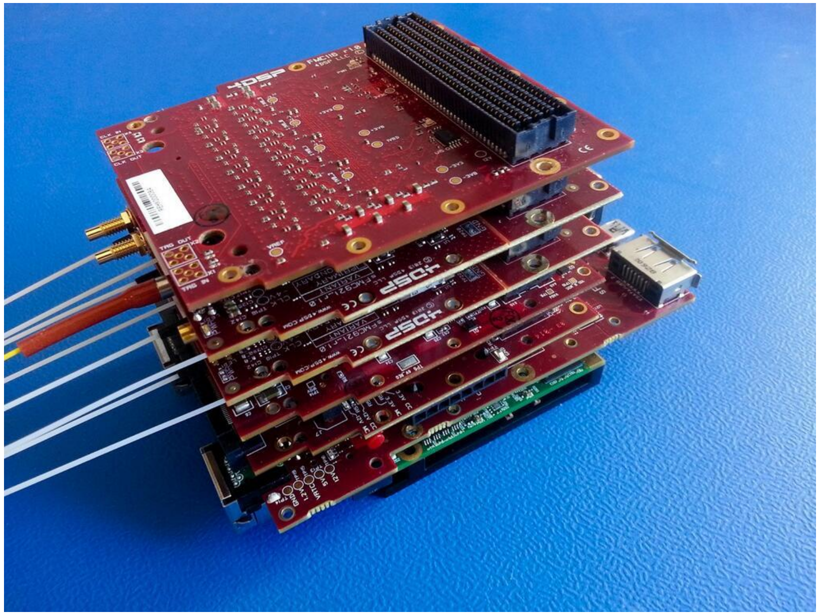
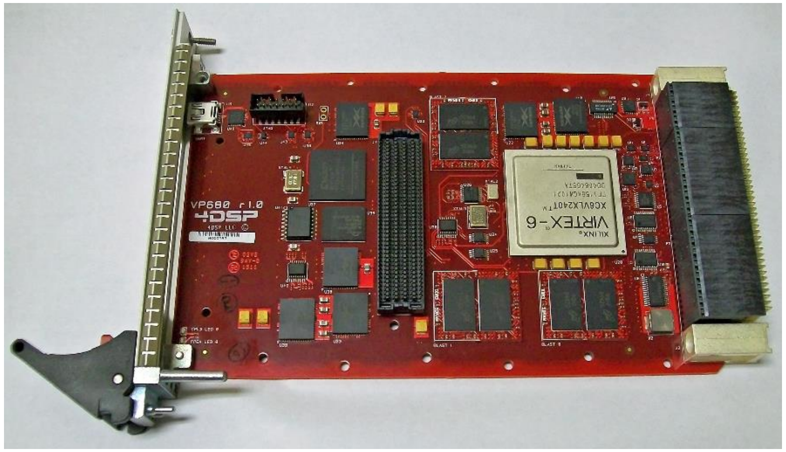
Shape Sensing using c-OFDR

Alex Tongue, 4DSP LLC.

