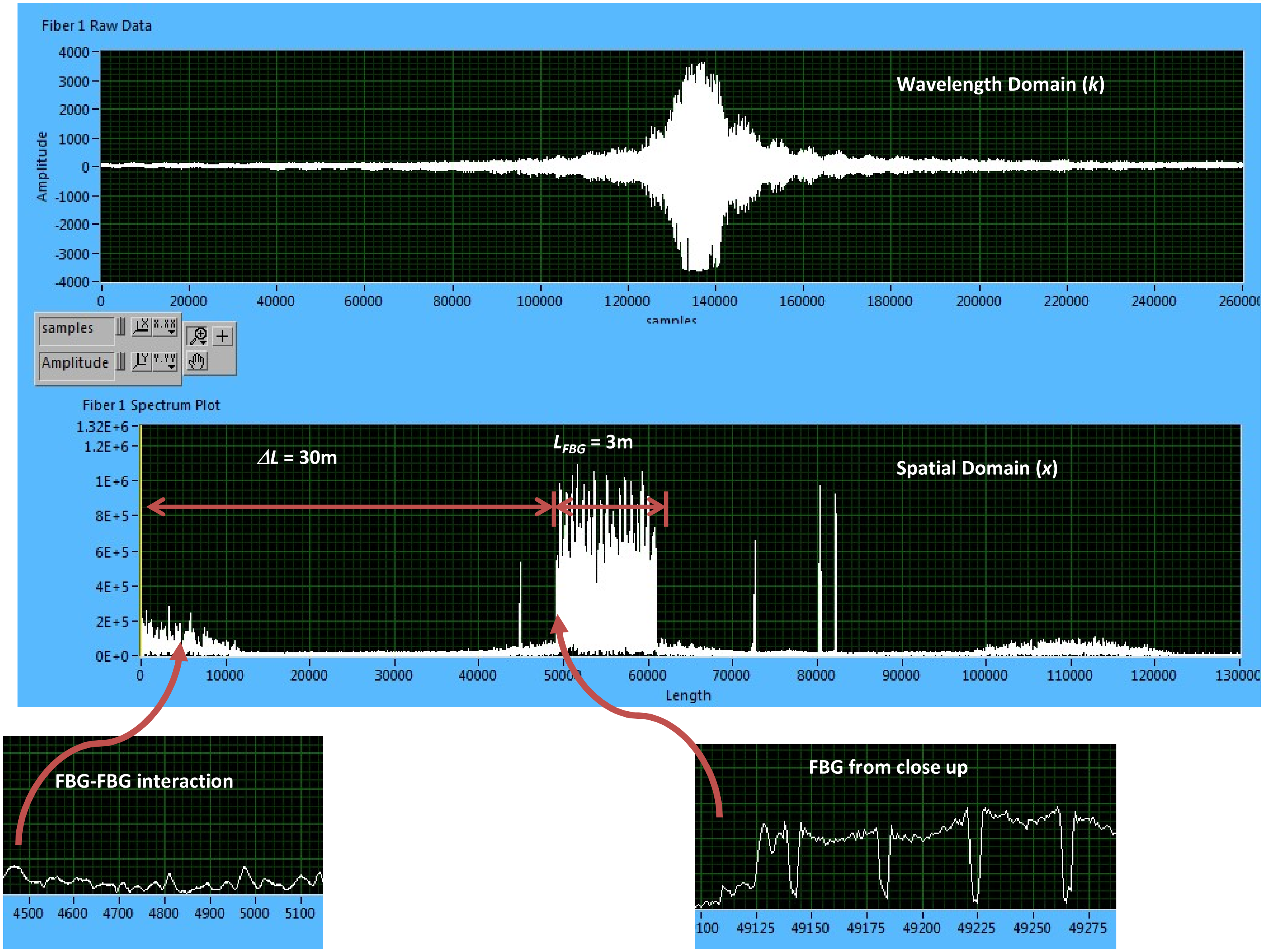
97.3 97.7 98.1

Sensor Frequency ID
(Broadcast Tower)
Determined via location of sensor



FFT/iFFT to "dial in" to particular sensor information
(Radio Tuner)

OFDR IN ACTION (FFT)



SUMMARY - FOSS IN BRIEF

- FOSS utilizes OFDR technique
  - Requirement for OFDR
    - Physics
      - Fast narrow-linewidth swept laser
      - Low reflectivity FBGs with identical Bragg wavelength
      - Optical network generating interferometry
      - Robust analog photo-detector
    - Electronics
      - Fast A/D acquisition card
      - Fast algorithm to perform FFT/iFFT (or similar) operation

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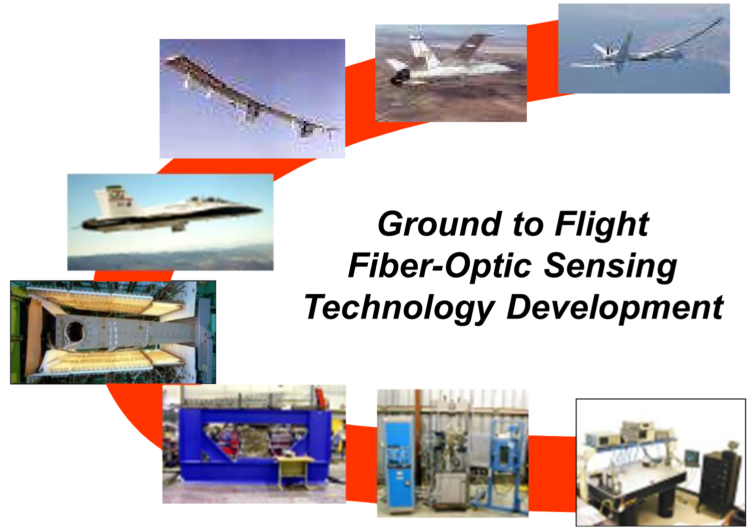
Background History

- **NASA AFRC (then Dryden)'s Aerostructures Branch initiated fiber-optic instrumentation development effort in the mid-90's**
    - Dryden effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique
- **Dryden collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft**
    - Focused on validating vendor's FO VHM system
        - Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
    - Contractor's system limited to *1 sample every 30 seconds*
- **Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight**



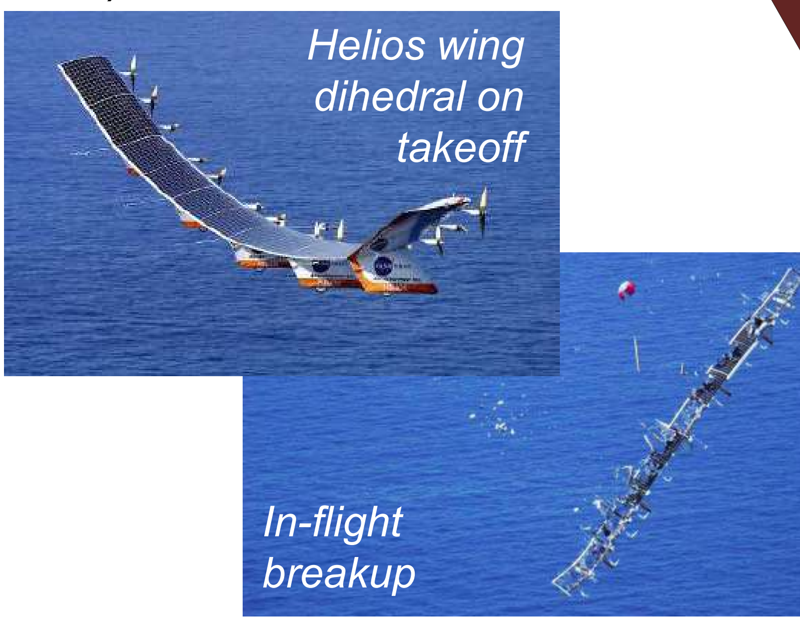
X-33 IVHM Risk Reduction Experiment

BACKGROUND OF TECHNOLOGY FOR FLIGHT MONITORING

Fiber Bragg Grating (FBG) sensors in optical fibers have been used for several years to determine the temperature, pressure, and strain to which a structure is subjected

This invention uses FBG sensor data and allows end users to continuously monitor strain distribution as well as determine many other engineering parameters (i.e. stress, buckling, shape, loads, etc.)

Motivation – Helios mishap (2003)



The technology was developed for monitoring the wing displacement of unmanned aerial vehicles (UAV) to proactively prevent crashes

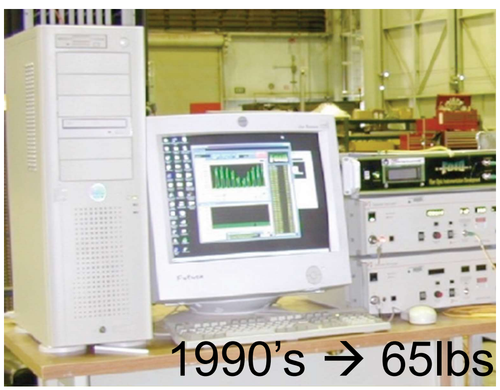
Helios Mishap Report – lessons learned

- Measurement of wing dihedral in real-time should be accomplished with a visual display of results available to the test crew during flight
- Procedure to control wing dihedral in flight is necessary for the Helios class of vehicle

AFRC's ROLE IN FIBER SENSING TECHNOLOGY

- Technology is first pioneered/patented at NASA Langley Research Center (LaRC) during the late 90's:
  - Laboratory-based system
  - One sample being taking every 30 second (one channel).

