FOSS (Fiber Optics Sensing System) at NASA AFRC - Overview

OPTICAL SENSORS FOR ENERGY APPLICATIONS

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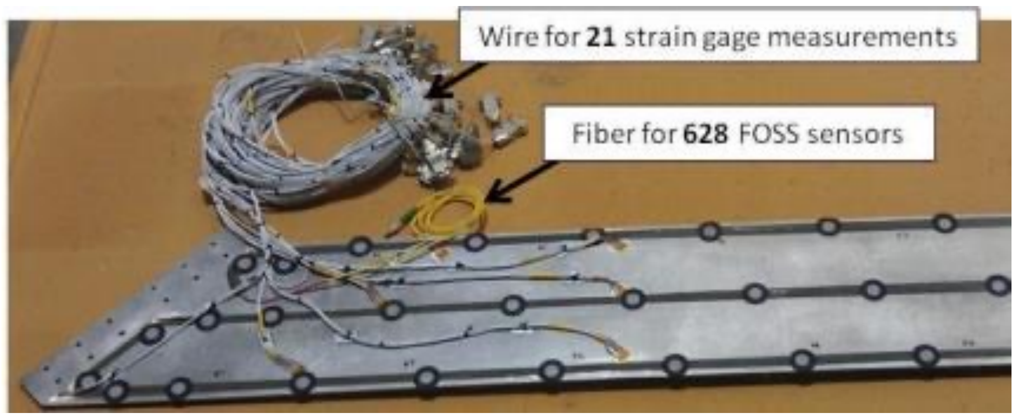
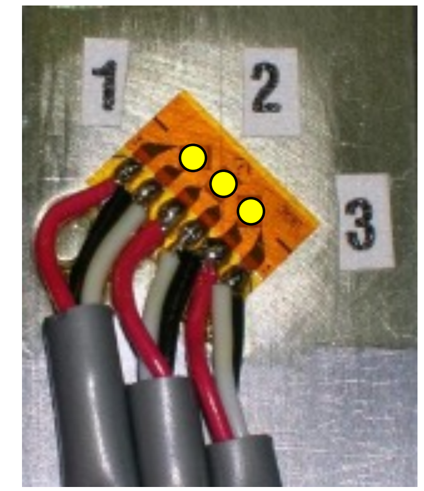
- Fiber Optics based sensors – how it works
  - Fiber bragg gratings
- Types of fiber optics based interrogator
  - WDM
  - OFDR – FOSS is based on this technology
- Advantage of OFDR
- AFRC's FOSS technology implemented

Why Choose Fiber Optic Sensors over Resistive Gages?

One Of These Things (is Not Like The Others)

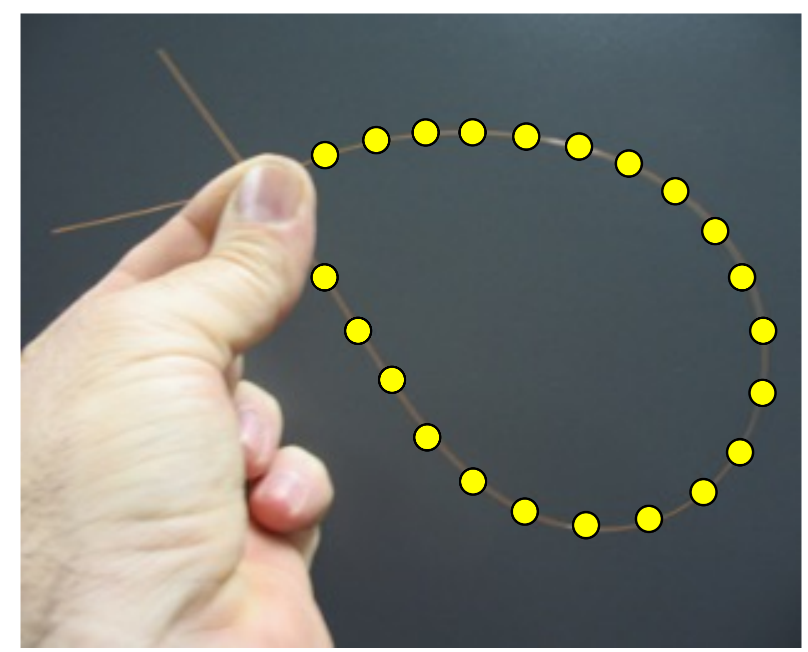


(Heavy)



(Big)

(Hard)

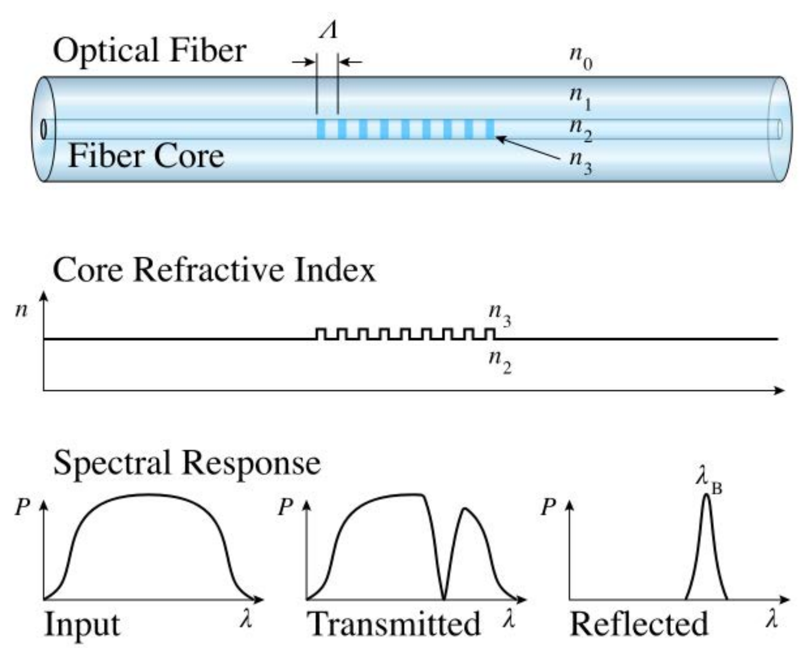


(Light, small, easy)

Fiber Bragg Grating (FBG) as sensor

Principle

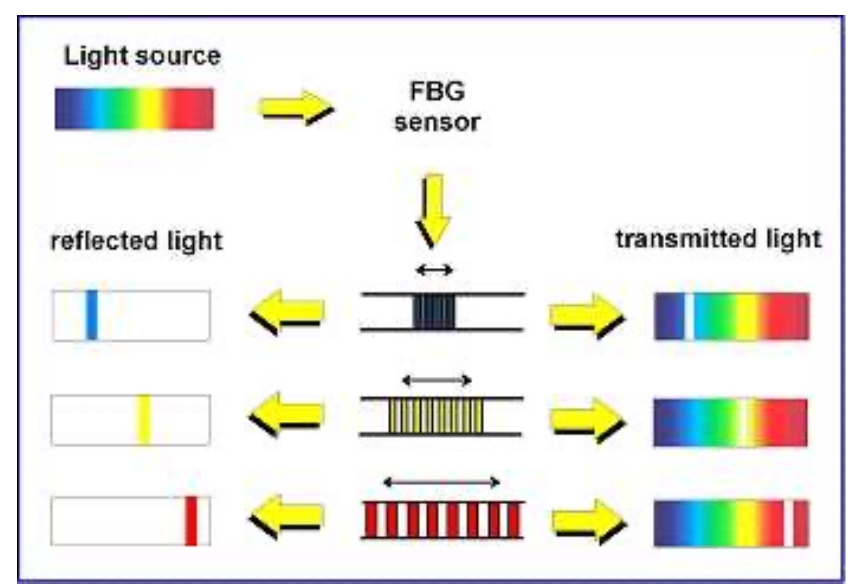
- Fiber Reflector that reflects a particular wavelength and transmit all others
- Bragg Wavelength: λ_B=2$n_e\Lambda$



Measuring Strain(ε) or Temperature (ΔT) via FBG sensor

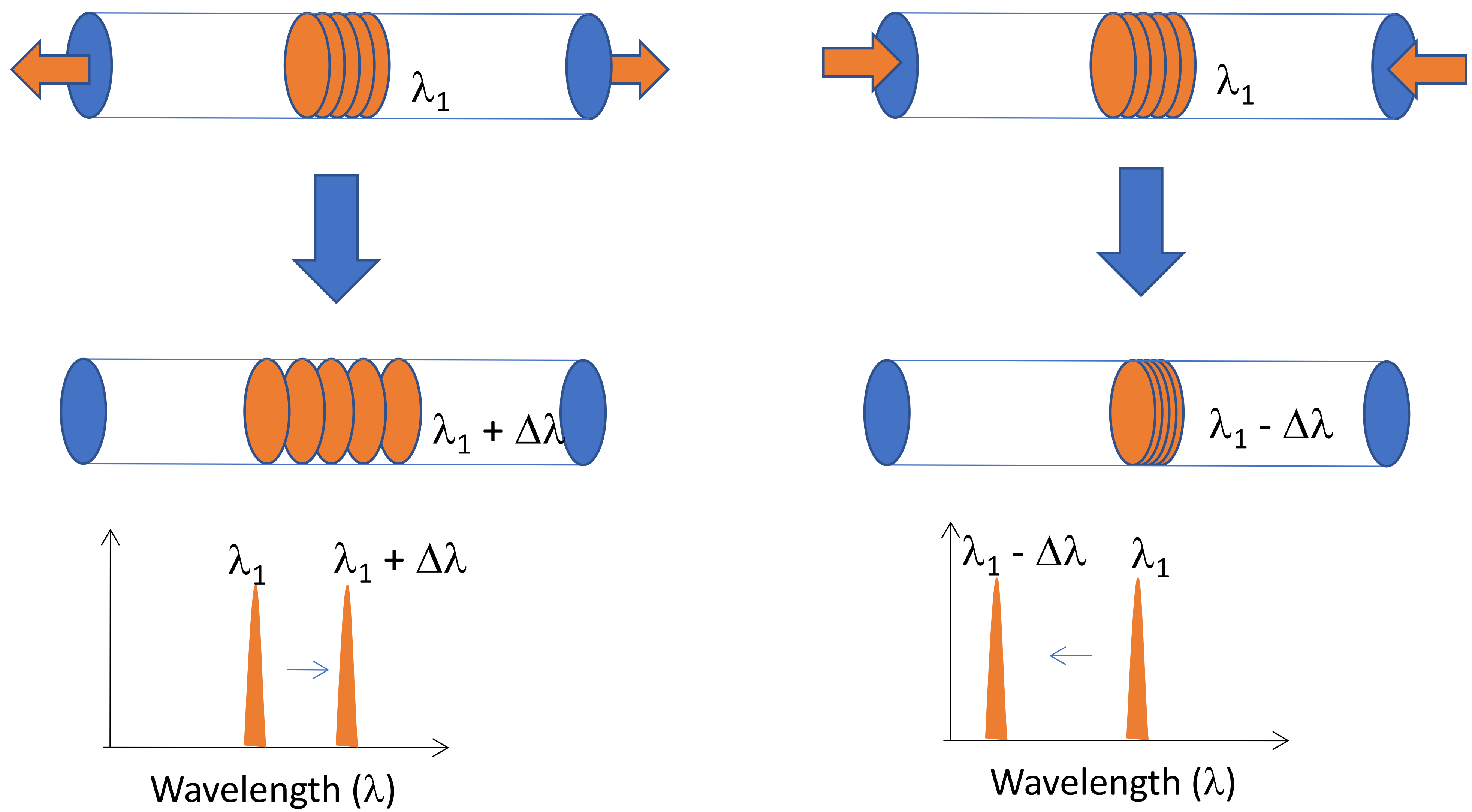
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

