# A NOVEL STRUCTURAL HEALTH MANAGEMENT APPROACH FOR STEEL BRIDGES

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# Report Documentation Page

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**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# Overview

- Problem Description
- Objectives
- Technical Approach
  - Team
- Technology Implementation
  - Fiber Bragg Grating
  - Acoustic Emission Sensors
  - Completed System
  - Data Acquisition and Analysis
- Next Steps
- Summary

# Problem Description

- Corrosion of steel bridges remains a critical infrastructure concern
  - Corrosion of U.S. highway bridges costs economy $8.3M annually *(Source: FHWA)*
  - 25% of U.S. bridges are structurally deficient or functionally obsolete *(Source: FHWA)*
  - 503 U.S. bridges failed over 11 year period (100 due to corrosion) *(Source: ERDC-CERL)*

# Problem Description (cont.)

- Current method of monitoring - routine inspection – has limitations
  - Several techniques employed - visual, dye penetrant, ultrasonic, radiographic non-destructive testing methods
  - May not detect hidden cracks in built-up structures
  - Unable to determine if defect is actively growing

# Objectives

- Demonstrate and validate state-of-the-art and emerging innovative technology approaches for remote structural health and corrosion degradation monitoring of steel bridges
- Employ system on two subject bridges to greatly reduce risk of catastrophic failure by providing advance warning of growing structural problems caused by corrosion/materials degradation

# Objectives (cont.)

- Subject Bridge 1 – I-20 Bridge, Vicksburg, MS
  - Steel truss through deck
  - About 23,000 vehicles per day
  - Westward movement of bridge piers E-1 and E-2 on east side


# Objectives (cont.)

- Subject Bridge 2 – Government Bridge, Rock Island, IL
  - Steel truss through deck
  - Built in 1893
  - About 10,300 vehicles per day (lower deck)
  - About five trains per day (upper deck)

# Technical Approach

- Conduct structural assessment of subject bridges to determine optimal types and locations of sensors
- Integrate optical and other sensors into a novel structural health monitoring system specifically tailored to the subject bridges
- Design software that can not only collect data but can also interpret to provide early warning of areas of concern

# Technical Approach (cont.)

- For the I-20 bridge, design and implement system utilizing:
  - Corrosion sensors – two types plus corrosion coupons
  - Accelerometers – modal response, monitor abnormal vibration characteristics
  - Strain gauges – monitor abnormal deflections
  - Tilt sensors
  - Deflection/displacement gauges – Monitor movement of piers and associated stress to structural members

# Technical Approach (cont.)

- For the Government Bridge, design and implement system utilizing:
  - Corrosion sensors – two types plus corrosion coupons
  - Accelerometers – modal response, monitor abnormal vibration characteristics
  - Strain gauges – monitor abnormal deflections
  - Acoustic Emission sensors – monitor crack growth