- AFRC miniaturized and developed an "one-box system" for aerospace application
  - Compact system for flight or ground test
  - Patented improved sampling rate to 100 samples per second (multiple channels)



Parker; US Patent 8,700,358

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AFRC's FOSS Capabilities

System specifications (2014)

Fiber count	8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Total sensors / system	16000
Max sample rate (flight)	100 sps
Power (flight)	28VDC @ 4.5 Amps
Power (ground)	110 VAC
User Interface	Ethernet
Weight (flight, non-optimized)	27 lbs
Weight (ground, non-optimized)	20 lbs
Size (flight, non-optimized)	7.5 x 13 x 13 in
Size (ground, non-optimized)	7 x 12 x 11 in

Environmental qualification specifications for flight system

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

Aircrafts supported: Ikhana, Global Observer, G-III

Flight System

Ground System

Ikhana in Flight

cFOSS v1.0 System Specifications

- **Specifications:**
  - Fiber count: 4
  - Max Fiber length: 40 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: NASA Curve A (DCP-O-018)
- **Applications:**
  - UAVs

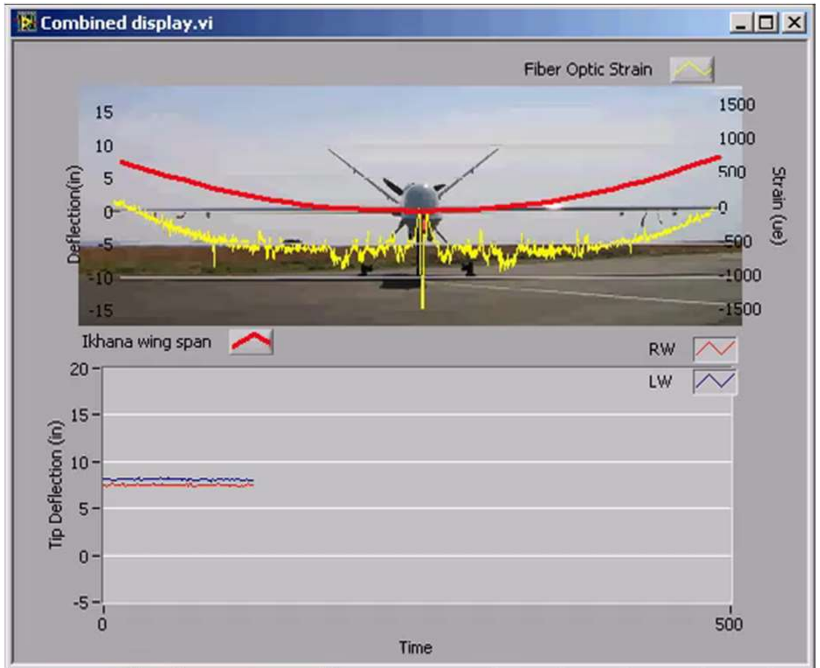
cFOSS v1.0

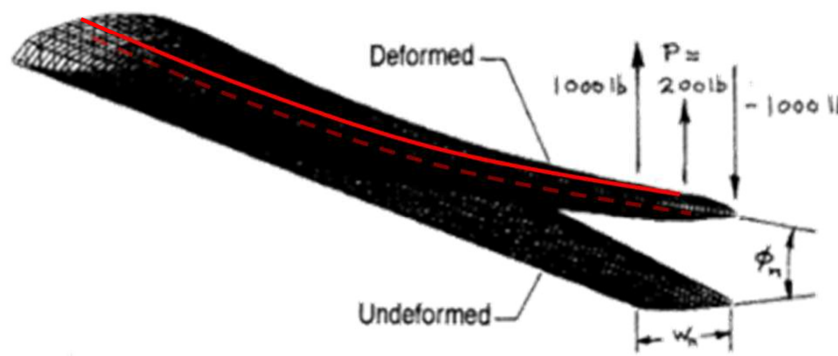
cFOSS v2.0 onboard X-56

cFOSS v1.0 onboard APV-3

STRUCTURAL ALGORITHMS USING FOSS

- **Structural Shape**
  - Real-time wing shape measurement using fiber optics sensors
    - (Ko, Richards; Patent 7,715,994)





Win-tip deflection measurement of AFRC's Predator B via FOSS

- **Externally applied loads**
  - Real-time applied loads on complex structures using fiber optic sensors (Richards, Ko; Patent 7,520,176)

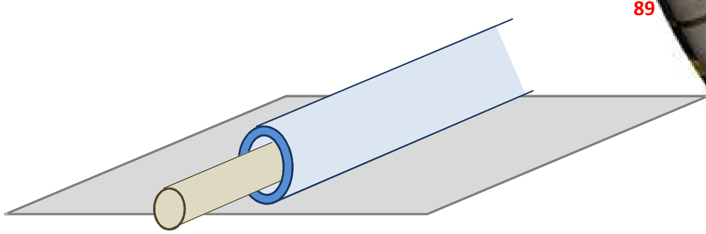
Combined Temperature and Strain Sensing

- Three fiber-optic channels measuring both strain and temperature:

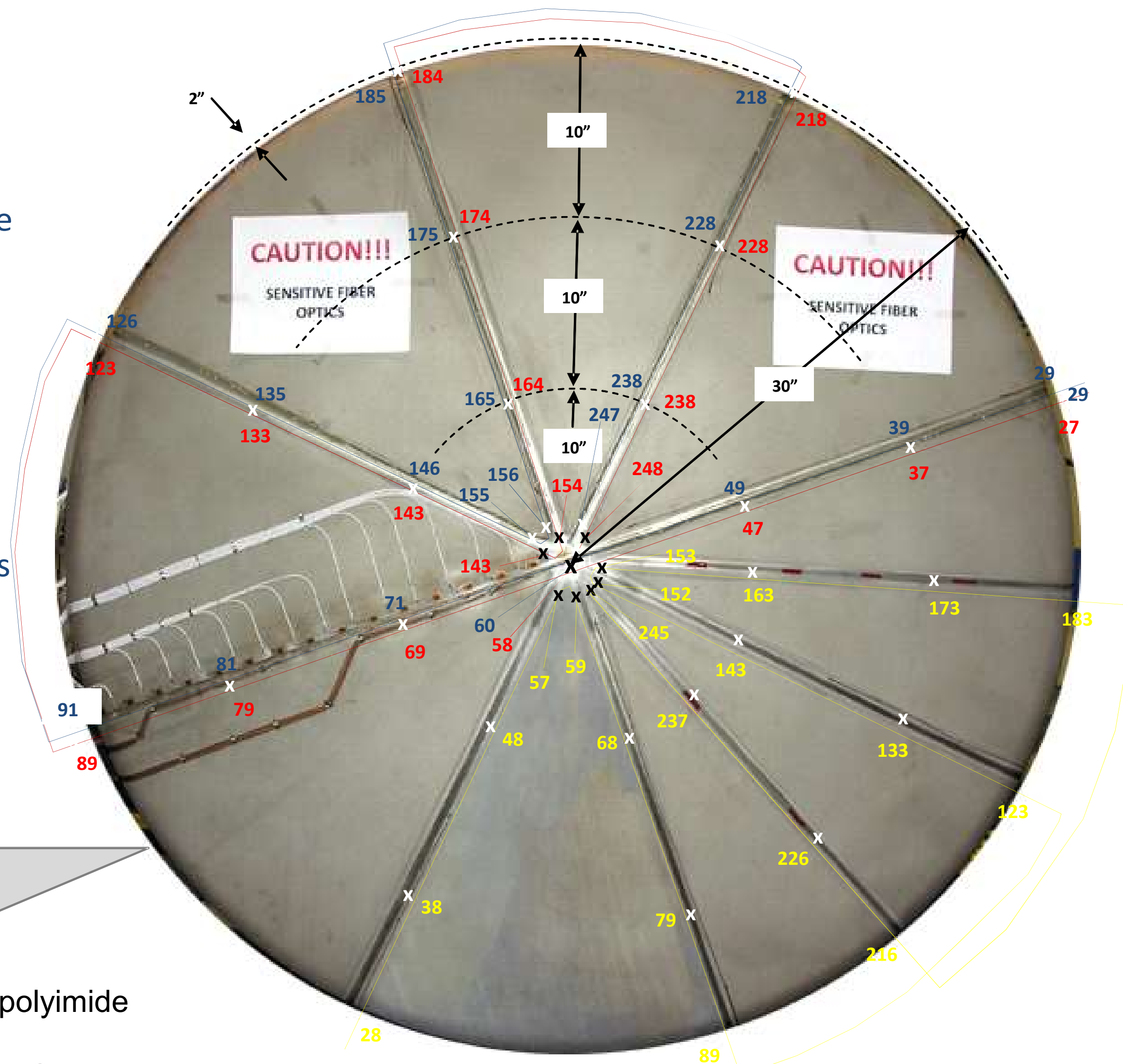
- **Red fiber** bonded and will measure strain and determine shape

- **Yellow fiber** is both bonded and unbonded through polyimide tubes

- **Blue fiber** is run in Polyimide tubes to decouple from substrate, measuring temperature only



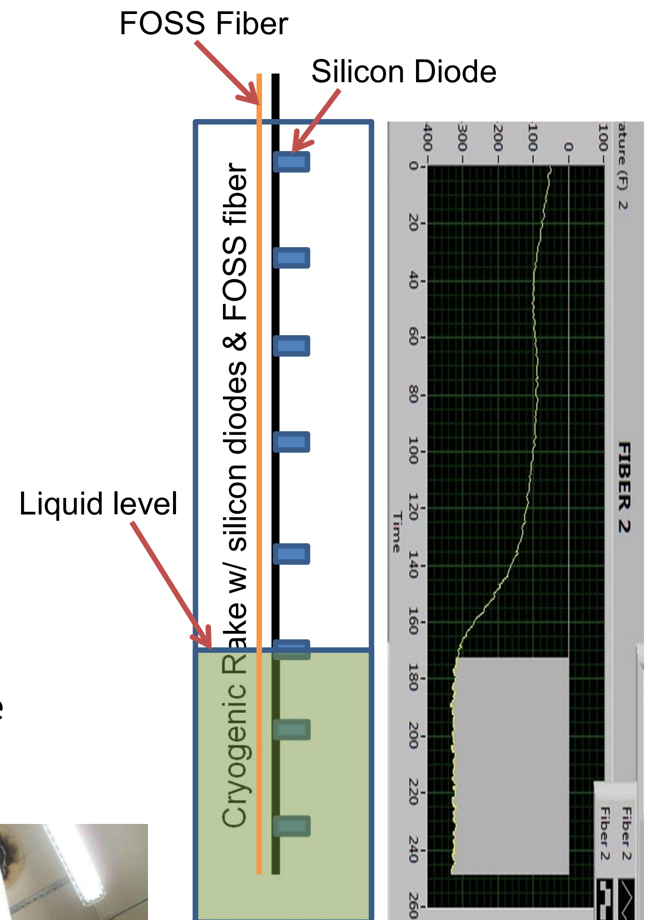
Fiber sensors move freely in polyimide tubing to decouple temperature with respect to strain