- $\Delta\lambda_B$= change in Bragg wavelength <u>due to environmental change</u>
- λ_B= Initial Bragg wavelength of FBG
- p_e= strain-optics coefficient
- α_Λ = Thermal expansion coefficient
- α_n = thermo-optic coefficient



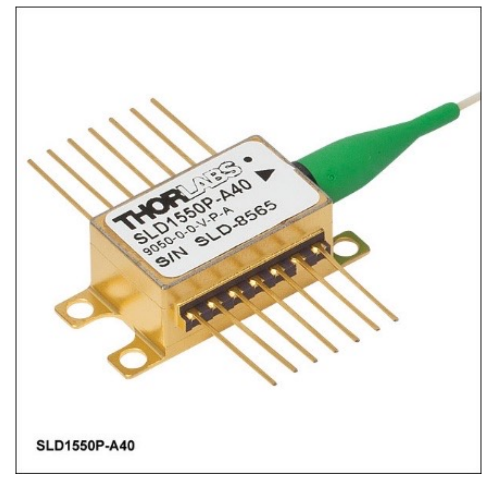
How do FBG sensors works?

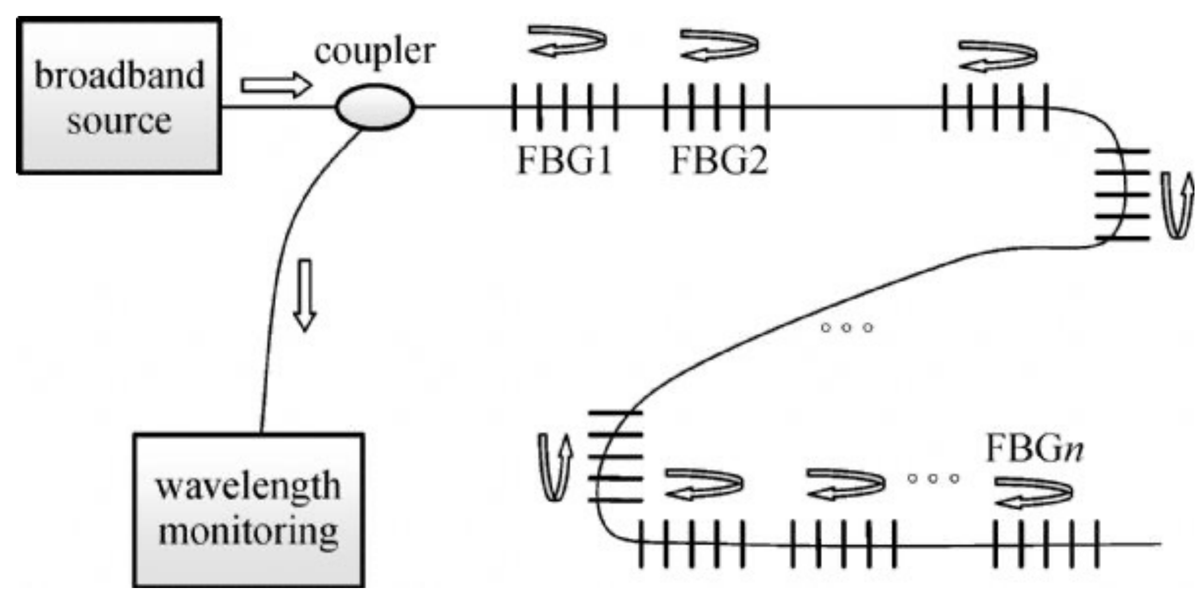
- Like an accordion → change in Bragg Wavelength



Typical FBG sensing via Wavelength Division Multiplexing (WDM)

- Excitation Source (light source)
  - LED
  - Laser
- Fiber Sensors (FBG)
- Photodetector (A/D)
- Detection Scheme (Optical Spectrum Analyzer)

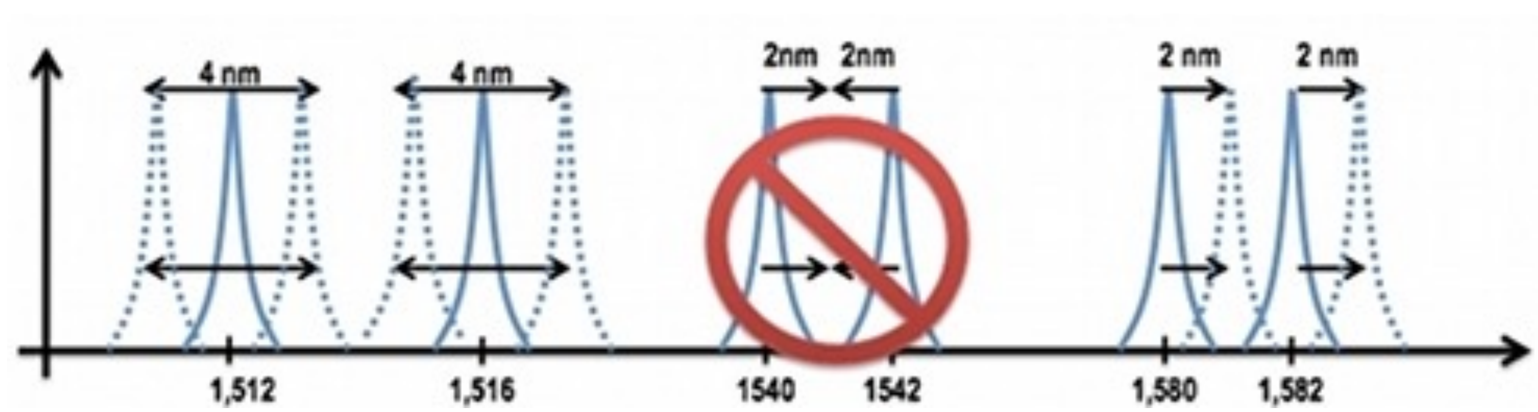




Pro/Con of WDM

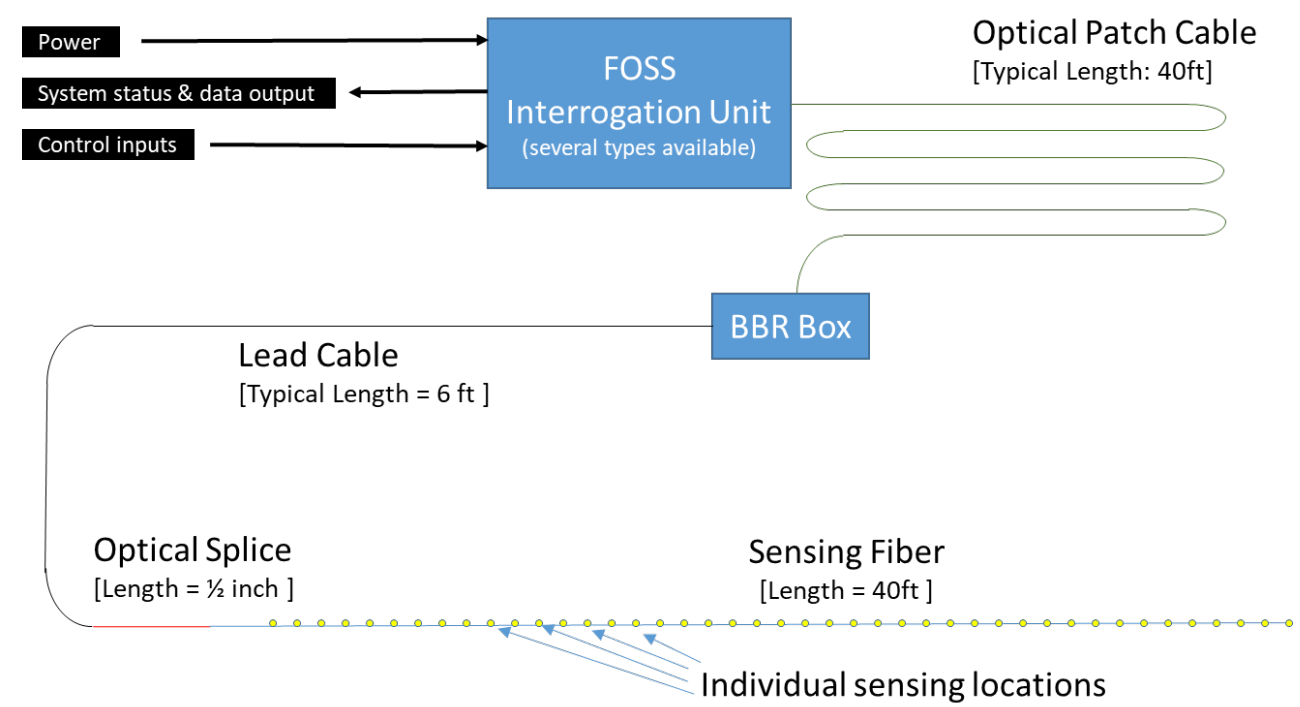
- Advantage
  - Sensors can be ~km away from interrogator
  - Relative Simple Measurement
  - Commercially Available
  - High Sampling Speed Available (~MHz)

- Disadvantage
  – Location of each sensor matters
  – Each sensors has to have unique wavelength
  – Only ~10 sensor can occupied 1 data channel
    - Aliasing effect
      – When 2 sensors intersects one another



