National Aeronautics and Space Administration

Advanced Fiber Optic-Based Sensing Technology for Unmanned Aircraft Systems

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UAS Payloads Conference

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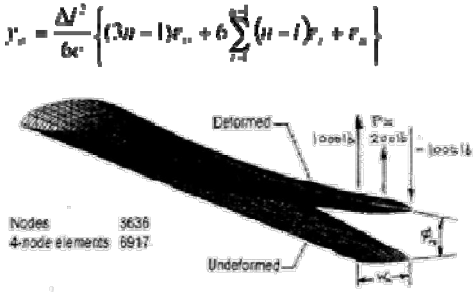
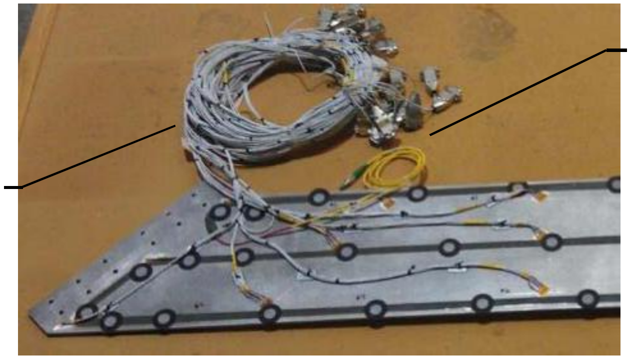
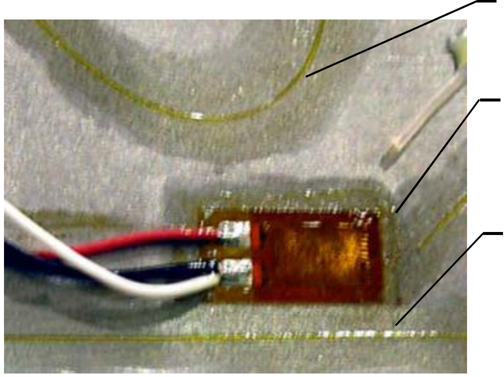
Fiber Optic Sensing for UAS Applications
Advantages over Conventional Measurements

- **Unrivaled density of sensors for spatially distributed 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 out-of-plane displacement and load at points along the fiber**
- **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 (cryo – 550F)**







Fiber Optic Sensing for UAS Applications

Anticipated Impact

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

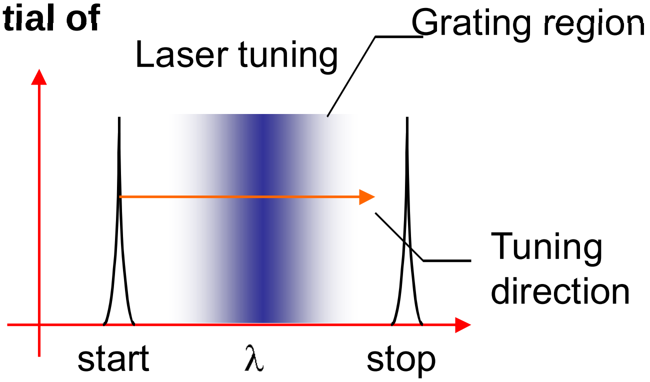
Source: COTS Journal

defenseindustrydaily.com

Fiber Optic System Operation Overview

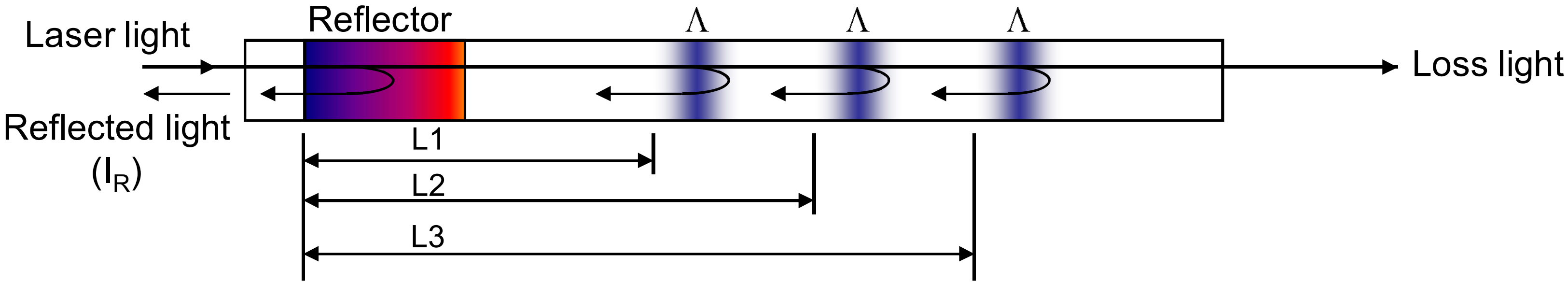
Fiber Optic Sensing with Fiber Bragg Gratings

- **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

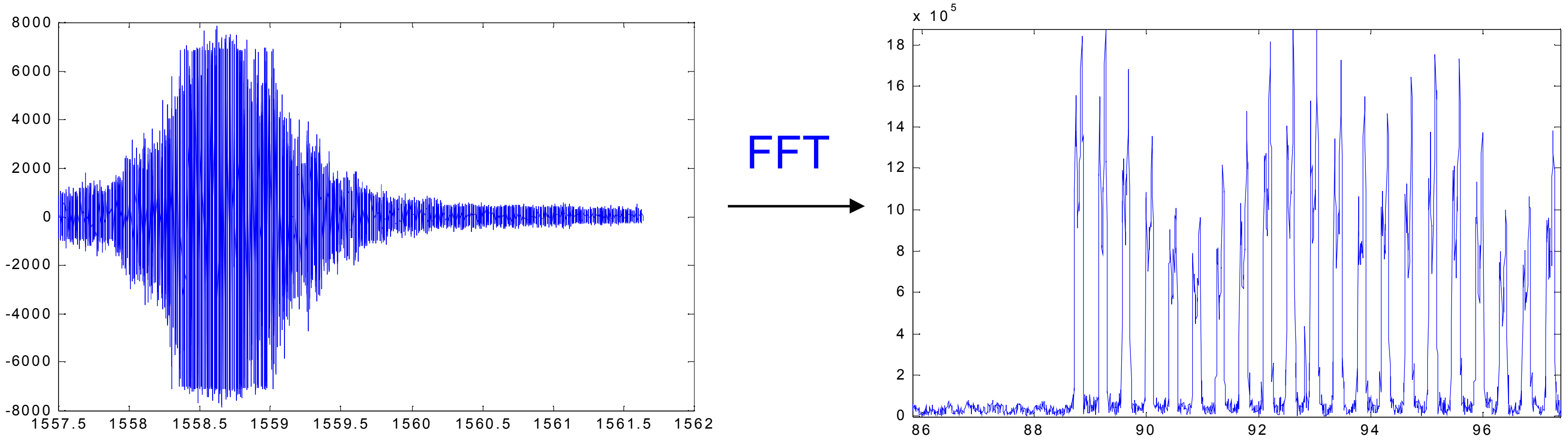


Fiber Optic System Operation Overview

- **Fourier transforms (both forward and inverse) are used to discriminate between gratings**
- **The Fourier transform separates the I_R waveform into sinusoids of different frequency which sum to the original waveform**

	FFT	**iFFT**
Traditional	**Time(T) > Frequency(F)**	**Frequency(F) > Time(T)**
Optical	**Wavelength(λ) > Length(L)**	**Length(L) > Wavelength(λ)**