TPS Heat Shield strain / temp loading with FOSS

CRYOGENIC LIQUID LEVEL-SENSING USING CRYOFOSS

- The Challenge
  - *<u>The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements</u>*
  - Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level
- FOSS Approach
  - While using anemometry methods the transitional phase can be mapped better
  - **Using a single continuous grating fiber high spatial resolution can be achieve**
  - In conjunction with the continuous grating fiber, Dryden's adaptive spatial density algorithm can resolve even higher spatial resolution targeting in the region where the actual level is located
- Applications:
  - Launch vehicles
  - Satellites
  - Civil Structures
  - Ground Testing
  - COPV bottles



Cryogenic Container

FOSS Test Results

Cryogenic Container located at MSFC (below deck)

CRYOFOSS DEPLOYED AS LH_2 LIQUID LEVEL SENSOR

Objective

- Experimentally validate Dryden-developed LH_2 liquid level sensor (cryo-FOSS) using Dryden's fiber optic strain system (FOSS) technology

Test Details

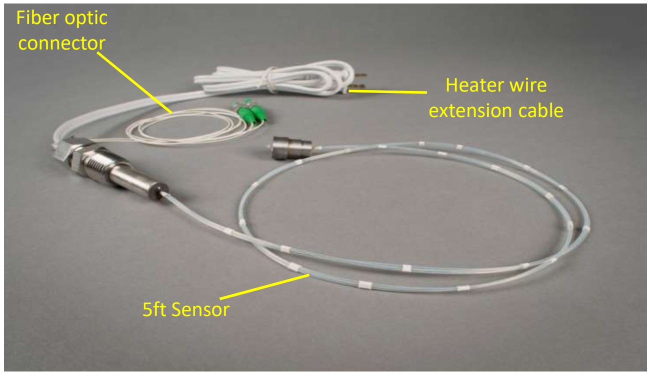
- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of ~20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH_2 liquid level sensor

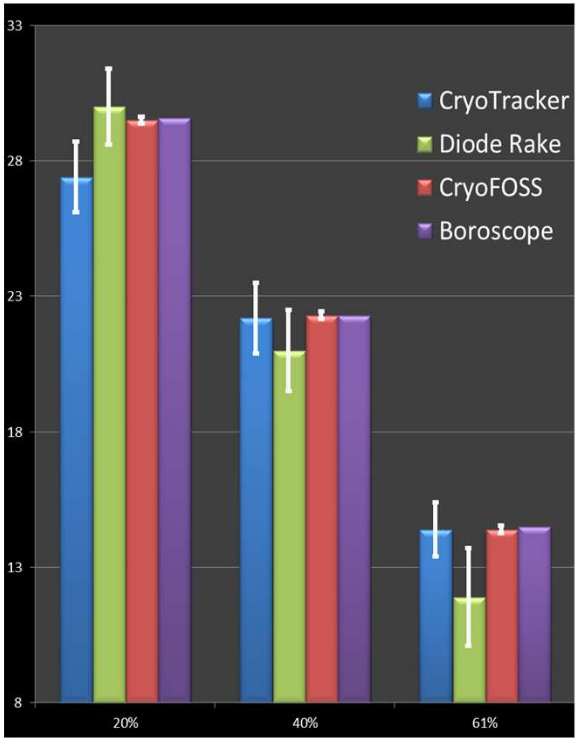
Results

- ***Cryo-FOSS sensor discerned LH_2 level to approx. ¼" in every case***
- Excellent agreement achieved between cryo-FOSS, boroscope, and silicon diode cryotracker

Bottom line

- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for the ground- and in-flight cryogenic fluid management of launch vehicles in the future

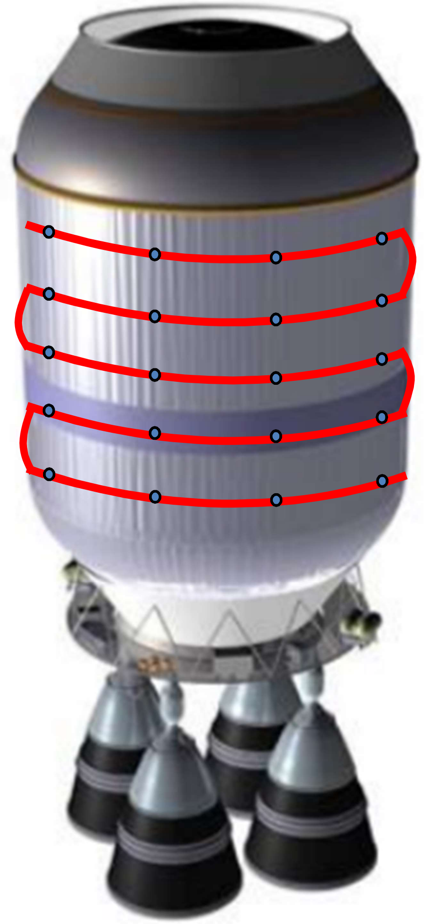




Parker Jr et al, USP 9074921

HYBRID FIBER OPTIC SENSING SYSTEM (HYFOSS)

- hyFOSS is a combination of two existing technologies both based on fiber Bragg gratings
  - Wavelength Division Multiplexing (WDM) allows for high speed (kHz) acquisition speed but low number of gratings per fiber
  - Optical Frequency Domain Reflectometry (OFDR) allows for high spatial resolution (1000s of grating) but inherently low sample rates(<100Hz)
- Combining both technologies coupled on to the same fiber
  - high spatial resolution (lower sample rates) along the entire length of the fiber using OFDR
  - high sample rates at strategic points along the fiber using WDM



Example hyFOSS fiber layout

Example hyFOSS fiber layout

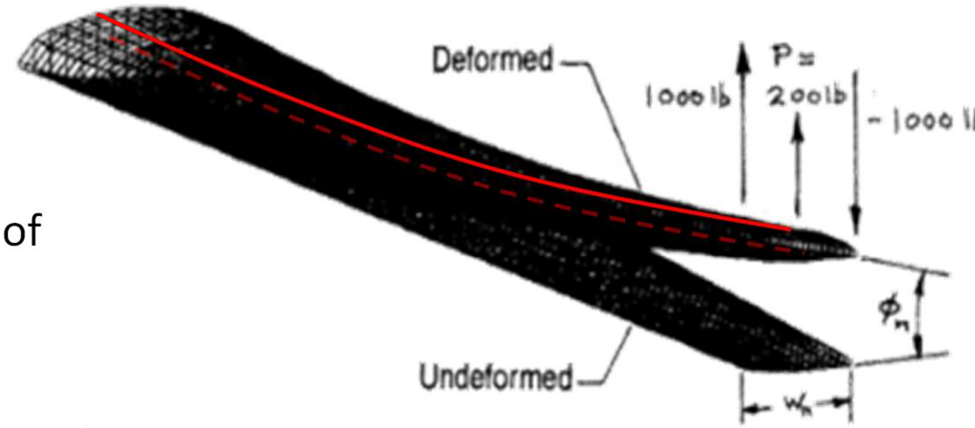
- High speed WDM sensor
- OFDR ¼” Spatial Resolution

Parker Jr et al, USP 9664506

Two Strain-Based Deflection Methods

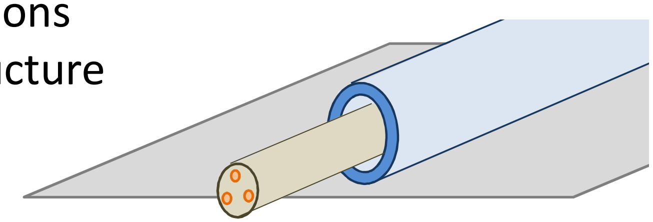
2D Shape Sensing Method

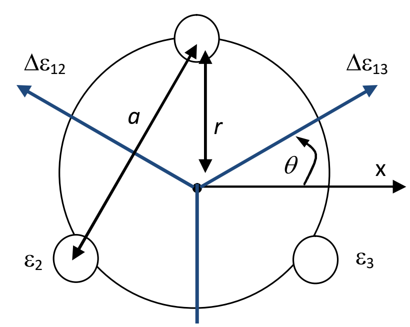
- Uses structural strains to get deflection in one direction
- Fibers on top and bottom surface of a structure (e.g. wing)



3D Shape Sensing Method

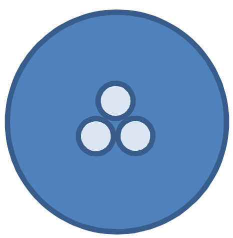
- Uses strains on a cylindrical structure to get 3D deflections
- 3 fibers 120 apart on a structure or a lumen



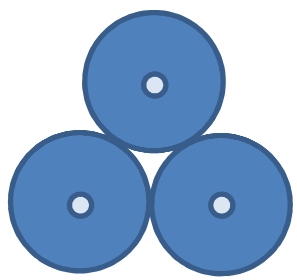


3-Core Shape Measurement

- From collaboration with NASA LaRC, shape sensing using fiber strain sensors has been realized
- Initial research focuses upon 3-core fiber
- This specialty fiber can be replaced with 3 conventional fibers superposition from one another at 120 degrees
- From knowing the strain value of each fiber, the 3-dimensional position of the fiber can be correctly rendered in real-time