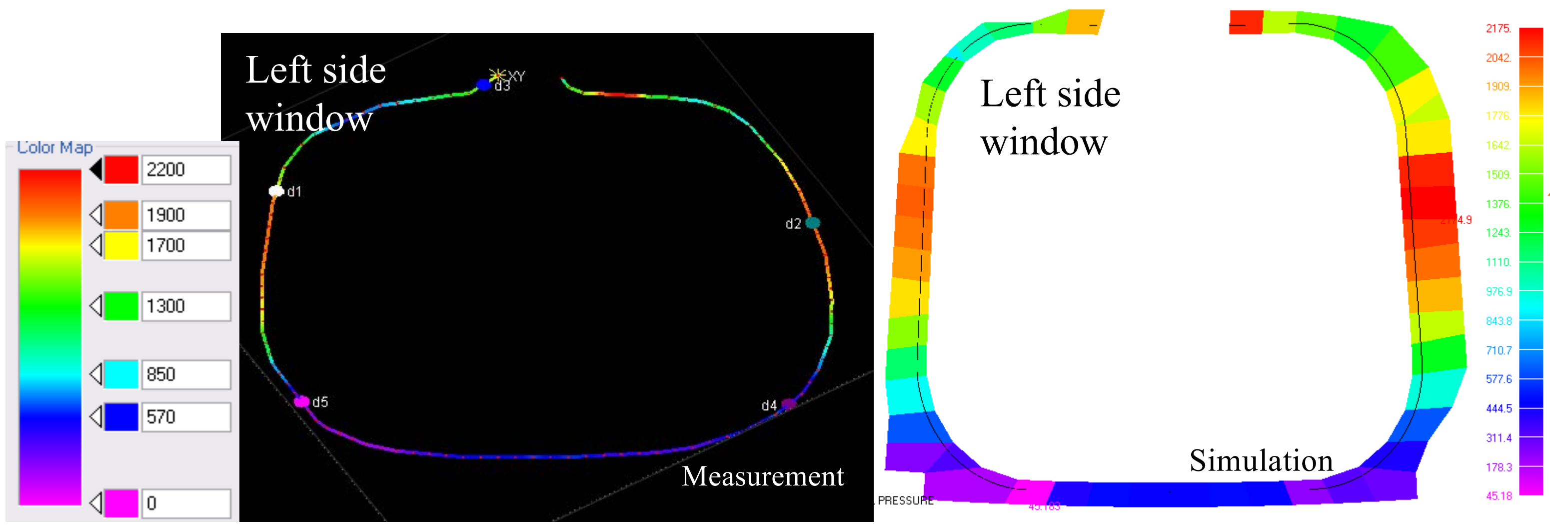
NASA's Unique FBG Interrogation Technique: OFDR

- Optical Frequency Domain Reflectometry (OFDR):
  - Based on laser interferometry
    - Single Longitudinal mode laser needed
  - Involves signal processing
    - Fourier Transform/inverse Fourier Transform
  - Use weak reflectivity FBG
    - Typical WDM FBG's R=80%
    - Typical OFDR FBG's R=0.05%
  - So why use OFDR for sensing instead?
    - Many advantages that WDM can't match



Advantage of OFDR over WDM

- High Spatial Density over WDM-based sensing
  - Up to 1000 FBGs can be multiplexed (OFDR)
    - At most 10 FBG sensors per fiber (WDM)
  - FEM type of data can be achieved through real-time testing



NASA Composite Crew Module Testing (2011)

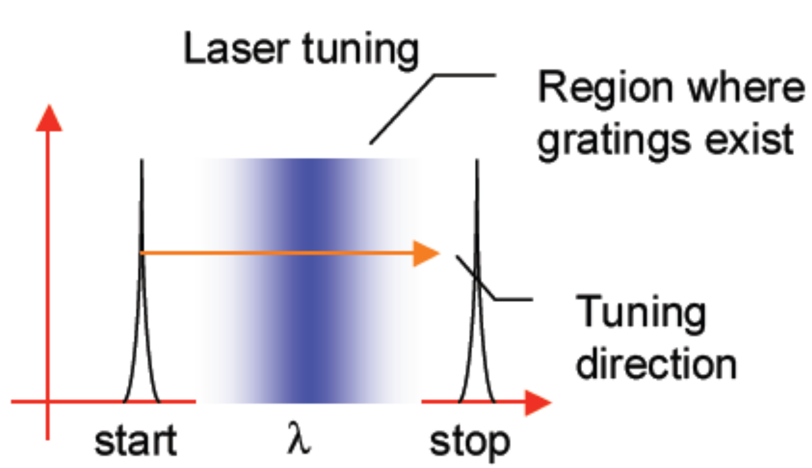
- Cost per sensor length is <u>dramatically reduce </u>vs WDM-based sensors
  - \$0.75/FBG (OFDR), about \$60 for 84 sensors
  - \$200/FBG (WDM)

Optical Frequency Domain Reflectometry

- All FBGs are written at the same wavelength (λ_B), instead of each having a unique wavelength (WDM)
  - Multiplexing of hundreds of sensor in single fiber
- A narrowband wavelength tunable laser source is used to interrogate multiple sensors.
- Each FBG sensor is only ½ inch long

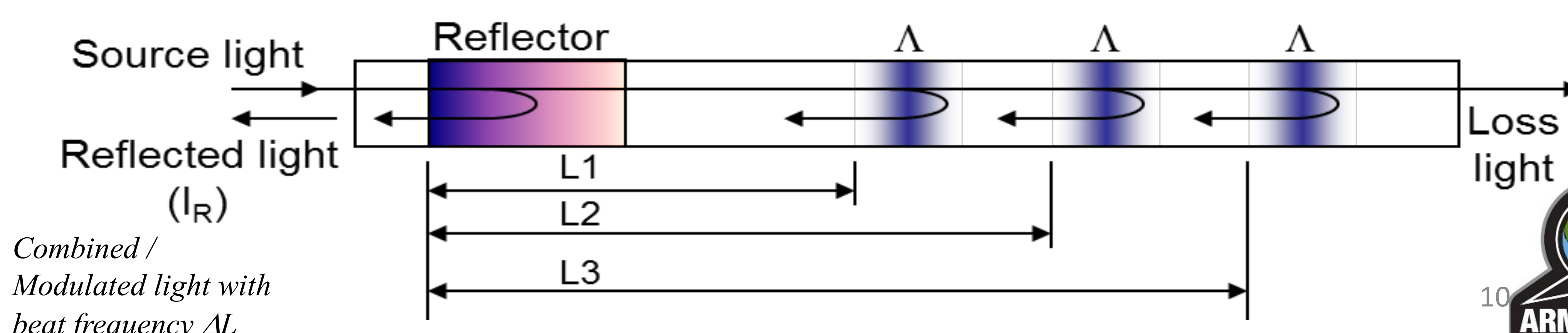
Principle of OFDR (Optical Frequency Domain Reflectometry)

- Combine 2 coherent waves to generate a beat frequency
  - This is an unique beat frequency based on the length difference ΔL
- Multiple sensors with unique beat frequencies (ΔL_{fbg}) are captured
- In Fourier Domain each sensor with unique frequency is separated, and iFFT to obtain its design wavelength (λ_B)

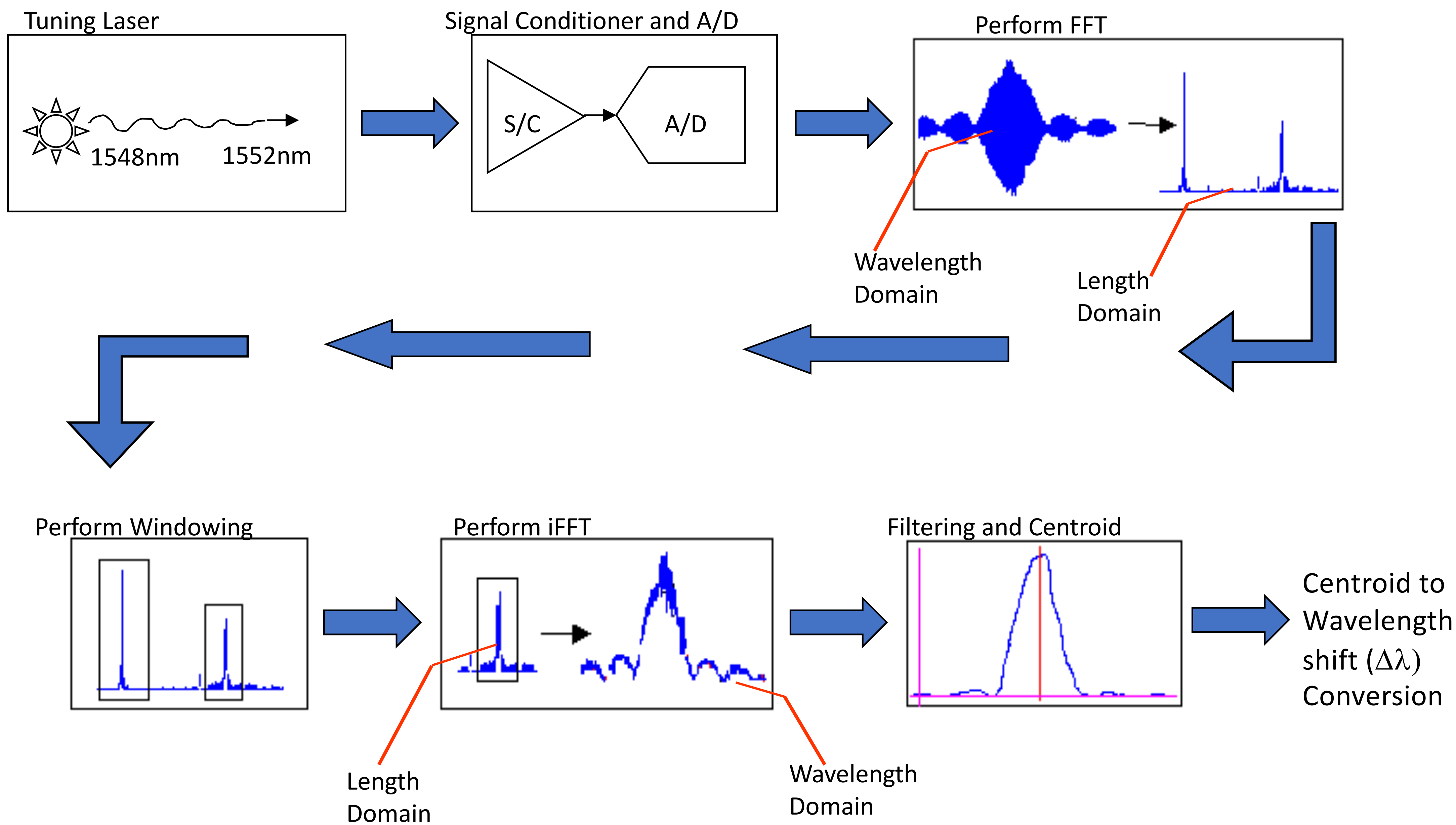


$$I_R = \sum_i R_i Cos(k 2 n_0 L_i) \qquad k = \frac{2\pi}{\lambda}$$

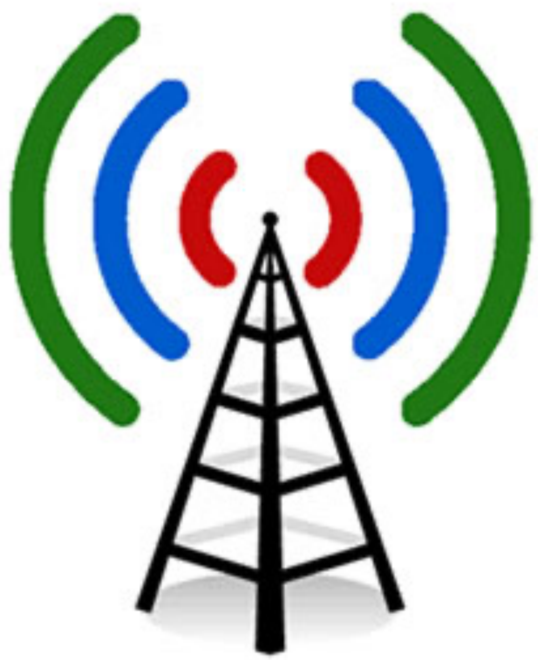
R_i – spectrum of i[th] grating
n_0 – effective index
L – path difference
k – wavenumber



