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Fiber Optic Wing Shape Sensing on NASA's Ikhana UAV

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February 7, 2008

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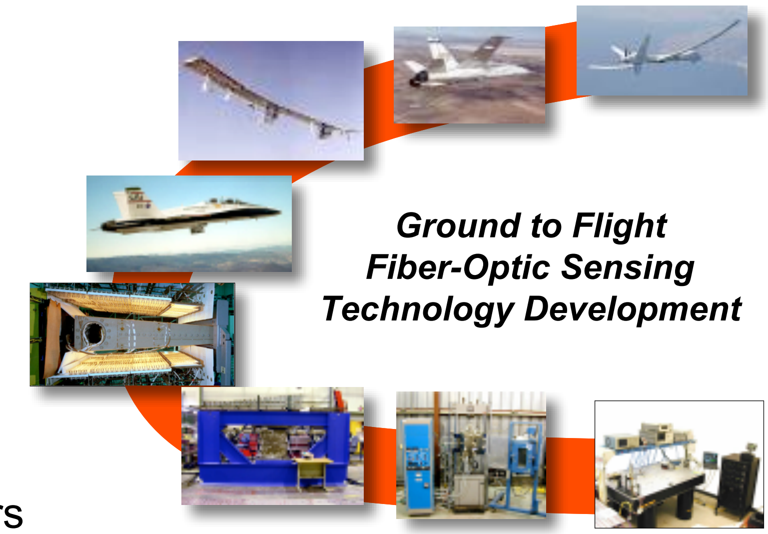
Background

- **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**

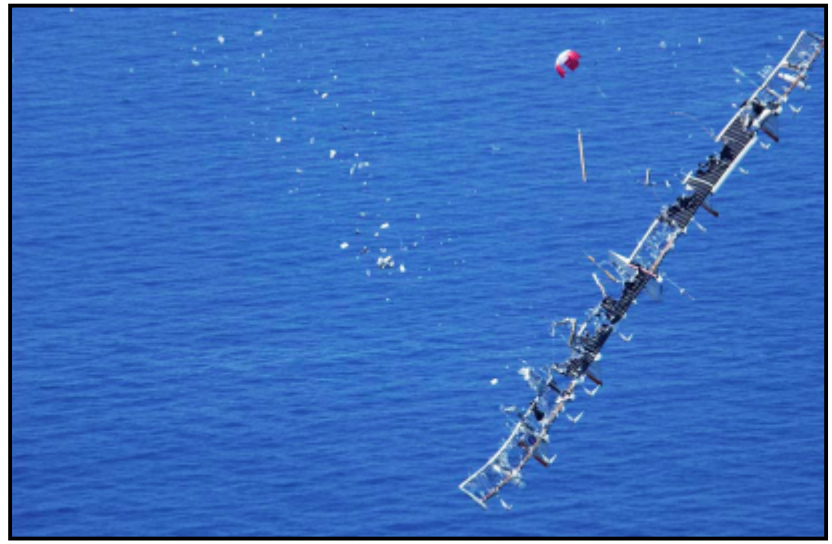


Ground to Flight Fiber-Optic Sensing Technology Development

X-33 IVHM Risk Reduction Experiment

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)**

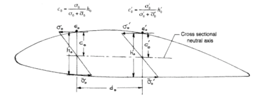
- **Assess technical viability and, if applicable, develop methodology and approach to incorporate wing shape measurements within the vehicle flight control system (FY08-FY09)**

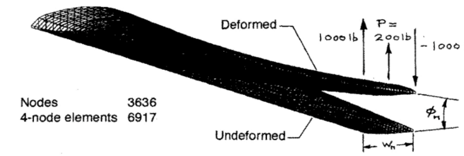
- **Develop and flight validate advanced approaches to perform active wing shape control using**
  - **conventional control surfaces (FY09-FY10)**
  - **active material concepts (FY09-FY11+)**