Spectral Mapping

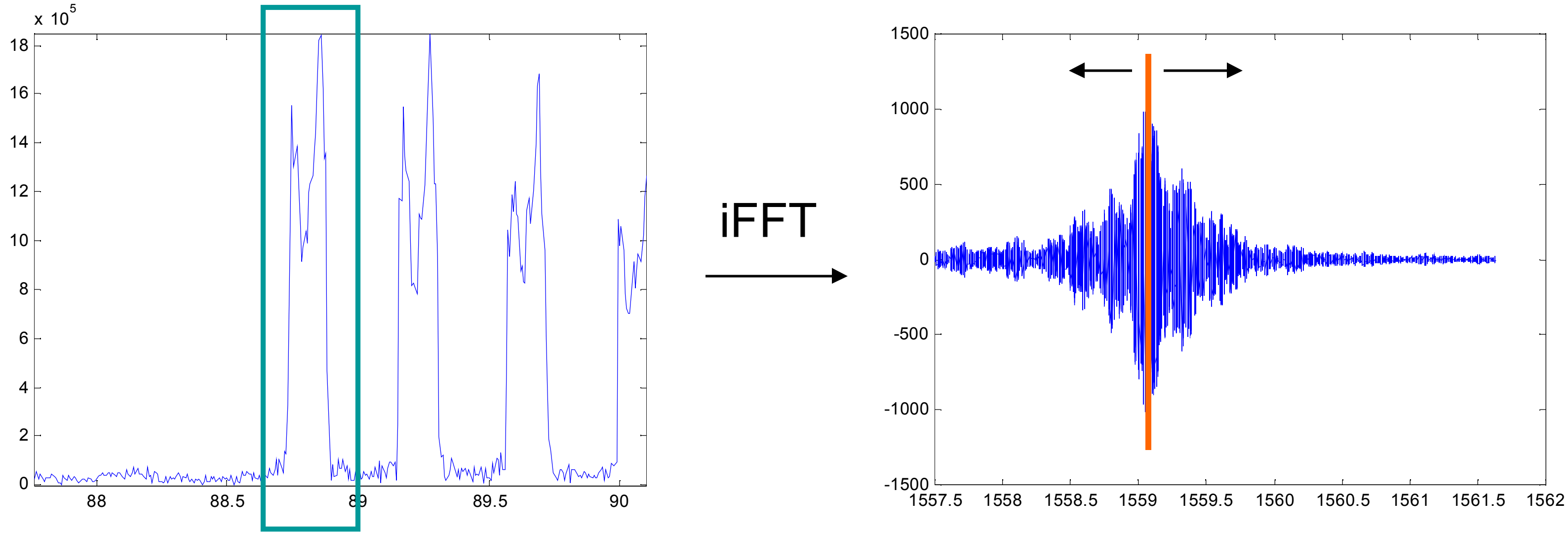


Wavelength(λ) domain

Length(L) domain

Fiber Optic System Operation Overview

- **By bandpass filtering around a specific frequency (grating location) within the length domain and performing an iFFT, the spectrum of each grating can be independently measured and strain inferred (FM radio)**



Length(L) domain (inches)

Wavelength(λ) domain

- **Using a centroid function the center wavelength can be resolved**
- **The wavelength change is proportional to the induced strain**

$$\boxed{\frac{\Delta\lambda}{\lambda} = K\varepsilon}$$

K **– proportionality constant (0.7-0.8)**

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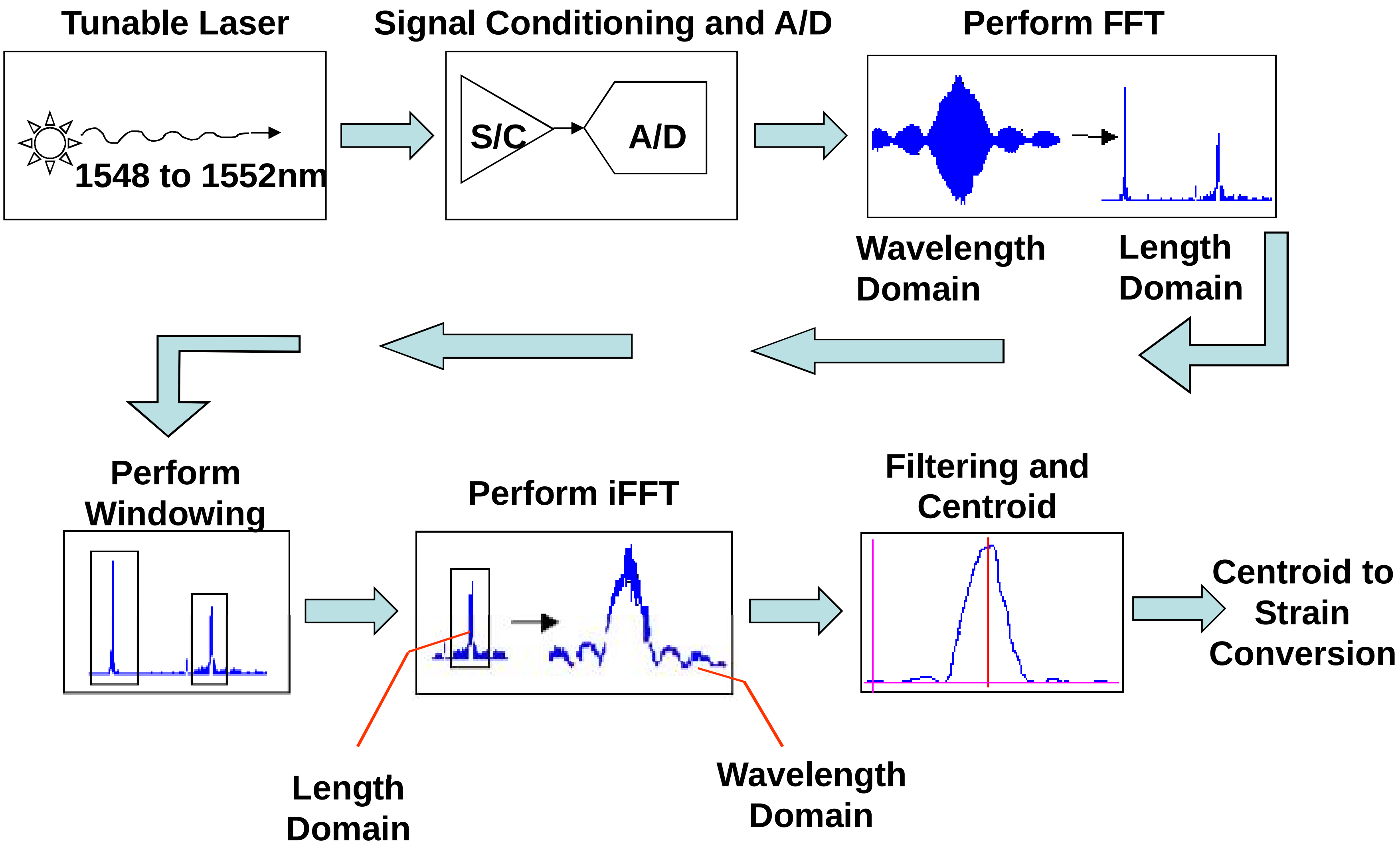
Interrogation Process