Flow-chart: OFDR Signal Processing (Pre-sensor)



Layman's Term: Tuning your favorite radio station!

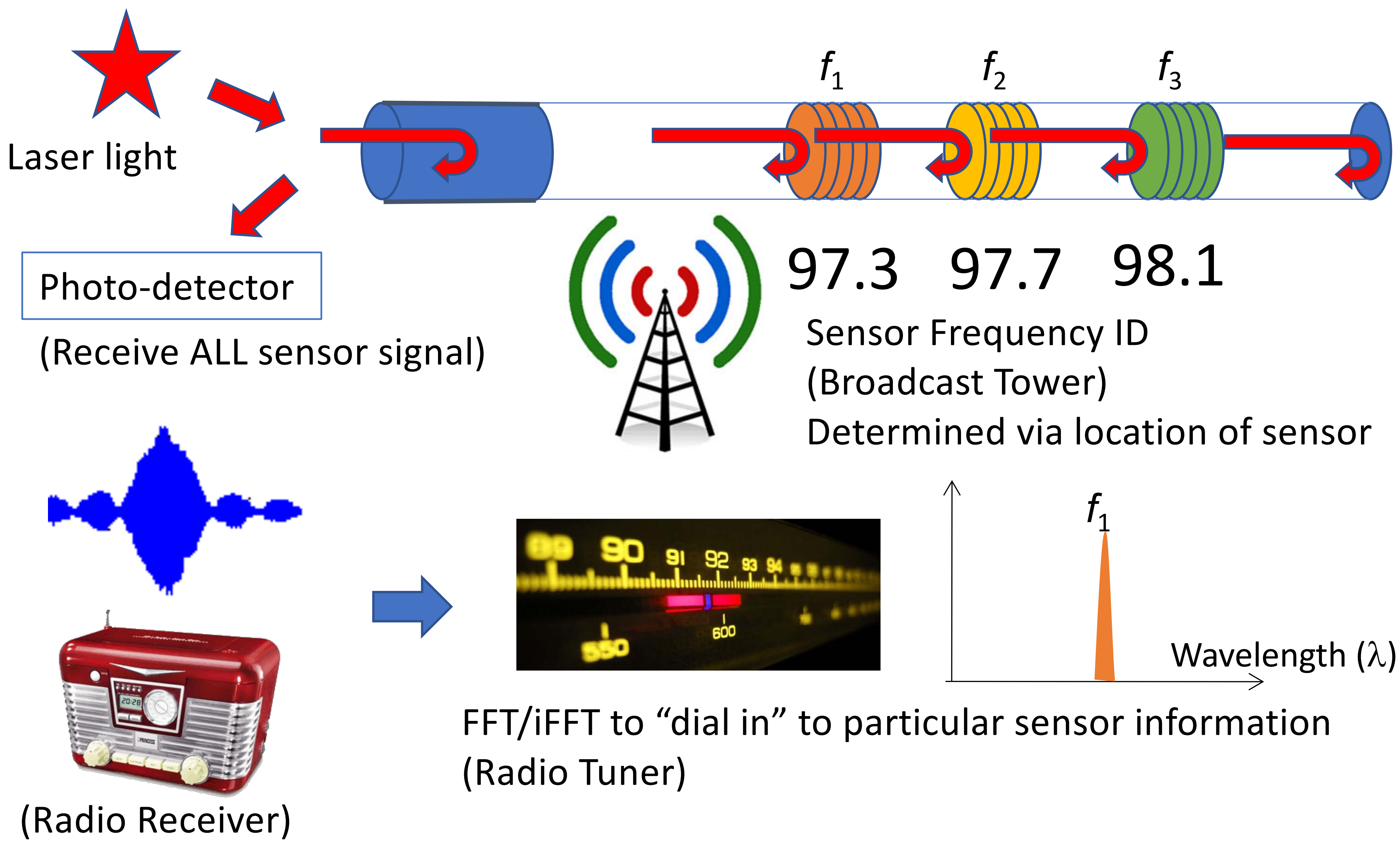


Radio receives ALL frequencies

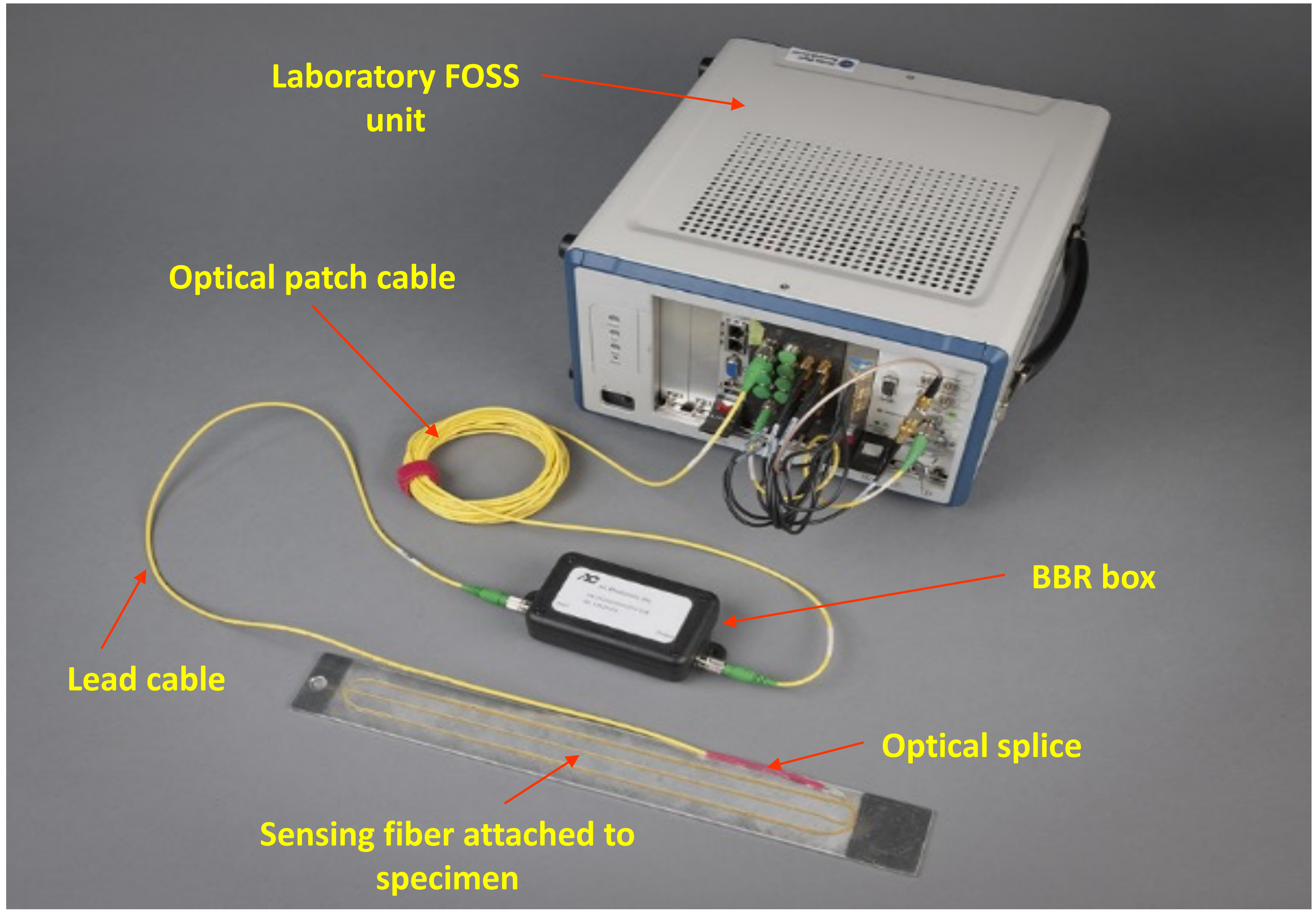
Radio tuner accepts ONE frequency

Multiple frequencies
are broadcasted on airwave

Radio analogy to Optical Frequency Domain Reflectometry



FOSS Components

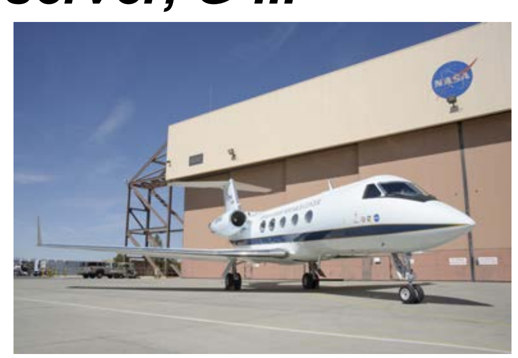


AFRC's Current FOSS Capabilities

Current system specifications

Fiber channels	2 to 4 to 8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Fiber type:	SMF-28
Max sample rate (flight)	50 Hz
Power (flight)	28VDC @ 4.5 Amps
Power (ground)	110 VAC
User Interface	Ethernet
Weight (flight, non-optimized)	27 lbs
Weight (ground)	7 to 25 lbs
Weight (launch)	35 lbs
Size (flight, non-optimized)	7.5 x 13 x 13 in
Size (ground, latest)	10 x 4 x 6 in
Size (launch)	19.25 x 9 x 6.25 in