Research Areas

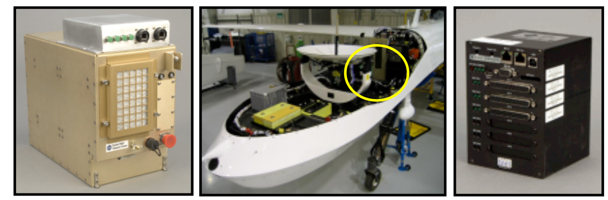
– **Algorithm Development**

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

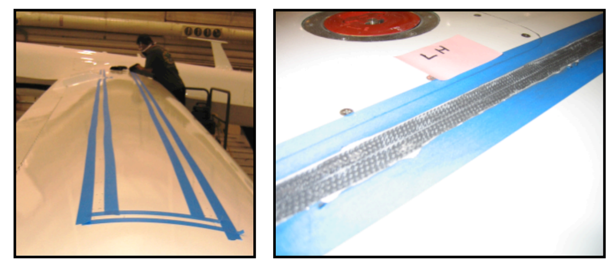




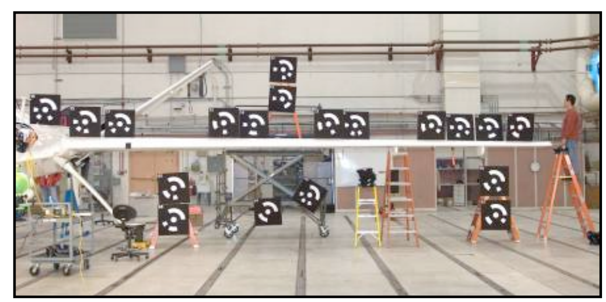
– **FBG System Development**



– **Instrumentation**



– **Ground Testing**



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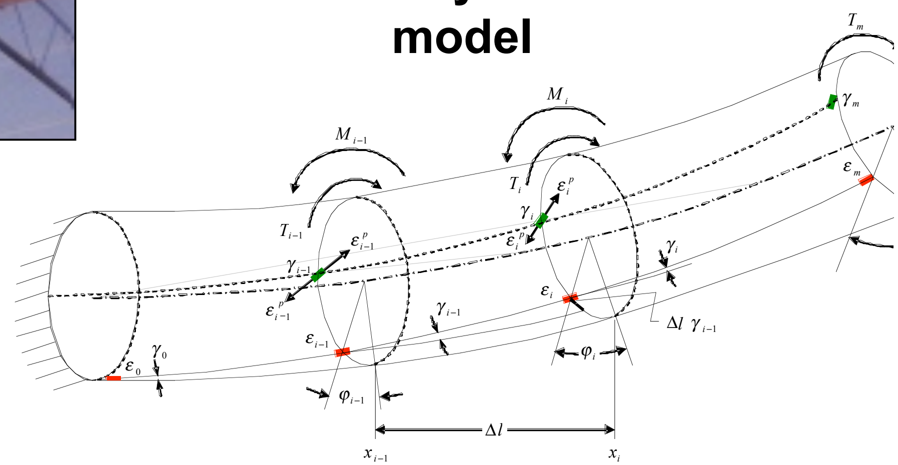
Algorithm Development (Pathfinder Plus)

