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Fiber-optic Sensing for In-Space Inspection

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Topics

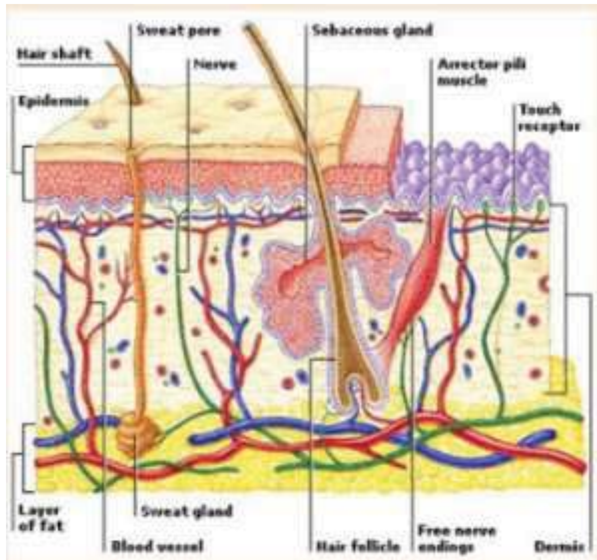
- Armstrong Fiber Optic Sensing System (FOSS)
  - Utilize distributed sensing network for validation of structural models
  - Continual condition based monitoring / event triggering
  - Observation of trending data for structural health monitoring parameters

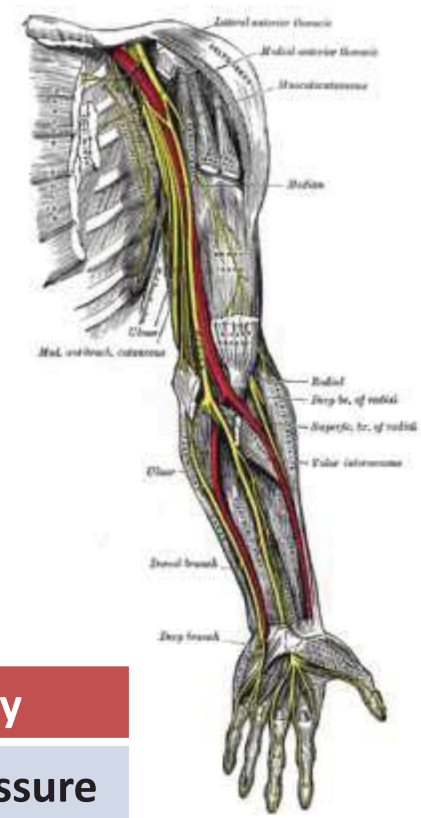
Background and Inspiration

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

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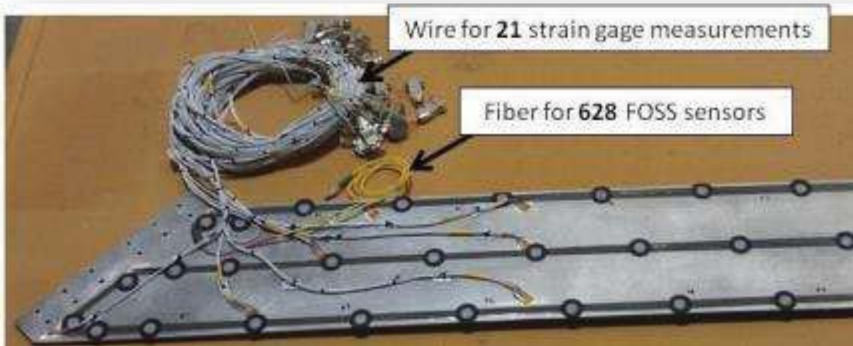
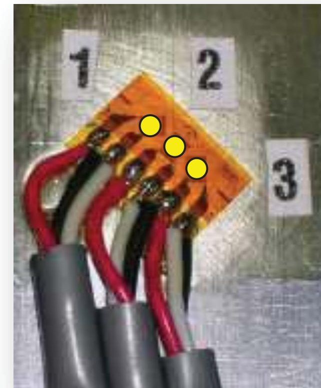
Why Fiber Optic Sensors?

One Of These Things (is Not Like The Others)

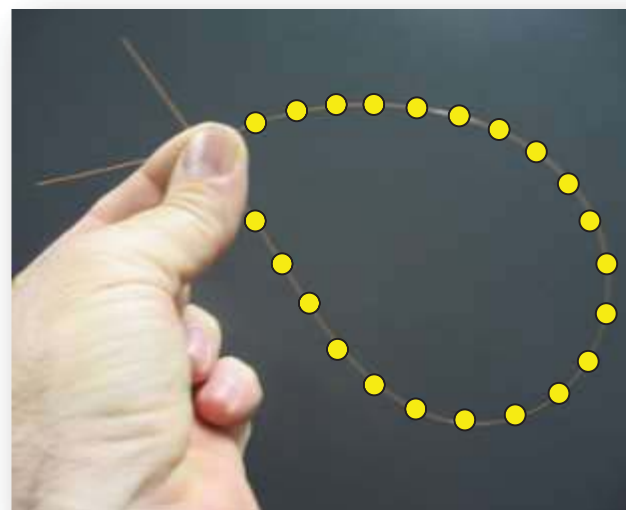


(Heavy)



(Big)

(Hard)

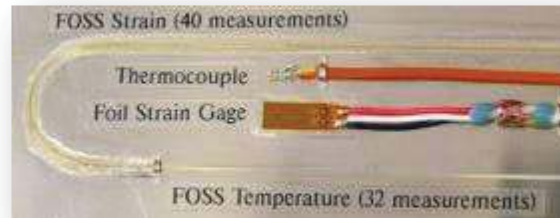


(Light, small, easy)

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

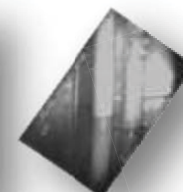
FBG-OFDR can dramatically improve structural and system efficiency for space vehicle applications by improving both affordability and capability by …

- 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, temperature, 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