Aircrafts supported: Predator-B, Global Observer, G-III



Flight System

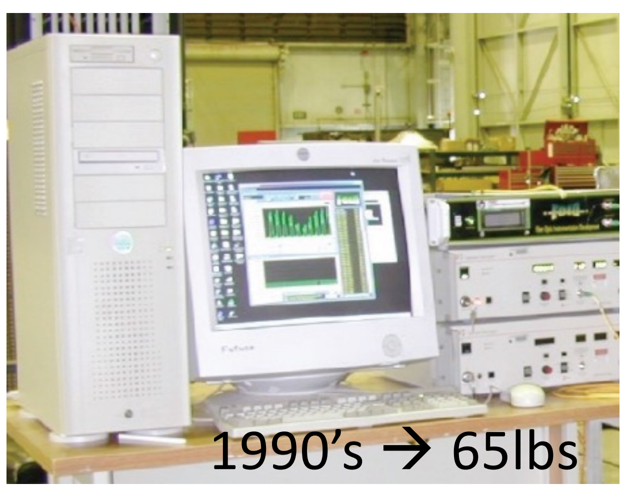
Ground Systems

Launch System

AFRC's role in fiber sensing technology

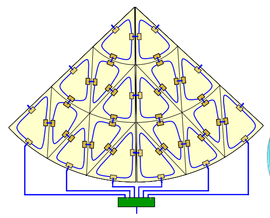
- Technology is first pioneered/patented at NASA Langley Research Center (LaRC) during the late 90's:
  - Laboratory-based system
  - One sample being taking every 30 second (one channel).

- AFRC miniaturized and developed an "one-box system" for aerospace application
  - Compact system for flight or ground test
  - Patented improved sampling rate to 100 samples per second (multiple channels)



Parker; US Patent 8,700,358

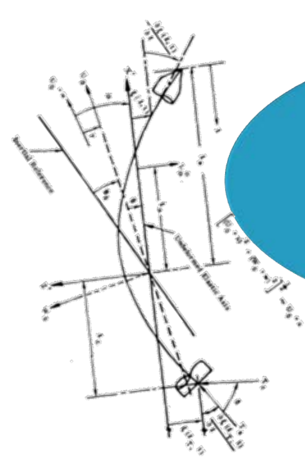
FOSS Fields of Operation



TPS Health Monitoring

Embedded Strain

Magnetic Field



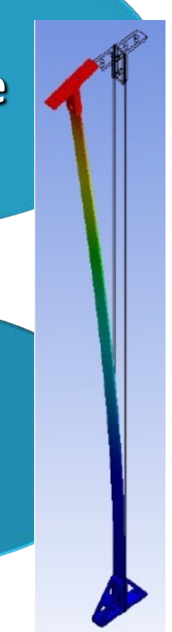
Applied Loads

Strain

Temperature and *Cryogenic* Liquid Level

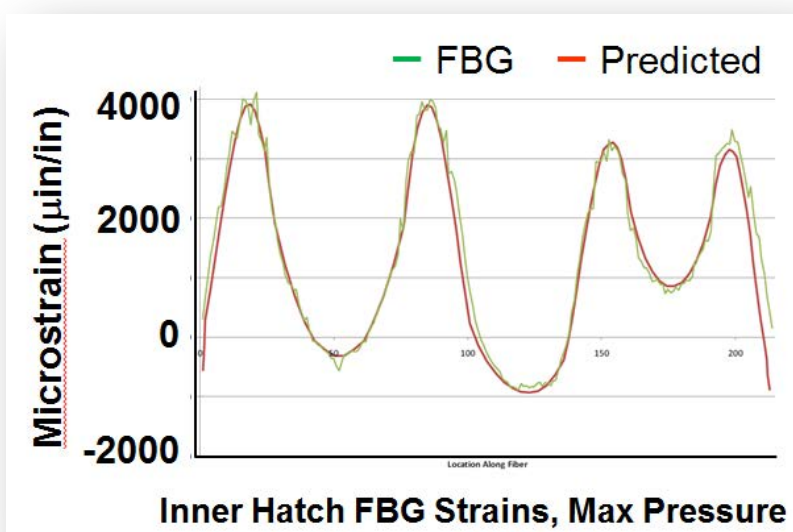
2D Shape

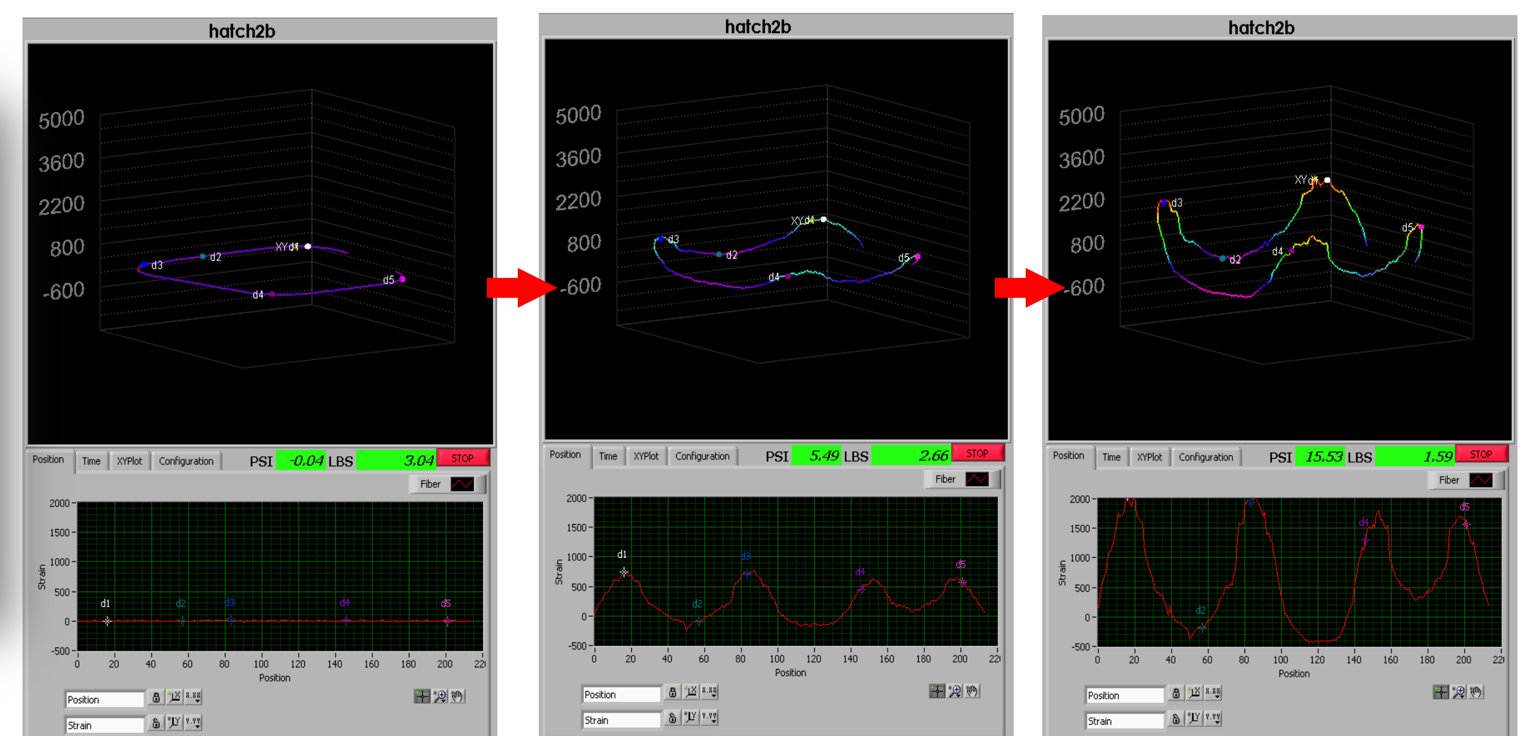
3D Shape



Composite Crew Module - NESC

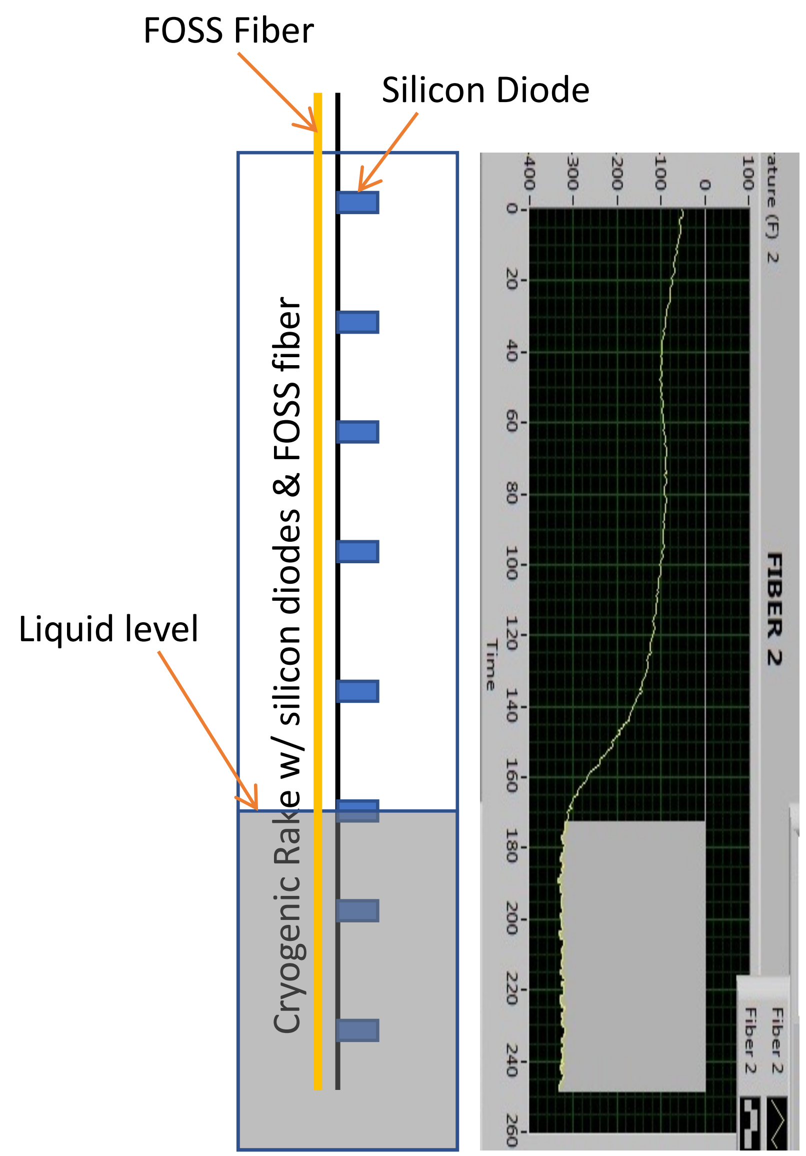
- Four fibers were installed around the module's three windows and one hatch
- Real-time 3D strain distributions were collected as the module underwent 200%DLL pressurization testing
- Measured strains compared and matched well to predicted model results
- Project Conclusion:
    - ""Fiber optics real time monitoring of test results against analytical predictions was essential in the success of the full-scale test program."
    - "In areas of high strain gradients these techniques were invaluable."