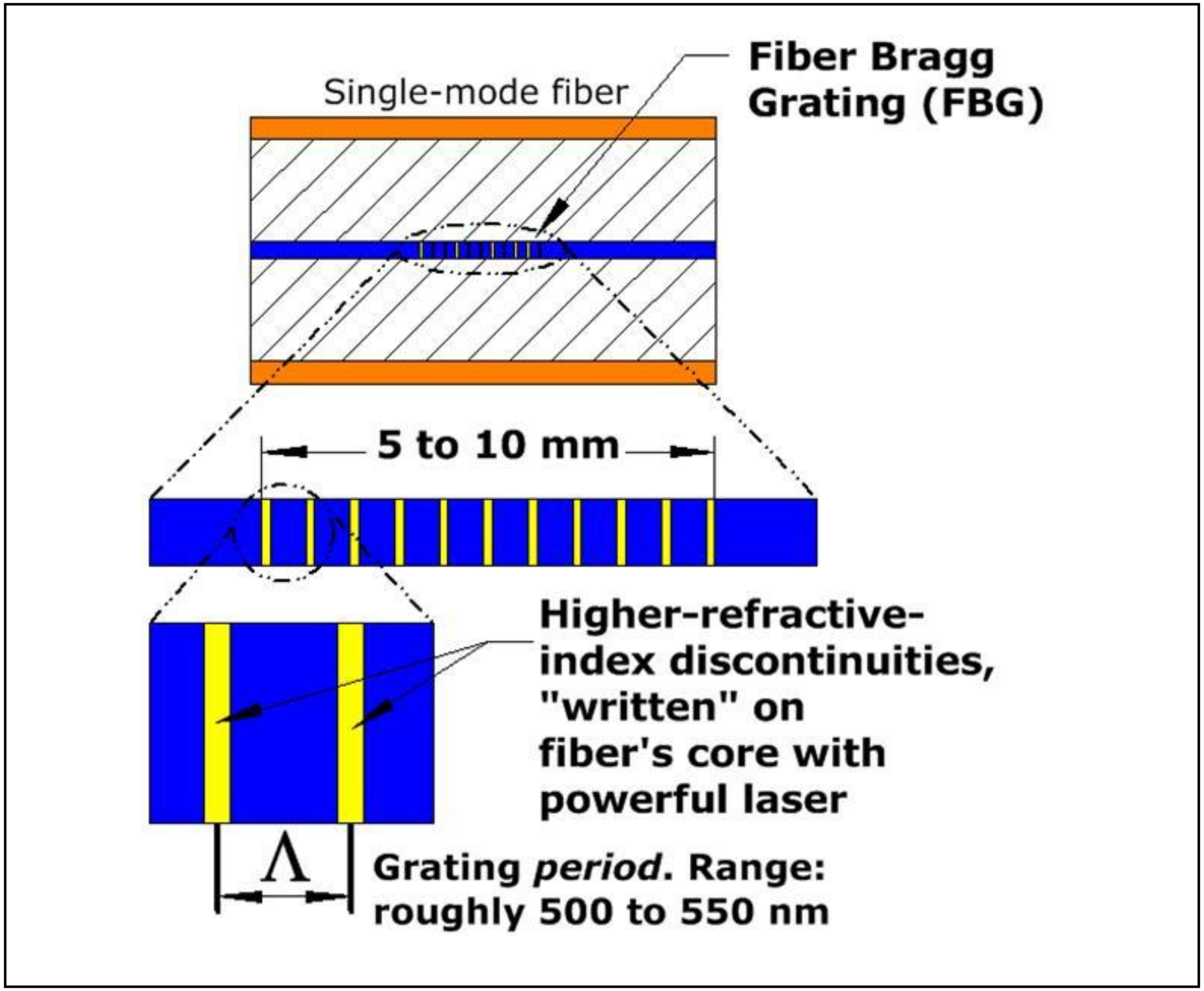
# Team Members

- U.S. Army Corps of Engineers, Engineer Research & Development Center Construction Engineering Research Laboratory (ERDC-CERL)
- Mandaree Enterprises Corporation (MEC)
- Concurrent Technologies Corporation (*CTC*)
- O'Donnell Consulting Engineers, Inc.
- Chandler Monitoring Systems, Inc.
  - Carlyle Consultants
  - Defense Science and Technology Office (DSTO), Australia
- Input from Office of the Secretary of Defense (OSD), other ERDC personnel, relevant Departments of Transportation (DOTs) and Directorates of Public Works (DPWs)

# Technology Implementation

- Optical Sensors – Fiber Bragg Gratings (FBGs)
  - Fiber cores with photo-imprinted FBGs to change refractive index
  - Laser input signals sent through fiber core reflect off FBGs
  - Each FBG sensor has different wave length and spectural operating window band
  - As pressure or temperature changes, reflected wave length changes, providing data

# Fiber Bragg Gratings

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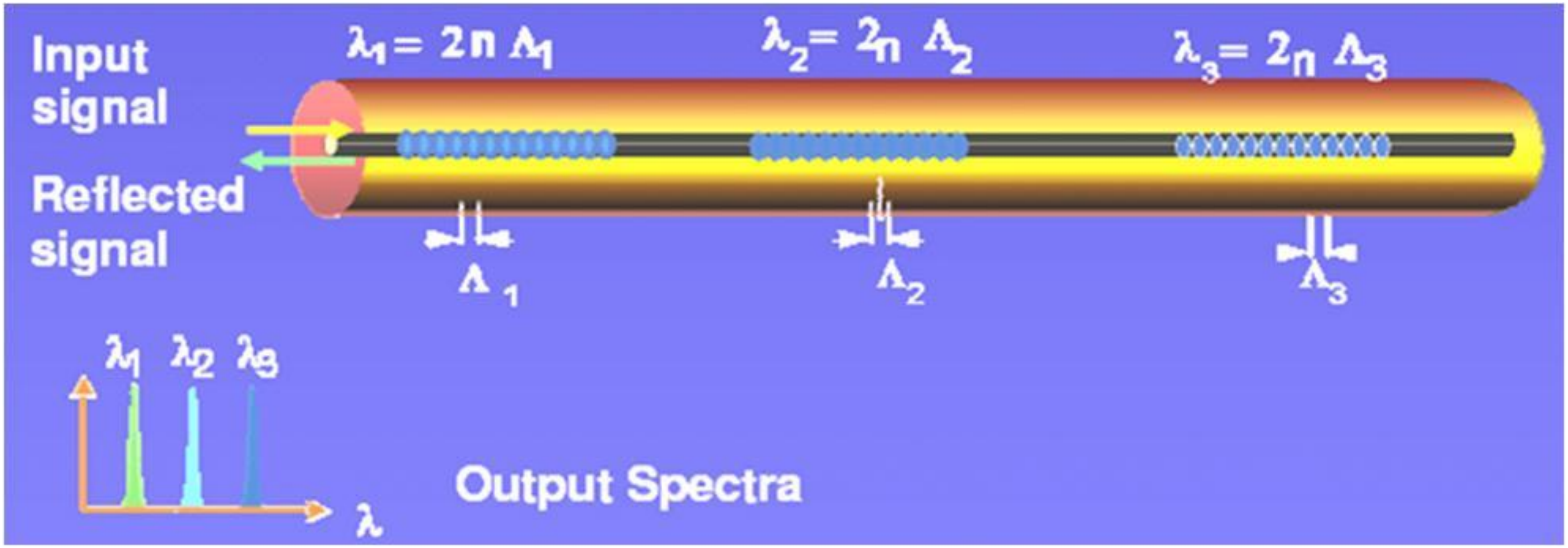
# Fiber Bragg Gratings (cont.)