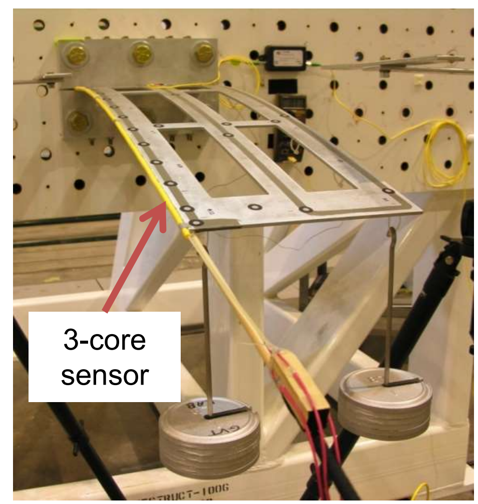
Multi-core fiber



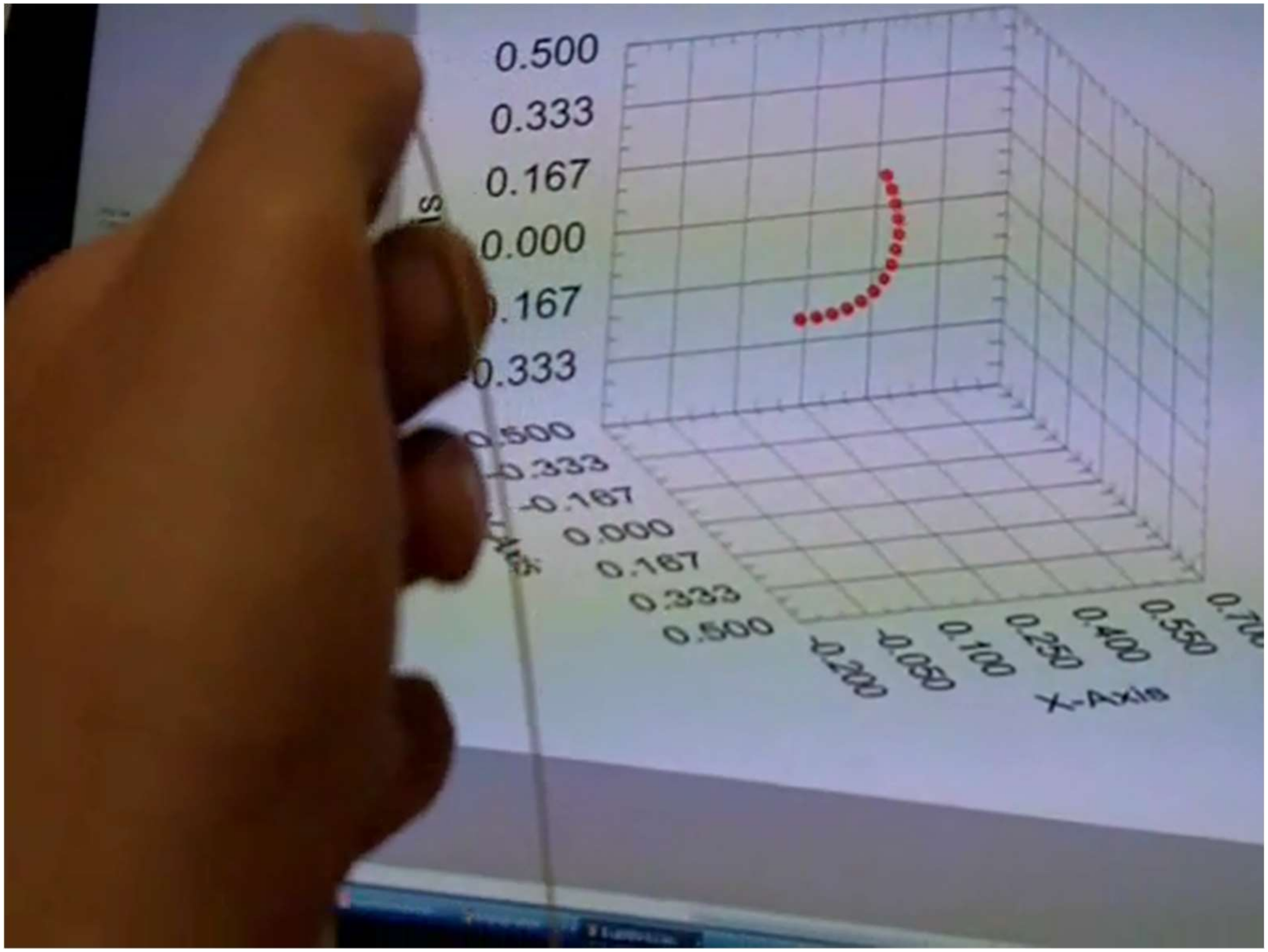
3 SMFs aligned in 120°

Chan et al, USP 8970845

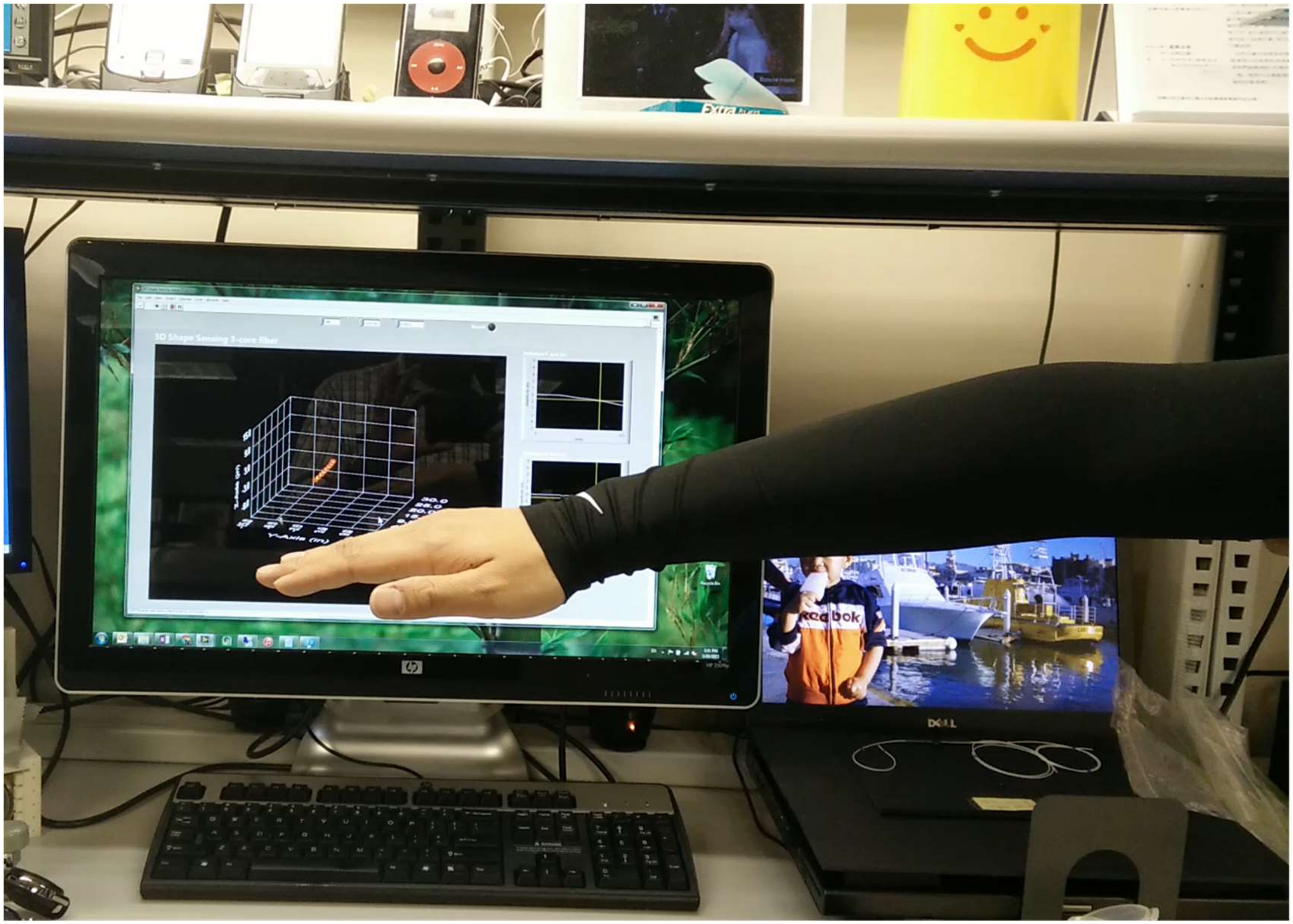
Fiber wrapped around object counter-clockwise is rendered in real-time



