National Aeronautics and Space Administration

Fiber Optic Wing Shape Sensing on NASA's Ikhana UAV

Dr. Lance Richards, Allen R. Parker, Dr. William L. Ko, Anthony Piazza

Dryden Flight Research Center

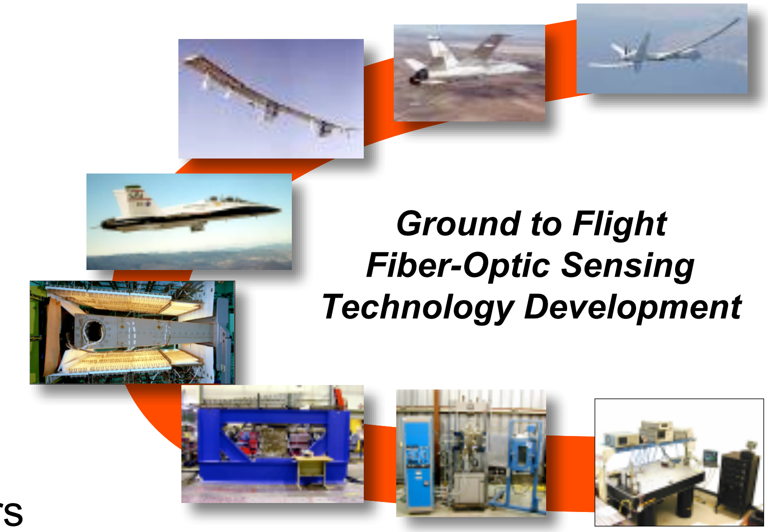
Edwards, CA

February 7, 2008

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**

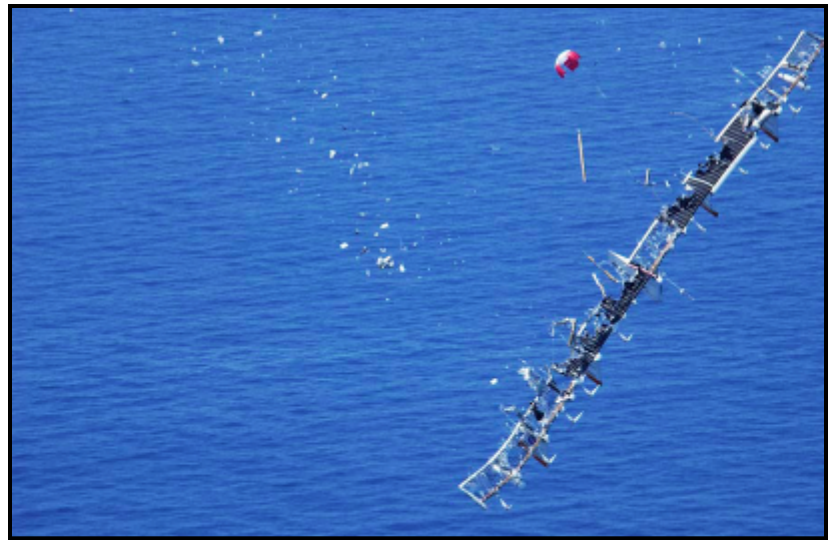


X-33 IVHM Risk Reduction Experiment

National Aeronautics and Space Administration

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

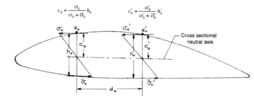
- **Flight validate fiber optic sensor measurements and real-time wing shape sensing predictions on NASA's Ikhana vehicle (FY08)**
- **Validate fiber optic mathematical models and design tools (FY08)**
- **Assess technical viability and, if applicable, develop methodology and approach to incorporate 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+)**

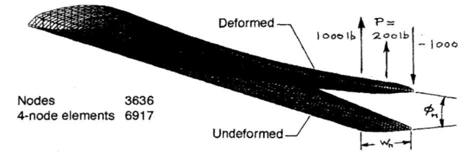
National Aeronautics and Space Administration

