Real-time In-Flight Strain and Deflection Monitoring with Fiber Optic Sensors

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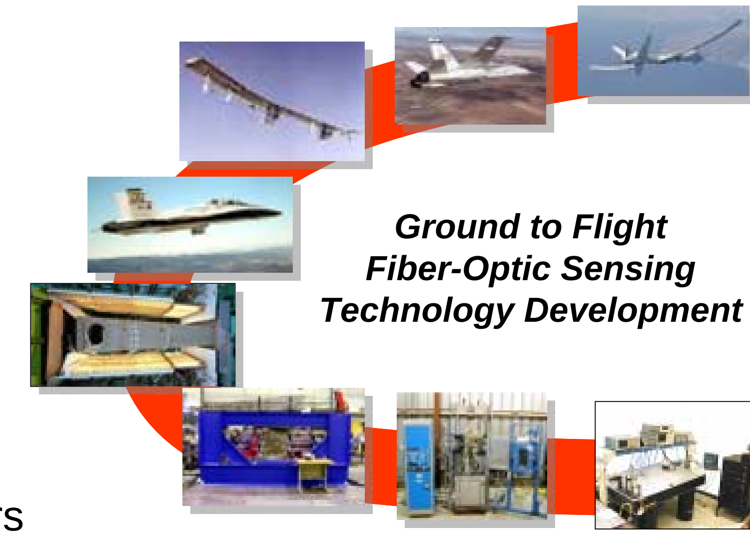
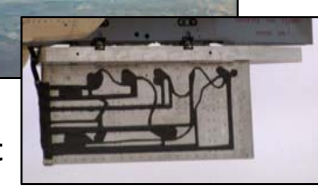
National Aeronautics and Space Administration

Background

- **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 OTDR demodulation technique
- **Dryden collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft**
  - Focused on validating Lockheed Sanders FO VHM system
    - Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
  - Lockheed Sanders 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**



Ground to Flight Fiber-Optic Sensing Technology Development



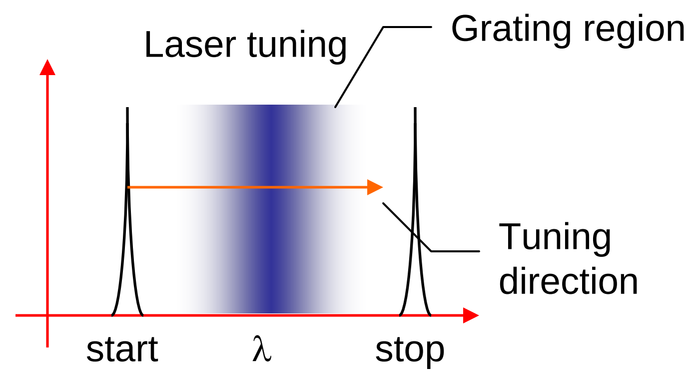
X-33 IVHM Risk Reduction Experiment

Fiber Optic System Operation Overview

National Aeronautics and Space Administration

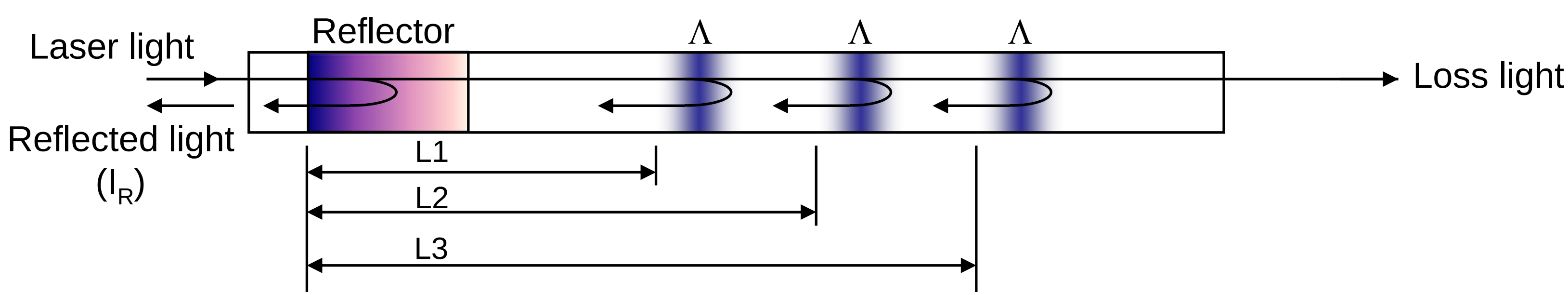
Fiber Optic Sensing with Fiber Bragg Gratings