- Typically can monitor up to +/-2500 microstrain ($\mu\varepsilon$)/FBG with up to 40 FBGs written-on or spliced-to each fiber, each FBG having a unique $\lambda_{Bragg}$
  - Interrogator scans for and finds each unique-$\lambda_{Bragg}$ peak
  - Software analyzes each unique-$\lambda_{Bragg}$ peak and numerically logs its precise $\lambda_{Bragg}$ value
- Can spread FBG locations over long distances of fiber
- Greatly simplifies cabling, instrumentation, and installation

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# Fiber Bragg Gratings (cont.)

- **Can monitor *many* sensors (>100 in some cases) on *one fiber***
  - Each sensor on fiber is wavelength-specific, providing implicit identification and ability to *multiplex* data.
  - Simplifies cabling and instrumentation:

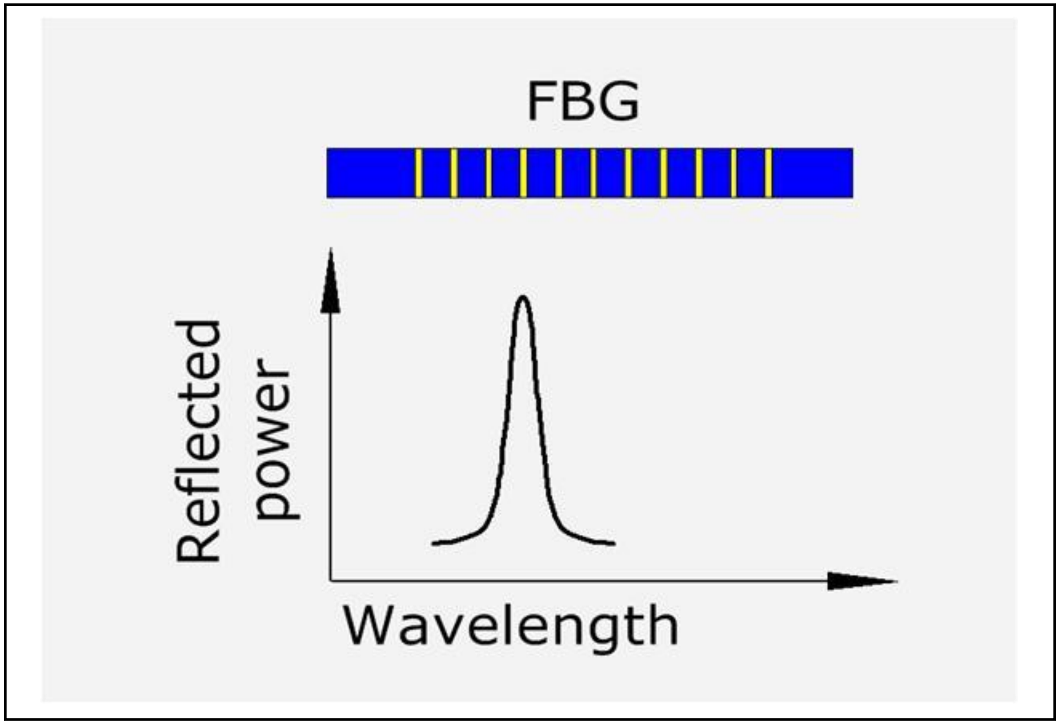
**Cabling and instrumentation for 400 *wired* strain sensors**

**Cabling and instrumentation for ≥ 640 multiplexed *fiber-optic* strain sensors, inside environmental enclosure with heat exchanger**

# Fiber Bragg Gratings (cont.)

For FBG strain sensor that is tack-welded/bonded to structure:

- Structure *strain* $\rightarrow$ FBG *stretch/compression*
- FBG stretch/compression $\rightarrow \Lambda$ (FBG period) stretch/compression
- $\Lambda$ stretch/compression $\rightarrow \lambda_{Bragg}$ increase/decrease



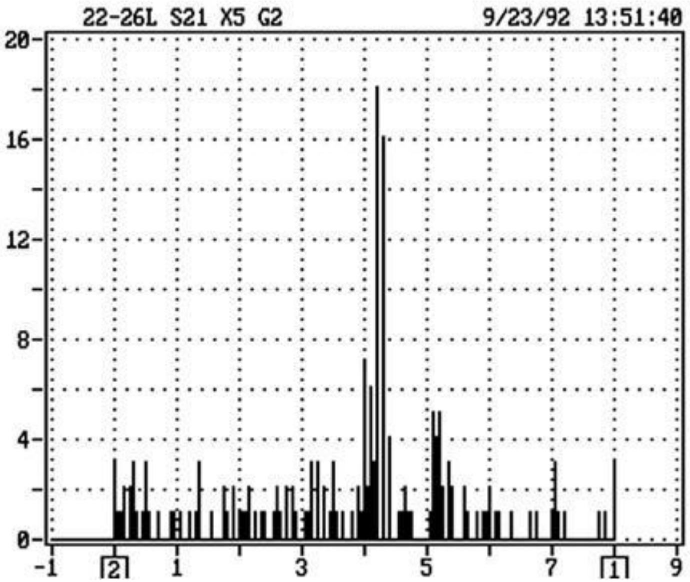
# Fiber Bragg Gratings (cont.)