Tunable Laser

Signal Conditioning and A/D

Perform FFT

Wavelength Domain

Length Domain

Perform Windowing

Perform iFFT

Filtering and Centroid

Centroid to Strain Conversion

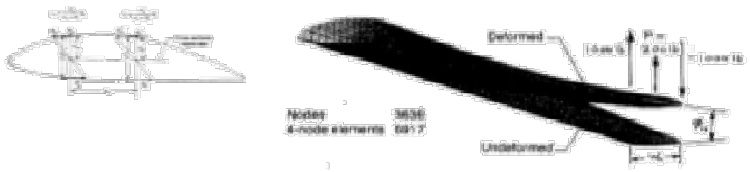
Length Domain

Wavelength Domain

Research and Technology Development Areas

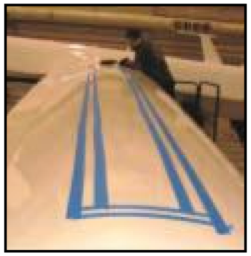
- **Algorithm Development**

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

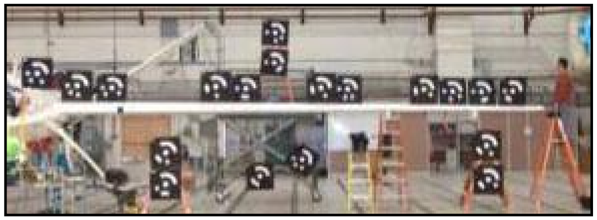


- **FBG System Development**

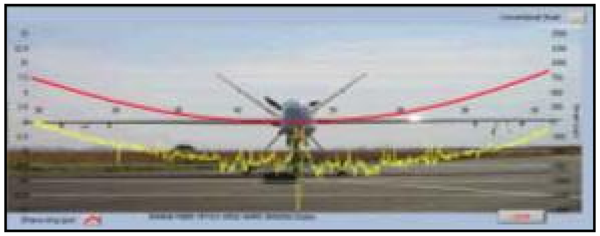
- **Instrumentation**



- **Ground Testing / R&D**



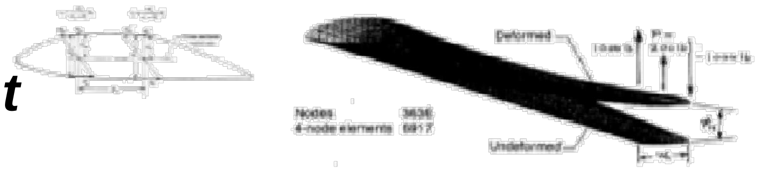
- **Flight Testing**

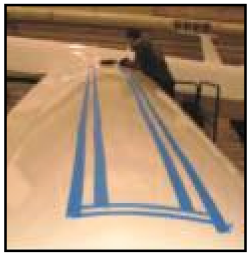


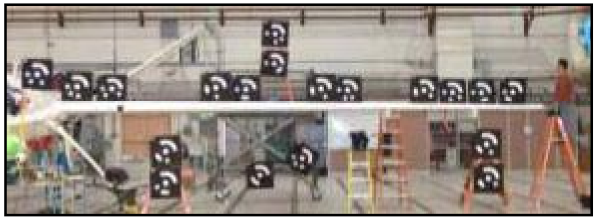
Research and Technology Development Areas

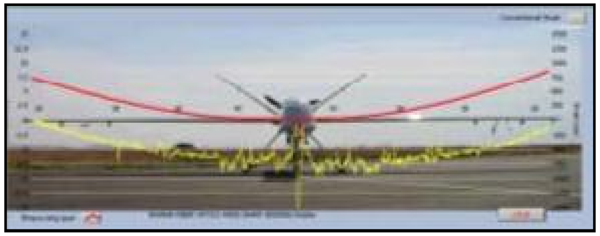
- **Algorithm Development**
  - ***Real-time wing shape measurement using fiber optics sensors***
    (Ko, Richards; Patent 7,715,994)
  - ***Real-time applied loads on complex structures using fiber optic sensors***
    (Richards, Ko; Patent 7,520,176)
  - ***Data processing algorithms***
    (Parker, US Patent Pending)
- **FBG System Development**
- **Instrumentation**
- **Ground Testing / R&D**
- **Flight Testing**

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









Real-time Wing Shape Measurement

Motivation – Helios UAV

Helios wing dihedral on takeoff

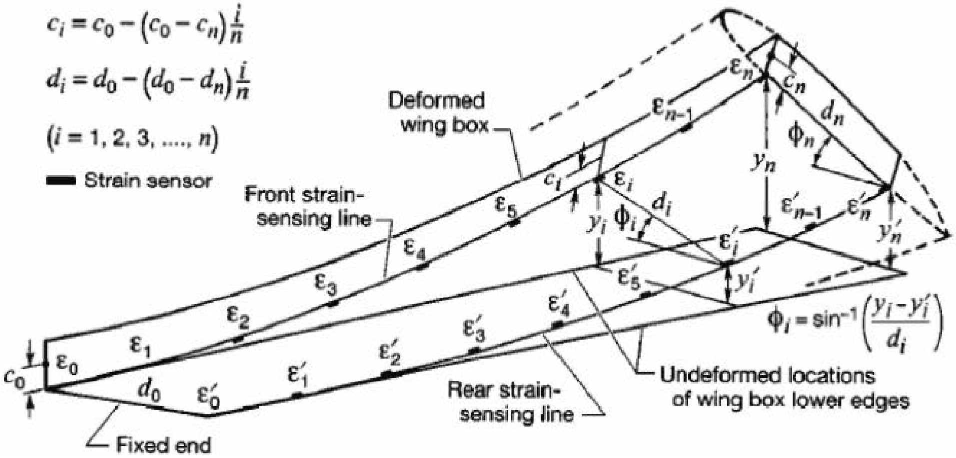
In-flight breakup

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**

Real-time Wing Shape Measurement

Theoretical Development



Deflection of a Single Fiber:

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

Slope:

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

Typically the first station is at the root:

$$y_0 = \tan\theta_0 = 0$$

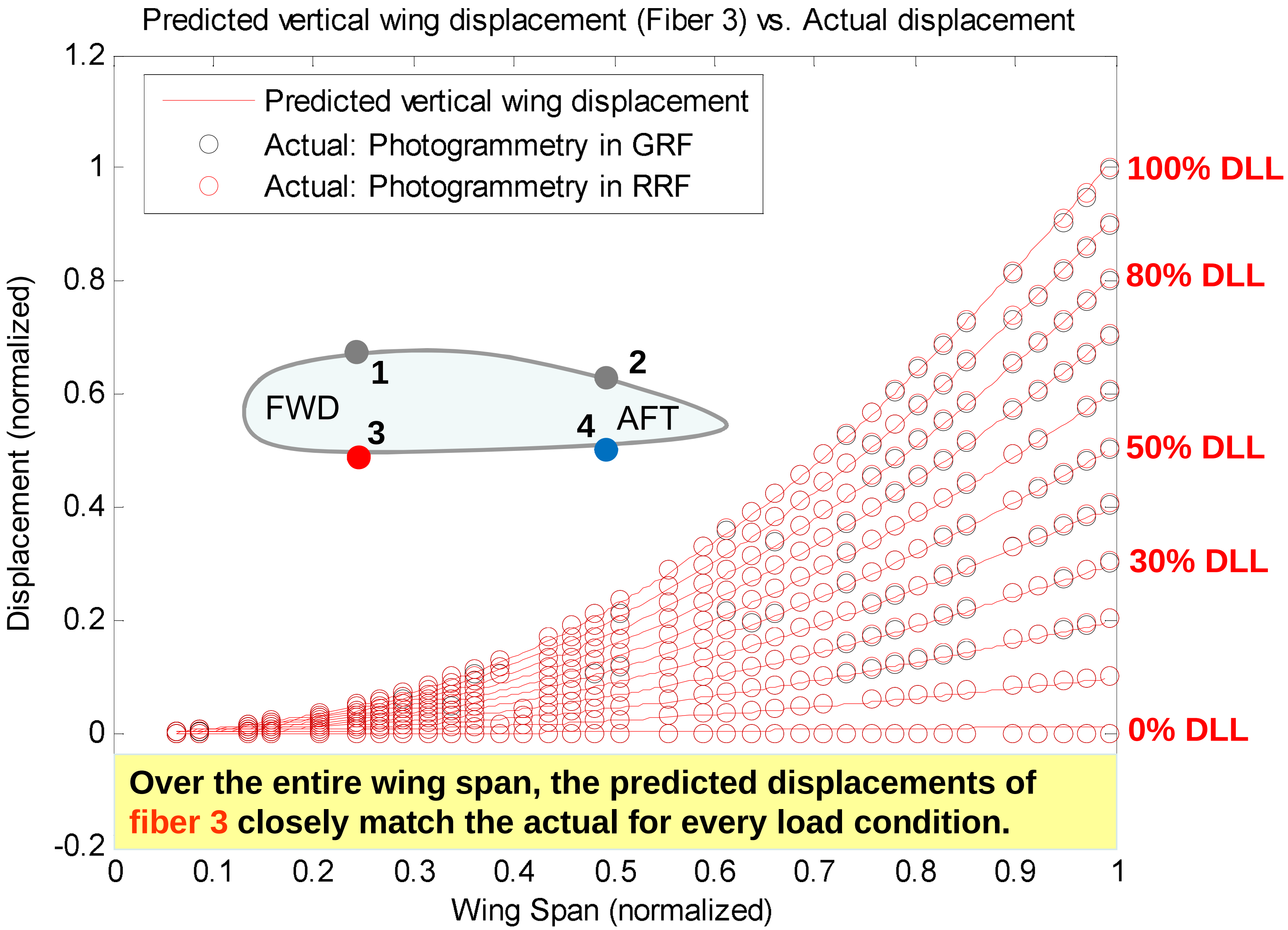
Real-time Wing Shape Measurement

Global Observer – Algorithm Validation Testing

- **Strain gages**
  - Validate the FBGs
  - Not used for shape prediction, used for structural evaluation
- **Photogrammetry**
  - Provided validation information for wing shape prediction
  - Measures actual displacement vectors at target points
  - 10 photogrammetry images taken per load condition