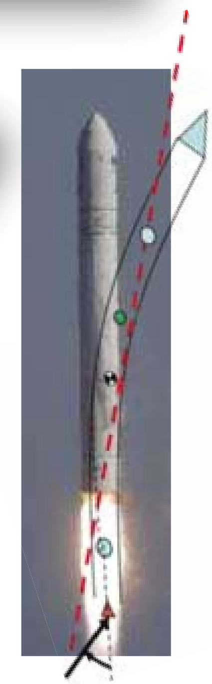
Metallic Coupon

Pressure monitoring



Liquid level sensing

ISS COPV strain & temp monitoring



Shape sensing for vehicle control

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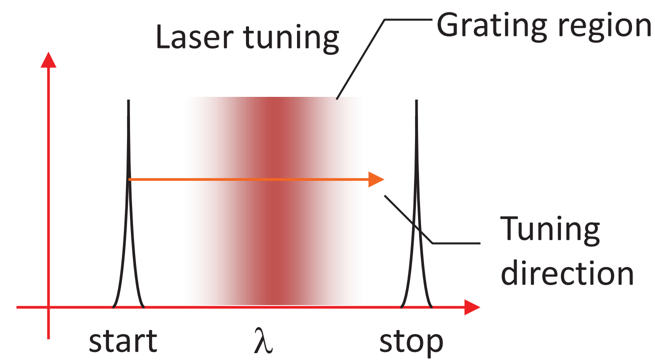
Fiber Optic Sensing System (FOSS)

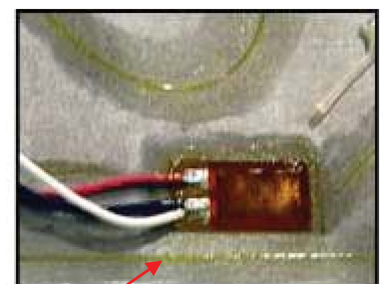
Operation Overview

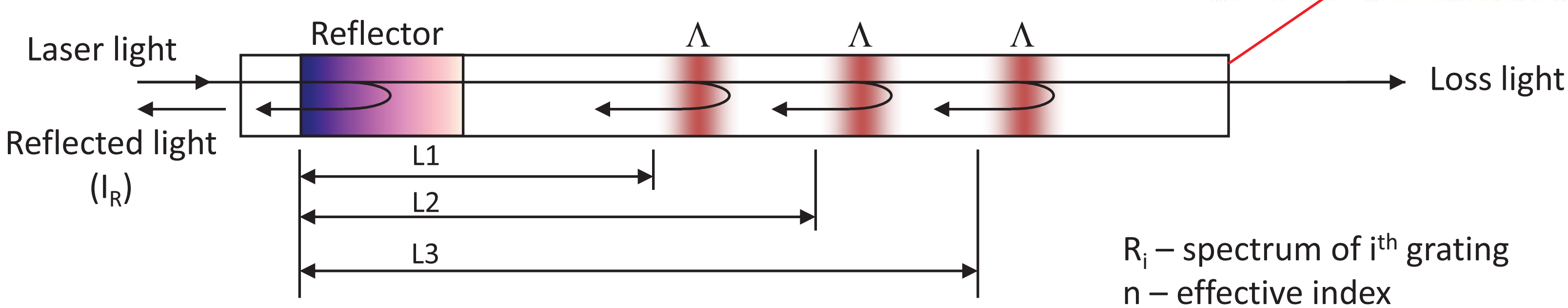
Fiber Optic Sensing with Fiber Bragg Gratings

- Multiplex 1000s of sensors onto one “hair-like” optical fiber
- All gratings are written at the same wavelength
- Uses a narrowband wavelength swept laser source to interrogate sensors
- In addition to measuring strain and temperature, these sensors can be used to determine a variety of other engineering parameters



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





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

Armstrong’s FOSS Technology
Current Capabilities

Current system specifications

Fiber count	8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Total sensors / system	16000
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

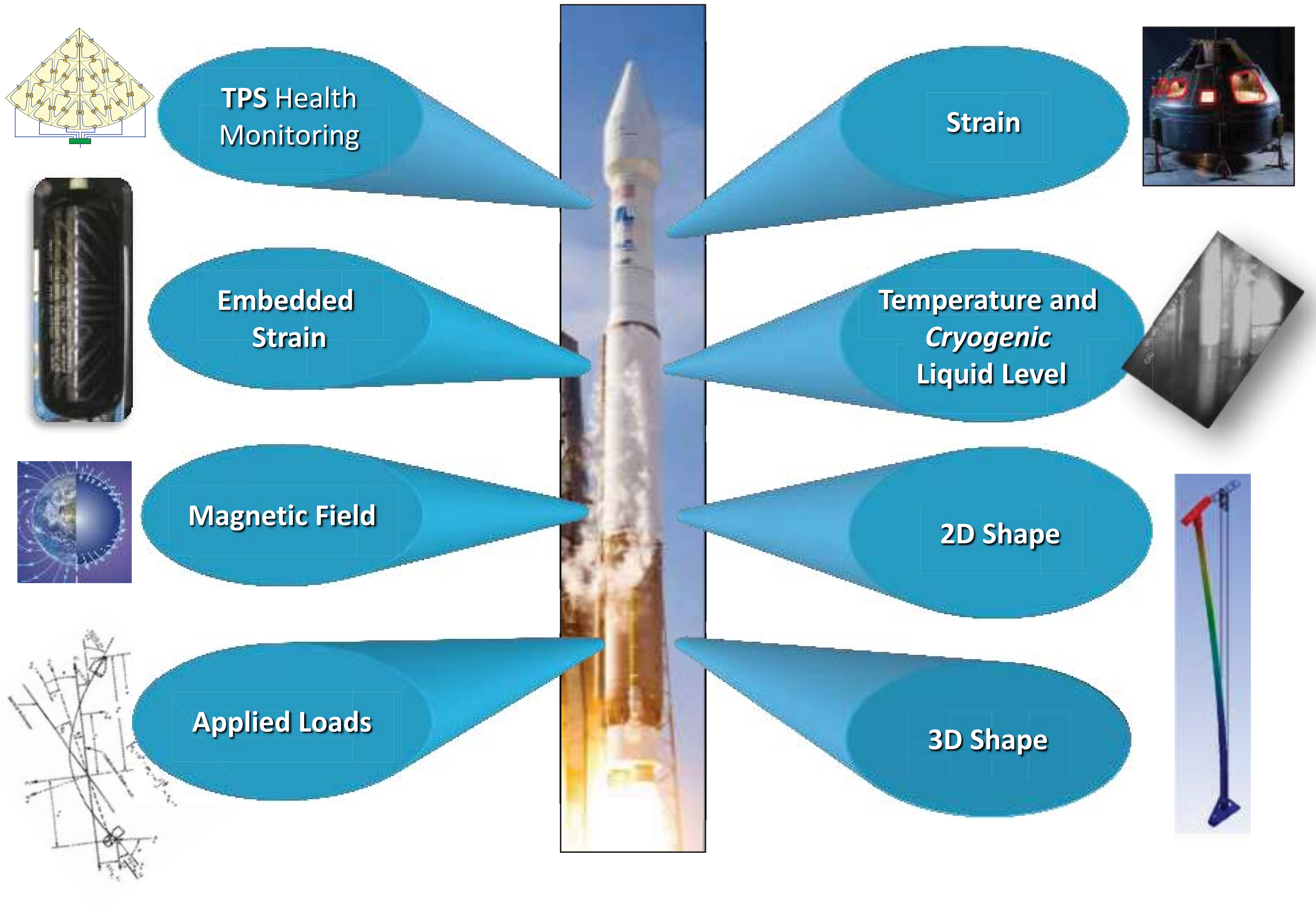
Shock	8g
Vibration	1.1 g-peak sinusoidal curve
Altitude	60kft at -56C for 60 min
Temperature	-56 < T < 40C