Research Areas

– **Algorithm Development**

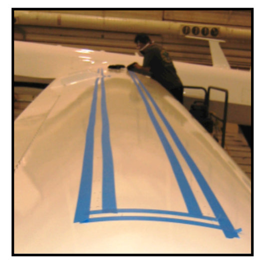
$$y_n = \frac{\Delta l^2}{6c}\left\{(3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1}(n-i)\varepsilon_i + \varepsilon_n\right\}$$

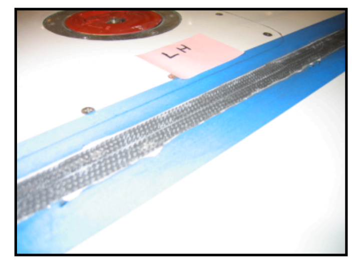




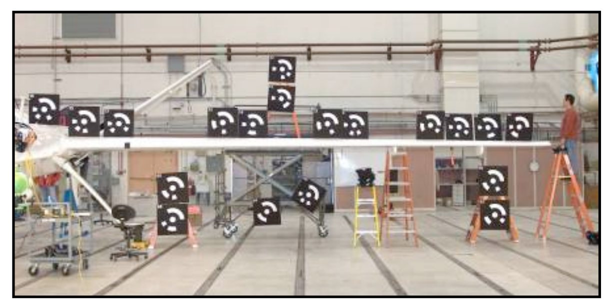
– **FBG System Development**

– **Instrumentation**





– **Ground Testing**

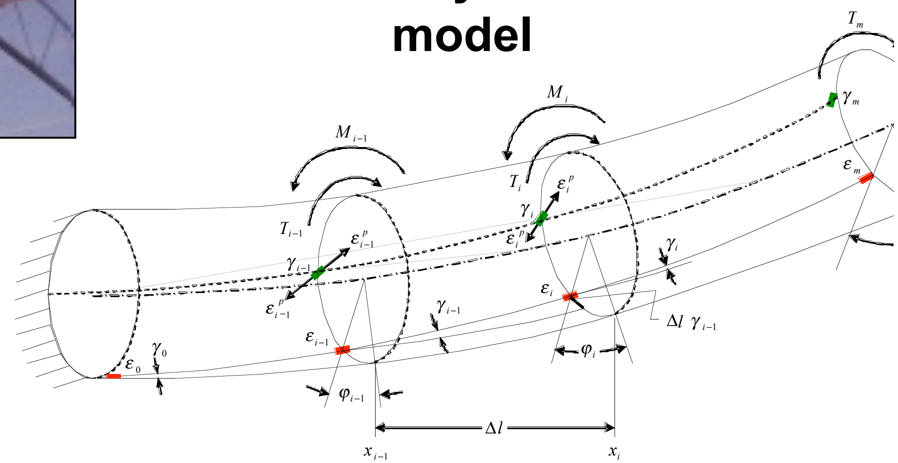


Algorithm Development (Pathfinder Plus)

National Aeronautics and Space Administration

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

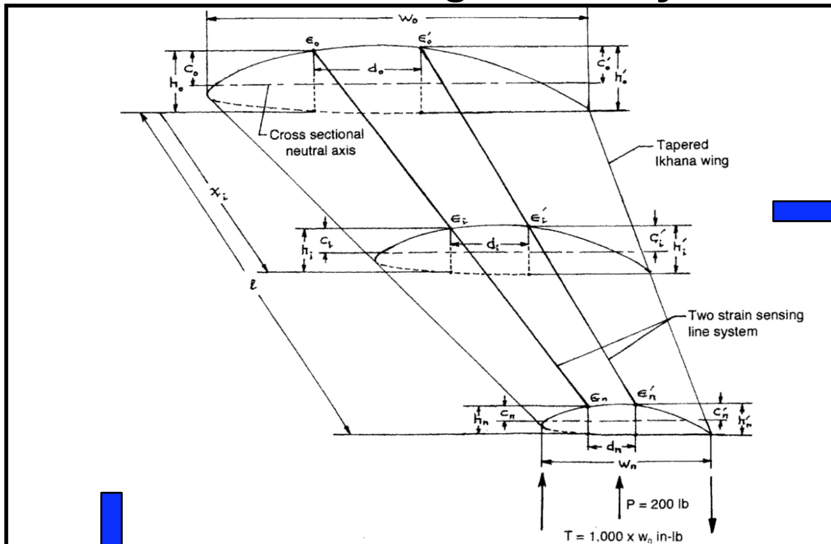
$$\phi_i = \frac{\Delta l}{c}\sum_{n=0}^{i-1} 2(1+v)\varepsilon_i^p$$