Helios Main Spar

Analytical model



Pure Bending

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

Pure Torsion

$$\phi_i = \frac{\Delta l}{c}\sum_{n=0}^{i-1} 2(1+v)\varepsilon_i^p$$

Combined Bending and Torsion

$$\overline{\varepsilon}_i = \frac{\varepsilon_i}{\cos\phi_i \cos\gamma_i}$$

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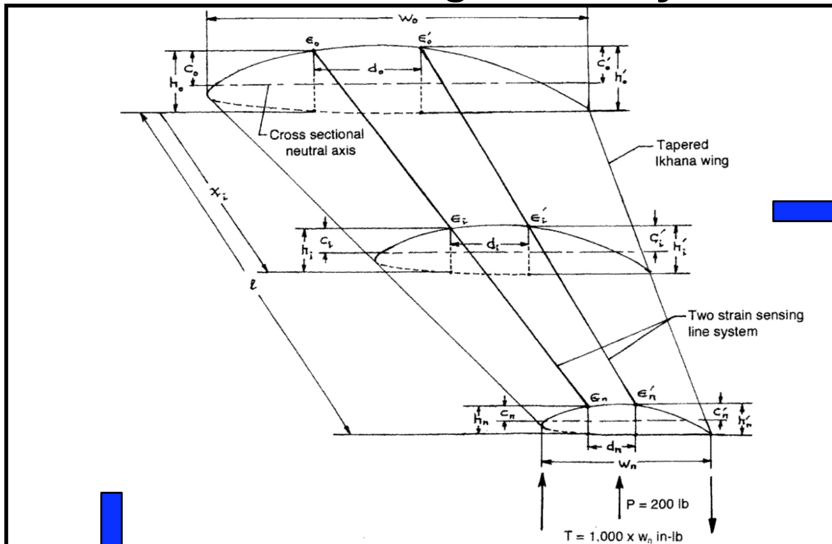
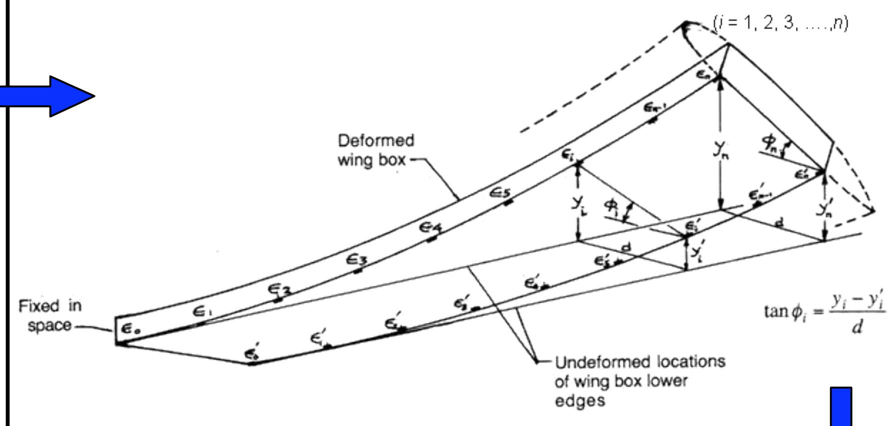
Algorithm Development (Ikhana)

Ikhana Wing Geometry

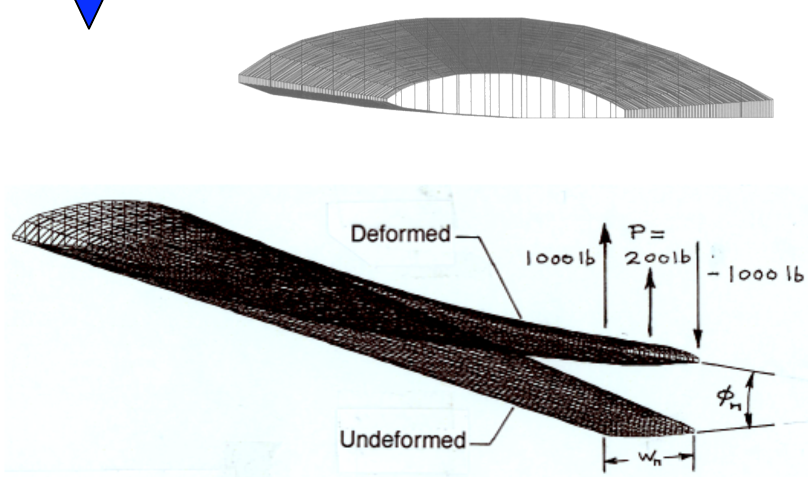


Analytical Models

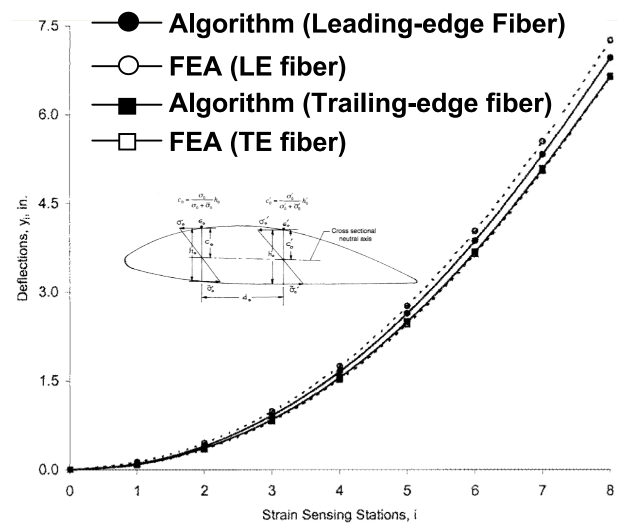
$$y_i = \frac{(\Delta l)^2}{6}\sum_{j=1}^{i}\frac{1}{c_{j-1}}\left\{\left[3(2j-1)-(3j-2)\frac{c_{i-j+1}}{c_{i-j}}\right]\bar{\varepsilon}_{i-j}+(3j-2)\bar{\varepsilon}_{i-j+1}\right\}+y_0+i\Delta l\tan\theta_0$$