- **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**
- **Typical gage lengths from 0.1mm to 100mm**
- **Uses a narrowband wavelength tunable laser source to interrogate sensors**
- **Typically easier to install than conventional strain sensors**



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

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

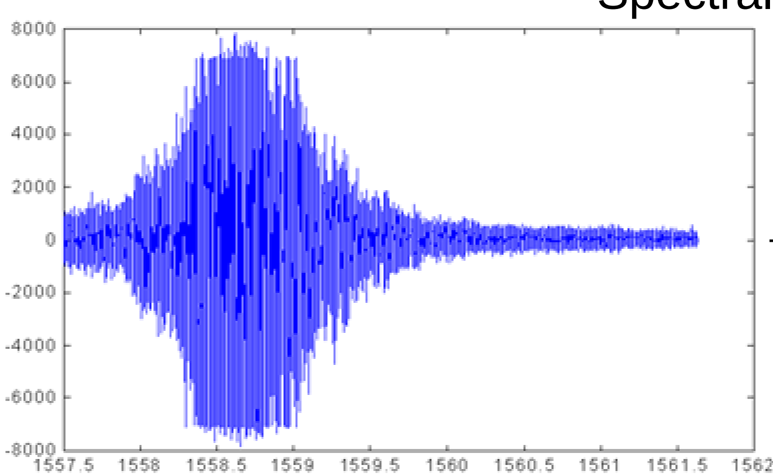


Fiber Optic System Operation Overview

- **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**

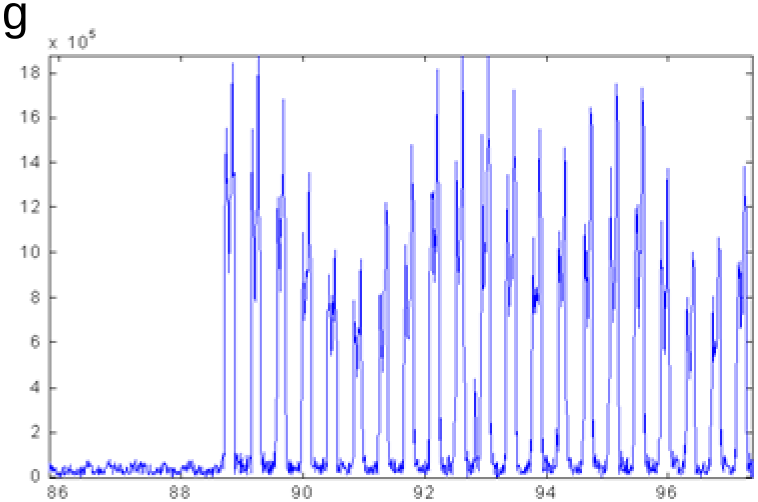
	FFT	iFFT
Traditional	**Time(T) > Frequency(F)**	**Frequency(F) > Time(T)**
Optical	**Wavelength(λ) > Length(L)**	**Length(L) > Wavelength(λ)**