3D SHAPE SENSING



3D Shape Sensing on wearable



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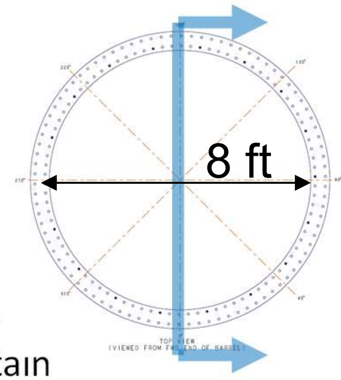
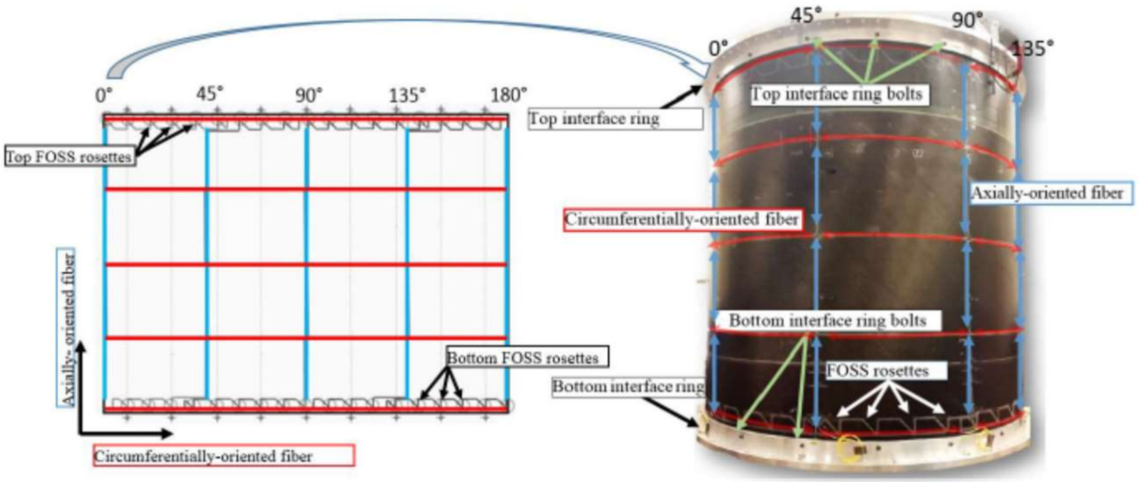
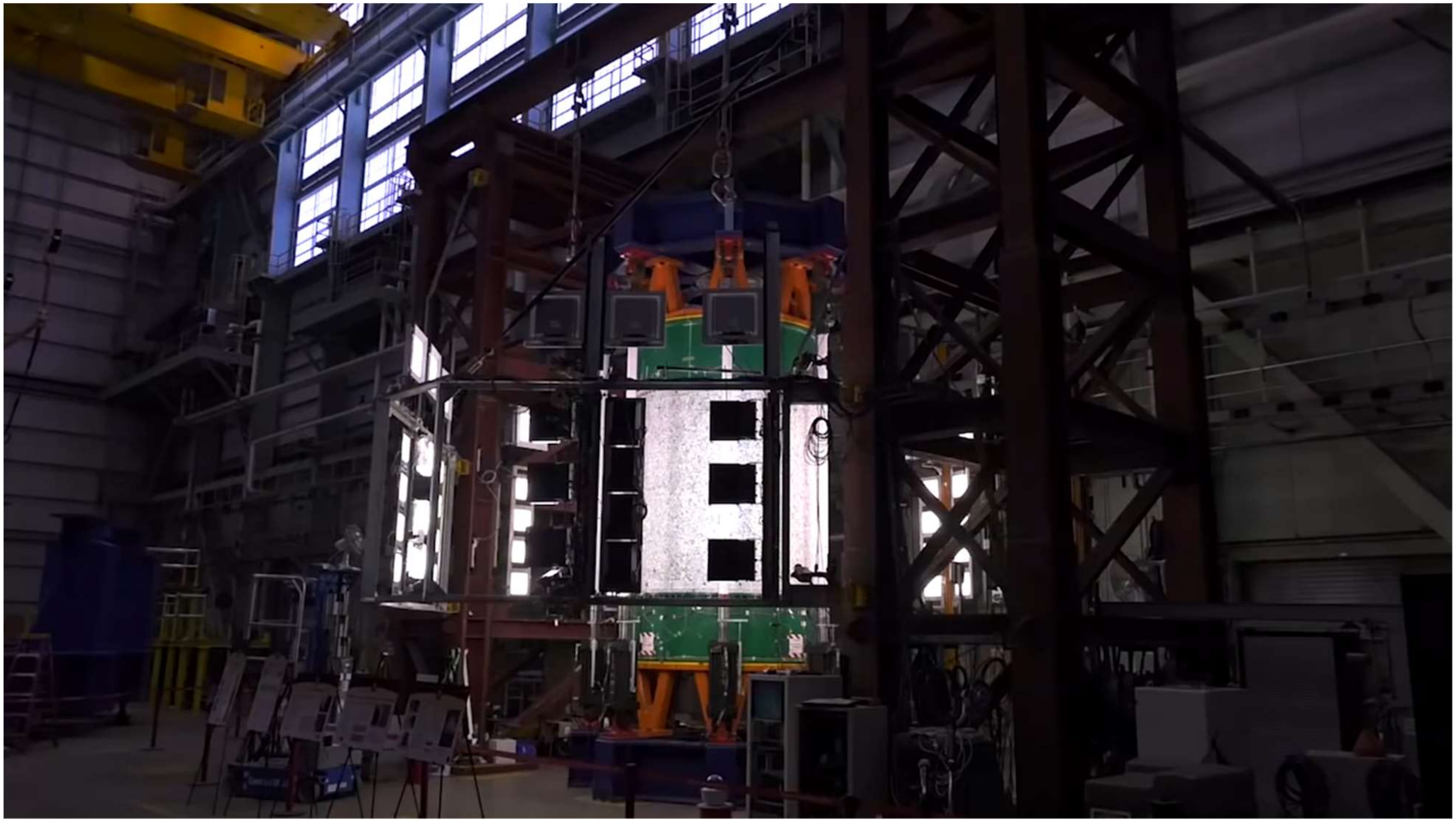
COMPOSITE SHELL BUCKLING KNOCKDOWN FACTOR (2016)

- Sponsor: NESC
- FOSS technology:
  - Strain monitoring
- Benefit to the project:
  - FOSS is being used to obtain experimen validation of knockdown factor margins
  - The ability to reduce margins and maintain safety could lead to significant weight savings

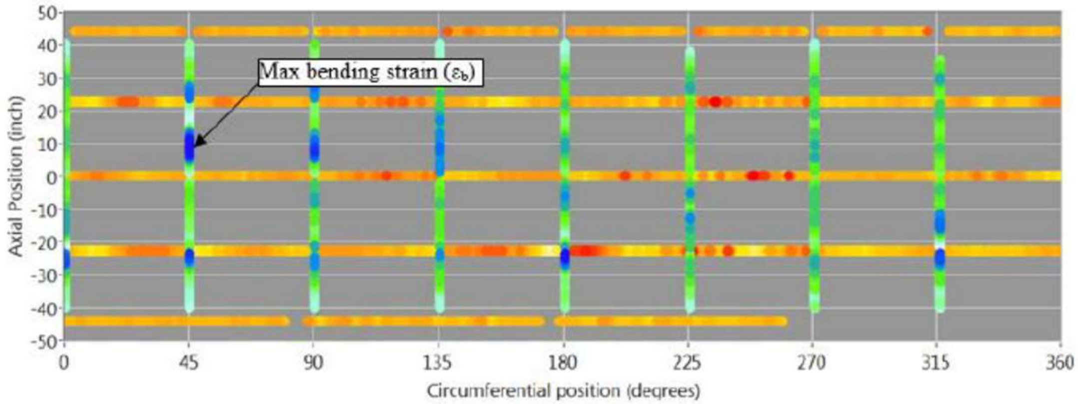




SBKF TEST



SBKF - RESULTS



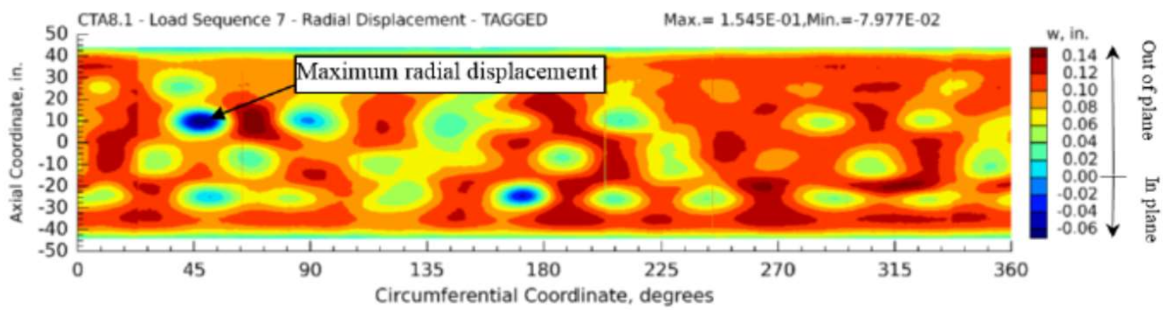


Fig. 14. Low-speed digital image correlation, outer mold line view, radial displacement contour plot incipient to failure.

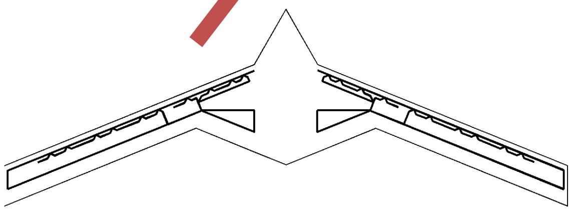
(Top) FOSS measured max bending strain (ε_b) distribution across SBKF article is consistent with DIC speckle-graph (Bottom) results