Cryogenic Liquid Level-Sensing using cryoFOSS

- The Challenge
  - The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements
  - Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level
- FOSS Approach
  - While using anemometry methods the transitional phase can be mapped better
  - Using a single continuous grating fiber high spatial resolution can be achieve
- Applications:
  - Launch vehicles
  - Satellites
  - Civil Structures
  - Ground Testing
  - COPV bottles



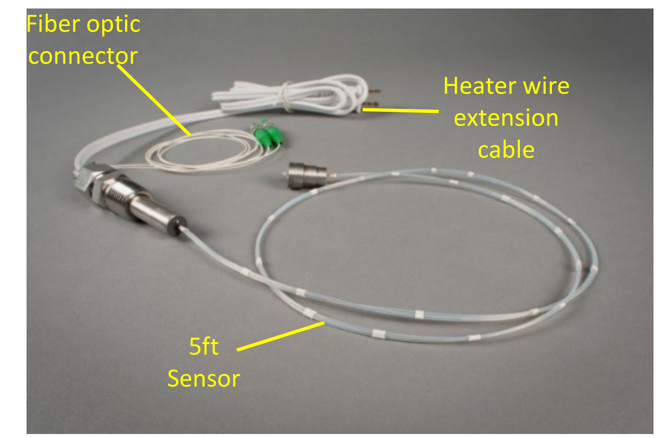
Cryogenic Container

FOSS Test Results

Cryogenic Container located at MSFC (below deck)

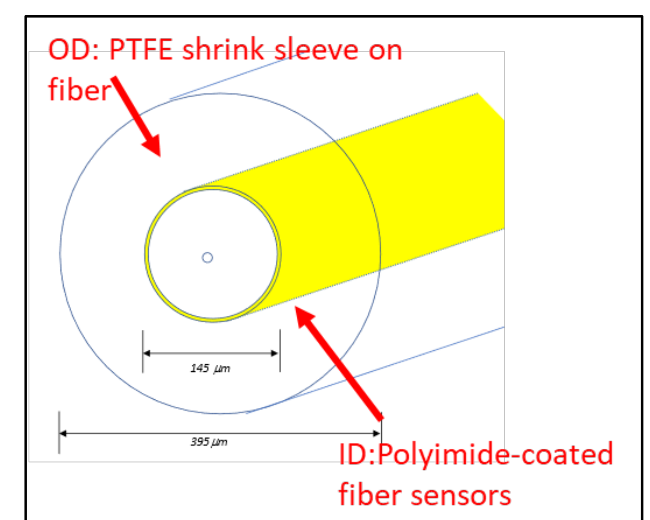
Two Types of cryoFOSS sensors

- Active sensors – via co-locating heating wire



Parker Jr et al, USP 9074921

- Passive sensors – via enhanced CTE values of a PTFE sleeve



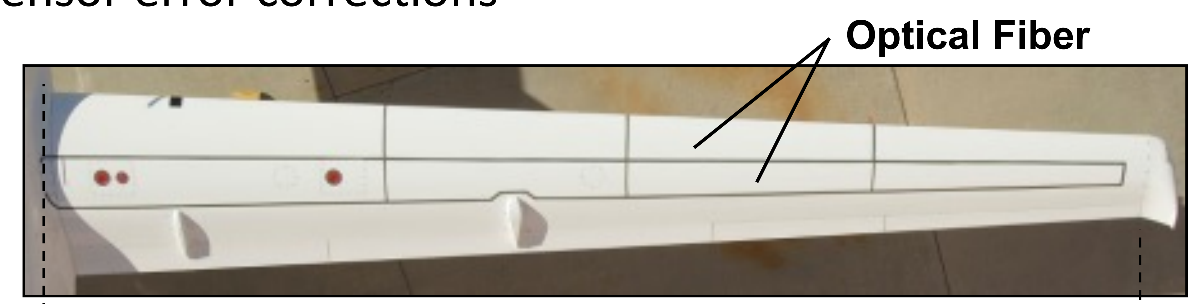
NASA/TM-20205009645

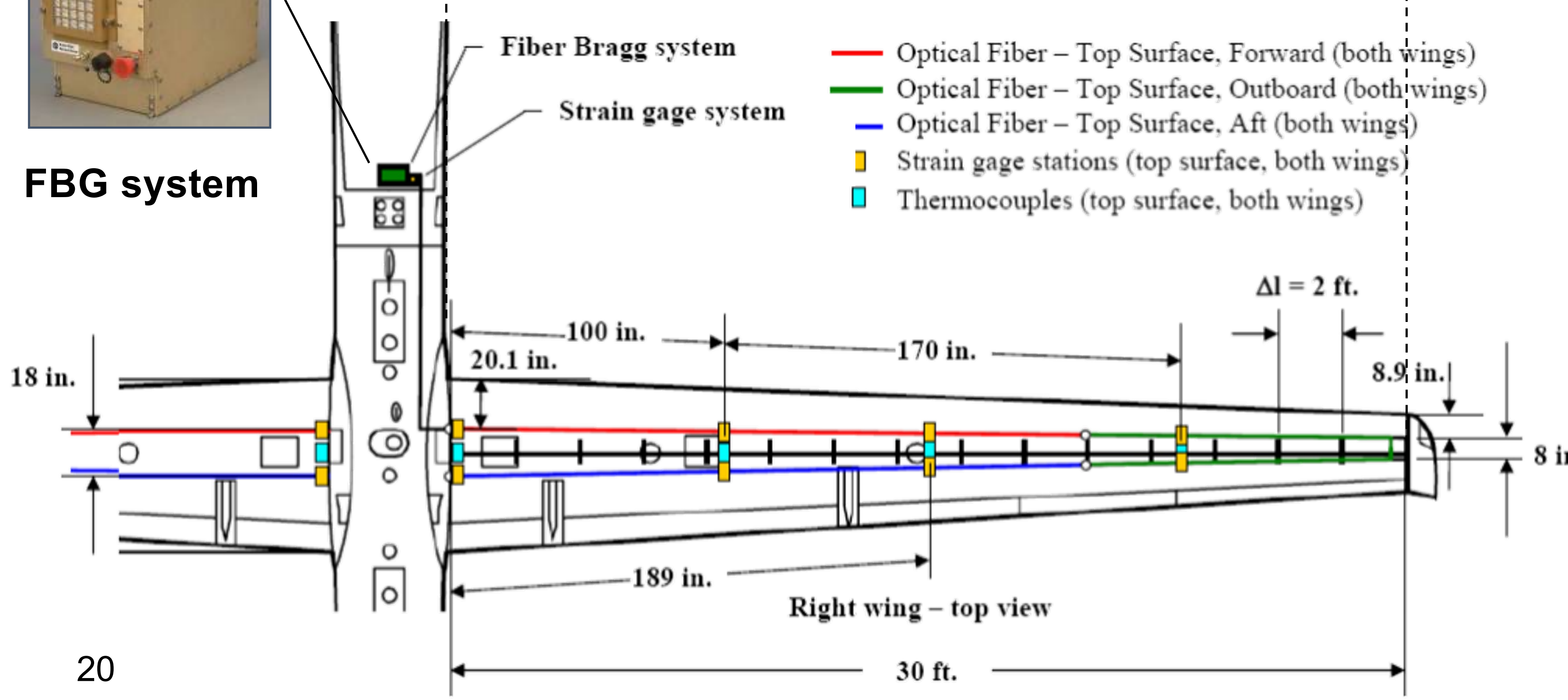
Example of Flight Validation - Predator-B (Ikhana) Flight Testing

- **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



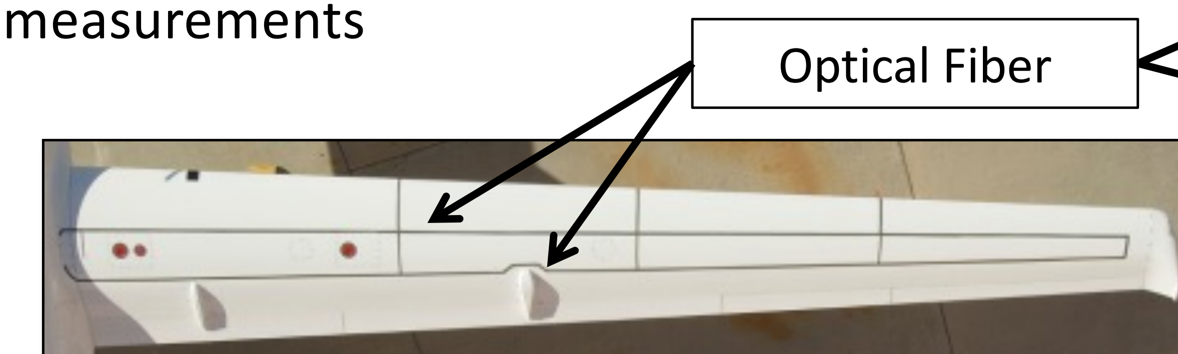


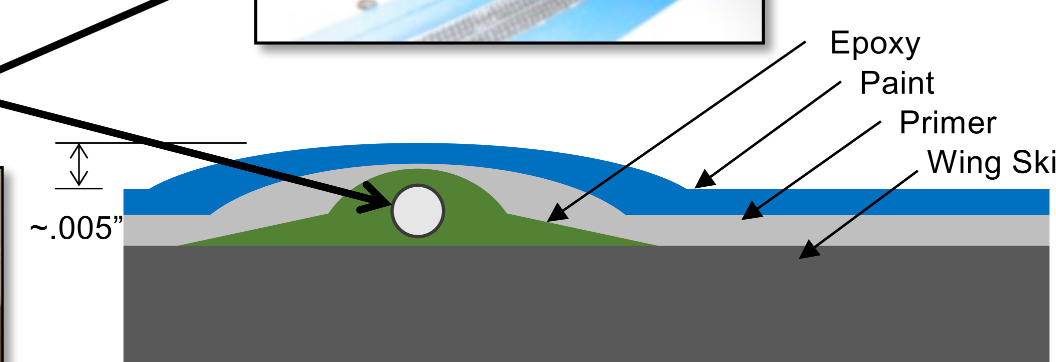
Installation Advantages

- Greatly reduced installation time compared to conventional strain gages
  - 2 man days for 40’ fiber (2000 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
- Can be installed on aerodynamic surfaces with little to no impact on performance