Computational Models



Analytical/Comp. Comparison



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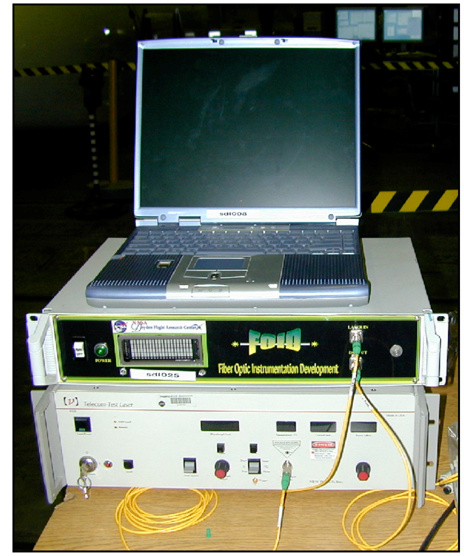
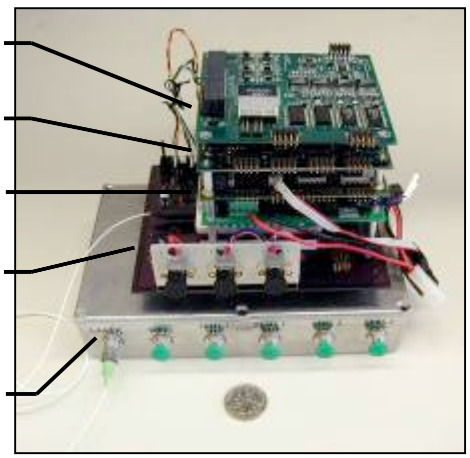
Fiber Optic System Development

- **Original Fiber-Optic Ground System (2004)**
  - **3 components (CPU, FOID Box, and 19” rack mount laser)**
  - **Laser physical specifications: 17”W x 18”L x 5”H**
  - **Max. 2.5 sps (limited by laser tuning rate)**
  - **Single fiber system, with 100s of sensors**
  - **Laser cost: $45K**
  - ***Total system weight – approx. 44 lbs.***



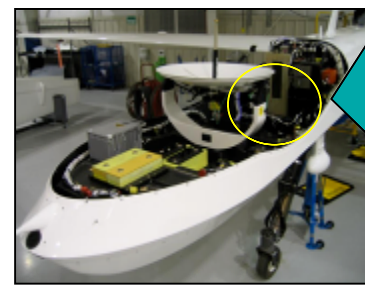
- **Pathfinder Plus Flight System (2006)**
  - **1 component (8”W x 6”L x 6”H)**
  - **Laser physical specifications: 2”W x 3”L x 0.5”H**
  - **Laser integrated within PC stack**
  - **Approx. 1 sps (limited by the laser tuning rate)**
  - **Two fiber system, 960 sensors over two 40-ft sections**
  - **Accuracy: 3-5% of surface mounted strain gages**
  - **Laser cost: $10K**
  - ***Total system weight - < 5 lbs.***



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 @ 36 sps; 4 fibers @ 22 sps
  - Power: 28VDC @ 4 Amps
  - User Interface: Ethernet
  - Weight: 23 lbs
  - Size: 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