Pena et al, AIAA 2018

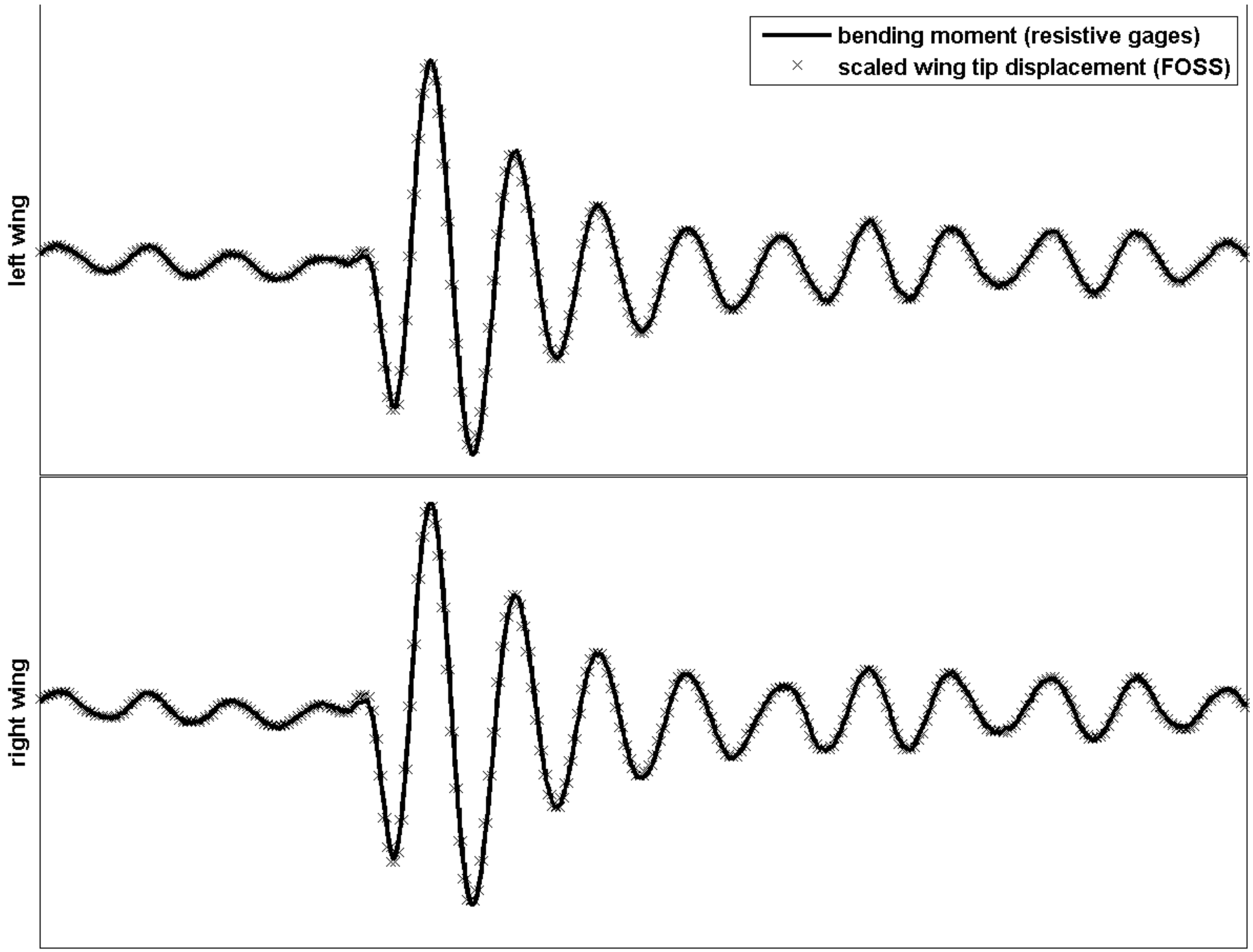
FOSS ON X56 (2017-CURRENT)

- X56:
  - Testbed for designing aircraft with highly flexible, lightweight wings.
  - Less structurally-rigid wings could be critical to future long-range, fuel-efficient airliners.
- FOSS on board to measure strain
  - 2D shape sensing to measure wing-deflection
  - Measure flutter modes if exists

cFOSS 2.0
On board X56

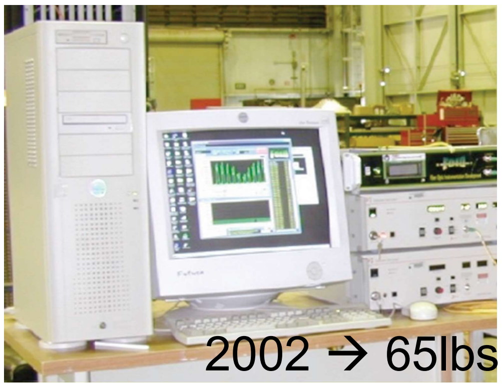


X56 FOSS DATA – WING TIP DISPLACEMENT

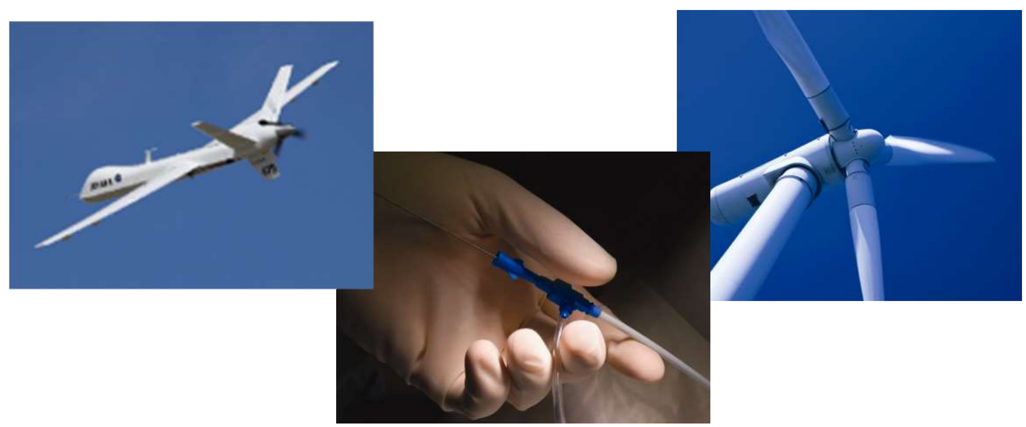


SUMMARY

- NASA AFRC has successfully develop fiber optics strain sensors (FOSS) technology from laboratory to real-world application



- Commercialization of technology is on-going via NASA Technology transfer
  - Aerospace Sector
  - Energy Sector
  - Biomedical Sector

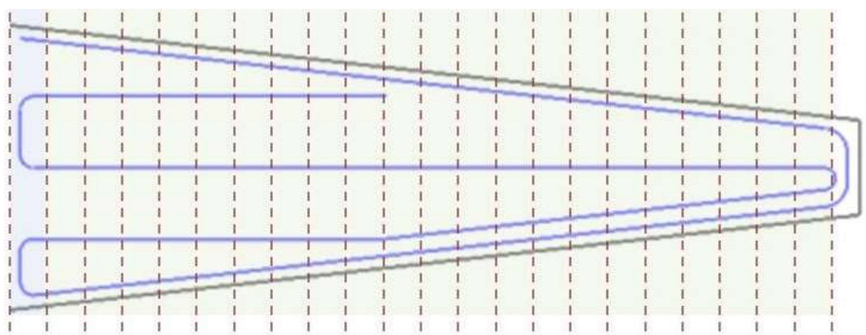


THANK YOU - FOSS TEAM AT AFRC

- Dr Lance Richards
  - Aircraft structures, strain measurement research
- Allen Parker
  - System Design and Development, Data Processing & Visualization
- Anthony Piazza
  - Sensor Characterization, Application & Interpretation
- Dr Patrick Chan; *hon.chan@nasa.gov*
  - Optics Development, Laser Research and Development
- Phil Hamory
  - Advanced System Algorithm Development
- Frank Pena
  - Mechanical Design & Development, Structural Simulation and Testing
- Paul Bean
  - Software/ Hardware development
- Ryan Warner
  - Real-time operating system implementation
- Shideh Nadari
  - Computer Processing, software development

DETERMINATION OF WING DEFLECTION

- Deflection Transfer Functions formulated by integrating the curvature equation for deformed beam elastic curve
  - Structure divided into analysis domains
  - Strain described by a linear function in each domain
  - Curvature equation integrated to yield slope and deflection equations
- No calibration test required



Deflection of a Fiber:

$$y_i = \frac{(\Delta l)_i^2}{6c_{i-1}}\left[\left(3 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + y_{i-1} + (\Delta l)_i \tan\theta_{i-1}$$

Slope:

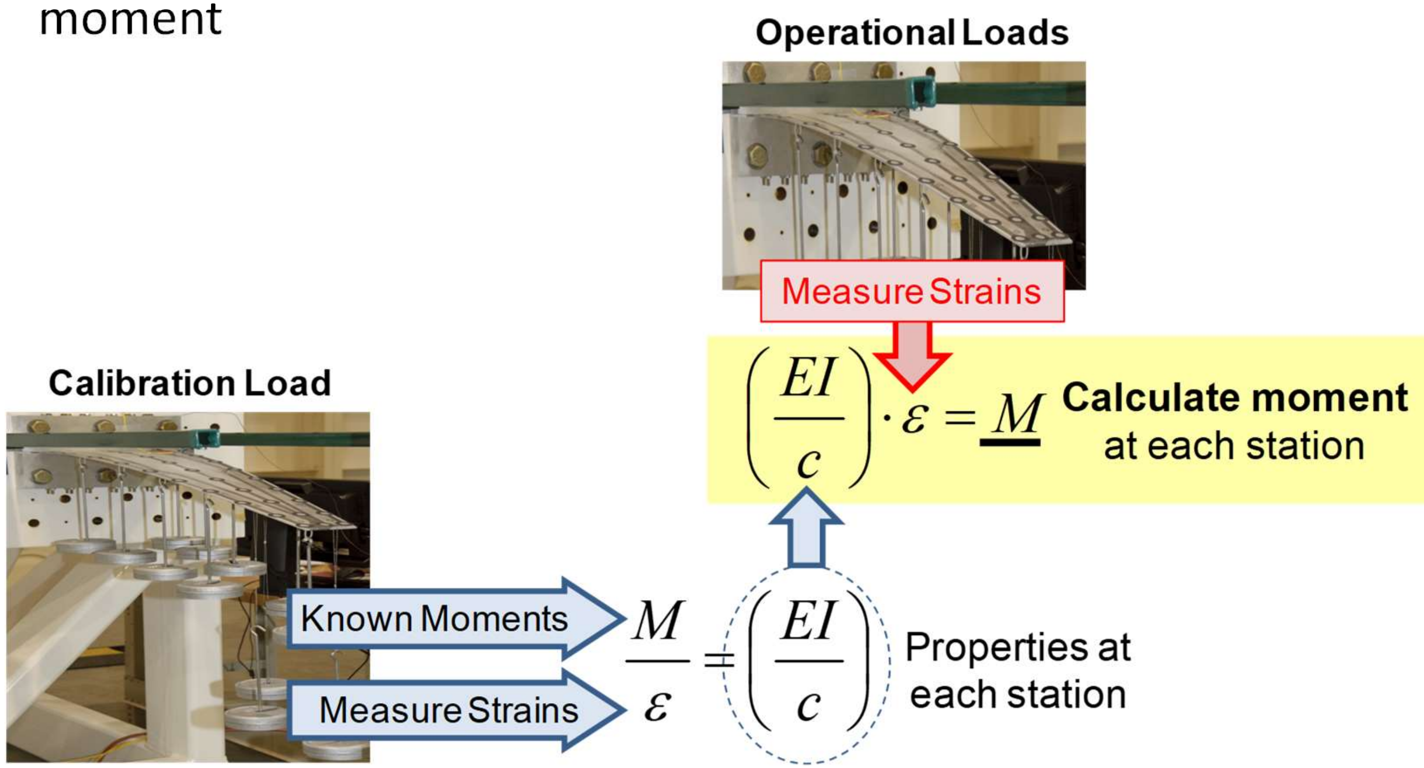
$$\tan\theta_i = \frac{(\Delta l)_i}{2c_{i-1}}\left[\left(2 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + \tan\theta_{i-1}$$