Real-time Wing Shape Measurement

Global Observer – Algorithm Validation Testing



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

Real-Time Externally-Applied Loads

Approach

- **Bending moment calculated at each analysis station**
- **Cross-sectional properties calculated by applying known load**
  - EI/c term backed out at each evaluation station
- **With properties known, strain can be directly related to bending moment**

Known moment

Measure strains

$$\frac{M}{\varepsilon} = \left(\frac{EI}{c}\right)$$

Get properties at each station

Unknown moment

Measure strains

$$\left(\frac{EI}{c}\right) \cdot \varepsilon = M$$

Calculate moment at each station

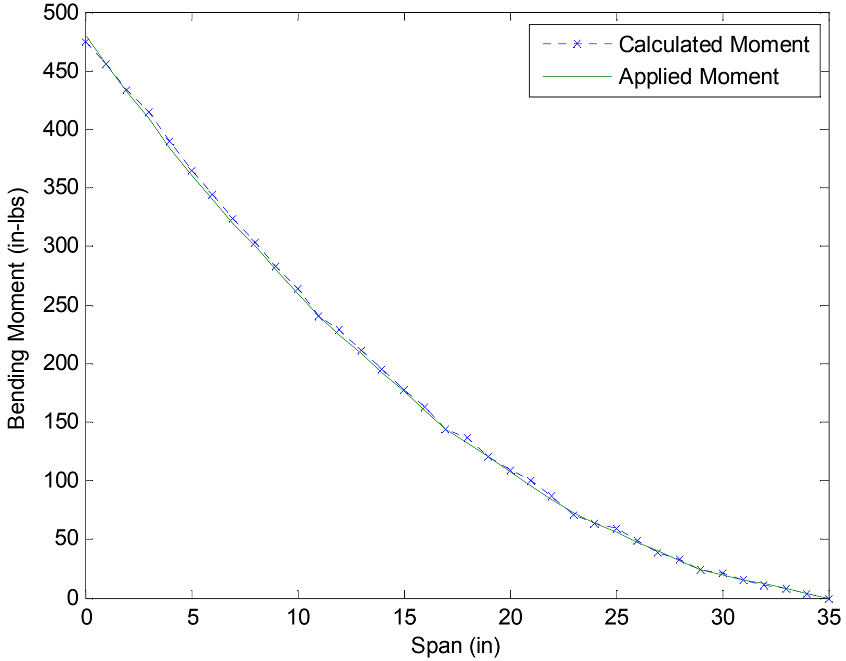
Real-Time Externally-Applied Loads

Swept Plate Loads Testing

Cross-sectional properties calculated using *Uniform* load calibration

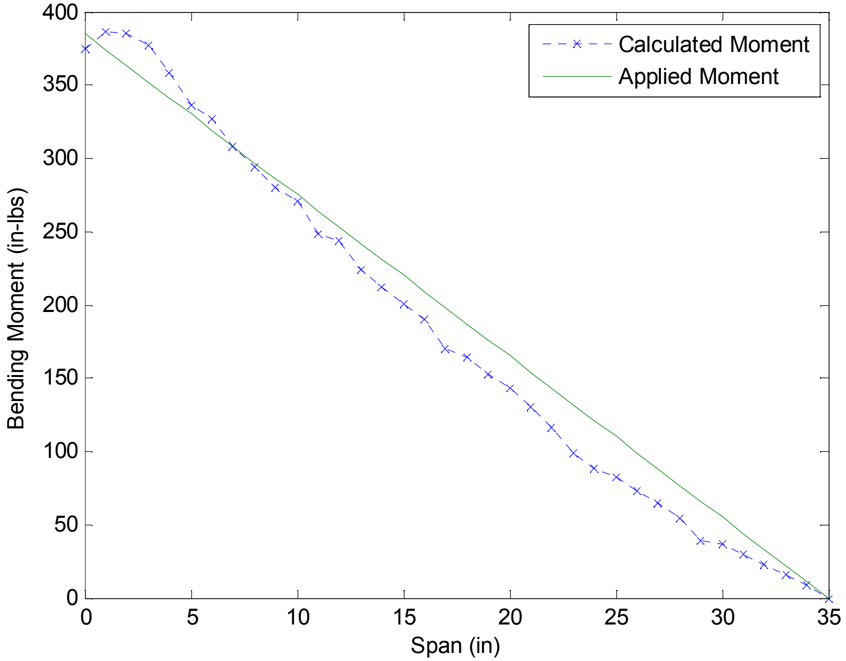
Uniform Load Case

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{UniformB}$$



Single Point Load Case

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{SinglePt}$$



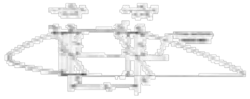
Wing Shape and Externally-Applied Loads

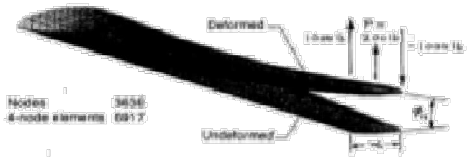
Results

- **Deflection calculations are accurate (within ~5%)**
  - Different test articles
  - Different load cases
  - Different load magnitudes
- **Load results will be improved**
  - Least-squares method
- **Developing methods to further use FOSS measurements**
  - Angle-of-twist
  - Improved deflection and load
  - Torque

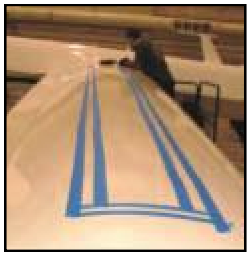
Research and Technology Development Areas

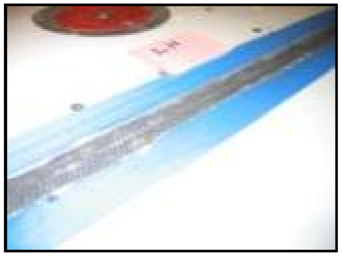
$$y_n = \frac{\Delta l^2}{6c}\left\{(3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1}(n-i)\varepsilon_i + \varepsilon_n\right\}$$

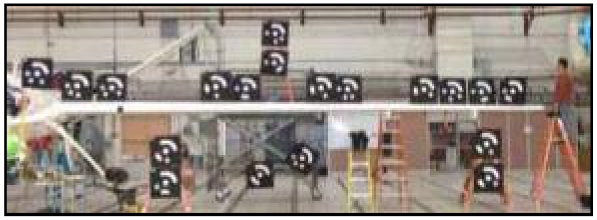


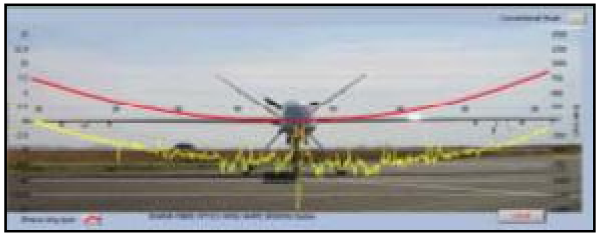


- – Algorithm Development
- – **FBG System Development**
- – Instrumentation
- – Ground Testing / R&D
- – Flight Testing









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NASA Technology FOSS Systems (4DSP)

- **Technical Highlights**
  - 4DSP has licensed NASA technology to commercially develop FOSS systems
    - http://www.4dsp.com/RTS150.php
  - Single laser greatly reduces cost per sensor
  - High fiber count systems
    - Modular design with 8 channels per card
    - Expandable
    - Up to 32 fibers possible
    - Up to sensing 80 feet per fiber
  - 11” x 7” x 12”
  - 100 Hz max sample rate
  - Lightweight system for multitude of sensors
    - Approximately 25 lbs
- **Cost**
  - 8 fiber system approx $100K
    - Up to 16,000 sensors
  - 32 fiber system approx $150K
    - Up to 64,000 sensors
  - System can be flight-certified (+$30K)
    - Low power requirements (<10 Amps at 28 Volts DC)
- **Applications**
  - Transport Aircraft, Ships, Civil Structures