- Benefits of FBG optical sensors
  - Established, proven technology
  - Fast, accurate, field-reliable
  - Resistant to fatigue and drift
  - Immune to electromagnetic interference
  - Resistant to corrosion, chemicals, water, and lightning
  - Large temperature range (-40 to +150˚C)
  - Signals can travel long distances (kilometers)
  - Small, light weight, easy to install
  - Surface mountable or embeddable into structures

# Technology Implementation

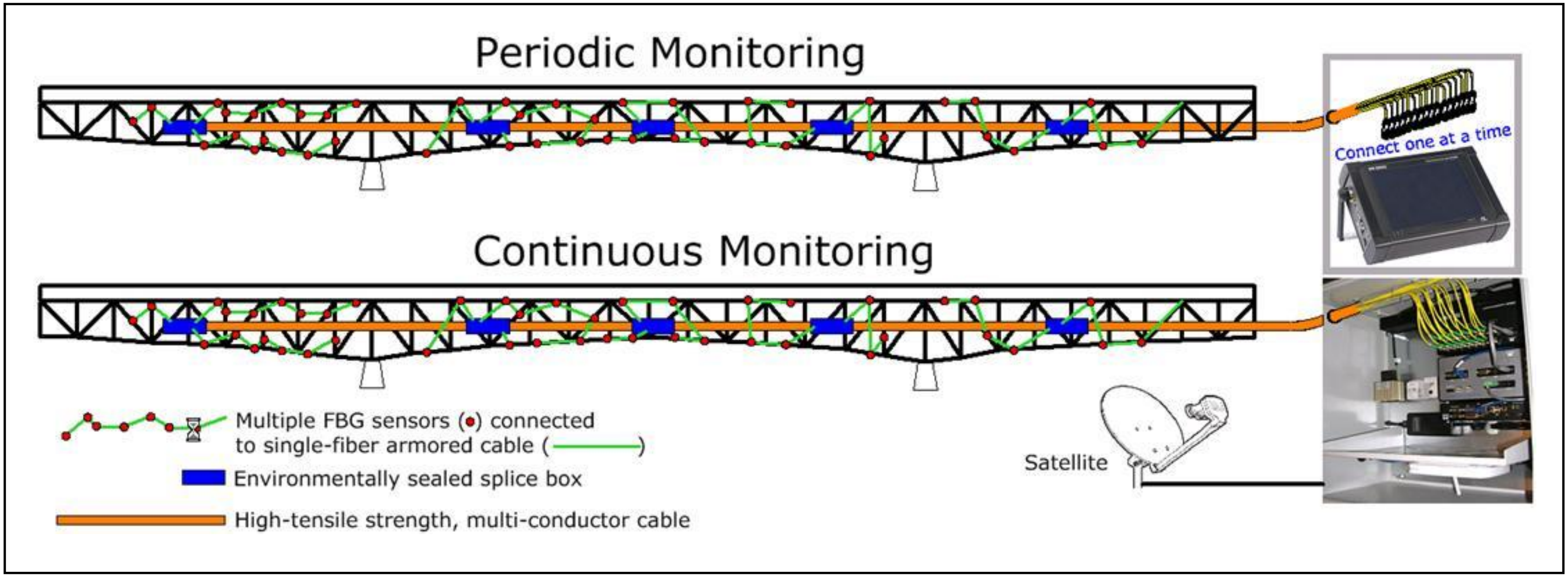
- Acoustic Emission (AE) Sensors
  - Detects and locates active, growing defects
  - Totally inspects monitored area for all defects, covering beams, gussets, stringers, and all hidden structural members
  - Only normal bridge traffic and/or wind loads needed
  - Works on both steel and composite bridges
  - Locates cracks by their actual growth
  - Corrosion revealed through reduction in local structural integrity
  - Computerized
  - Quick - results are available in real-time during testing

# Acoustic Emission Sensors




- I-80 Bryte Bend bridge
  - Box-beam design
  - Inappropriate material selection resulted in cracks
  - AE detected 1/16" long fatigue crack, hidden under paint but growing under traffic loading