Flight System

Ground System

Predator -B in Flight

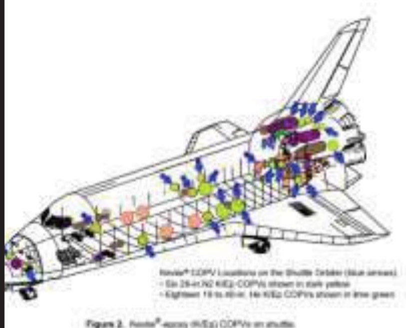
FOSS Fields of Operation



Composite Overwrapped Pressure Vessels (COPVs)

Problem Statement

- COPVs are increasingly more ubiquitous as they play a critical role in storing cryogenic fuels both for aerospace and automobile applications.
- COPVs for NASA applications are remotely deployed on space platforms, such as the International Space Station, and are therefore inaccessible for most conventional nondestructive evaluation methods.
- The failure characteristics of COPVs are not physically well-understood; there are no early warning indicators that mitigate or eliminate catastrophic composite rupture hazards, posing a risk to existing and future exploration spacecraft and crews.



McLauglan & Grimes-Ledesma (2011)

McLauglan & Grimes-Ledesma (2011)

McLauglan & Grimes-Ledesma (2011)

COPV Project Objectives

- **Perform real-time in-situ structural monitoring of COPVs by acquiring fiber Bragg grating measurements from sensors embedded within the composite structure and on the surface of the COPV**
- **Provide finite-element-like experimental strains plots**
  - **Model validation to improve future designs**
  - **Potential for health monitoring on ISS**
- **Develop a robust “early-warning” indicator of COPV catastrophic failure**

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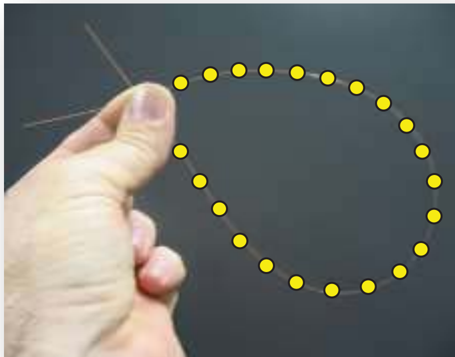
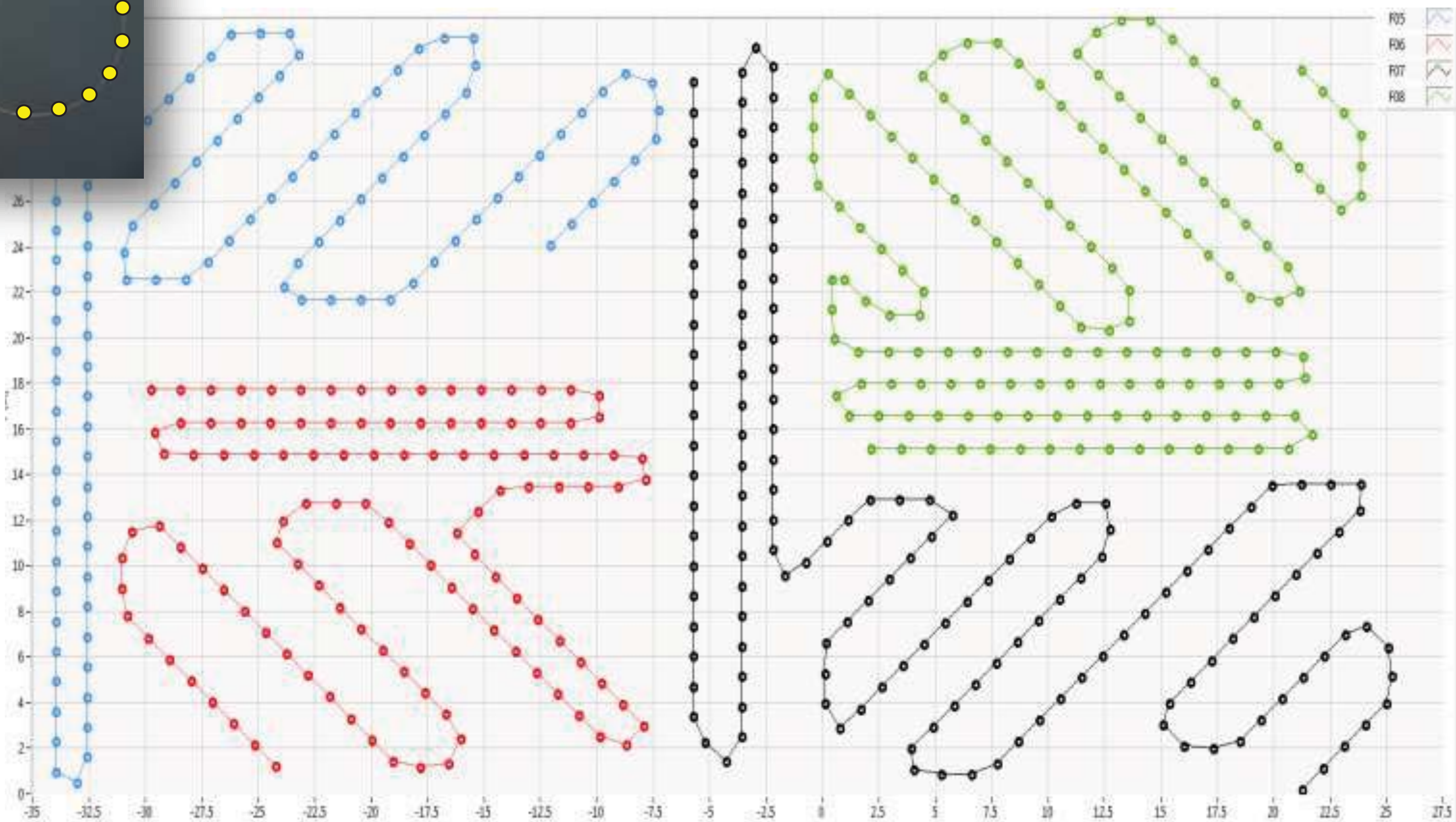
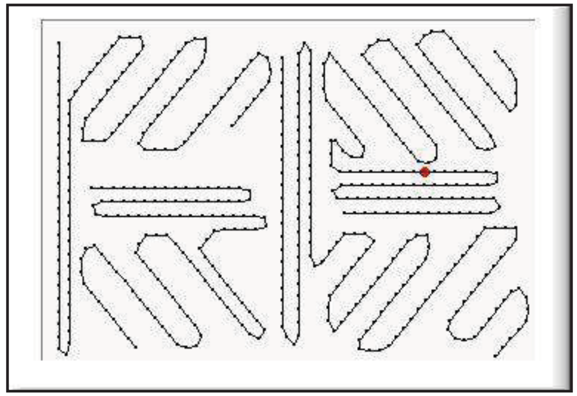
COPV Sensor Mapping – Surface Mounted Fiber