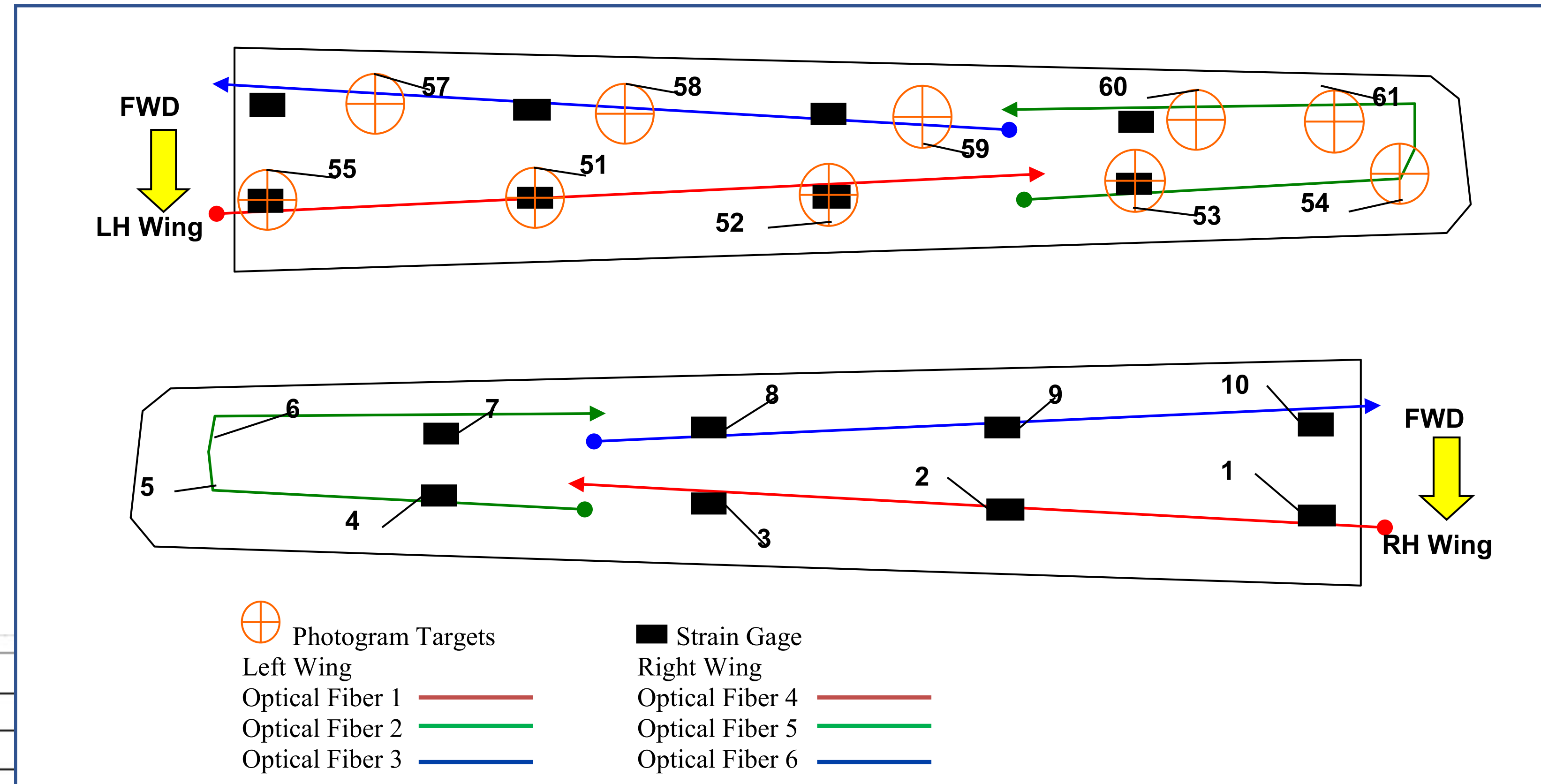
Installation Challenges

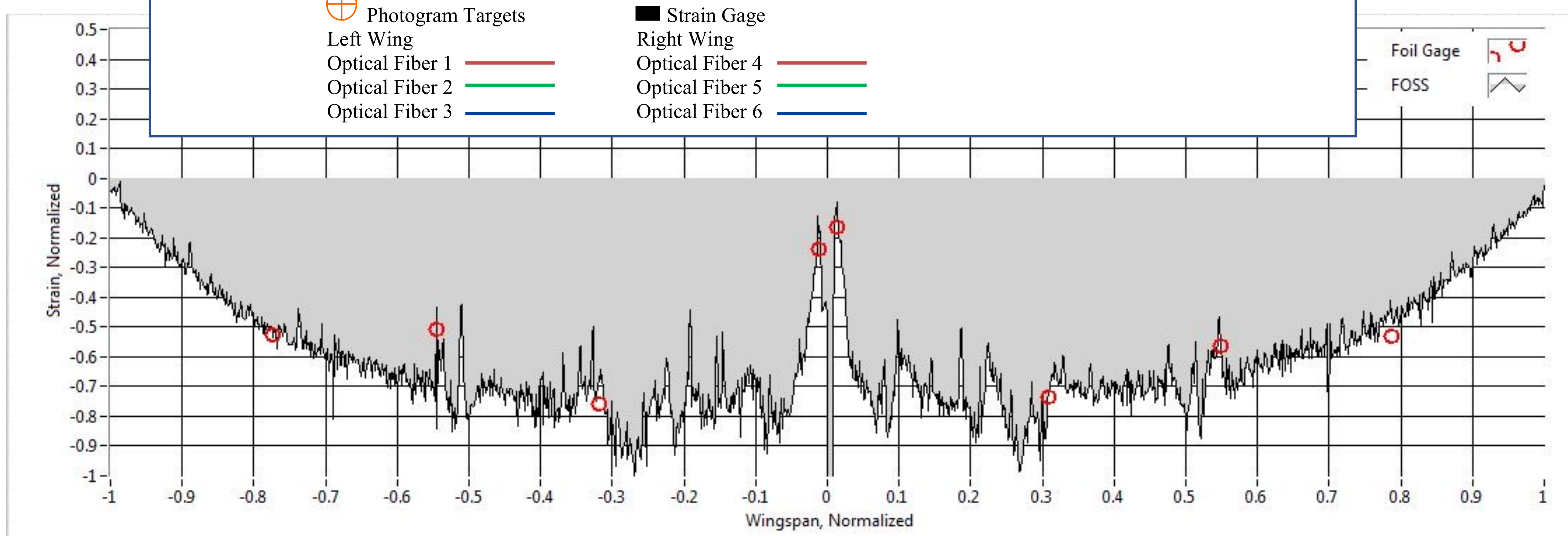
- Optical fiber more fragile than conventional strain gages
- Some measurement locations not practical due to fiber minimum bend radius
- Not practical if only interested in spot measurements





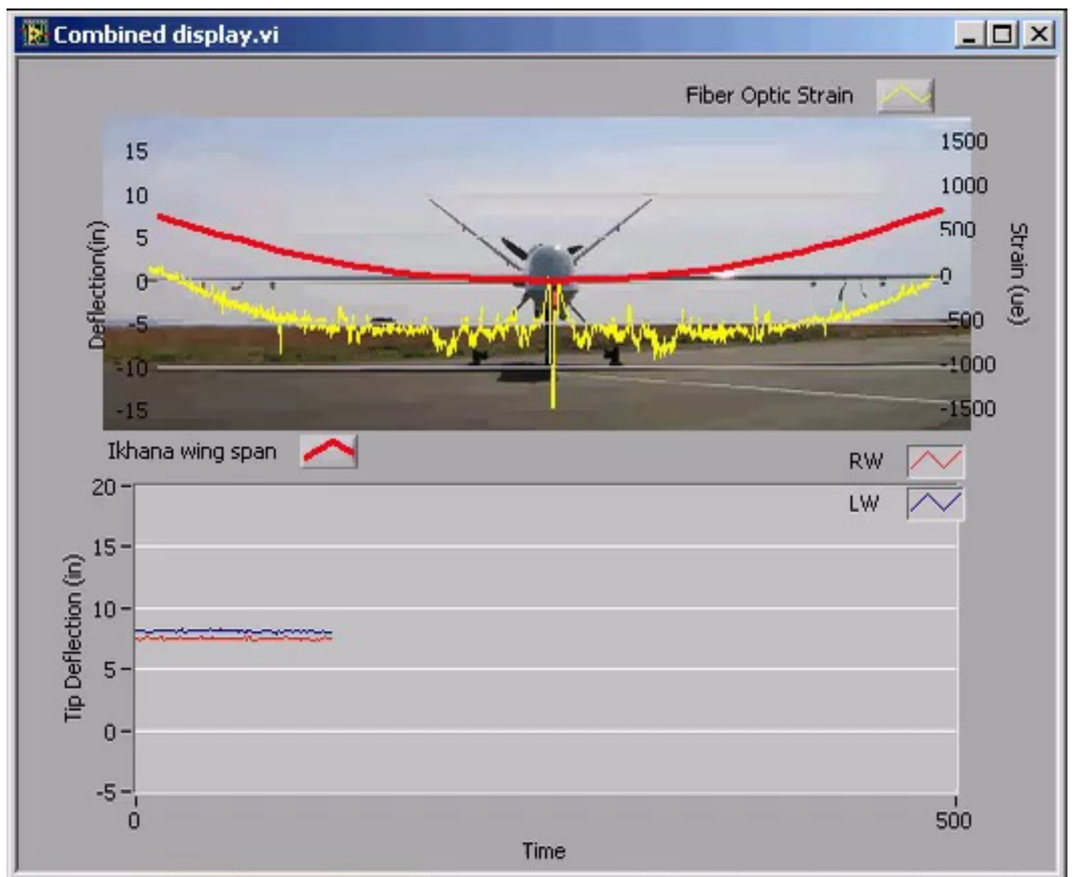
Flight Test Validation - Ikhana

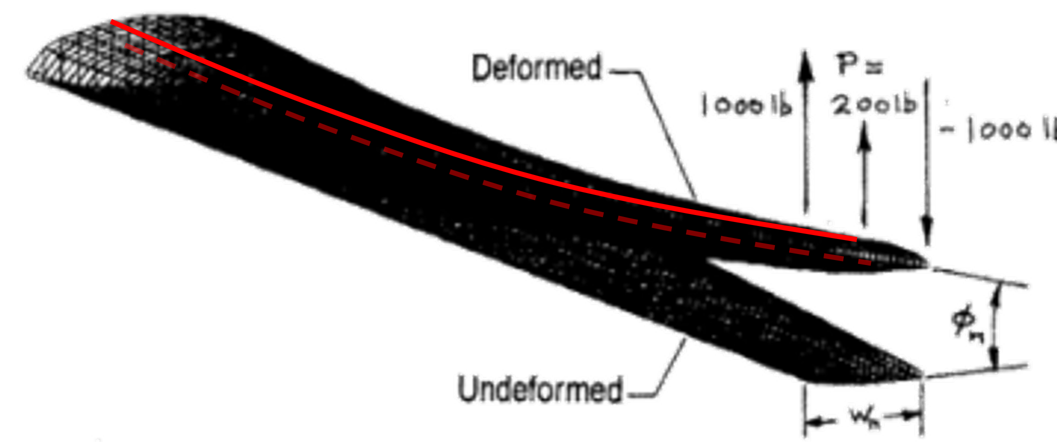




Structural Algorithms using FOSS

- **Structural Shape**
  - Real-time wing shape measurement using fiber optics sensors
    - (Ko, Richards; Patent 7,715,994)