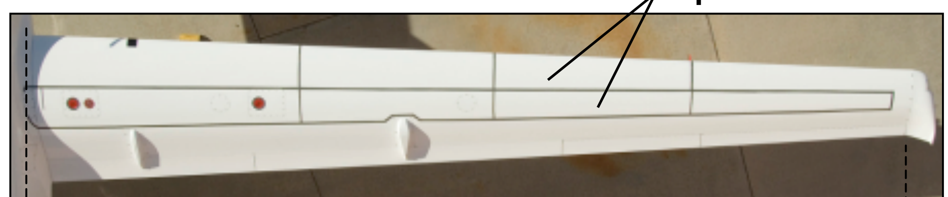
Ikhana in Flight

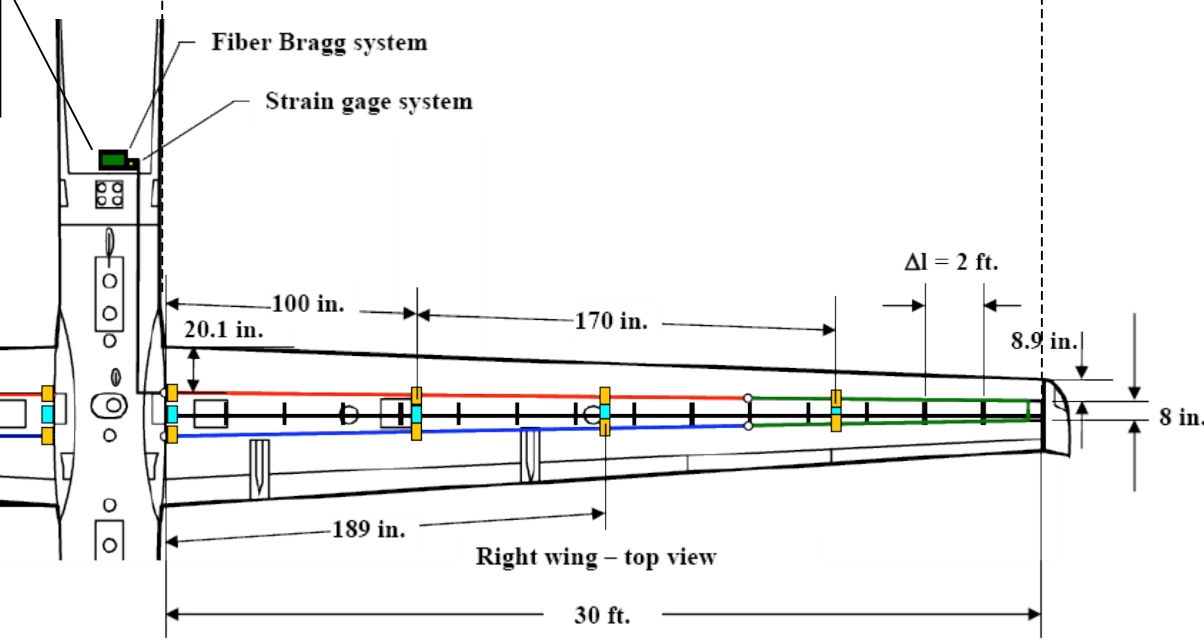
Flight Instrumentation

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

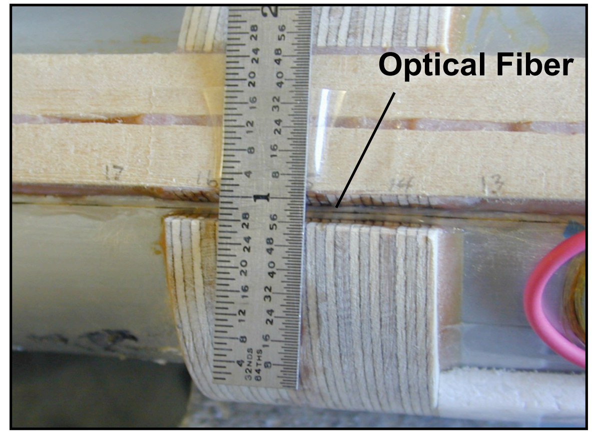
Strain gage system

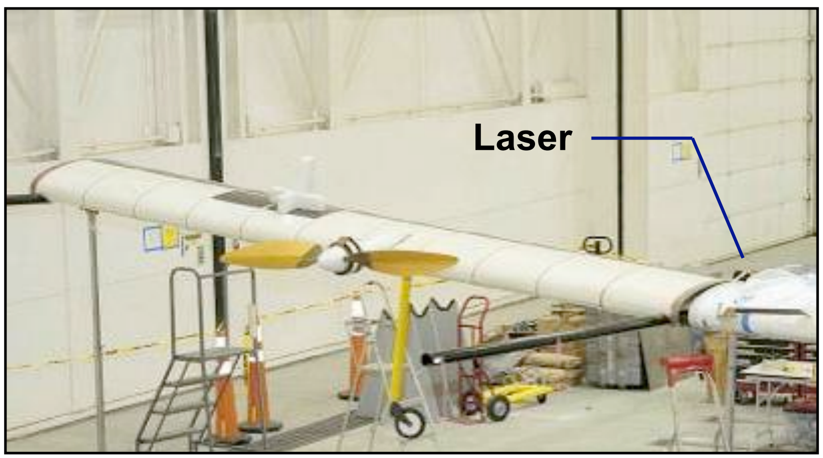
FBG system