530 Surface strain measurements

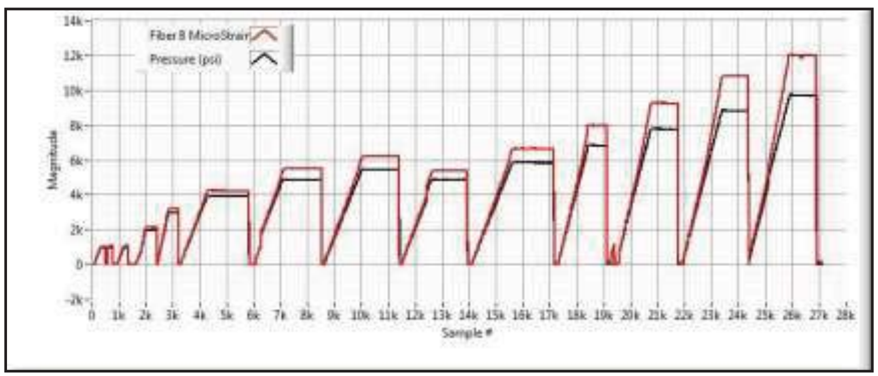
Stiffness / Pressure Monitoring, Individual Sensor



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

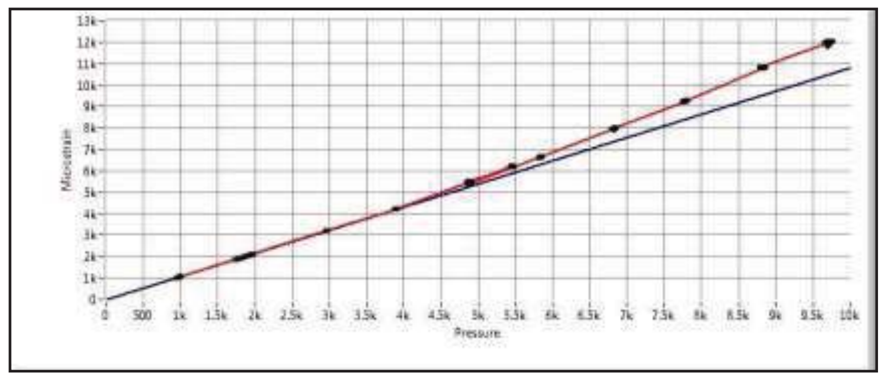
Fiber line #8, FBG #97,

Micro-strain & Pressure (psi) Vs. Time



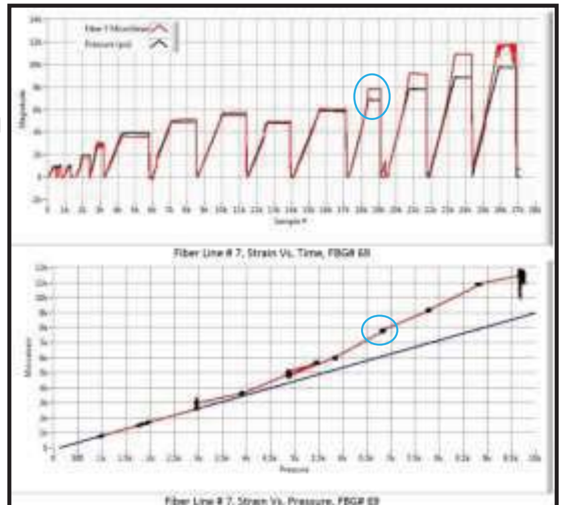
Fiber line #8, FBG #97,

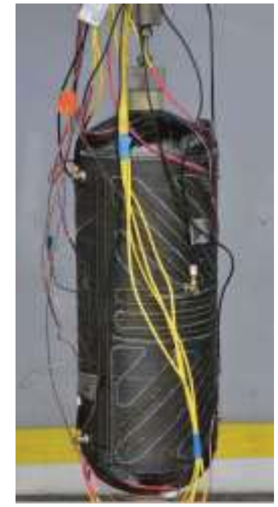
Micro-strain Vs. Pressure (psi)