Distance to neutral axis:

$$c_{top} = \left(\frac{\varepsilon_{top}}{\varepsilon_{bottom} - \varepsilon_{top}}\right)h$$

LOAD TRANSFER FUNCTION PROCESS

- Load Transfer Functions used to calculate bending moment at each analysis station
  - Cross-sectional properties term calculated by applying known load
    - EI/c term backed out at each evaluation station
  - With properties term known, strain is directly related to bending moment

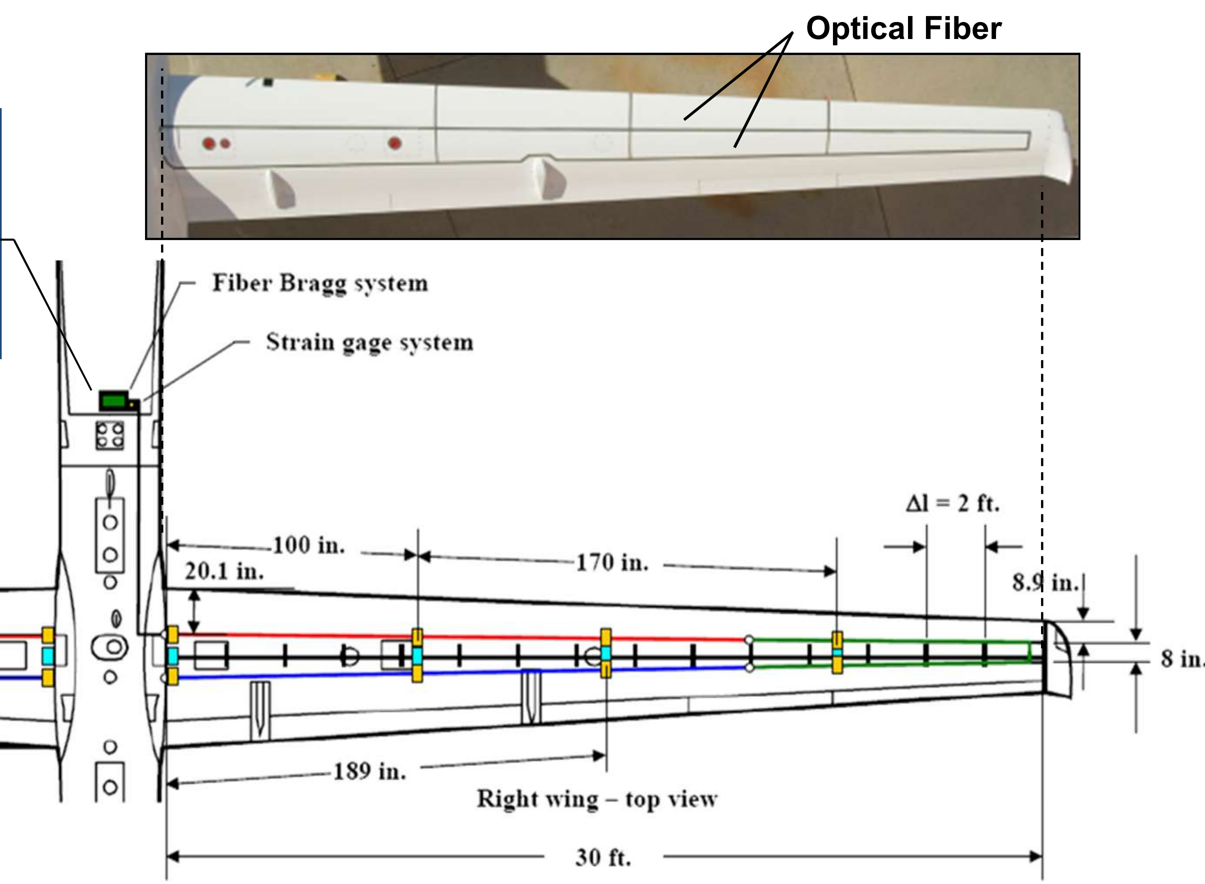


PREDATOR-B (IKHANA) FLIGHT TESTING

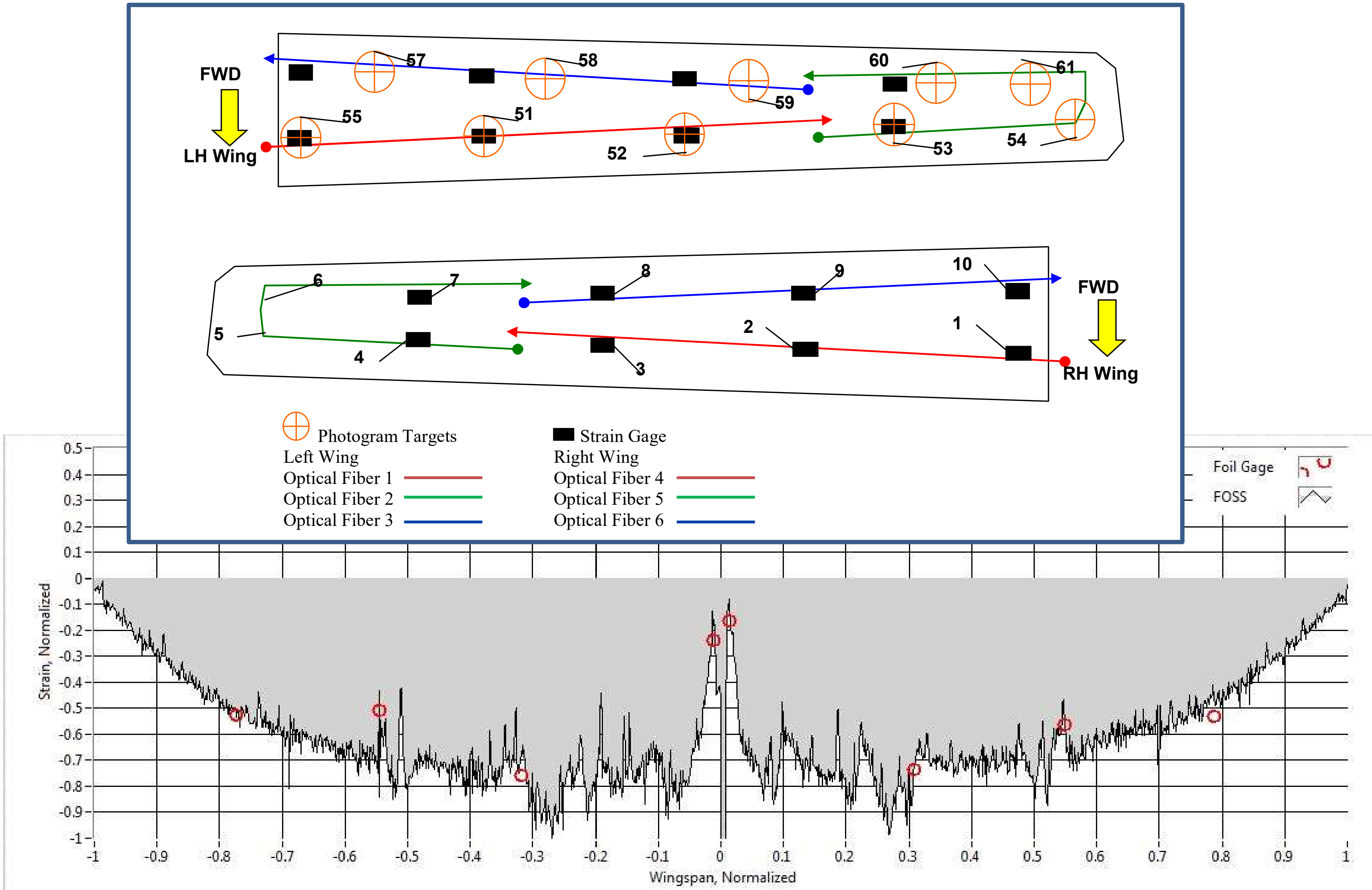
- **Instrumentation**
  - 2880 FBG strain sensors (1920 recorded at one time)
  - 1440 FBG sensors per wing
  - User-selectable number of FBG sensors for real-time wing shape sensing
  - 16 strain gages for FBG sensor validation
  - 8 thermocouples for strain sensor error corrections