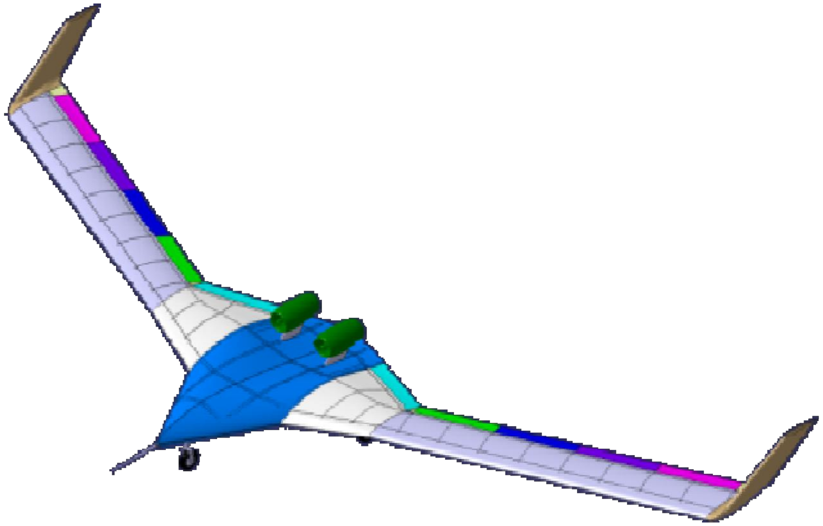
Ground system

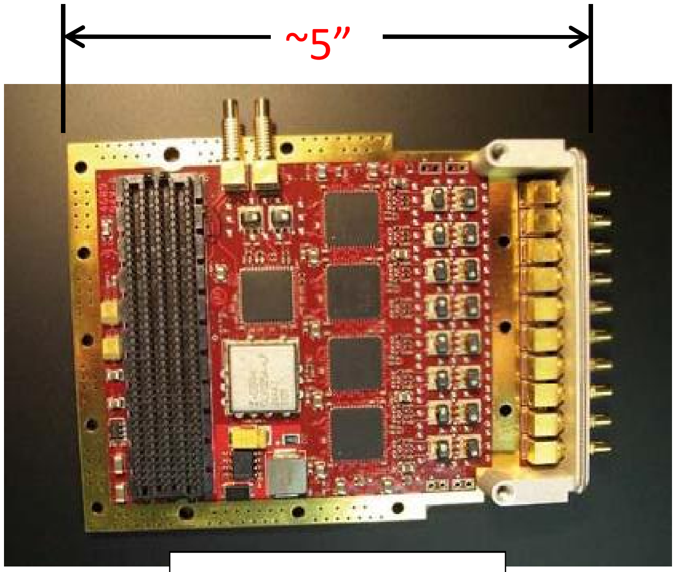
Flight system

Compact FOSS (cFOSS) System

In Development

- **Lightweight, ruggedized system**
  - Packaged within a 6” cube
- **Targeted specifications:**
  - Fiber count: 8
  - Max Fiber length: 80 ft
  - Max # sensors/system:15,360
  - Max Sample rate: 100 Hz
  - Power: 50W @ 28Vdc
  - Weight: <10 lbs
  - Size: 5 x 6 x 6 in
  - Vibration and Shock: NASA Curve B
  - Altitude: 65kFt
- **Applications:**
  - Fighter aircraft
  - UAVs
  - Launch vehicles
  - Spacecraft
- **Target system cost: $50K**
- **Availability: End of 2012**



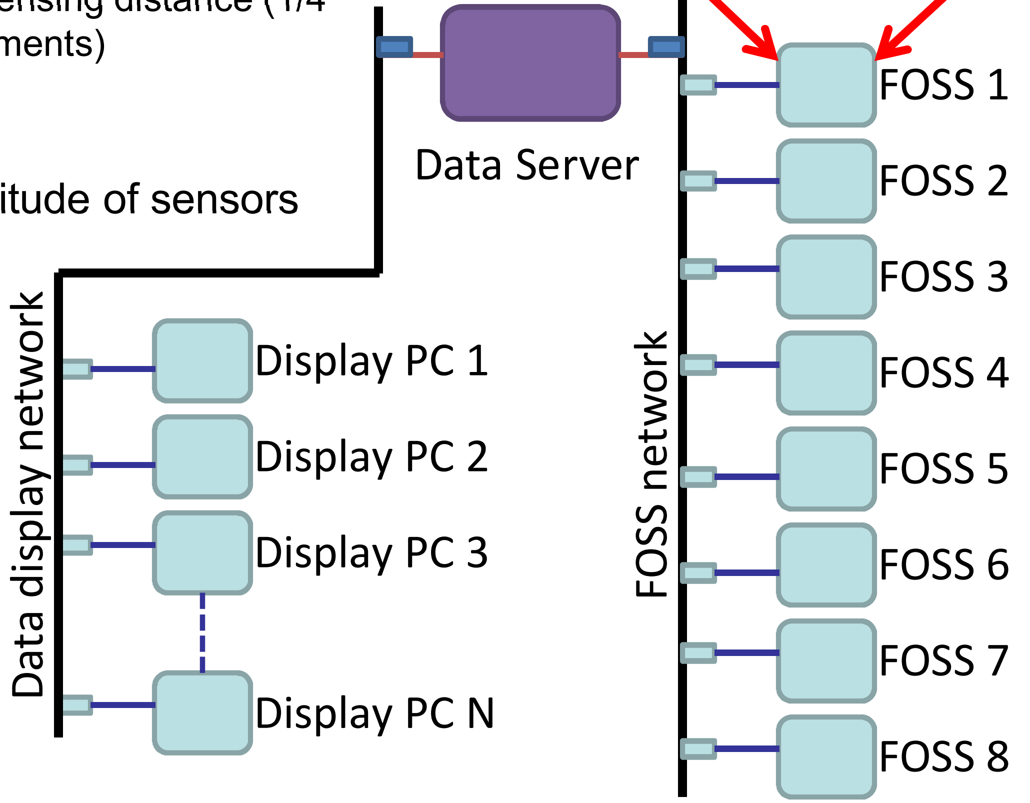


8-Fiber Card

Large Scale FOSS (LsFOSS) Technology

- **Technical Highlights**
  - Single laser greatly reduces cost per sensor
  - High fiber count systems
    - Up to 16 fibers monitored simultaneously/system
    - Each fiber can be up to 40ft long
    - Each fiber at 40ft long can have up to 2000 measurements (total of 32,000 /system)
    - Up to 8 systems can be networked together yielding approx. 1 mile of sensing distance (1/4” spacing, 256,000 measurements)
  - 11” x 7” x 12”
  - 100 Hz max sample rate
  - Lightweight system for multitude of sensors
    - Approximately 25 lbs
- **Applications:**
  - Transport Aircraft
  - Ships
  - Civil Structures
  - Ground Testing
  - Structures Laboratory

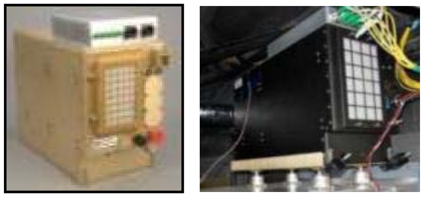
FOSS Ground System



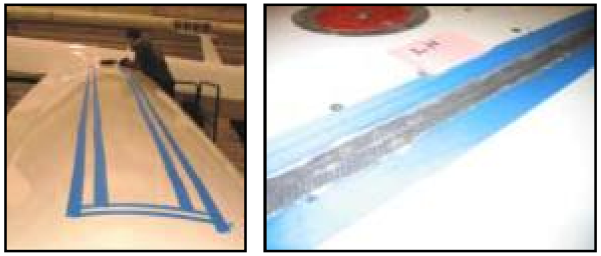
Research and Technology Development Areas