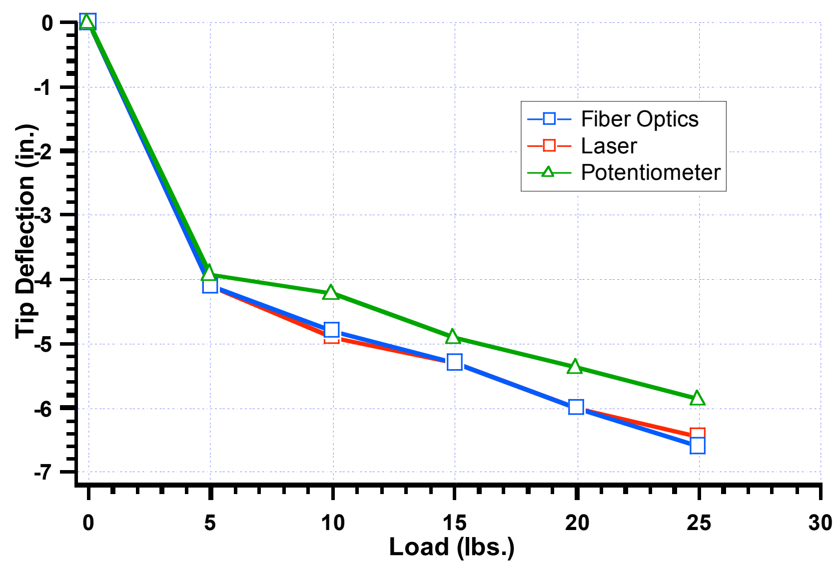


Ground Test Validation – Pathfinder Plus





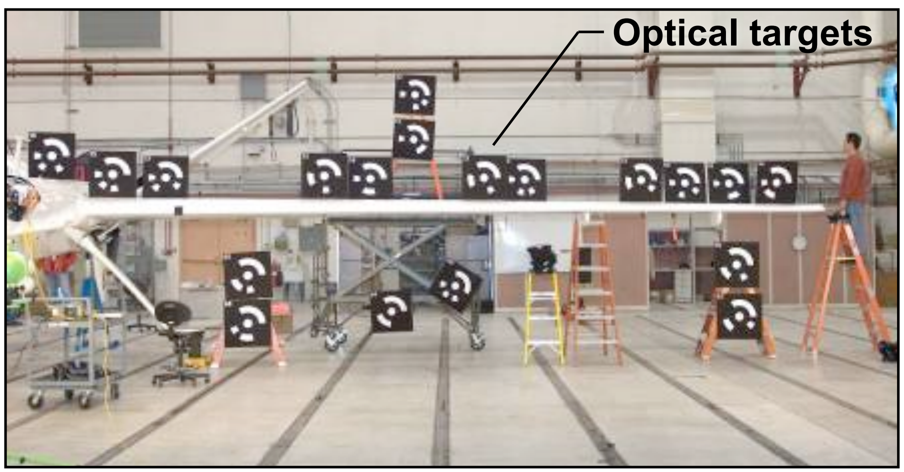
Ground test setup



Test Results

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
  - *Preliminary* agreement with FOWSS ~ 6%
  - Data reduction process on-going