# Technology Implementation - Complete Sensor System

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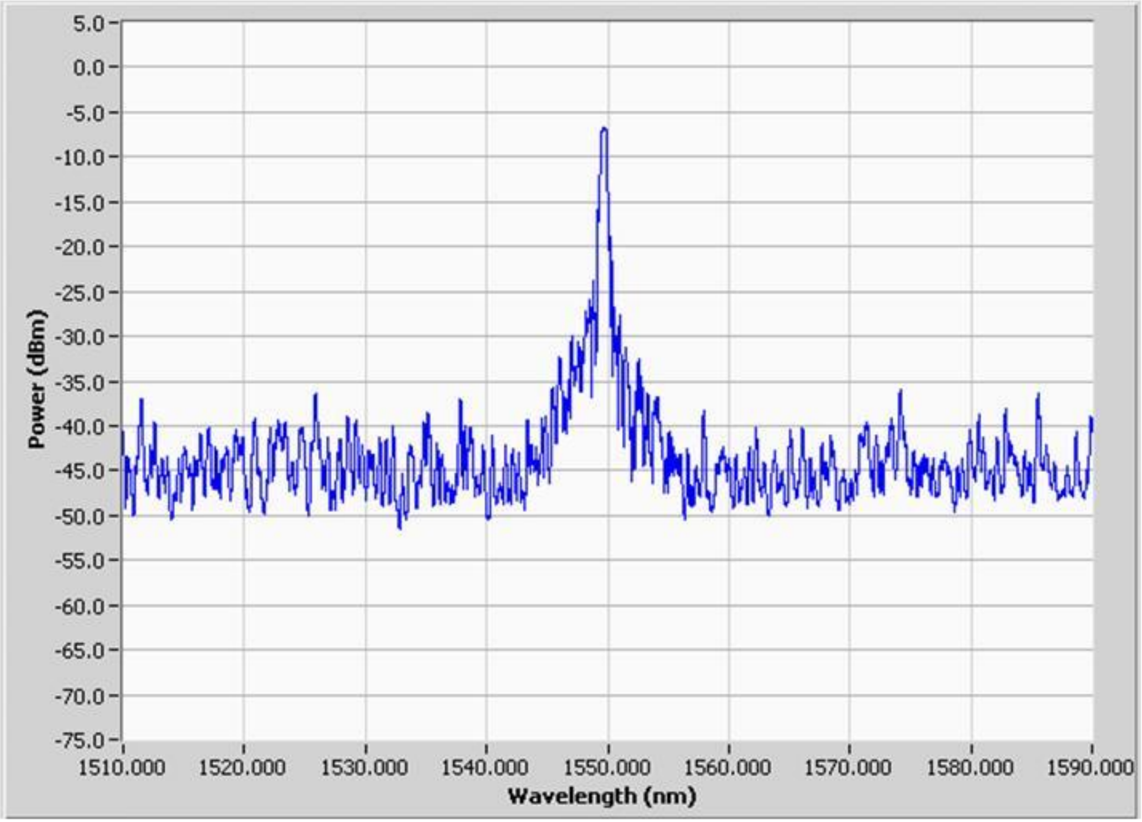
# Data Acquisition and Analysis

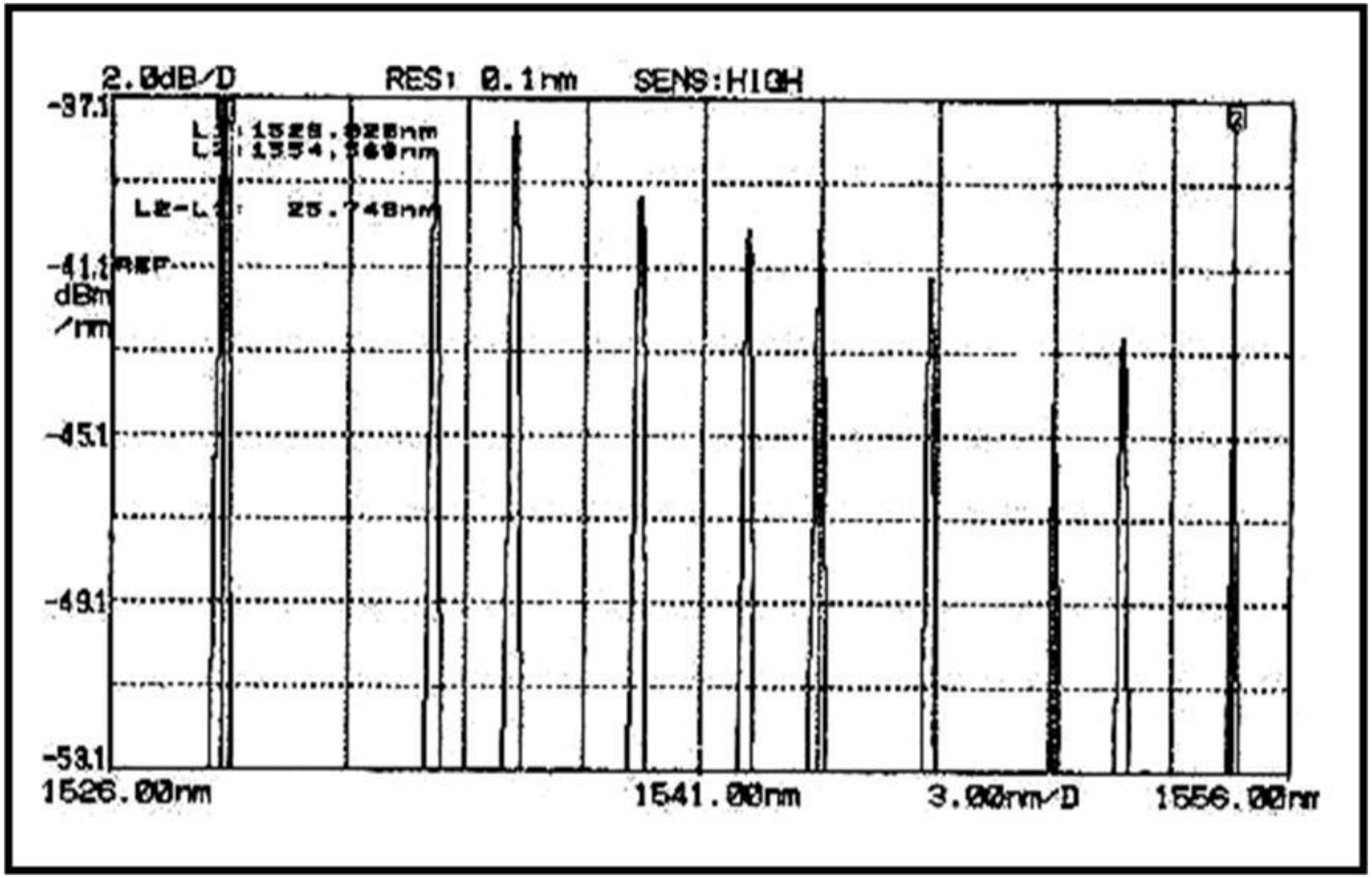
## FBG Instrumentation — Typical Scan Results