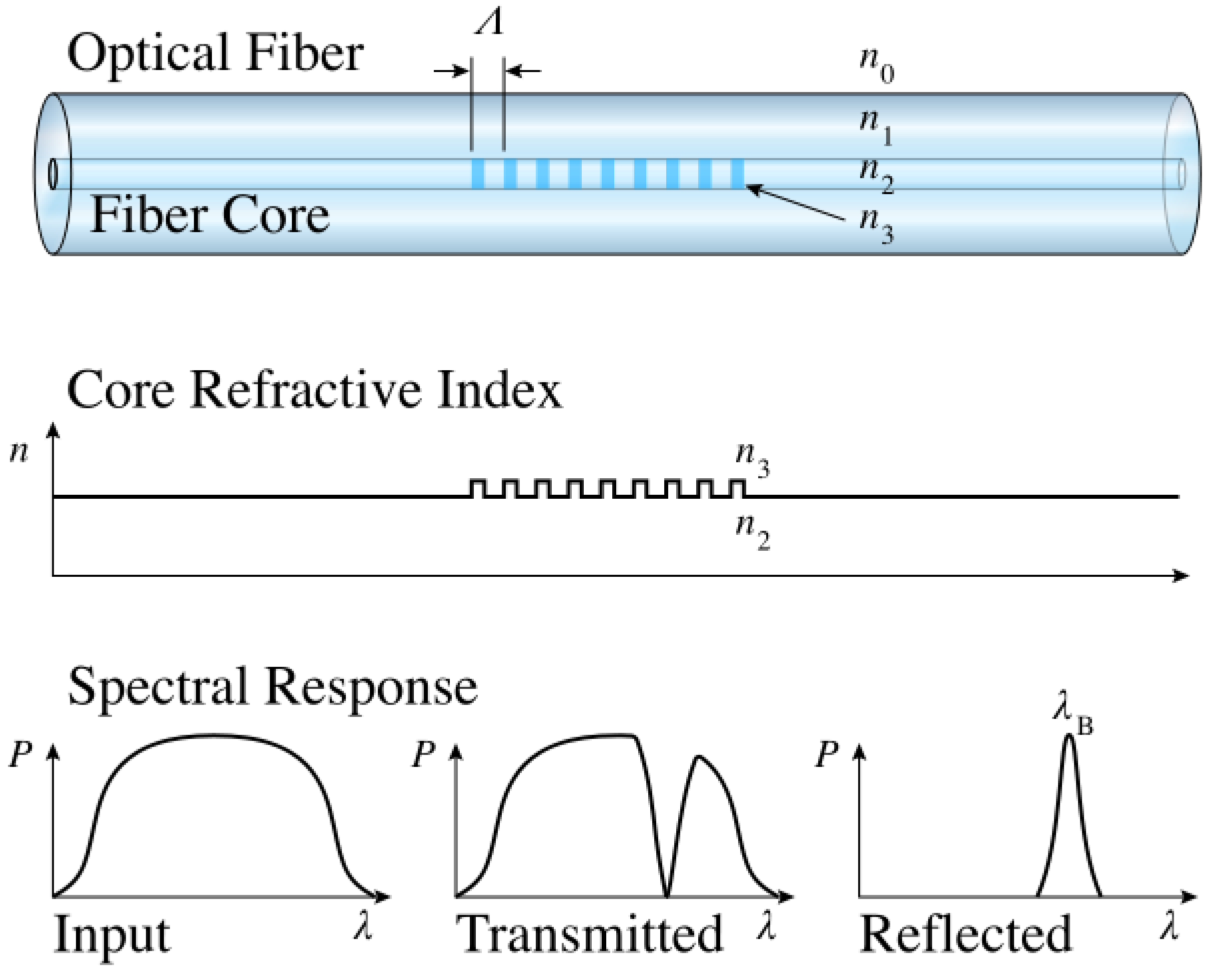
4DSP Background

- Founded in 2003
- US and Netherlands offices
- ~25 employees
- NASA fiber optic technology license in 2011
- High speed D/A & A/D hardware and FPGA design