Combined Bending and Torsion

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

Algorithm Development (Ikhana)

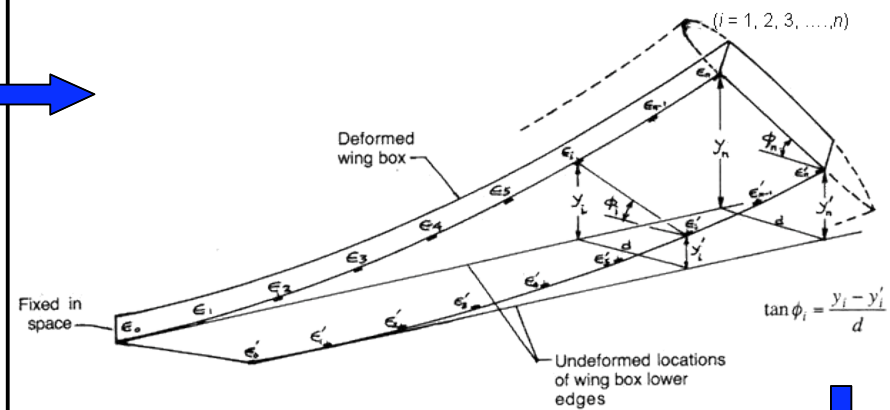
Ikhana Wing Geometry



Analytical Models

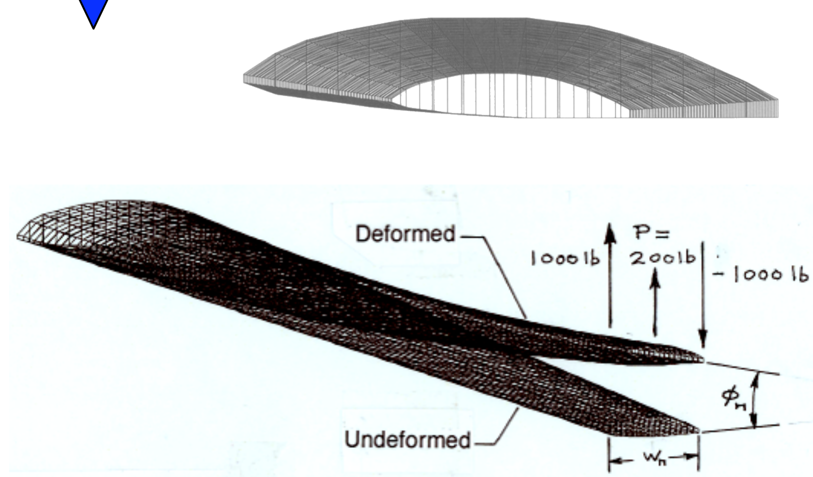
$$y_i = \frac{(\Delta l)^2}{6} \sum_{j=1}^{i} \frac{1}{c_{j-1}} \left\{ \left[3(2j-1) - (3j-2)\frac{c_{i-j+1}}{c_{i-j}} \right] \bar{\varepsilon}_{i-j} + (3j-2)\bar{\varepsilon}_{i-j+1} \right\} + y_0 + i\Delta l \tan\theta_0$$