Spectral Mapping



Wavelength(λ) domain

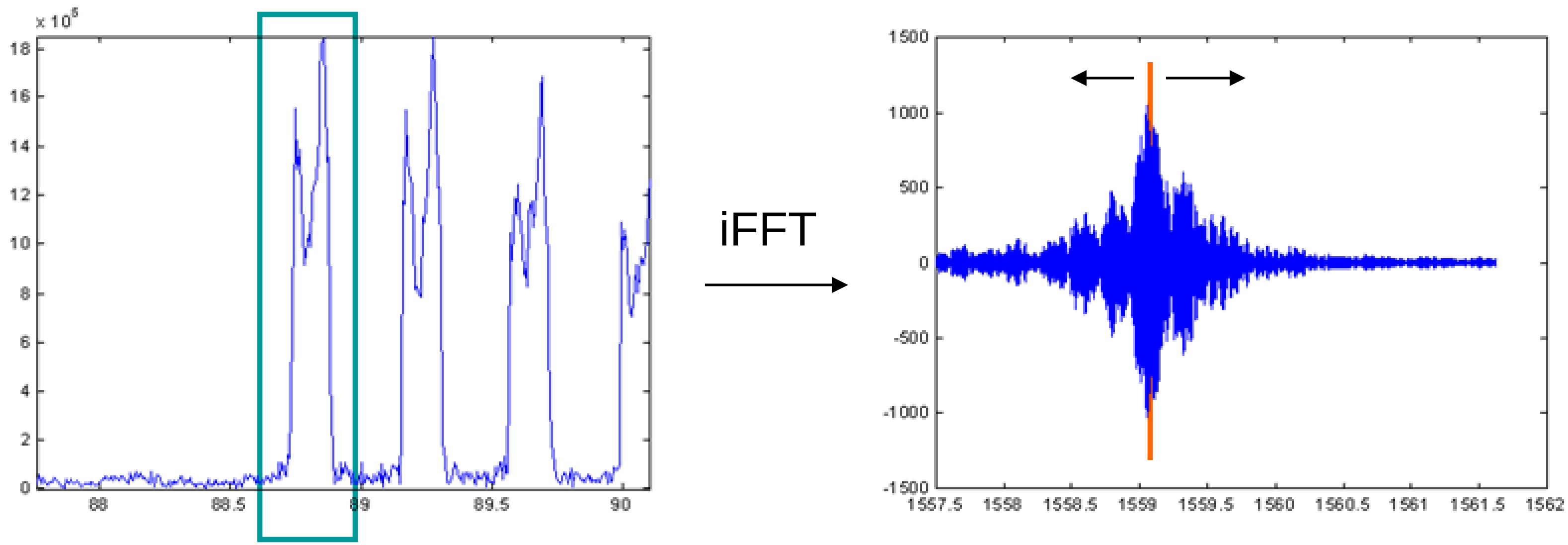
FFT



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**

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

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

Motivation – Helios Mishap

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**

Wing Shape Sensing Background

- **Current Wing Displacement Techniques**
  - **Optical Methods (Flight Deflection Measurement System)**
    - **1980s - Highly Maneuverable Aircraft Technology (HiMAT)**
    - **2000s - F/A-18 Active Aeroelastic Wing (AAW)**
  - **Strain Gage Approaches**

- **Limitations**
  - **Current techniques utilize approaches that are too heavy and not appropriate for weight-sensitive, highly-flexible structures**

Research Objectives for Ikhana

- Flight validate fiber optic sensor measurements and real-time wing shape sensing predictions on NASA's Ikhana vehicle (FY08)

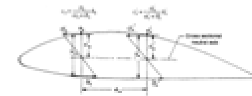
- Validate fiber optic mathematical models and design tools (FY08)

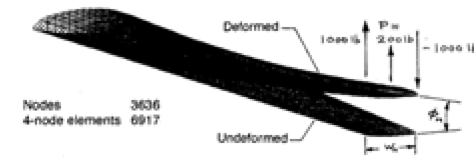
- Assess technical viability and, if applicable, develop methodology and approach to incorporate wing shape measurements within the vehicle flight control system (FY08-FY09)