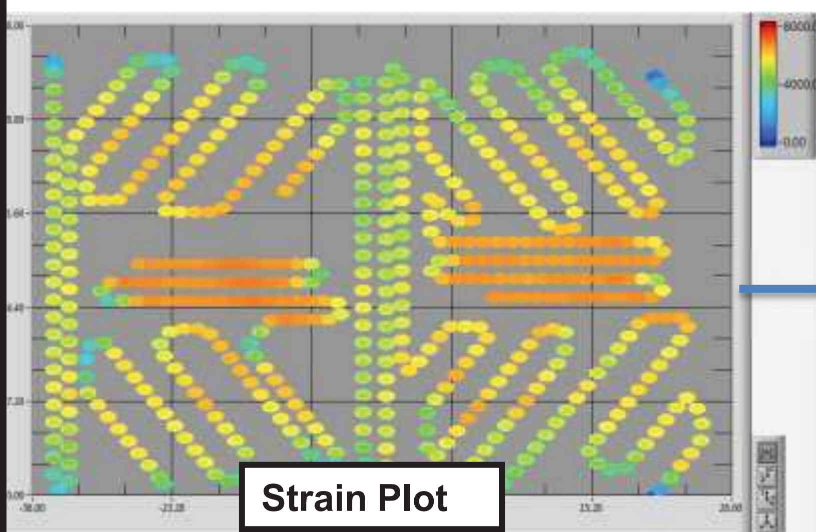


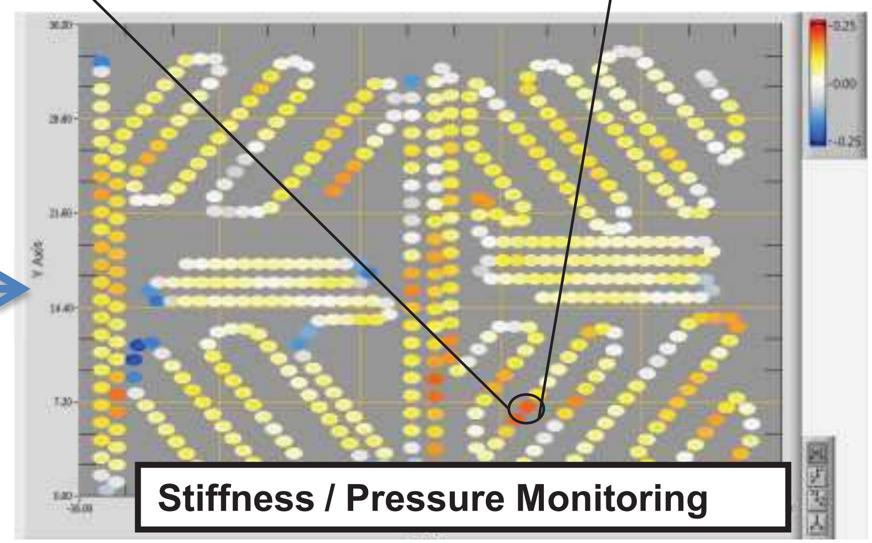
Stiffness / Pressure Monitoring, Global COPV SHM

- **Expands previous studies performed by the Dryden 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**









Thermal Protection System Health Monitoring CSIRO Australia / NNWG

- Combined AE / Fiber Optic thermal monitoring of impact damage to TPS
  - Uses AE sensors to detect and locate impact location
  - An external heat source (e.g. solar) and embedded thermal sensors then monitor local anomalies in the thermal conductivity of the TPS to evaluate functional effects of damage
  - Fiber Bragg grating (FBG) sensors may be used for efficient high-density thermal and strain measurement which is essential for TPS performance validation
  - A modular, distributed agent-based architecture is proposed for robust, scalable operation of the AE and FBG sensing modalities
  - CSIRO Australia has worked with NASA LaRC to develop and demonstrate monitoring of impact damage with multi-agent architecture

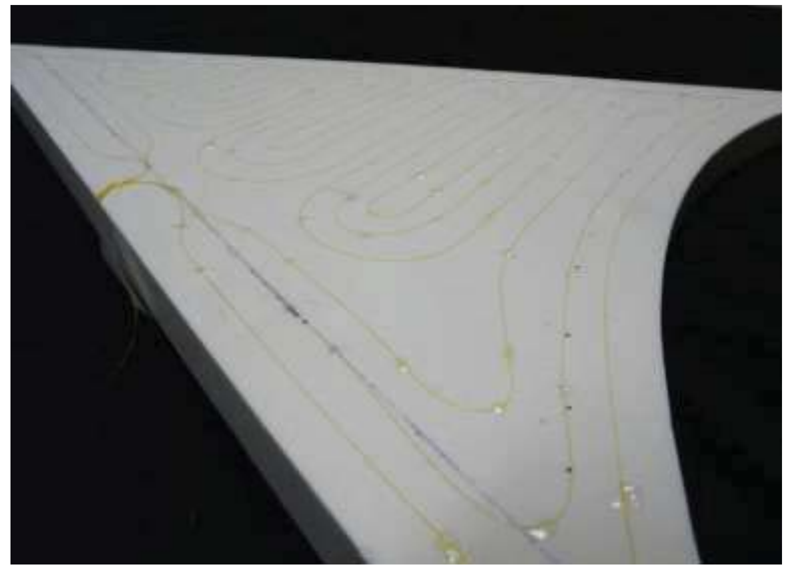
Vehicle Re-entry (conception)

NASA /CSIRO
Concept Demonstrator

Large-scale testing at Armstrong

Temperature Sensing

- Optical Fiber Bragg Gratings (FBGs) are sensitive to strain and temperature
- The gratings have a center frequency of 1542nm and are spaced at 10mm intervals along the fiber
- Each tile has three strands of fiber measuring approximately 3 meters in length (approximately 300 sensor per strand)
- The fibers are bonded to the insulation material 10mm apart as shown



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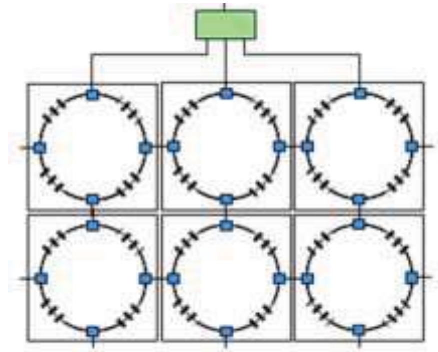
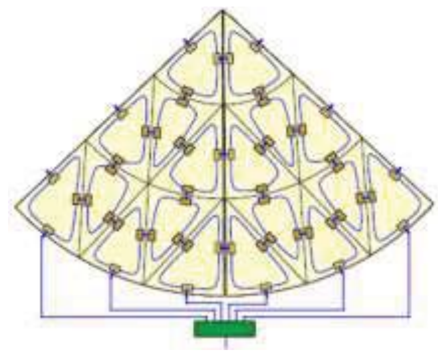
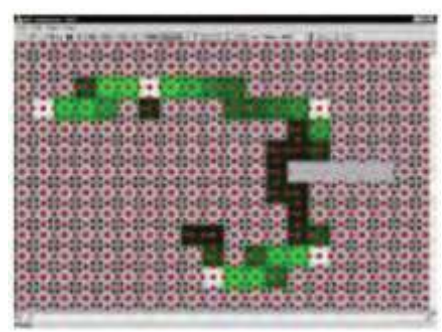
Thermal Protection System Health Monitoring
CSIRO Australia / NNWG

- Robust reconfigurable optical fiber network
  - Use modular agent-based (cellular) architecture, with electronically-switchable fiber segments.
  - Multiple routing configurations enable light to reach any local region
  - Bench-top network will be set up an evaluated as first step, with central control of routing
  - Cellular structure for segmented TPS
- Self-organized configuration control
  - CSIRO technology for self-organized control (e.g. using ant colony optimization algorithm) to define shortest undamaged path to region of interest.
  - Demonstrate on segmented test structure.