- Valuable data but must be interpreted!

# Data Acquisition and Analysis (cont.)

Multi-point $\lambda_{Bragg}$ peaks as displayed by interrogator




- Valuable data but must be interpreted!

# Data Acquisition and Analysis (cont.)

Sensor-location and in-situ graphical data screen

# Next Steps/Upcoming Events

- Schedule

| MILESTONE CHART | |
|---|---|
| **EVENT** | **TIME** |
| ~~Project Coordination Meeting~~ | ~~October 2008~~ |
| ~~Submit Work Plan~~ | ~~October 2008~~ |
| ~~Kickoff Meetings at Two Subject Bridges~~ | ~~November 2008~~ |
| **Structural Evaluation on Both Bridges** | **March 2009** |
| ~~Technologies Selected for System~~ | ~~April 2009~~ |
| **Procure Technologies and Assemble System** | **May 2009** |
| **Demonstrate System on Prototype** | **July 2009** |
| **Install System on Two Bridges** | **August 2009** |
| **Confirm Functionality** | **August 2009** |
| Submit Systems Manual | October 2009 |
| One-Year System Inspection | August 2010 |
| Complete ROI Validation | August 2010 |
| Complete Interim Technical Report | July 2010 |
| Complete Documentation (includes Interim Tech Report, Procurement Specification, etc.) | August 2010 |

# Summary

- The corrosion of steel bridges continues to be a critical infrastructure concern
- A novel sensor system, based on optical FBG sensors but incorporating other unique types of sensors and technologies, is envisioned for the structural health monitoring of these bridges
- The system will provide 24-hour, thorough evaluations of bridge structures, including instantaneous warnings of potential failure spots (visible or not)

# Acknowledgments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- The authors wish to thank
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  - Dr. Doug Neale and Mr.  Larry Cranford, Mandaree Enterprises Corporation
  - Mr. Kirk Galien and Louisiana DOT
  - Mr. Mitch Carr and Mississippi DOT
  - Mr. Christian Hawkinson and Rock Island DPW
  - Mr. Colby Talbot and C.E.C., Inc.