- Develop and flight validate advanced approaches to perform active wing shape control using
  - conventional control surfaces (FY09-FY10)
  - active material concepts (FY09-FY11+)

Research Areas

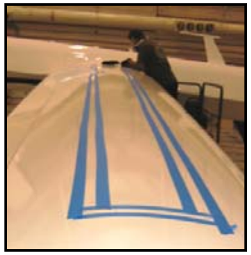
$$y_n = \frac{\Delta l^2}{6c}\left\{(3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1}(n-i)\varepsilon_i + \varepsilon_n\right\}$$

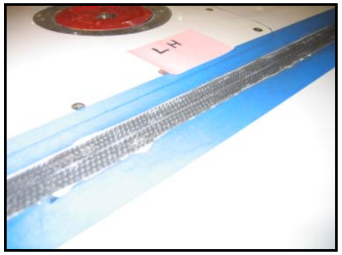




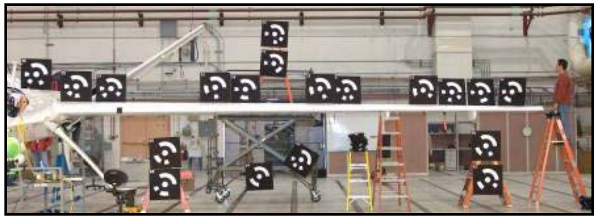
- **Algorithm Development**

- **FBG System Development**

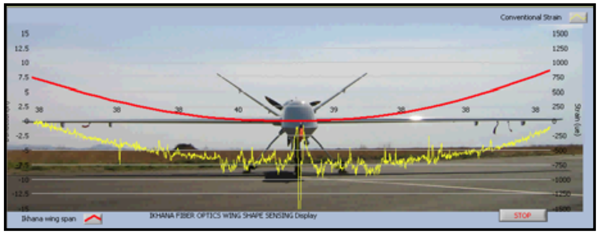