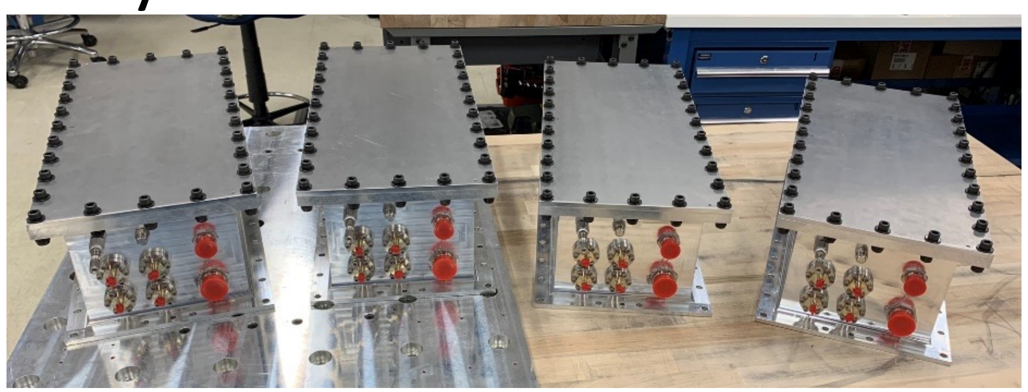


Win-tip deflection measurement of AFRC's Predator B via FOSS

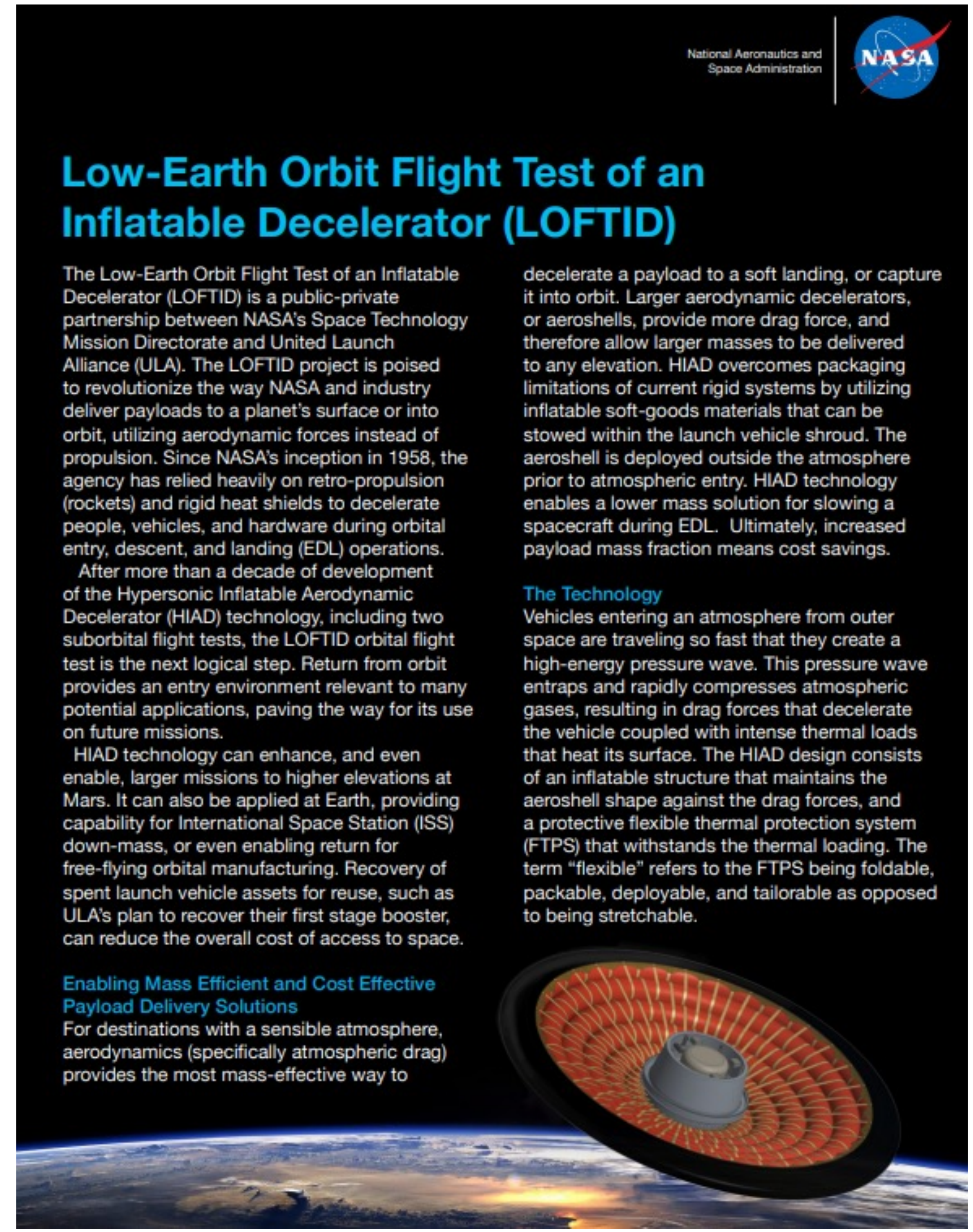
- **Externally applied loads**
  - Real-time applied loads on complex structures using fiber optic sensors (Richards, Ko; Patent 7,520,176)

FOSS project - LOFTID

- A launch capable version of FOSS is being developed to support LOFTID
- FOSS is integrated into LOFTID to monitor nose-cone temperature during reentry



- FOSS conducted and pass all environmental testing
  - EMI testing
  - Burn-In
  - Thermal vacuum cycling (TVAC)
  - Vibration testing
- Launched on Nov 1st 2022



National Aeronautics and Space Administration

NASA

Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) is a public-private partnership between NASA's Space Technology Mission Directorate and United Launch Alliance (ULA). The LOFTID project is poised to revolutionize the way NASA and industry deliver payloads to a planet's surface or into orbit, utilizing aerodynamic forces instead of propulsion. Since NASA's inception in 1958, the agency has relied heavily on retro-propulsion (rockets) and rigid heat shields to decelerate people, vehicles, and hardware during orbital entry, descent, and landing (EDL) operations.

After more than a decade of development of the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology, including two suborbital flight tests, the LOFTID orbital flight test is the next logical step. Return from orbit provides an entry environment relevant to many potential applications, paving the way for its use on future missions.

HIAD technology can enhance, and even enable, larger missions to higher elevations at Mars. It can also be applied at Earth, providing capability for International Space Station (ISS) down-mass, or even enabling return for free-flying orbital manufacturing. Recovery of spent launch vehicle assets for reuse, such as ULA's plan to recover their first stage booster, can reduce the overall cost of access to space.

Enabling Mass Efficient and Cost Effective Payload Delivery Solutions

For destinations with a sensible atmosphere, aerodynamics (specifically atmospheric drag) provides the most mass-effective way to decelerate a payload to a soft landing, or capture it into orbit. Larger aerodynamic decelerators, or aeroshells, provide more drag force, and therefore allow larger masses to be delivered to any elevation. HIAD overcomes packaging limitations of current rigid systems by utilizing inflatable soft-goods materials that can be stowed within the launch vehicle shroud. The aeroshell is deployed outside the atmosphere prior to atmospheric entry. HIAD technology enables a lower mass solution for slowing a spacecraft during EDL. Ultimately, increased payload mass fraction means cost savings.

The Technology

Vehicles entering an atmosphere from outer space are traveling so fast that they create a high-energy pressure wave. This pressure wave entraps and rapidly compresses atmospheric gases, resulting in drag forces that decelerate the vehicle coupled with intense thermal loads that heat its surface. The HIAD design consists of an inflatable structure that maintains the aeroshell shape against the drag forces, and a protective flexible thermal protection system (FTPS) that withstands the thermal loading. The term "flexible" refers to the FTPS being foldable, packable, deployable, and tailorable as opposed to being stretchable.

ARMSTRONG
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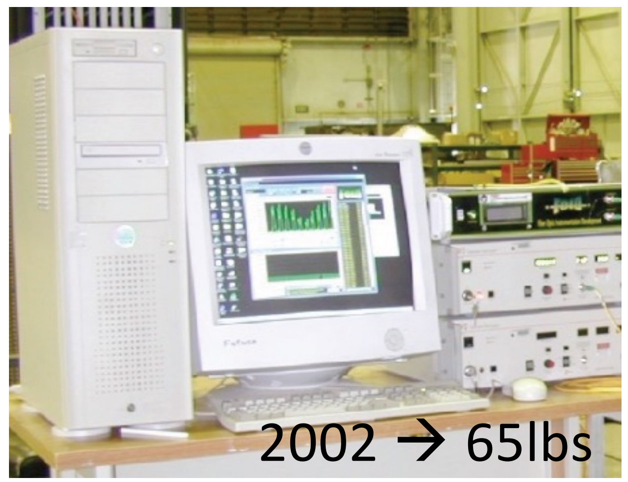
Summary

- NASA AFRC has successfully developed fiber optics strain sensors (FOSS) technology from laboratory to real-world application



- Commercialization of technology is on-going via NASA Technology transfer
  - Aerospace Sector
  - Energy Sector
  - Biomedical Sector