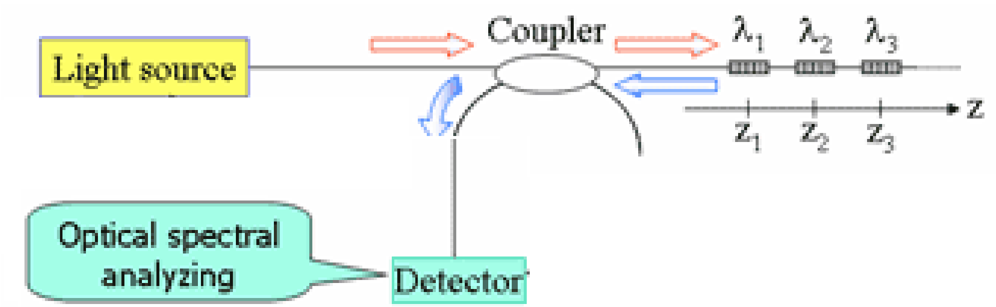


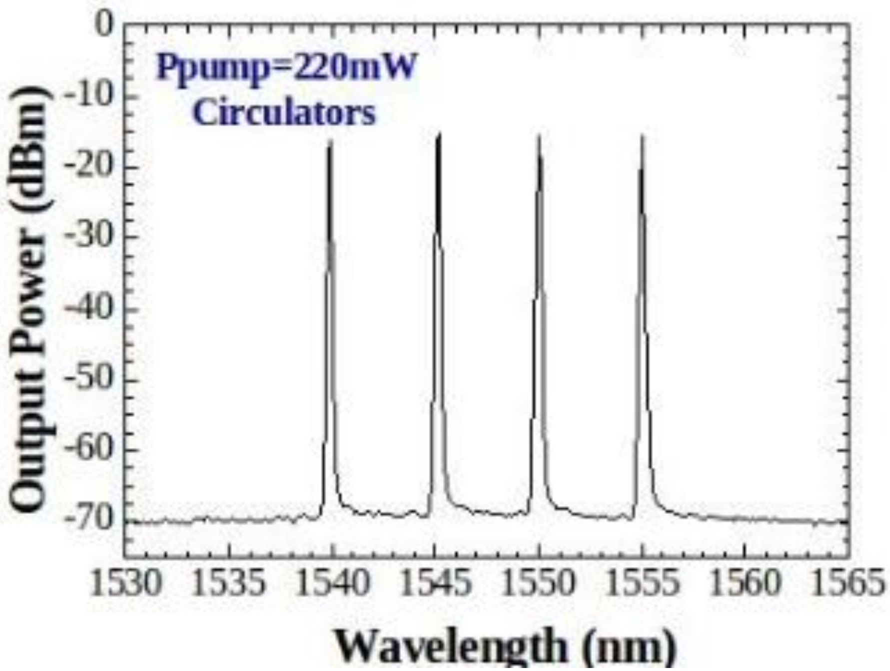
The Fiber Bragg Grating



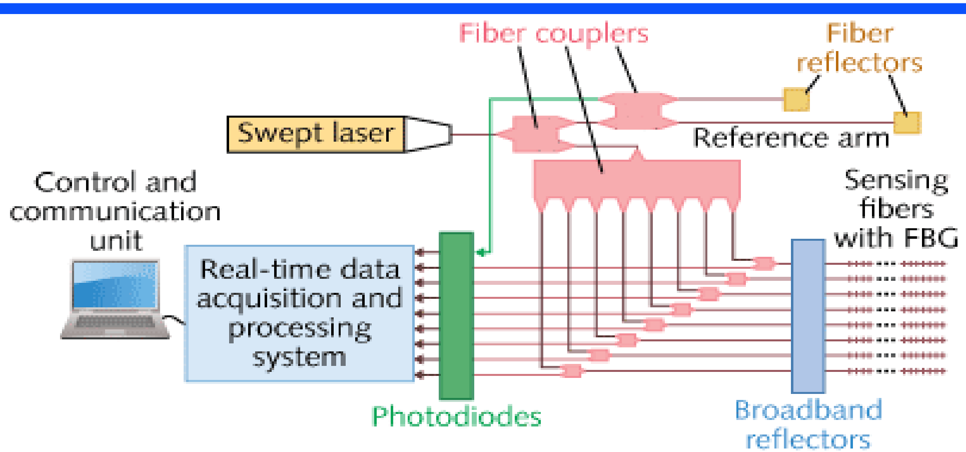
$$\frac{\Delta\lambda}{\lambda} = K\varepsilon$$