- **Instrumentation**



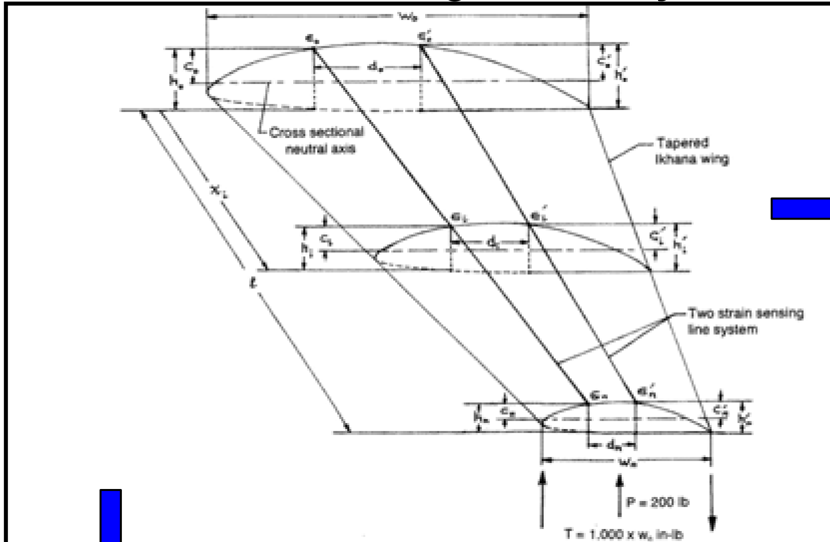
- **Ground Testing**



- **Flight Testing**

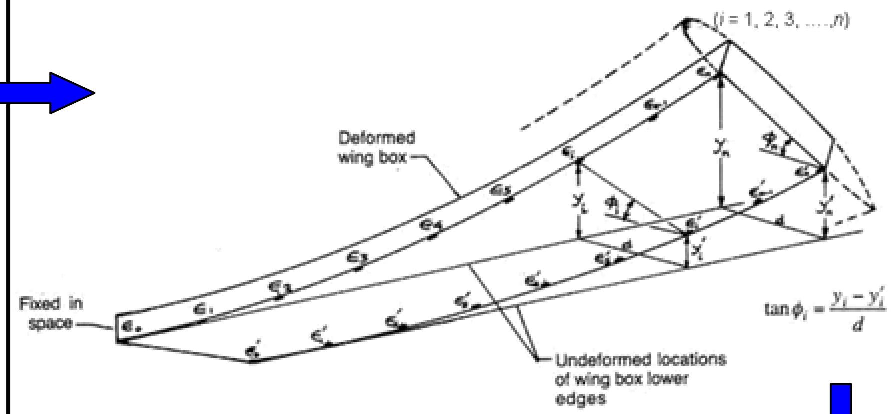
Algorithm Development (Ikhana)

Ikhana Wing Geometry

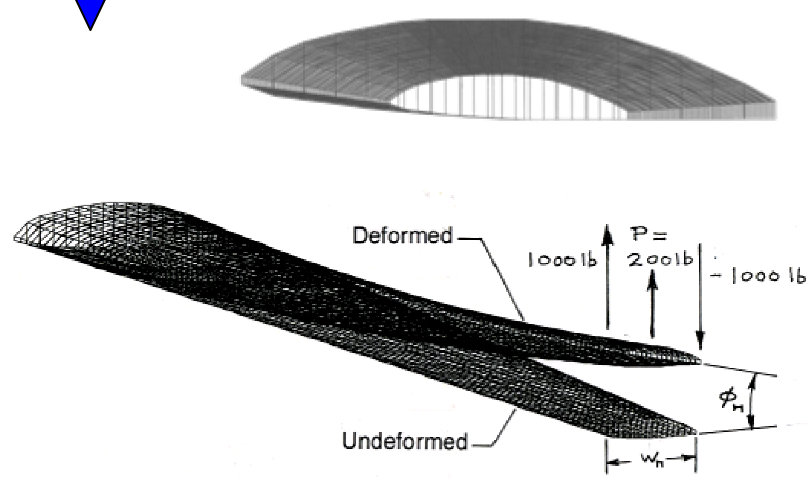


Analytical Models

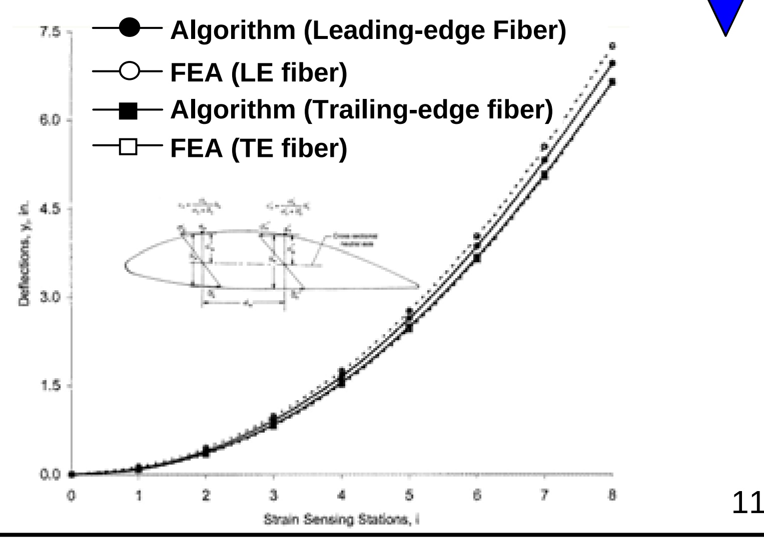
$$y_i = \frac{(\Delta l)^2}{6} \sum_{j=1}^{i} \frac{1}{c_{j-1}} \left\{ \left[3(2j-1) - (3j-2) \frac{c_{i-j+1}}{c_{i-j}} \right] \varepsilon_{i-j} + (3j-2)\varepsilon_{i-j+1} \right\} + y_0 + i \Delta l \tan\theta_0$$