$(i = 1, 2, 3, \ldots, n)$

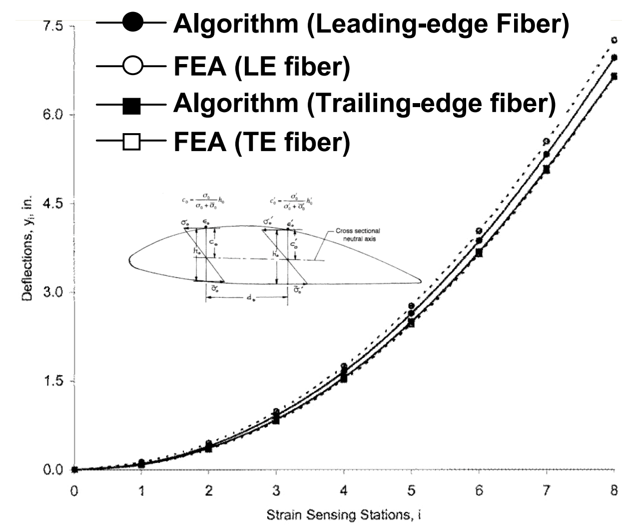


$$\tan\phi_i = \frac{y_i - y_i'}{d}$$

Computational Models

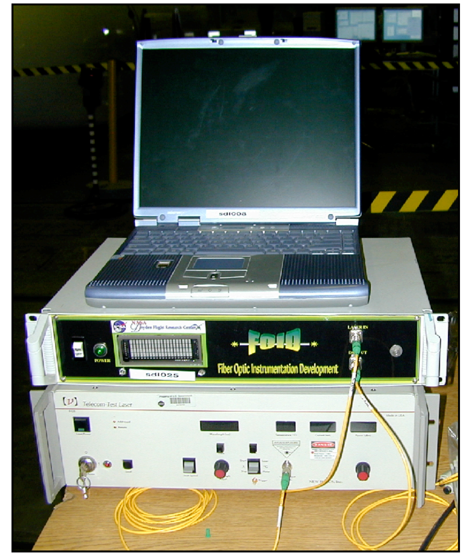


Analytical/Comp. Comparison

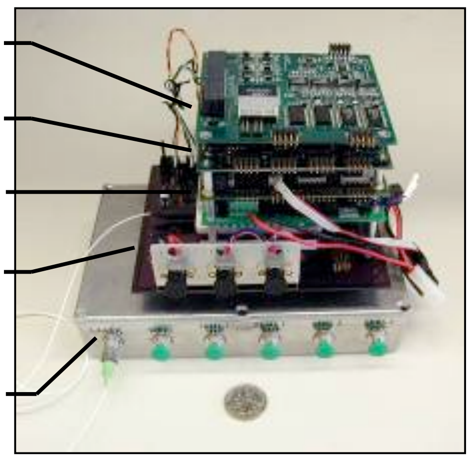


Fiber Optic System Development

- 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

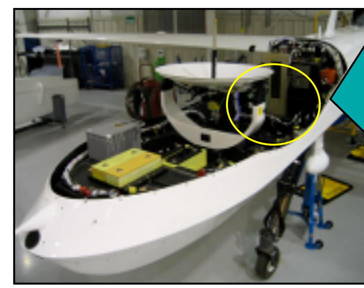
- **Current flight system specifications**