Left wing – aft view

Left wing – inboard view

Concluding Remarks

- **Fiber Optic Wing Shape Sensing on Ikhana involves four 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
- **Current Status**
  - Dryden FOWSS system successfully qualified for Predator-B flight environment
  - FOWSS system currently being installed on Ikhana aircraft
  - Flights currently planned from February to April 2008

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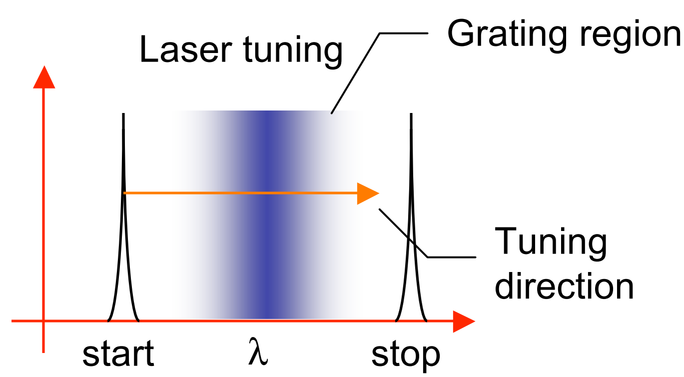
Backup Slides

Fiber Optic System Operation Overview

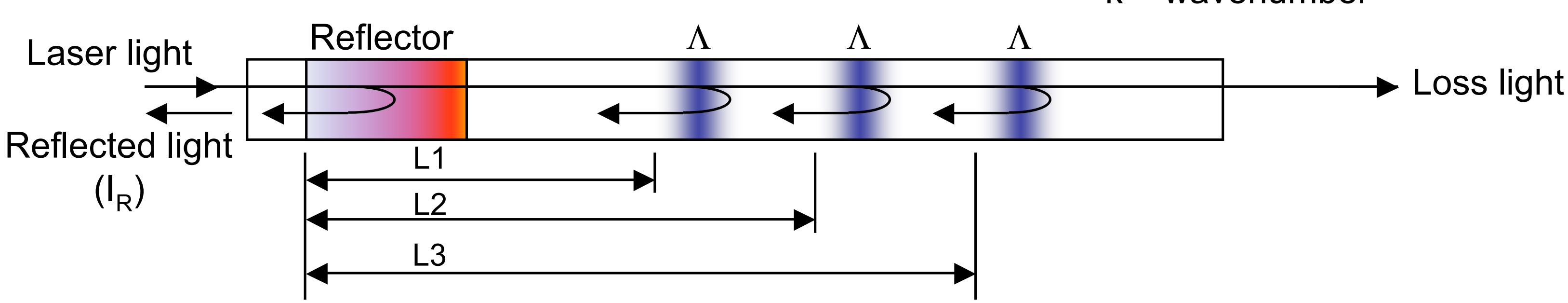
Fiber Optic Sensing with Fiber Bragg Gratings

- 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
- 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



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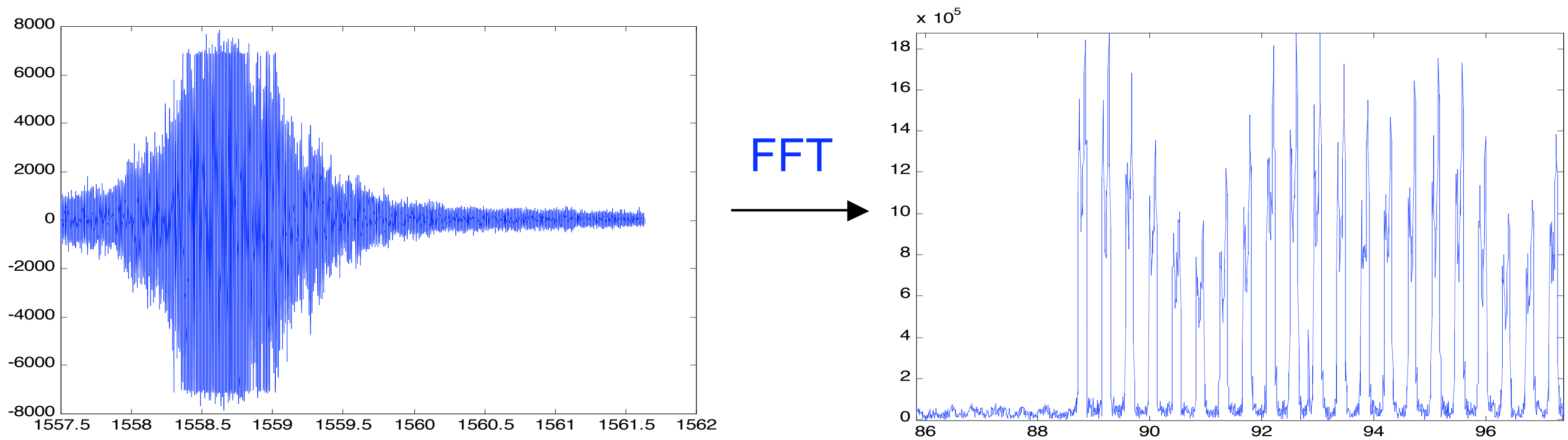
Fiber Optic System Operation Overview