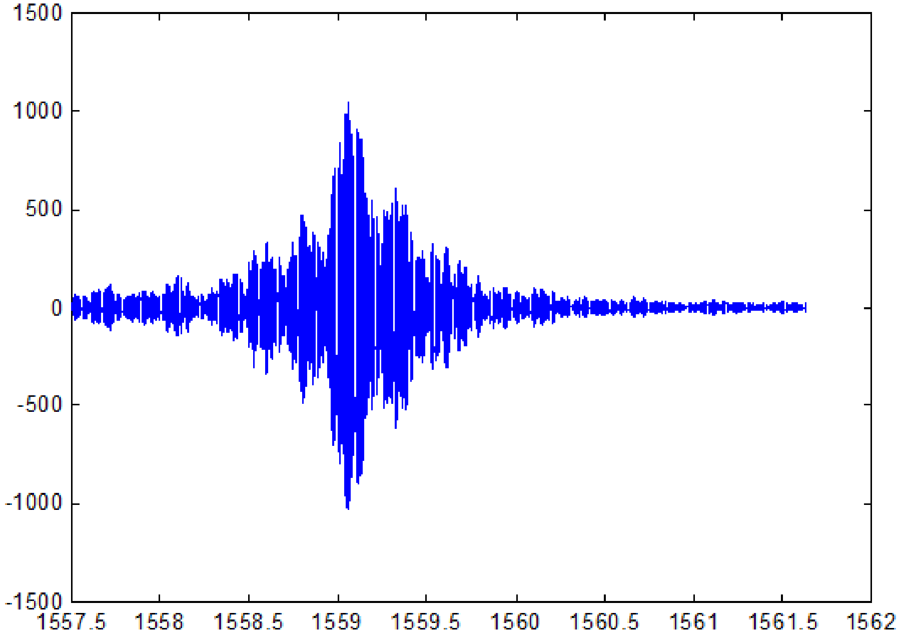
Fiber Interrogation - Traditional





Fiber Interrogation – c-OFDR

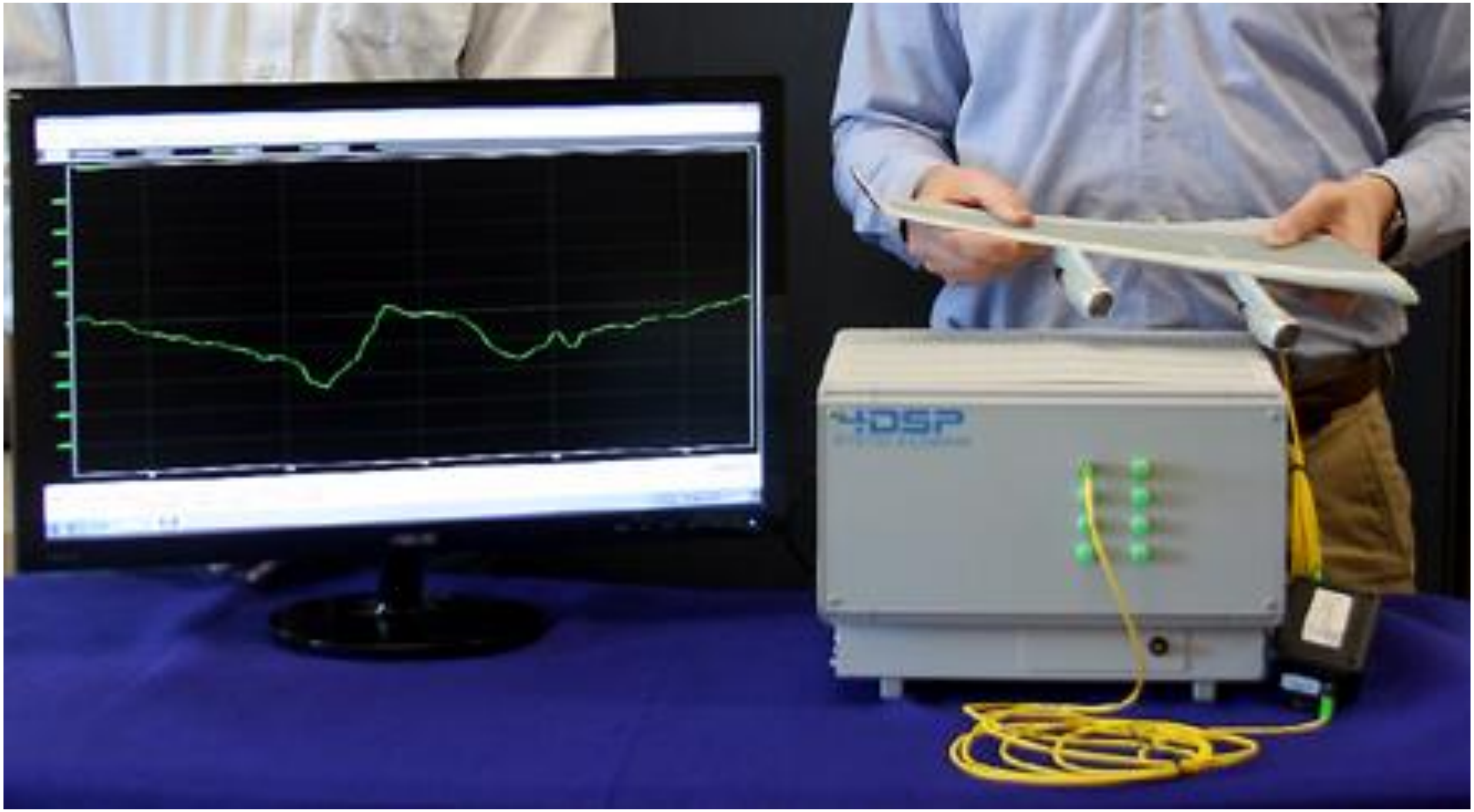




4DSP c-OFDR Interrogator

- 8 or 16 Channels
- 2048 sensors per channel
- Up to 100 Hz refresh rate
- User selectable spatial resolution down to 1mm
- Strain, temperature, liquid level, 2- and 3-D shape

RTS: Distributed Sensing



2D Shape Sensing - Motivation

Design & System Integration

- Helios wing dihedral deflection reached 40 feet during flight
- Exceeded limits and suffered in-flight breakup
- Needed a way to monitor and control deflections during flight and display data to test flight crew

2D Shape Sensing - Theory

- Strain ⟷ Displacement
- In the case of beams: $\varepsilon_x = -z\frac{d^2w}{dx^2}$
- Thus, cOFDR → $\varepsilon(x)$ → $w(x)$
- Paired with cOFDR, this led to the development of the Dryden Displacement Theory:
  - 2D deflection profile
  - Internal shear and moments
  - Applied loads
  - Only a single fiber optic cable required
  - Bonding of the fiber to the substrate is required