– 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

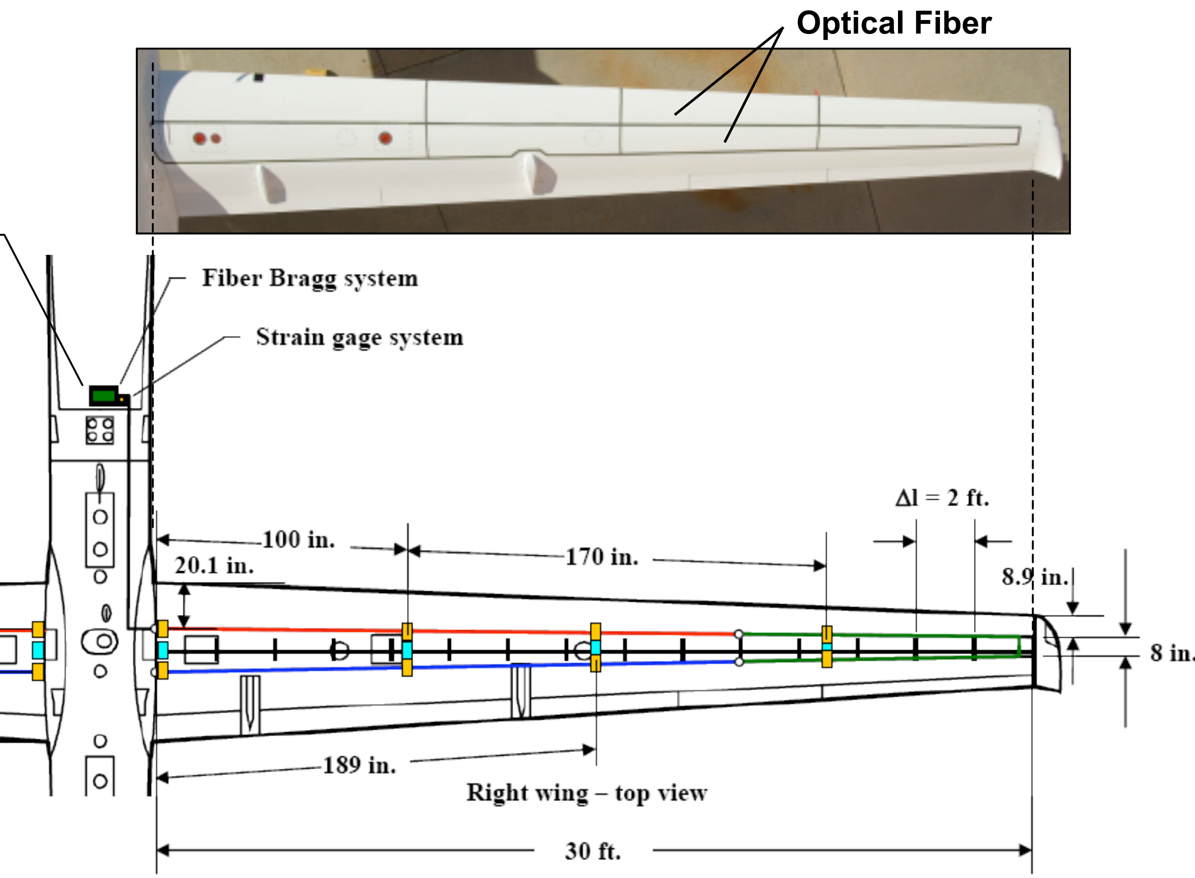
National Aeronautics and Space Administration

Flight Instrumentation

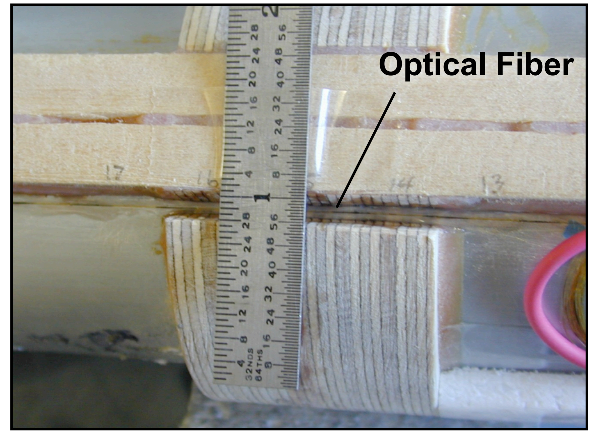
- **Instrumentation**
  - 2880 FBG strain sensors (1920 recorded at one time)
  - 1440 FBG sensors per wing
  - Select optimal number of FBG sensors for real-time wing shape sensing
  - 16 strain gages for FBG sensor validation
  - 8 thermocouples for strain sensor error corrections