Computational Models



Analytical/Comp. Comparison



Ikhana Fiber Optic Flight System

- **Current flight system specifications**

Fiber count	4
Max fiber length	40 ft
Max sensing length	20 ft
Max sensors / fiber	480
Total sensors / system	1920
Sample rate	2 fibers @ 50 sps 4 fibers @ 24 sps
Power	28VDC @ 4 Amps
User Interface	Ethernet
Weight (non-optimized)	23 lbs
Size (non-optimized)	7.5 x 13 x 13 in

- **Environmental qualification specifications**

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

Fiber Optic Flight System

Ikhana Avionics Bay

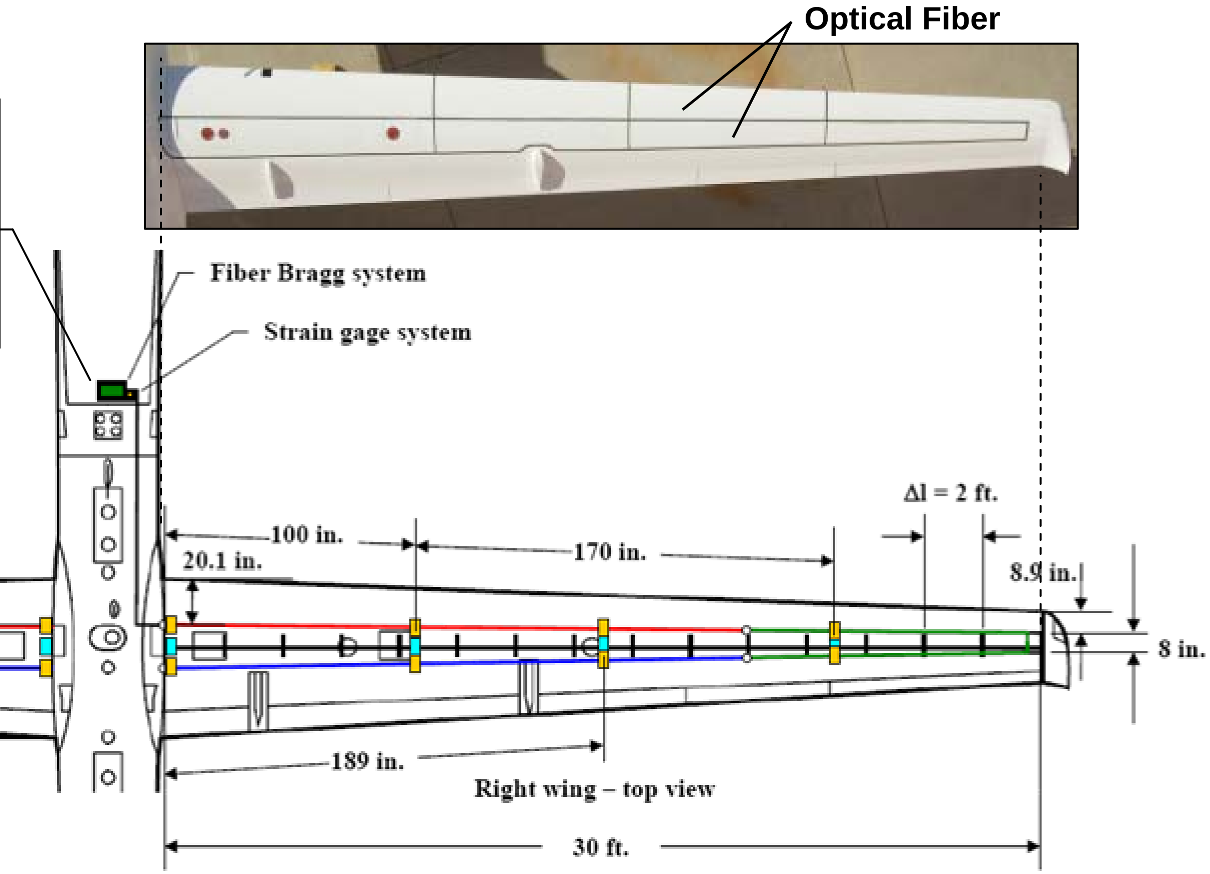
Ikhana in Flight

Flight Instrumentation

- **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

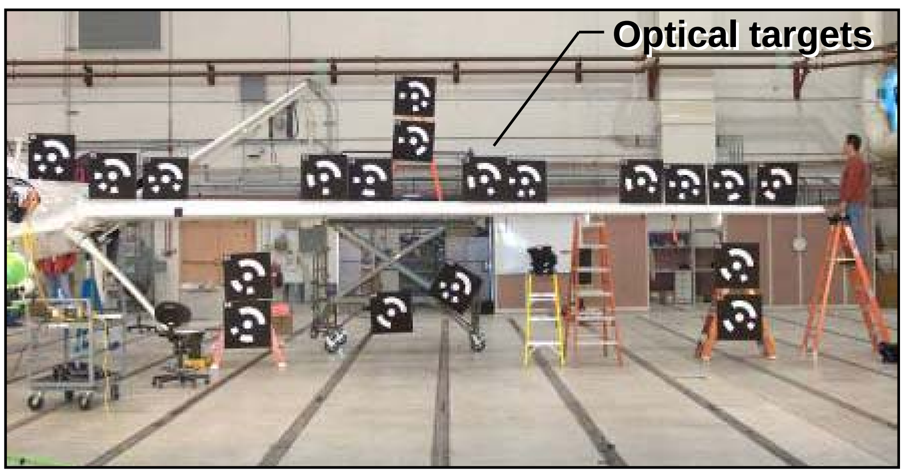
Strain gage system

FBG system



Ground Test Validation - Ikhana

- **Ground validation testing**
  - Conducted ground validation testing January 16-18, 2008
  - Used Dryden's high resolution / high speed optical measurement system as validation standard
  - 10 measurement stations placed on left wing (1 on center fuselage)
  - Five load cases applied
  - Good agreement between FOWSS and optical system



Left wing – aft view

Left wing – inboard view

Flight Test Validation - Ikhana

- **Flight validation testing**
  - 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
  - FOWSS system performed well throughout entire flight – no issues
  - Data reduction and correlation on going

Video clip of flight data (from taxi to take-off) superimposed on Ikhana photograph