2D Shape Sensing - Theory

Design & System Integration

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

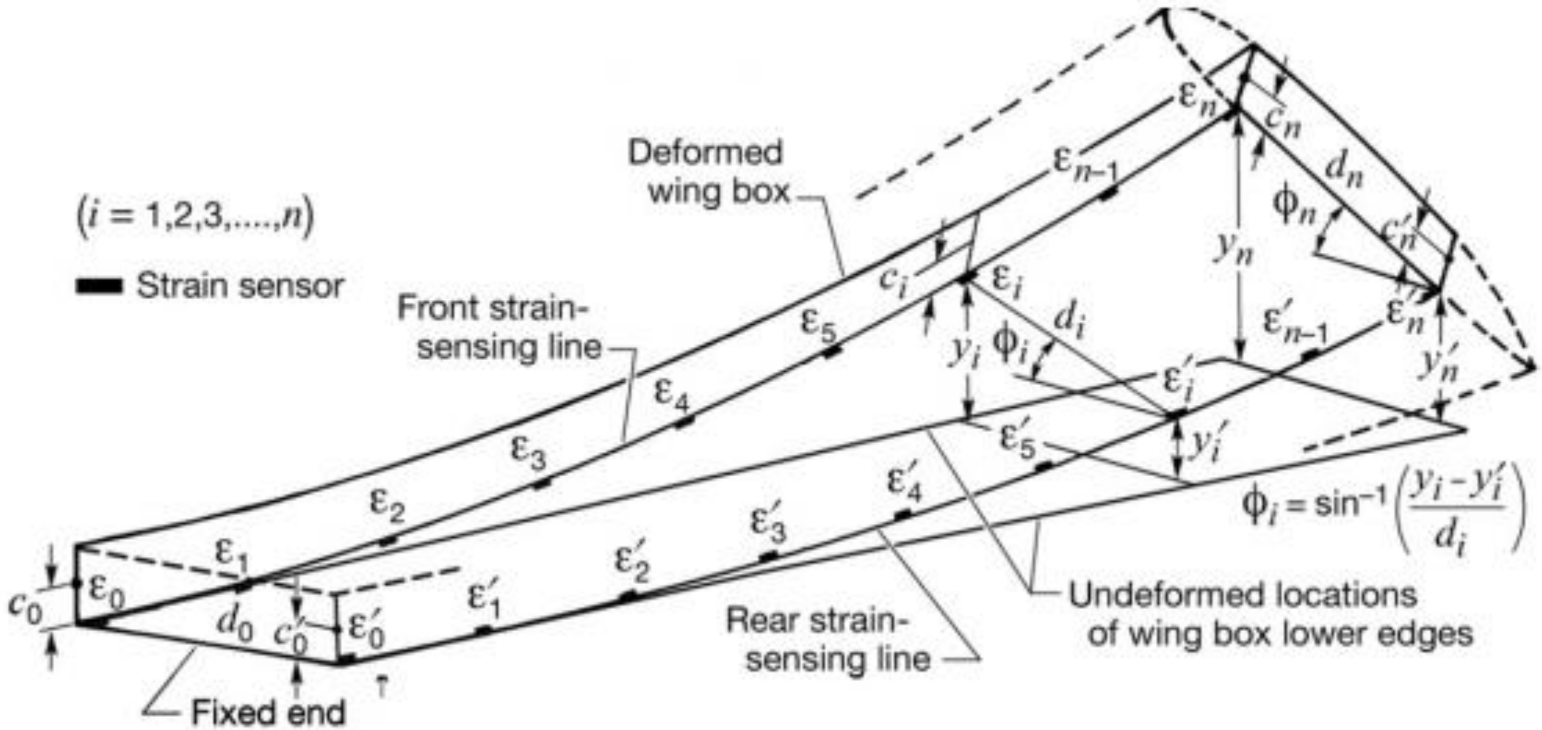
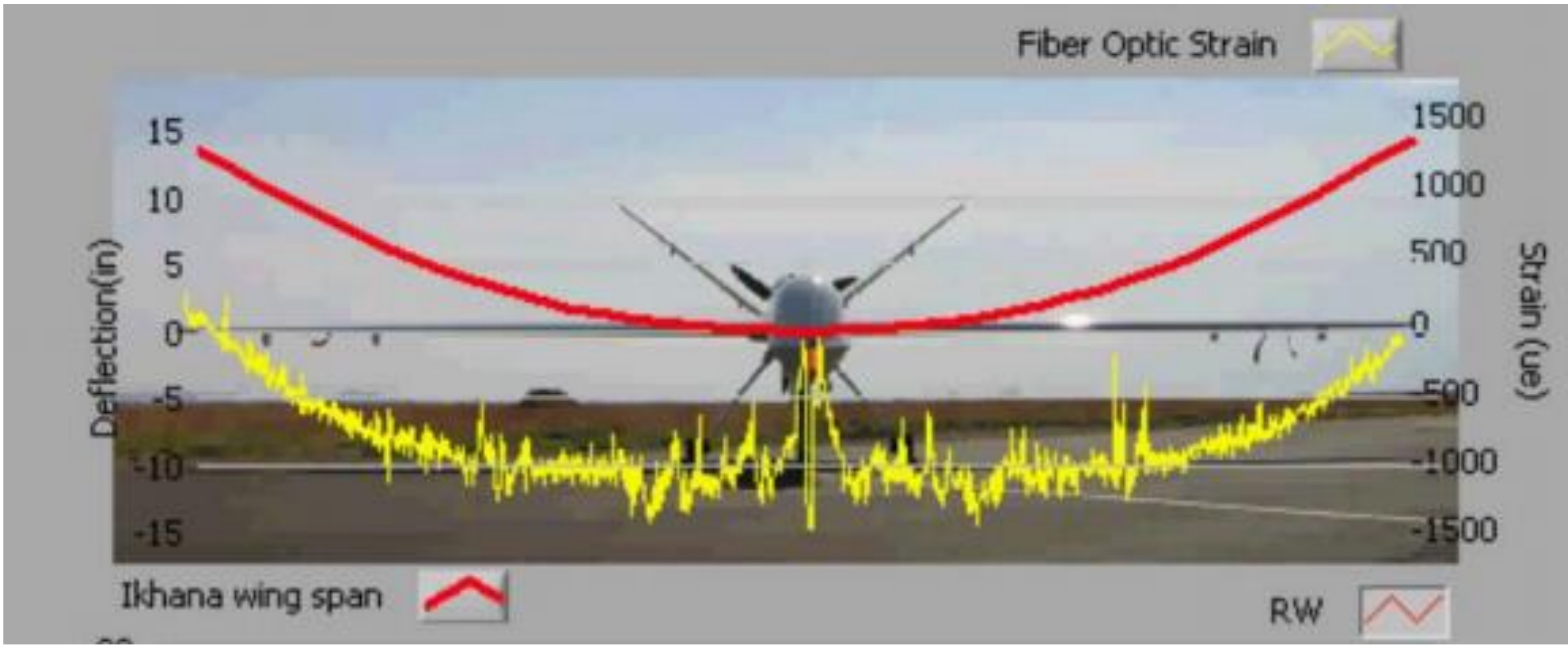
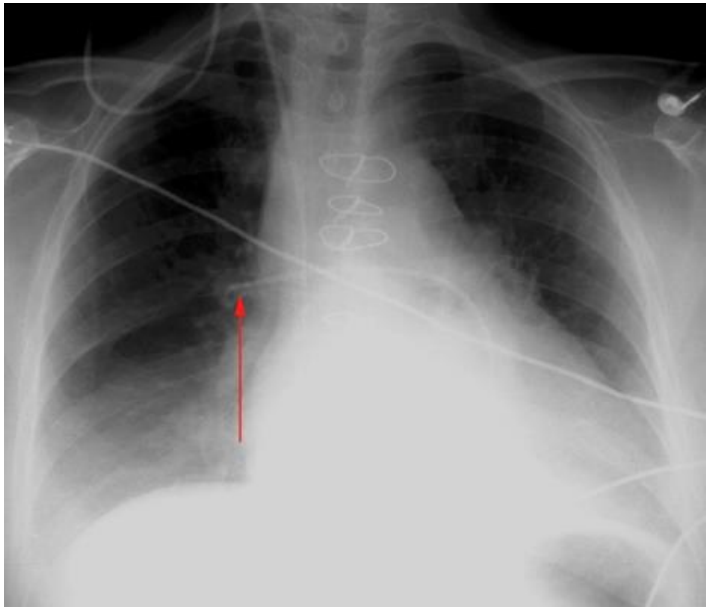