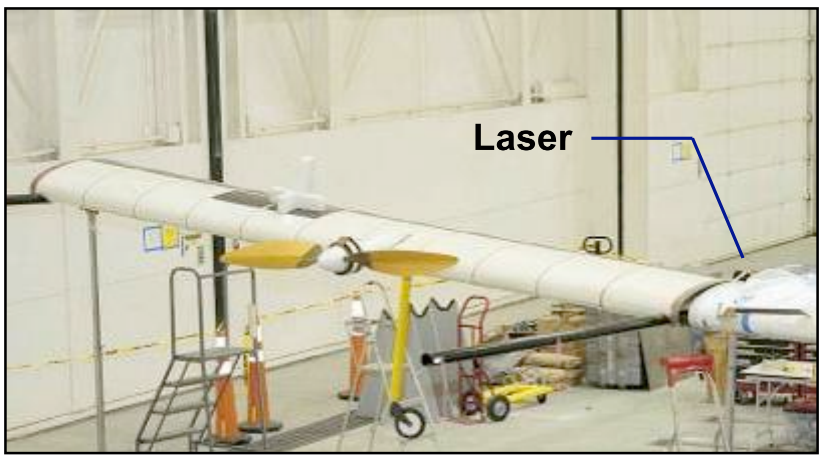
Strain gage system

FBG system

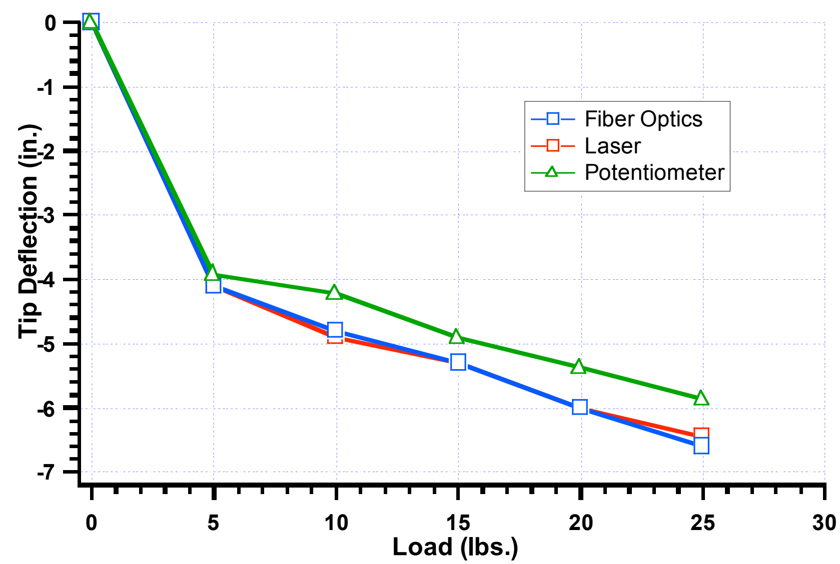


Ground Test Validation – Pathfinder Plus





Ground test setup

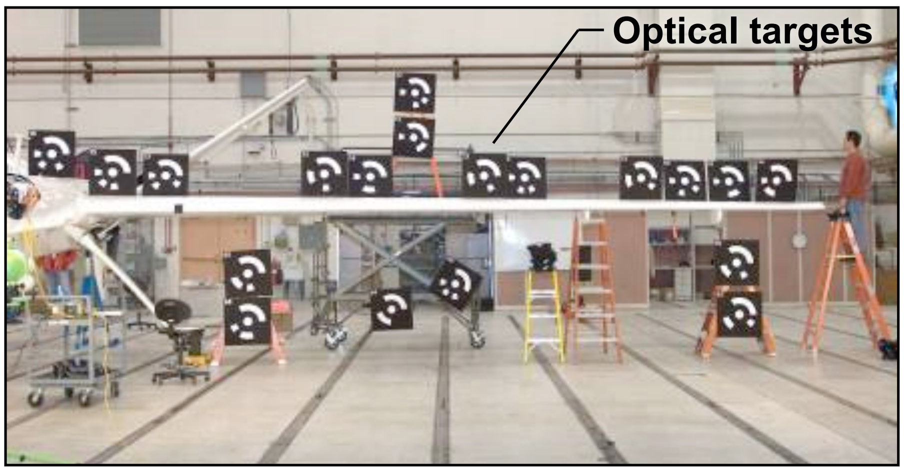


Test Results

National Aeronautics and Space Administration

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