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

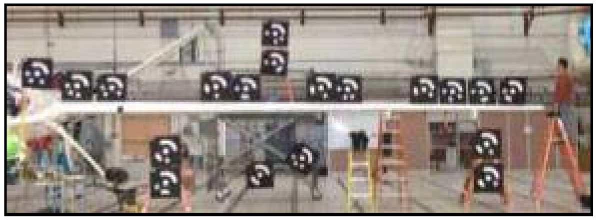
- Algorithm Development



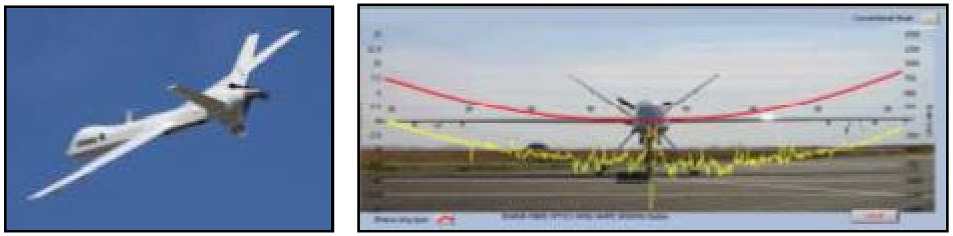
- FBG System Development



- **Instrumentation**



- Ground Testing / R&D



- Flight Testing

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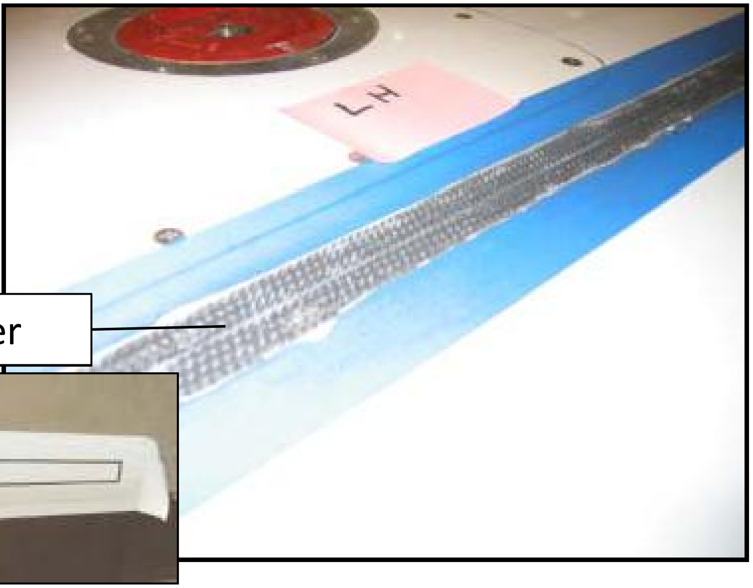
FOSS Installation Advantages and Challenges

Installation Advantages

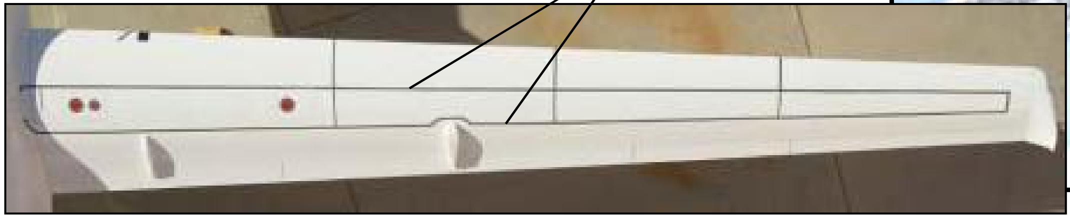
- **Greatly reduced installation time compared to conventional strain gages**
  - 2 man-days for 40’ fiber (1000 strain sensors for a continuous surface run)
  - Multiple sensors installed simultaneously
  - Same surface preparation and adhesives as conventional strain gages
  - Minimal time spent working on vehicle
  - All connectors can be added prior to installation, away from part
  - No soldering
  - No clamping pressure required
  - Circular cross-section eliminates possibility of trapping air between sensor and part (eliminates repeat installations)
- **Can be installed with little or no impact to OML**

Installation Challenges

- **Optical fiber more fragile than strain gages**
- **Some measurement locations not practical due to fiber minimum bend radius**
- **Not practical if only interested in spot measurements**



Optical Fiber



Research and Technology Development Areas

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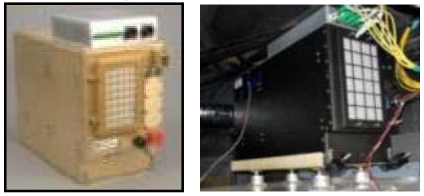
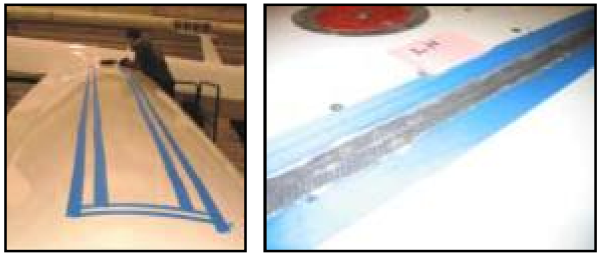
- Algorithm Development

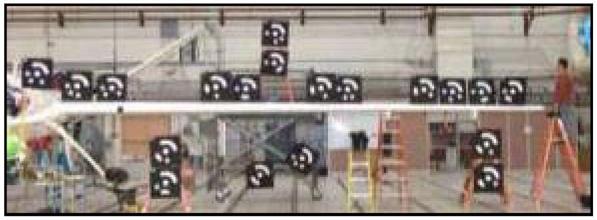
- FBG System Development



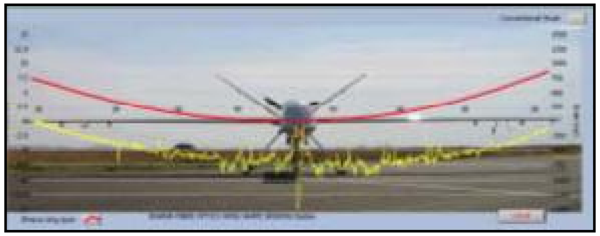
- Instrumentation



- **Ground R&D**



- Flight Testing



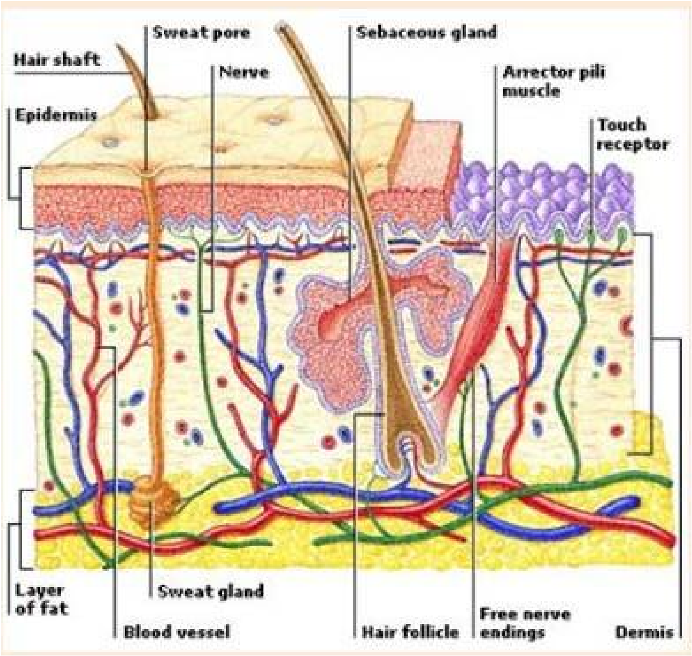
Embedment of Fiber Optic Sensors within Composites

Biological Inspiration of FOSS

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

One square-inch of human skin



Source: Biswas, Aman. Explore the Human Body.