Figure 5-2: Tapered Wing Box Instrumented with Two-Line Strain-Sensing System.

2D Shape Sensing - Application



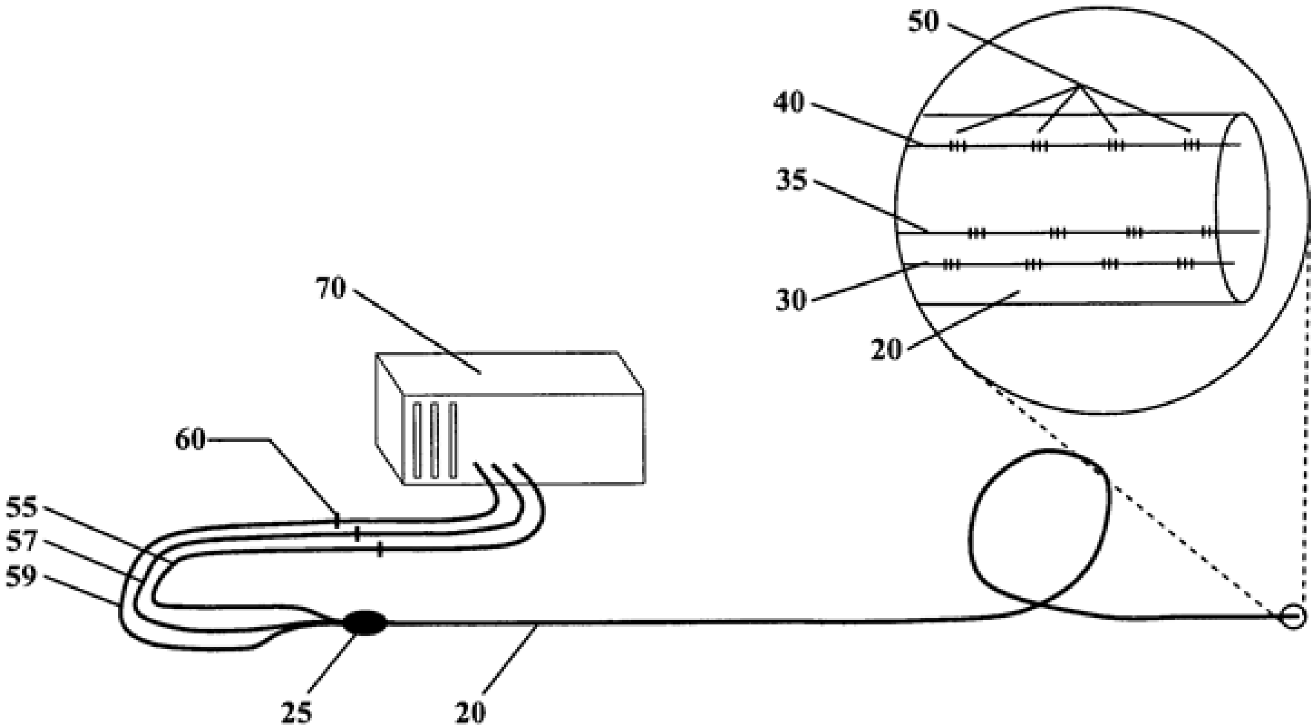
3D Shape Sensing - Motivation



- Many other structures may benefit from knowledge of deflection shapes which do not remain in a 2D plane
- Many cabled applications traditionally only track the end location
  - Borescopes
  - Submersible vehicles
- Tracking medical devices often requires additional foreign material and radiation