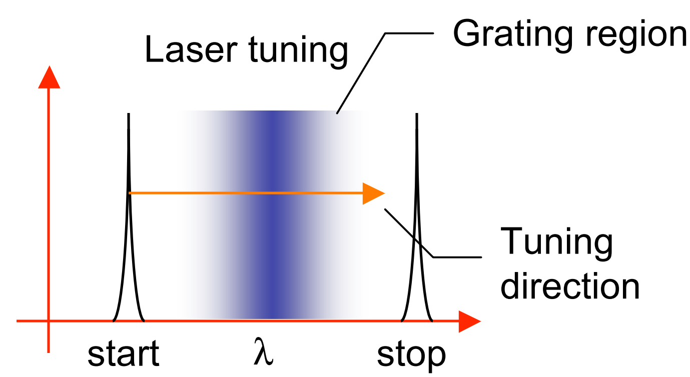
National Aeronautics and Space Administration

Backup Slides

Fiber Optic System Operation Overview

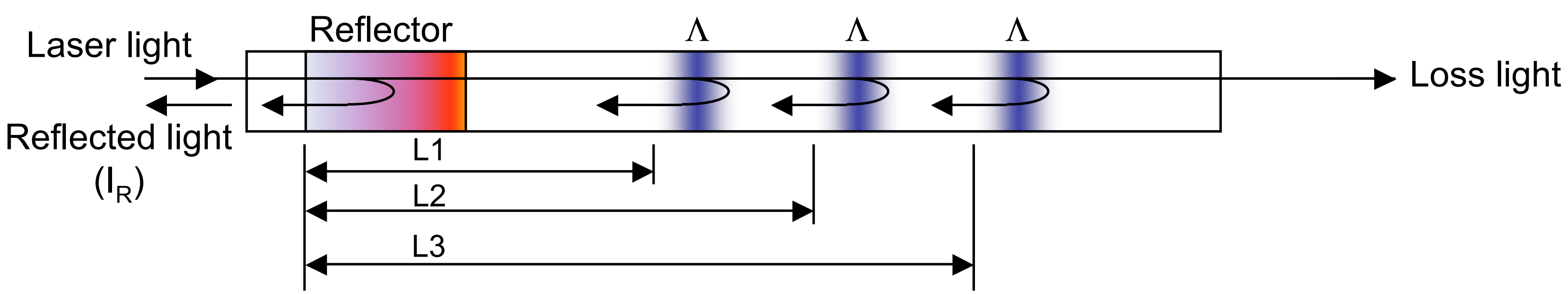
Fiber Optic Sensing with Fiber Bragg Gratings

- **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



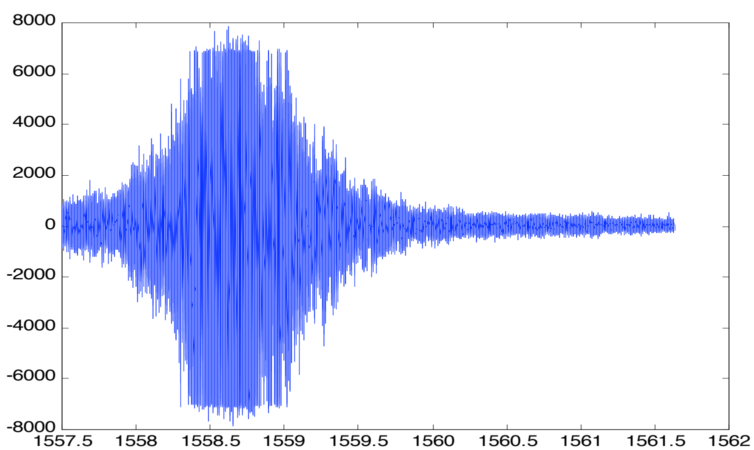
National Aeronautics and Space Administration