Embedment of Fiber Optic Sensors within Composites

The Multidisciplinary Challenge

- **Fiber Optic Sensors embedded within Composite Overwrapped Pressure Vessels**
- **Goal is to understand embedded FBG sensor response**
  - Requires comprehensive, multi-disciplinary approach

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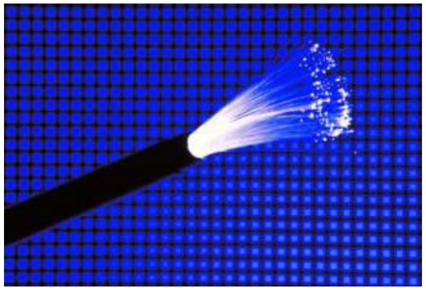
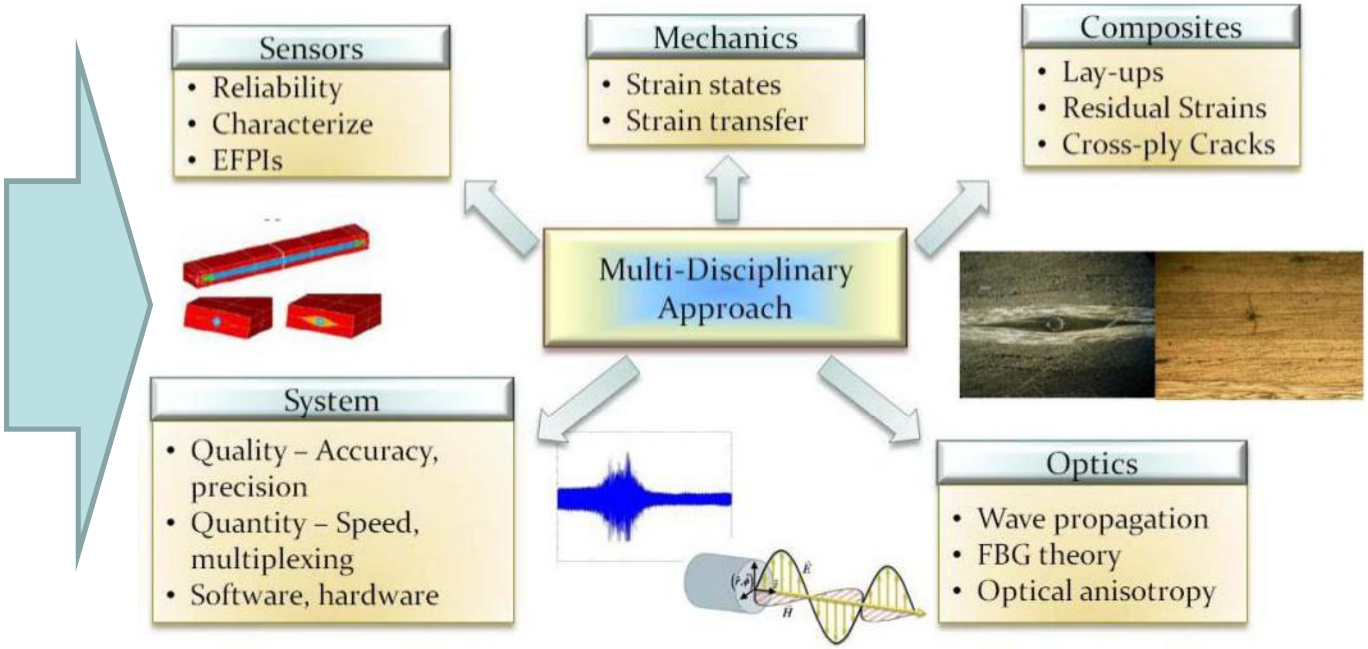




Sensors
- Reliability
- Characterize
- EFPIs

Mechanics
- Strain states
- Strain transfer

Composites
- Lay-ups
- Residual Strains
- Cross-ply Cracks

Multi-Disciplinary Approach

System
- Quality – Accuracy, precision
- Quantity – Speed, multiplexing
- Software, hardware

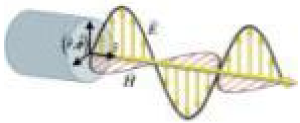
Optics
- Wave propagation
- FBG theory
- Optical anisotropy

Courtesy: M Emmons, GP Carman, UCLA

Embedment of Fiber Optic Sensors within Composite Overwrapped Pressure Vessels (COPVs)

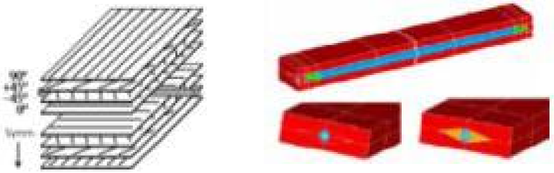
The Goal: Characterize measurement response of fiber Bragg sensors embedded in COPVs

- Determine overall sensor accuracy as a function of its orientation relative to the layered materials in the structure
- Use finite element techniques to understand the thermal/mechanical loads present in the fiber optic, lenticular resin rich region, and the adjacent composite material as well as issues related to ingress/egress.
- Experimentally evaluate the accuracy and long term durability of the embedded sensor / host material system when subjected to quasi-static thermal mechanical loading



Theoretical development

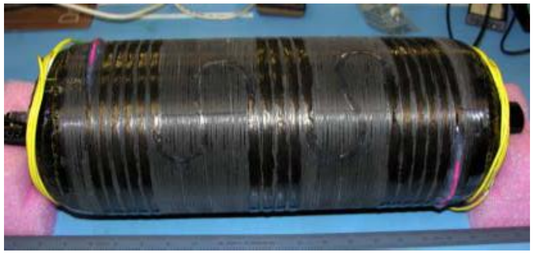
Coupon testing



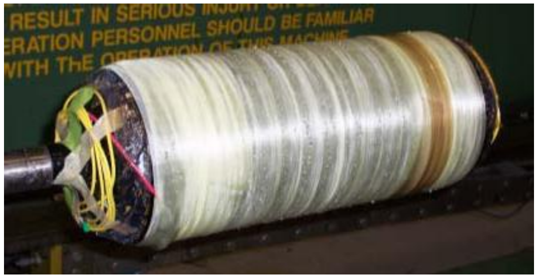
Analysis and Modeling

The Approach: Evaluate accuracy and long term durability of a fiber optic sensors embedded within COPVs

- Analytical modeling of the fiber optic sensor
- Epoxy composite fabrication
- Quasi-static testing of coupons
- Long term fatigue testing
- Testing of representative aerospace