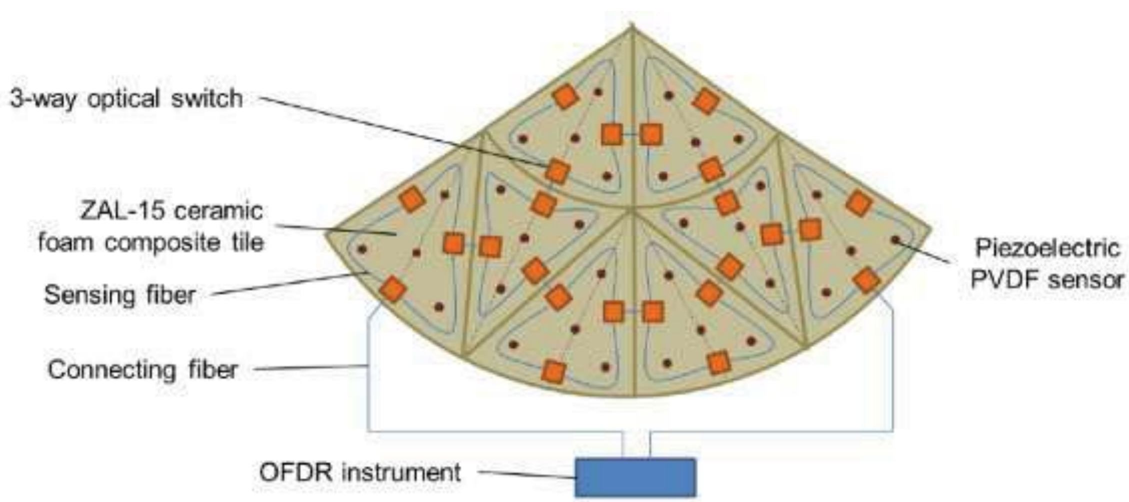






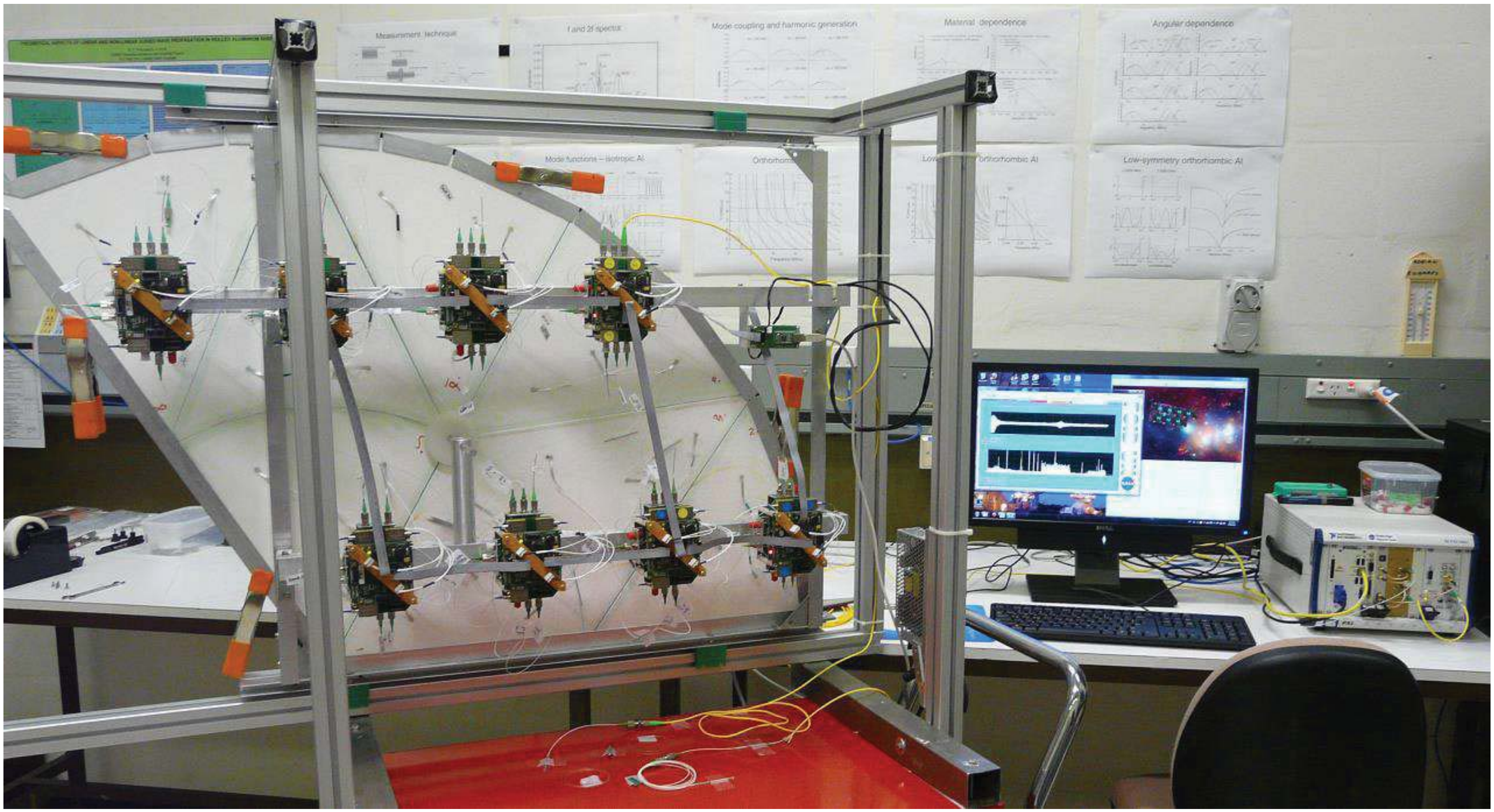
Final System Design

- The final design of the systems consists of 8 triangular tiles
- The 8 tiles will cover a 120 degree segment of a 5 foot diameter circle
- Each tile has an optical and electrical connection to their adjacent neighbor
- OFDR instrument has 2 channels to connect to the sensing network



Schematic of Demonstrator
(plan view)