# Thank You!

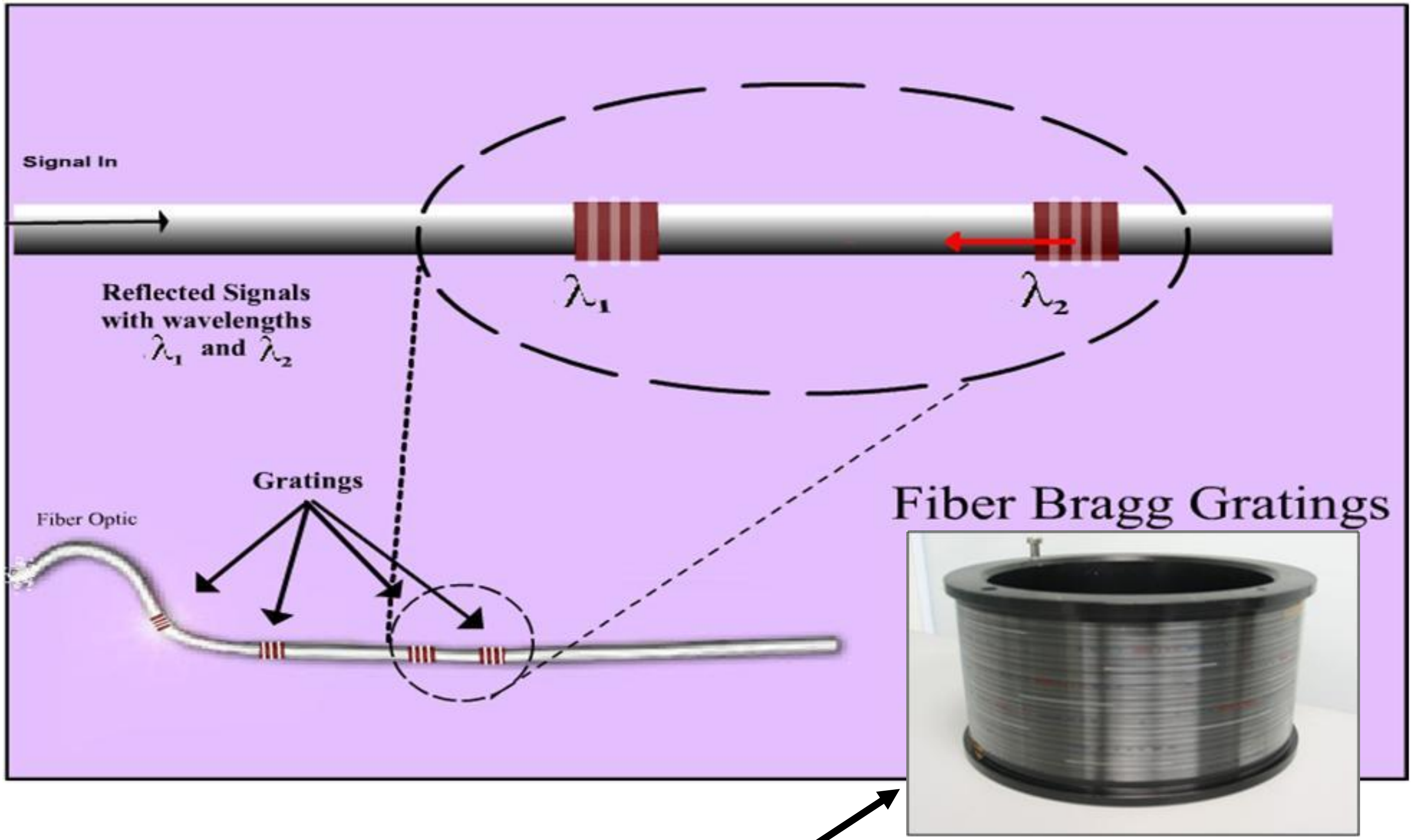
# Questions?

# BACKUP SLIDES

# Overall Program Objective (from SOW)

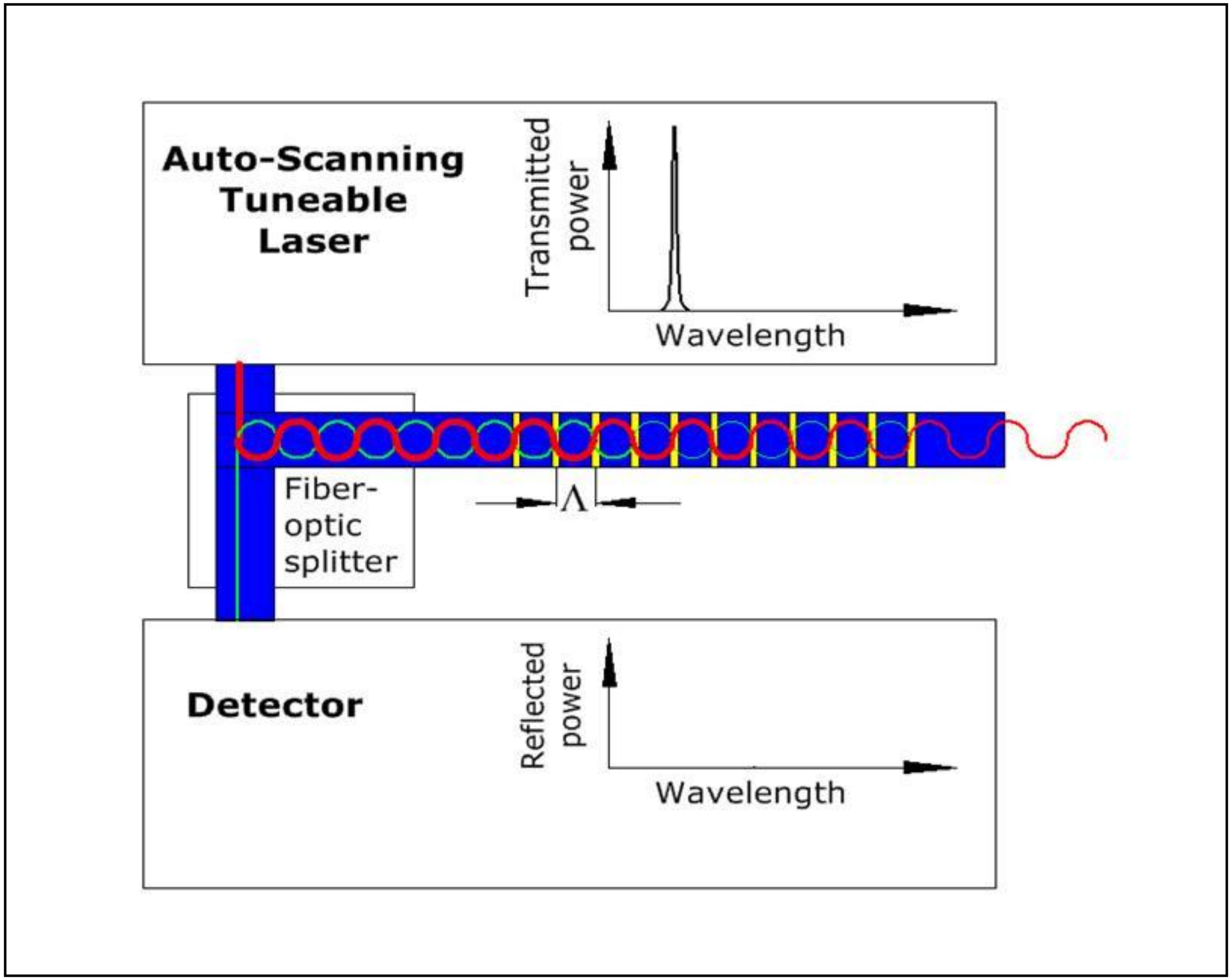
- *"The objectives of this project are to demonstrate and validate state-of-the-art and emerging innovative technology approaches for the remote structural health and corrosion degradation monitoring of steel bridges. The intent of a monitoring system is to greatly reduce the risk of a catastrophic failure by providing advance warning of a growing structural problem caused by corrosion/materials degradation with an opportunity for repair before catastrophic failure. This project will help demonstrate the capabilities of such systems and validate the potential benefits for future possible application by the Army and the rest of the Department of Defense (DoD) on mission critical bridges and similar load bearing structures."*