Sensor Installation

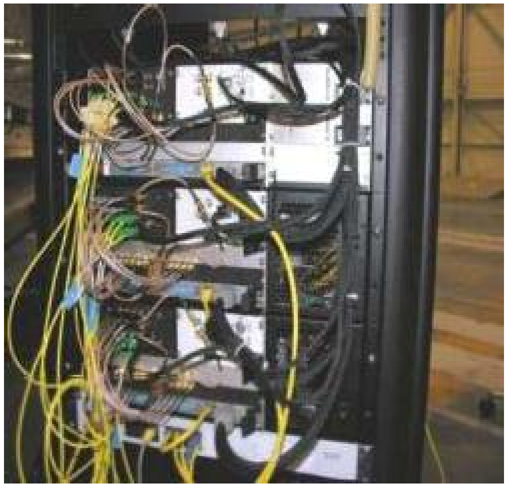


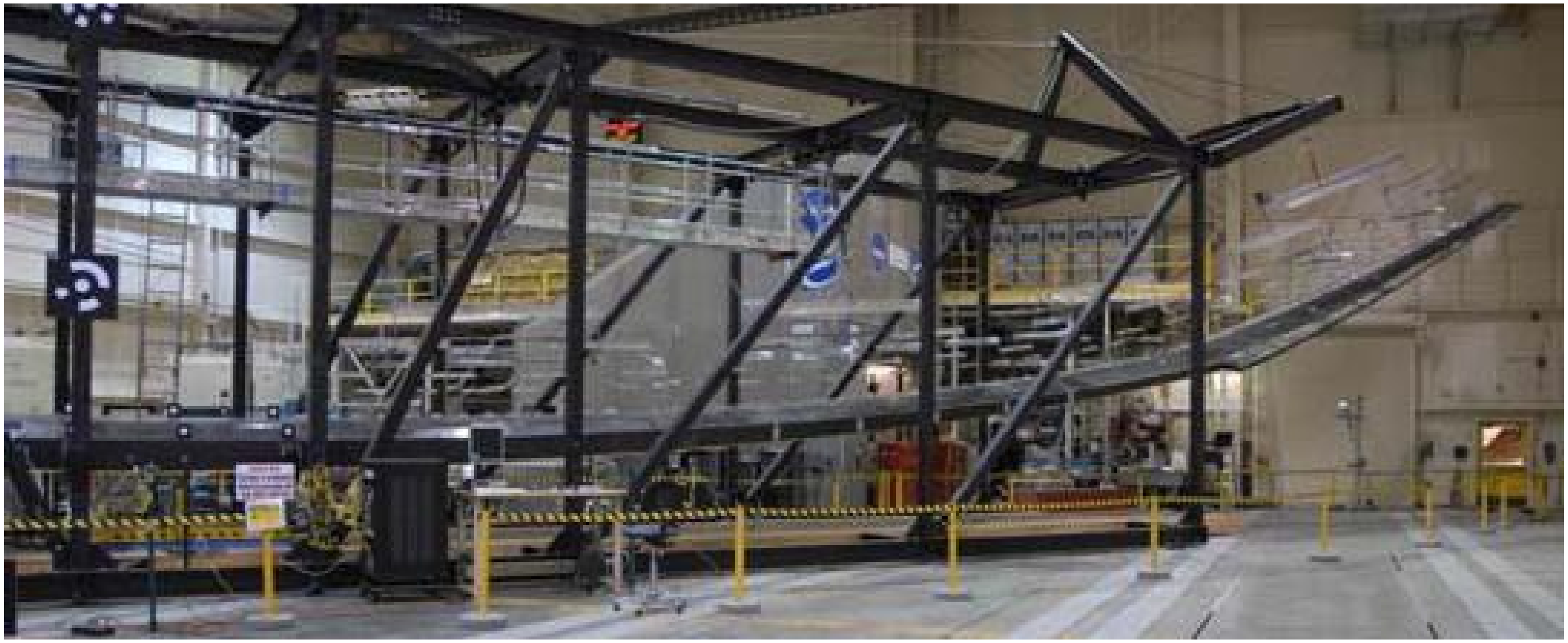
Embedding / Fabrication

Failure Testing

AeroVironment's Global Observer Wing Loads Tests at NASA Dryden

- Validate strain predictions along the wingspan
- Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.
- FO Strain distribution measurements are being used to interpret shape using Dryden's single fiber shape algorithm
- A 24-fiber system was designed of which 18 fiber 40ft (~17,200 gratings) fibers were used to instrument this wing

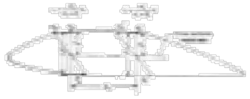


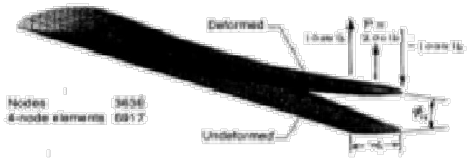


Research and Technology Development Areas

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

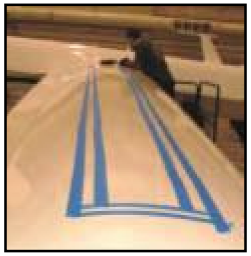
- Algorithm Development

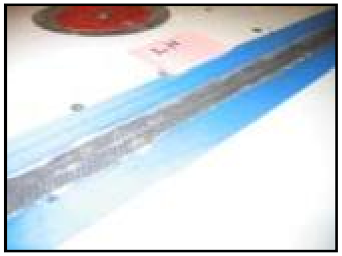




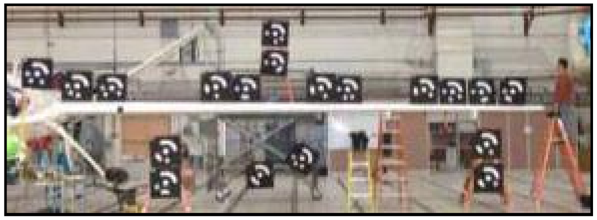
- FBG System Development

- Instrumentation

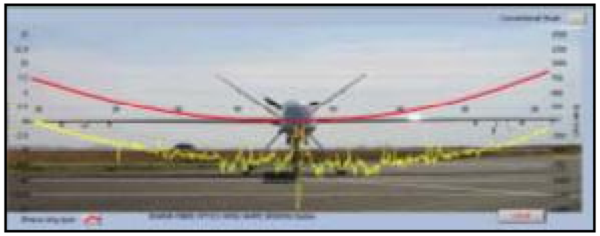




- Ground Testing / R&D



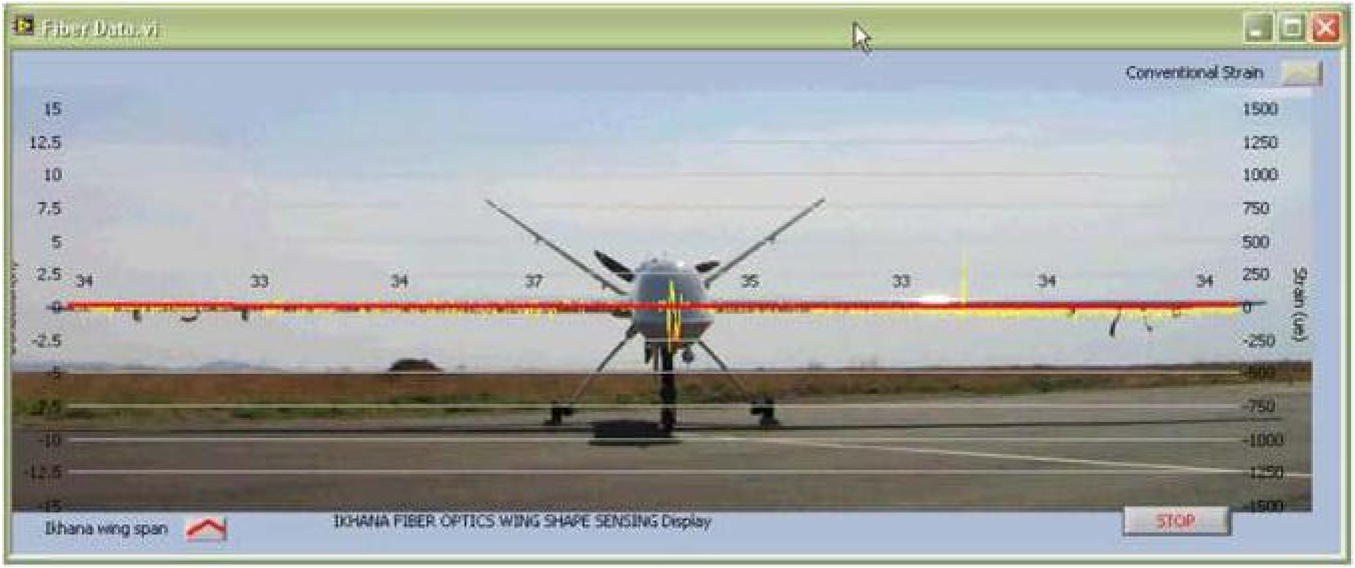
- **Flight Testing**



Flight Test Results

Predator-B

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



Video clip of flight data superimposed on Ikhana photograph

AeroVironment's Global Observer

Flight Testing

- Validate strain predictions along the left wing using 8, 40ft fibers
- An aft fuselage surface fiber was installed to monitor fuselage and tail movement
- Strain distribution were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.
- 8 of the 9 total fibers are attached to the system at any give time

Concluding Remarks

Fiber Optic Wing Shape Sensing toward UAS applications involves five major areas

- **Algorithm development**
  - Real-time wing shape and applied loads algorithms using fiber optics sensors were in good agreement with conventional measurements
- **FBG system development**
  - Current Flight Systems in Operation: 4 and 8 Fiber Systems
    - Flown on Ikhana and Global Observer, resp.
  - Future Systems underdevelopment:
    - 64 Fiber ‘Large-Vehicle’ System
    - 4 Fiber ‘Compact’ System
- **Instrumentation**
  - Installation Advantages
    - Greatly reduced installation time compared to conventional strain gages
  - Installation Challenges
    - Optical fiber more fragile than strain gages
- **Ground Testing / R&D**
  - A 24-fiber system was used on Global Observer; 18 fiber 40ft (~17,200 gratings) fibers were to measure strain and wing shape in real-time
- **Flight Testing**
  - Predator-B; Ikhana
    - Real time fiber Bragg strain measurements successfully acquired and validated in flight (4/28/2008)
    - Real-time fiber optic wing shape sensing successfully demonstrated in flight
  - Global Observer