Complete TPS Monitoring System Demonstrator



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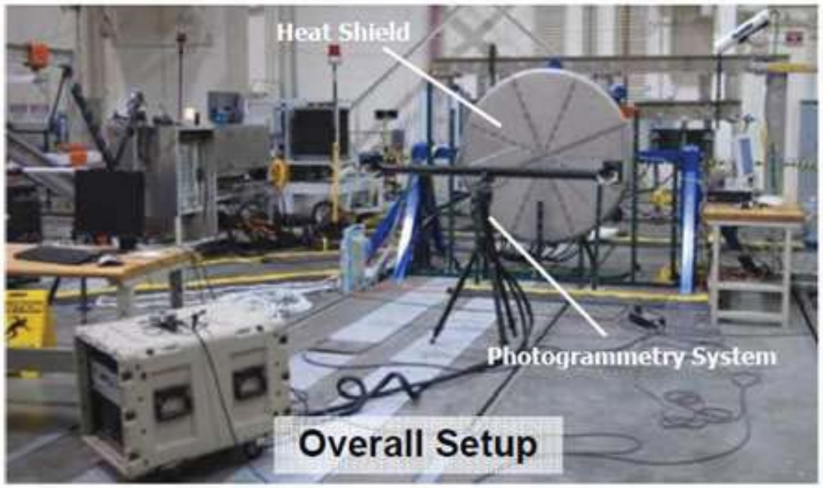
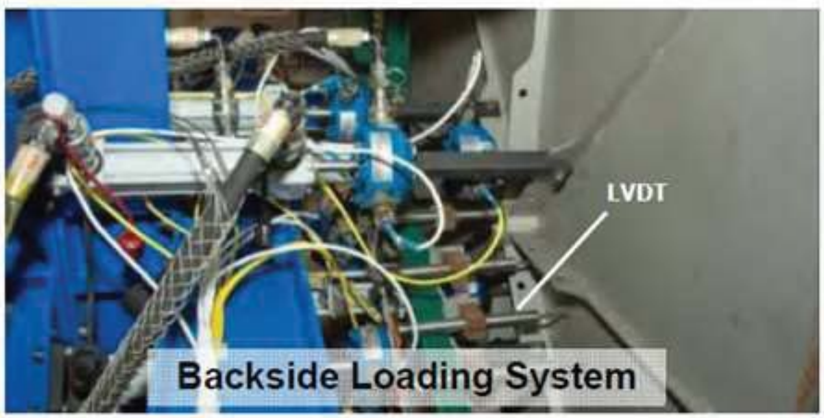
TPS Heat Shield