- **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**

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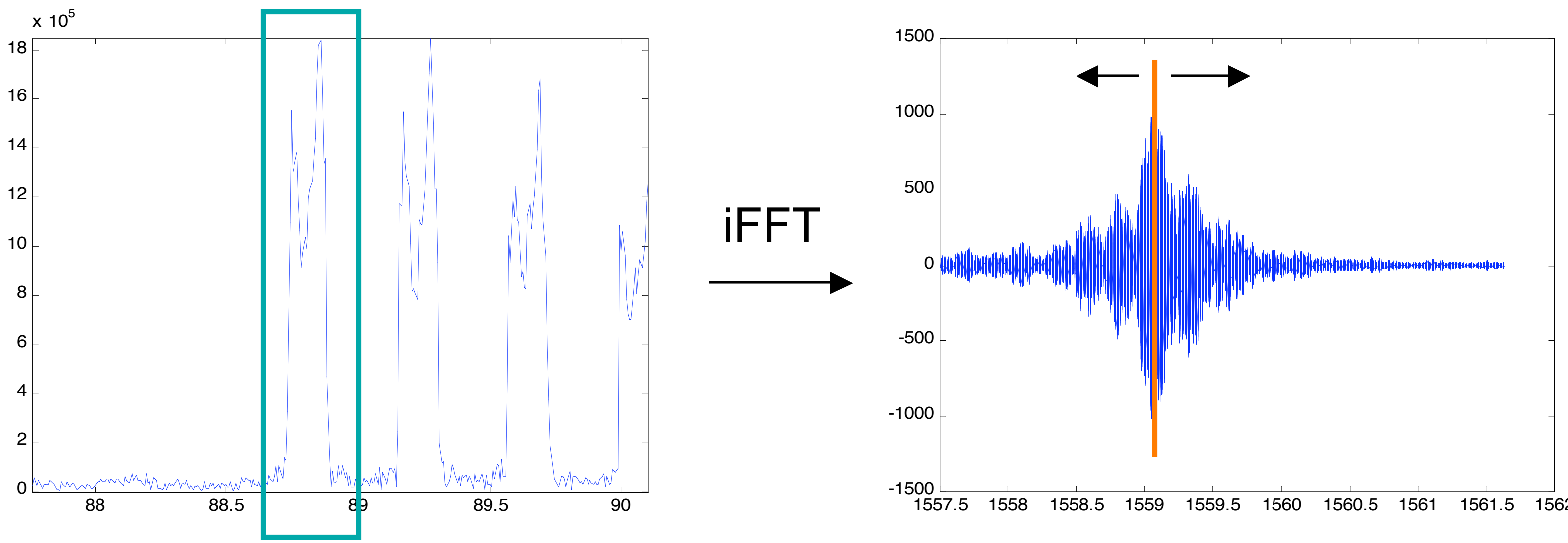
Fiber Optic System Operation Overview

- **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)**

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 @ 36 sps 4 fibers @ 22 sps
– Interface	Gigabit Ethernet
– Power	120 VAC
– Weight	12 lbs
– Size	9 x 5 x 11 in