Strain gage system

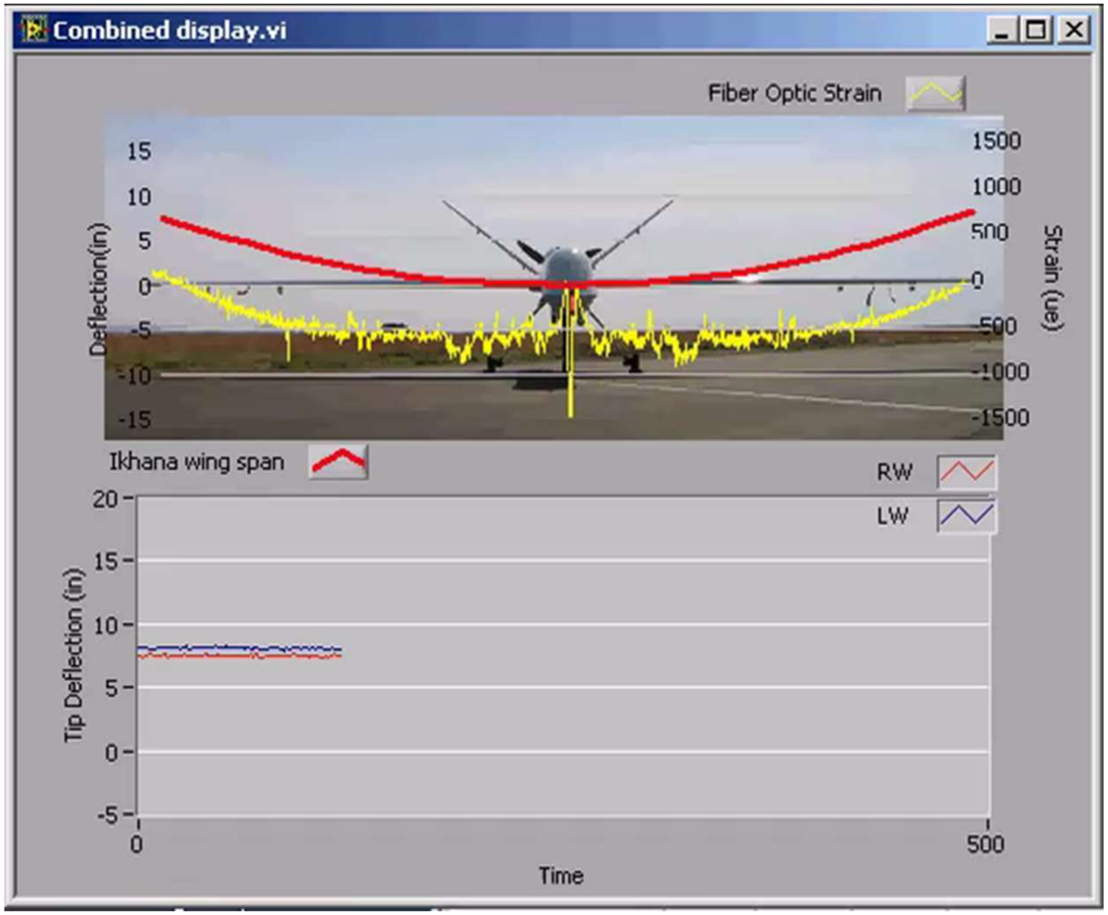
FBG system



FLIGHT TEST VALIDATION - IKHANA



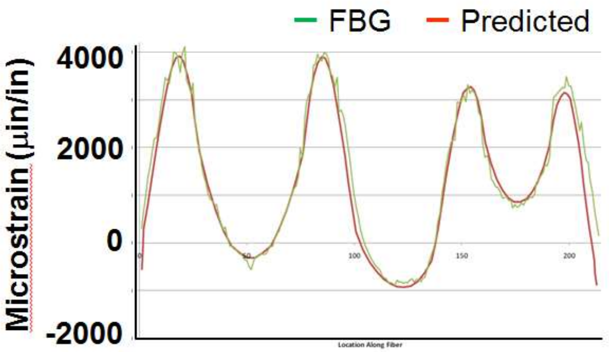
Flight Test Validation - Ikhana



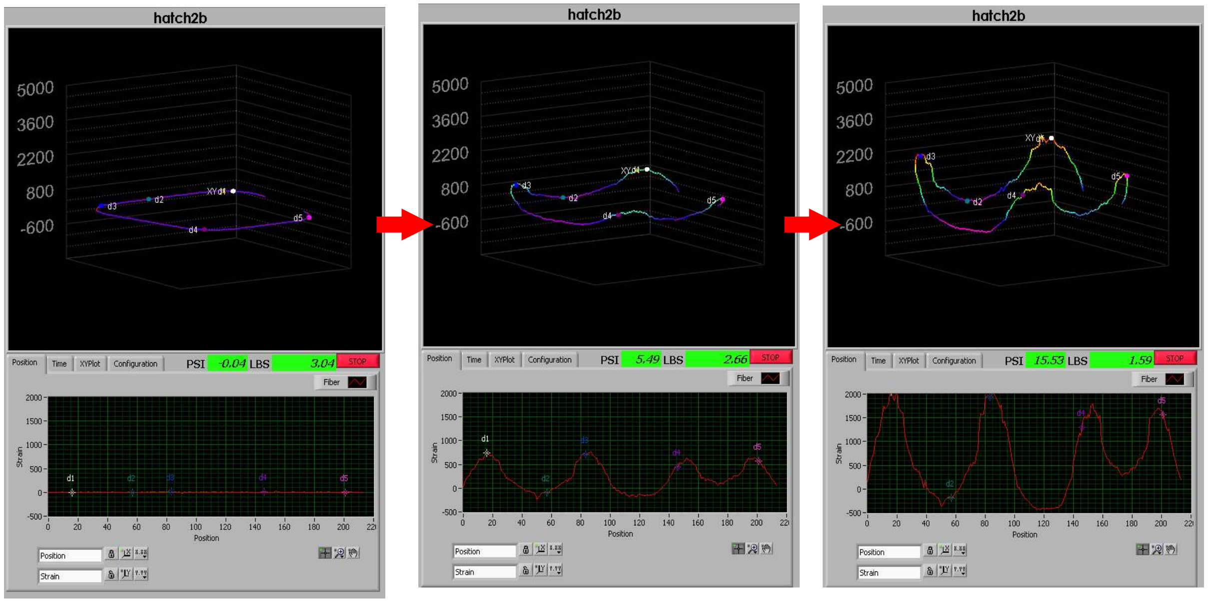
- 18 flights tests conducted; 36 flight-hours logged
- Conducted first flight validation testing April 28, 2008
- Believed to be the first flight validation test of FBG strain and 2D wing shape sensing
- Multiple flight maneuvers performed
- Two fiber configurations
- Fiber optic and conventional strain gages show excellent agreement
- FBG system performed well throughout entire flight – no issues

Composite Crew Module

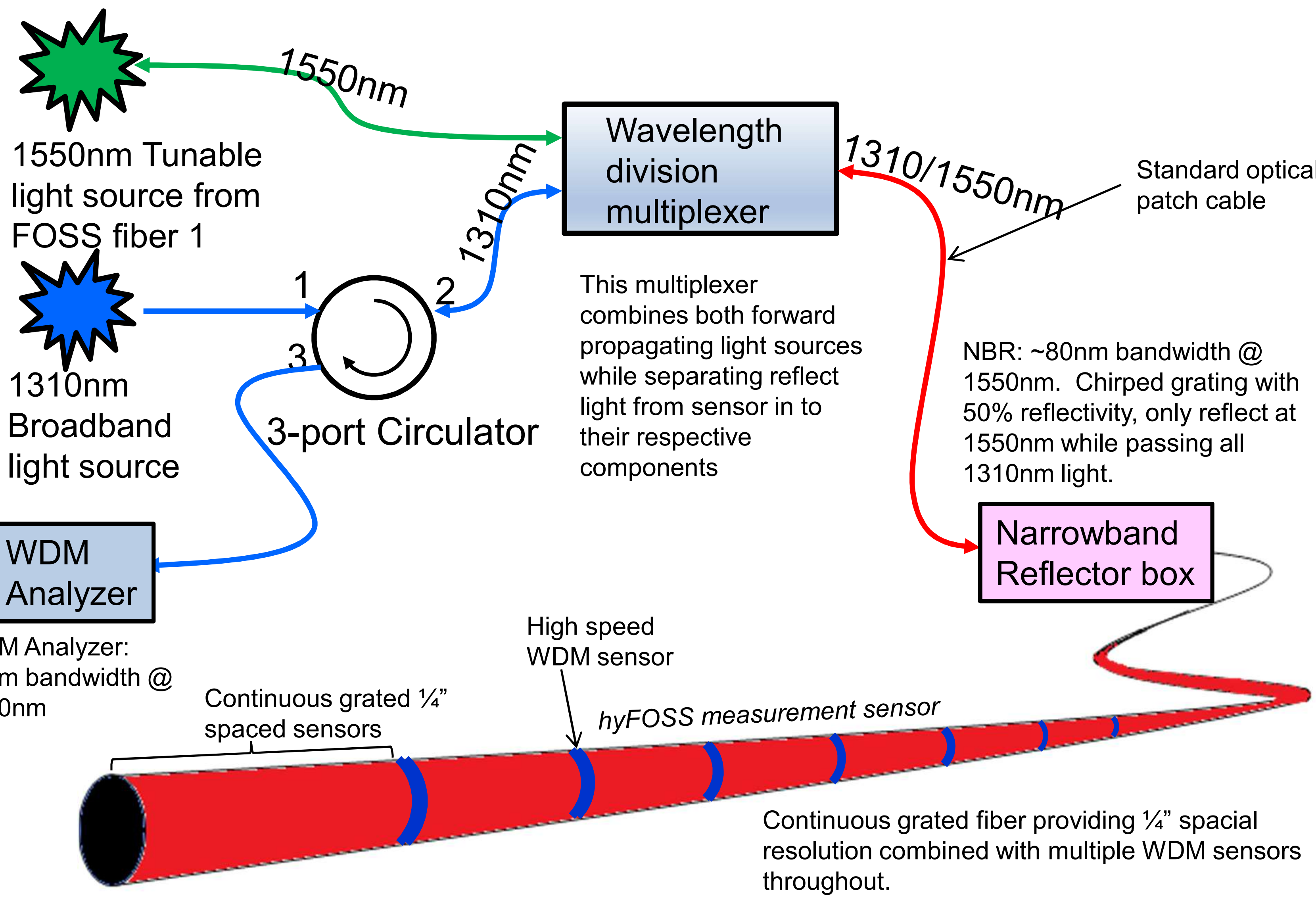
- Four fibers were installed around the module's three windows and one hatch
- Real-time 3D strain distributions were collected as the module underwent 200%DLL pressurization testing
- Measured strains compared and matched well to predicted model results
- Project Conclusion:
  - ""Fiber optics real 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



HYFOSS MULTIPLEXER DIAGRAM



Parker Jr et al, USP 9664506

CRYOTE 3

- Sponsor: LSP (KSC)
- FOSS technology:
  - Strain sensing, Temperature sensing, Liquid Level sensing
- Benefit to the project:
  - CRYOTE 3 being used as a test bed to further develop the Liquid Level sensing capability of FOSS
  - FOSS Temperature and strain sensing capabilities are helping to provide high fidelity data in the transition from liquid to gas state in cryogenic tanks
  - Data being used to validate models for the liquid level boundary region