Concluding Remarks

- **Fiber Optic Wing Shape Sensing on Ikhana involves five major areas**
  - Algorithm development
    - Local-strain-to-displacement algorithms have been developed for complex wing shapes for real-time implementation (NASA TP-2007-214612, patent application submitted)
  - FBG system development
    - Dryden advancements to fiber optic sensing technology have increased data sampling rates to levels suitable for monitoring structures in flight (patent application submitted)
  - Instrumentation
    - 2880 FBG strain sensors have been successfully installed on the Ikhana wings
  - Ground Testing
    - Fiber optic wing shape sensing methods for high aspect ratio UAVs have been validated through extensive ground testing in Dryden's Flight Loads Laboratory
  - Flight Testing
    - 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
- **Current Status**
  - Dryden FOWSS system successfully qualified for Predator-B flight environment
  - FOWSS system currently installed on Ikhana aircraft
  - Flights being conducted from April - May 2008

Backup Slides

Dryden Fiber Optic System

- **Current ground system specifications**

– Fiber count	4
– Max. fiber length	40 ft
– Max sensing length	20 ft
– Max. sensors / fiber	480
– Total sensors per system	1920
– Min. grating spacing	0.5 in
– Sample rate	2 fibers @ 50 sps 4 fibers @ 24 sps
– Interface	Gigabit Ethernet
– Power	120 VAC
– Weight	12 lbs
– Size	9 x 5 x 11 in