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**

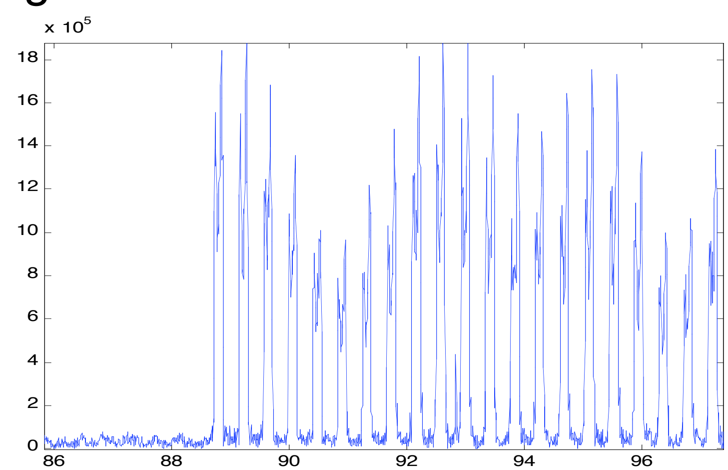
	FFT	**iFFT**
Traditional	**Time(T) > Frequency(F)**	**Frequency(F) > Time(T)**
Optical	**Wavelength(λ) > Length(L)**	**Length(L) > Wavelength(λ)**

Spectral Mapping



Wavelength(λ) domain

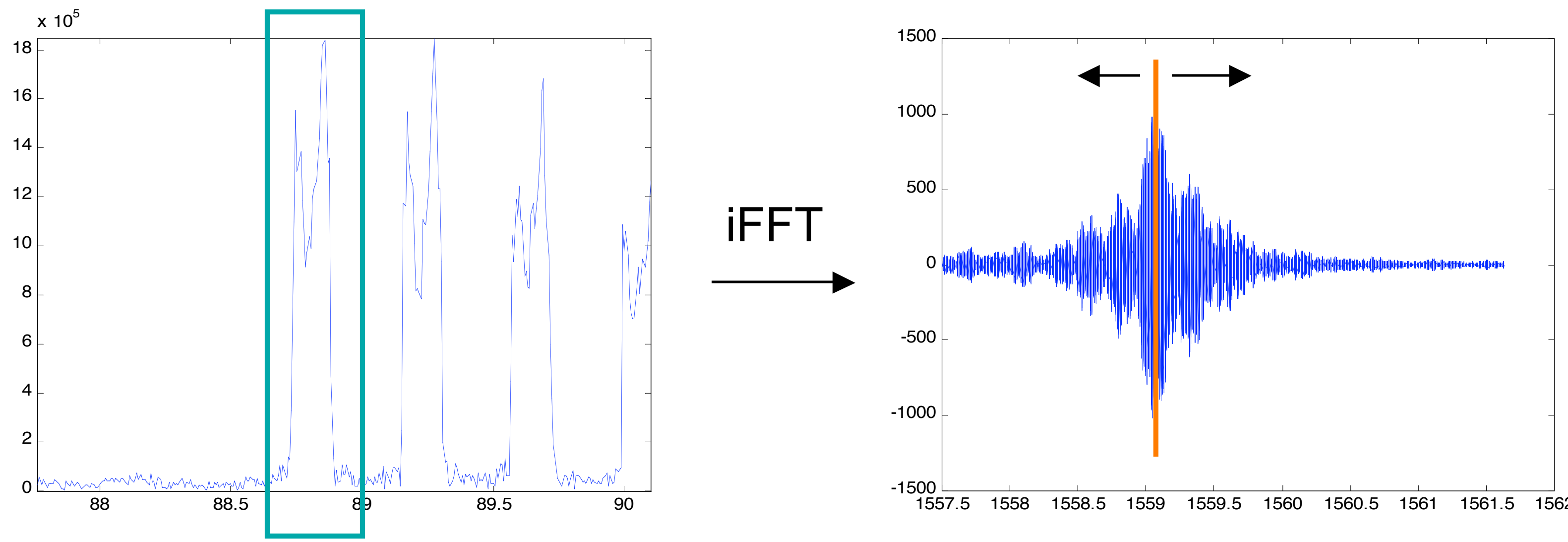
FFT



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)**

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