3D Shape Sensing - Theory

- Based on the same strain-displacement principle as the 2D case
- Requires curvature in multiple directions → must use multiple fibers
- Fibers are brought together with a constant cross-sectional geometry
- Connected to the system via a fan-out and three individual connectors

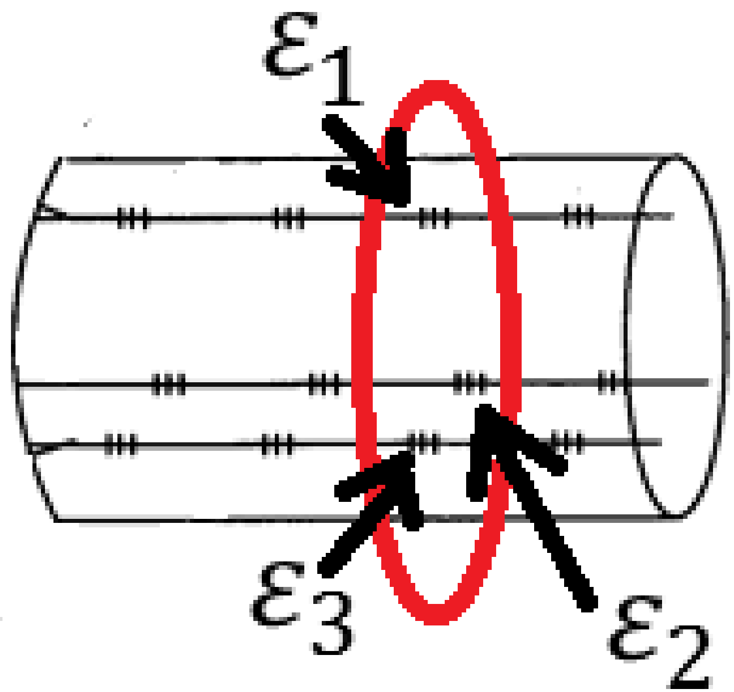


3D Shape Sensing - Theory

Design & System Integration

Differential strains are obtained at each sensor “triad”:

$$\Delta\varepsilon_{12} = \varepsilon_1 - \varepsilon_2$$
$$\Delta\varepsilon_{23} = \varepsilon_2 - \varepsilon_3$$
$$\Delta\varepsilon_{31} = \varepsilon_3 - \varepsilon_1$$



Through known geometry, strain-displacement relations, and mathematical descriptions of a curve:

$$\left.\begin{matrix}\Delta\varepsilon_{12}\\ \Delta\varepsilon_{23}\\ \Delta\varepsilon_{31}\end{matrix}\right\} \Rightarrow \left.\begin{matrix}\Delta k_{12}\\ \Delta k_{23}\\ \Delta k_{31}\end{matrix}\right\} \Rightarrow \overrightarrow{r(s)}$$

This method yields a sensor which is insensitive to both axial elongation and temperature

3D Shape Sensing – Current and Future

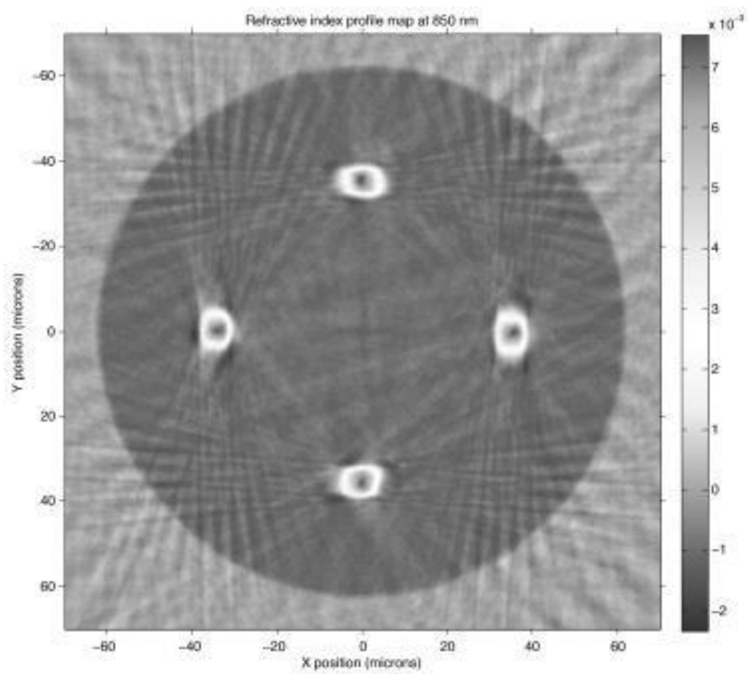
Design & System Integration

Current:

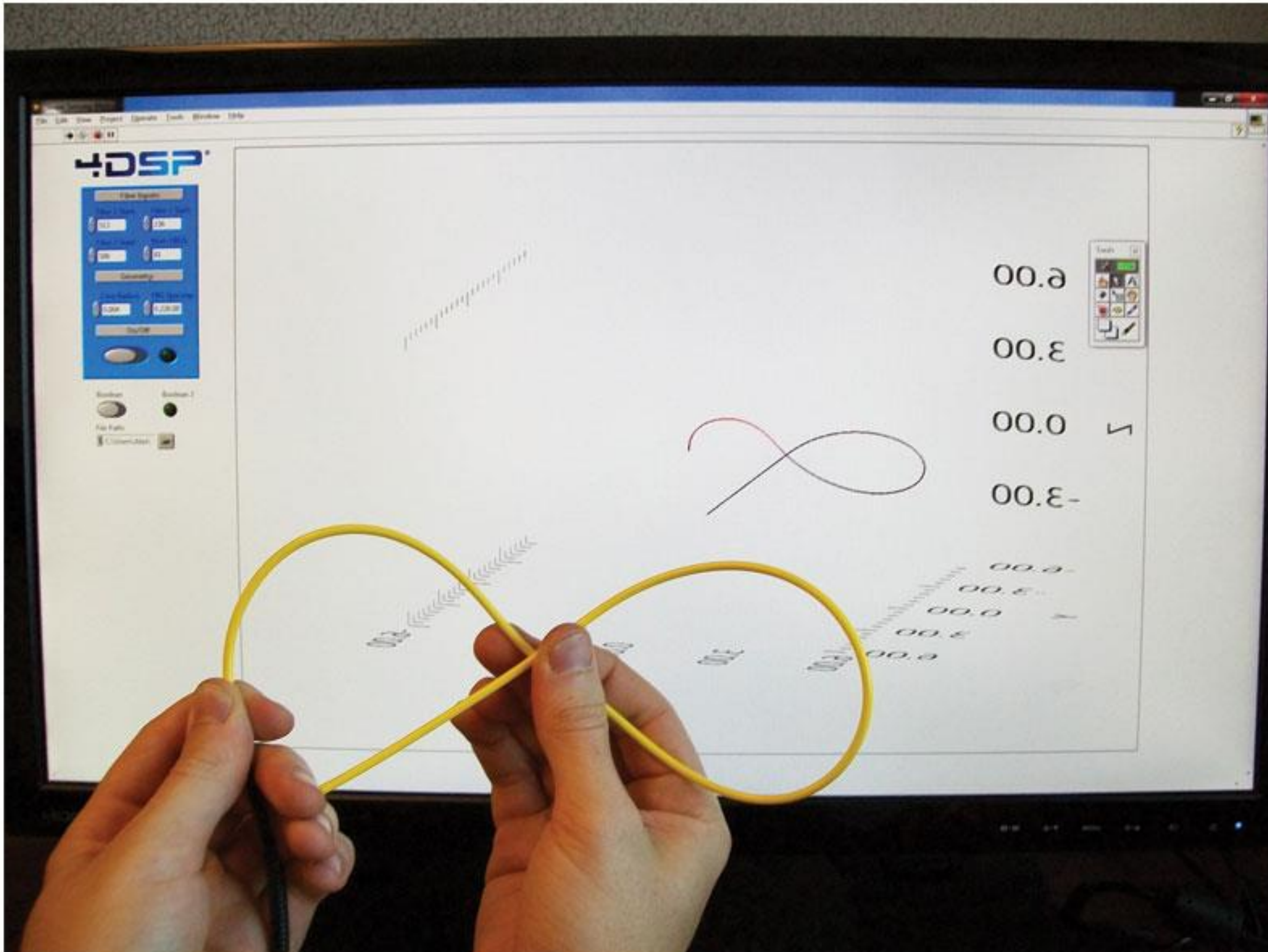
- Sensor integration is currently done by hand and automated production is under development
- Despite being handmade, an initial study for the medical industry yielded positive accuracy and repeatability results
    - 2D testing due to nonuniform cross section
    - Accuracy: 1-3% of arc length
    - Repeatability at end of sensor: <1% of total length
- Lengths of up to 100 m per sensor
- Sensor diameter down to 500 microns

Future:

- Working with fiber provider (FBGS) on a multicore fiber
- Accuracy <1%
- Twist mitigation
- Sensor diameter down to 330 microns



3D Shape Sensing - Output



3D Shape Sensing – Output

Design & System Integration

Thank You

Questions?