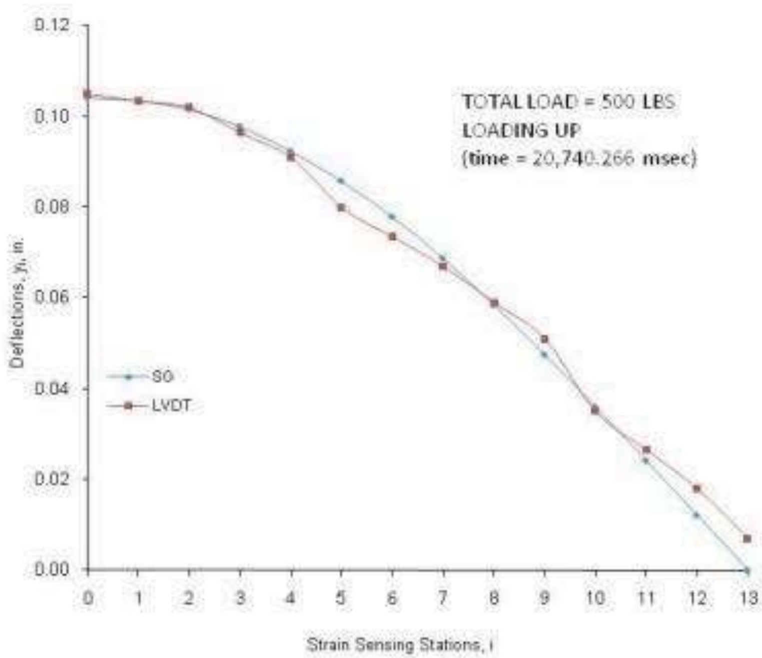


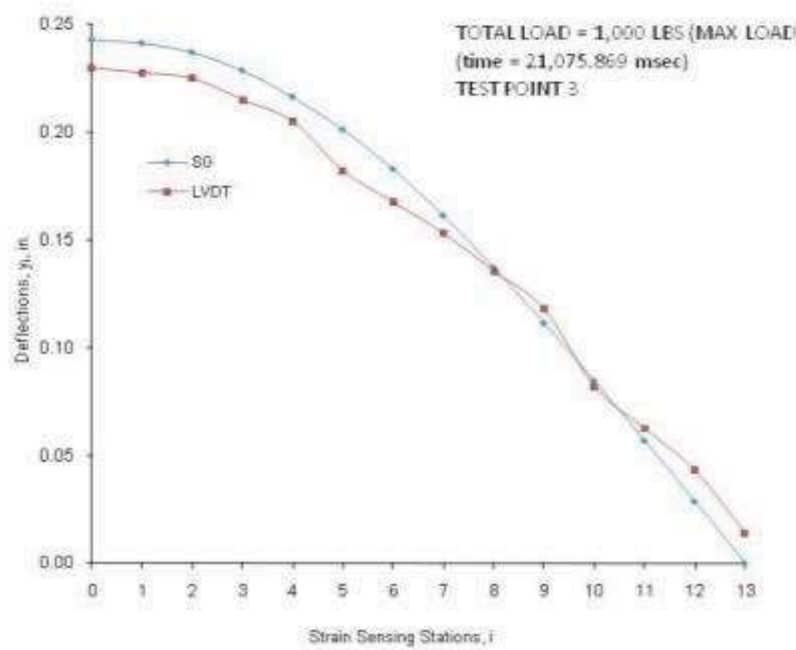
TPS Shape Sensing Algorithm

Completed room-temperature mechanical loading test to 1000 lbs

Demonstrated Displacement Theory using strain gages

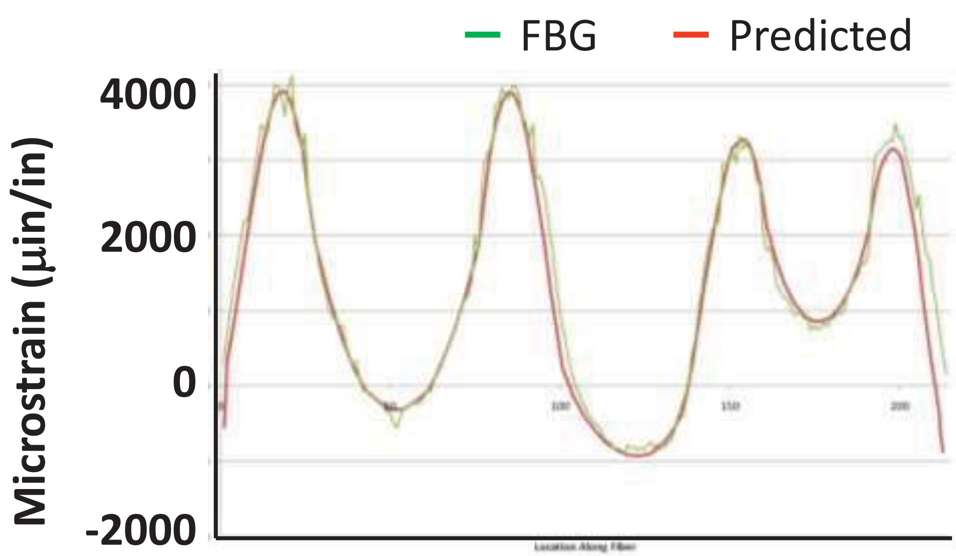
- Good correlation with LVDT measurements
- Processing fiber optic strain results for displacement theory application





Strain Sensing
Composite Crew Module

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



Inner Hatch FBG Strains, Max Pressure

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

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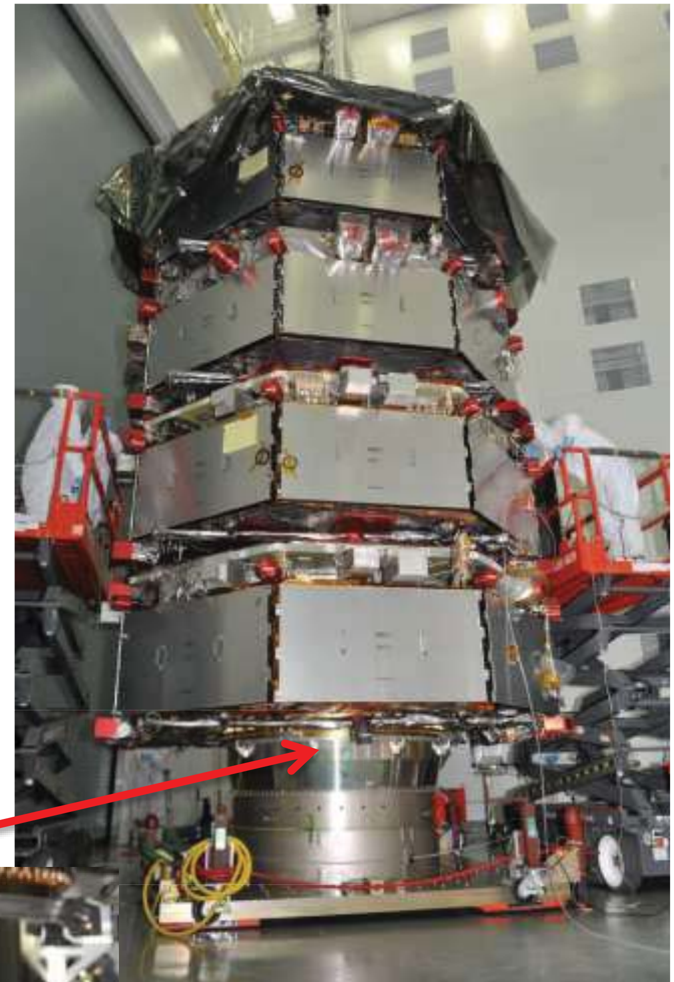
Installation of FOSS on Magnetospheric Multiscale Mission (MMS) Clamping Band

The purpose of this task is to provide FOSS support for environmental testing of the MMS stacked structure. The goal is to monitor the strain distribution throughout the various stages of testing to understand how the clamping load redistributes around the band.

Sensor installation:

- Two 20ft fiber optic sensing runs were installed on this 1.5” wide, 66” diameter band, one at the top of the band and the other at the bottom (see photo below)
- This installation was performed at GSFC in their spacecraft staging cleanroom
- A sensor zero was measured during a relaxed position for the clamping band and will be used as reference throughout all test stages



MMS Stacking Procedure

FOSS Sensing fiber mounted onto the clamping band

FOSS lead fiber

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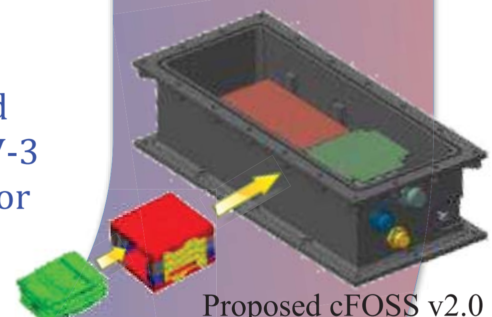
Compact Fiber Optic Sensing System (cFOSS)

- cFOSS has been 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 is 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.

Milestones

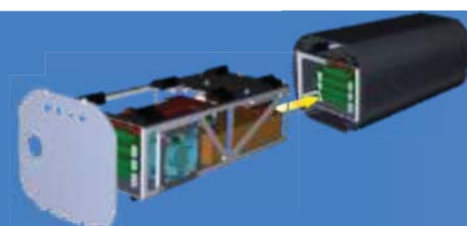
- Completed the design and development of cFOSS v1.0 convection cooled
- Flight demonstrated cFOSS v1.0 onboard NASA Dryden's small UAV, APV-3
- Completed design and fabrication of components for cFOSS v2.0 ready for system integration
- Collaborating with KSC and Orbital to fly cFOSS v2.0 on Antares in FY15
- The previous generation FOSS was a 2013 R&D 100 Winner

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



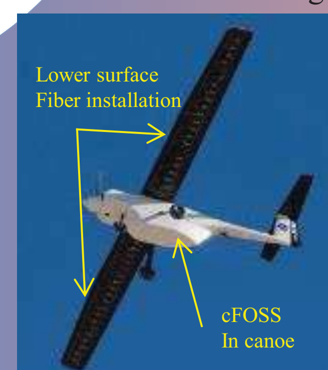
Proposed cFOSS v2.0 Design (FY13-14)

Original Flight FOSS System Onboard Global Observer



Proposed cFOSS v1.0 Design

cFOSS v1.0



cFOSS v1.0 onboard APV-3

Anticipated Impact of Fiber Optic based SHM

- 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

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Questions?