# Multi-Point Sensing with One Fiber




Spool containing an FBG array: multitude of FBGs laser-*written* at discrete points along a single fiber. Can also *splice* many FBGs/sensors into one fiber.

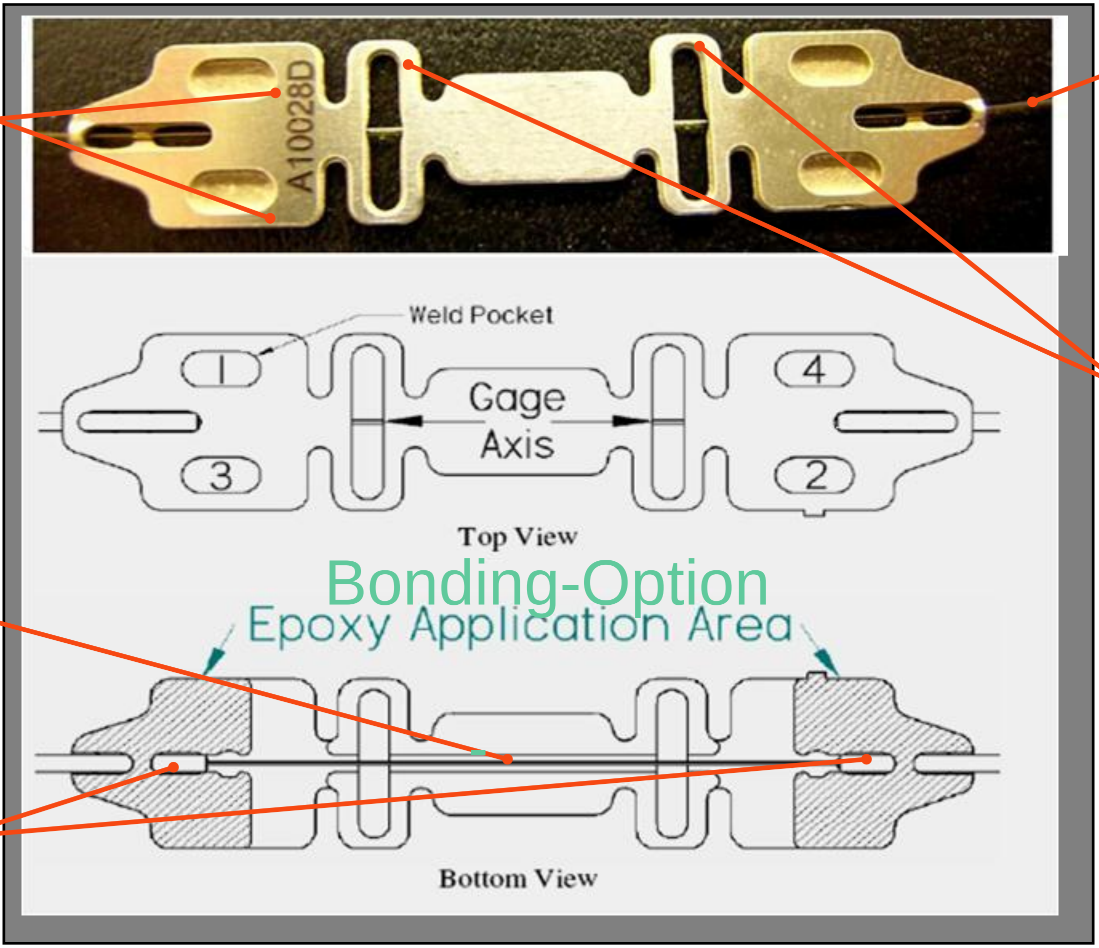
# Fiber Bragg Gratings



# FBG Sensor Hardware

Tack-weldable/bondable FBG strain sensor

Tack-weld pockets. Weldable with laptop-size, battery-powered welder.




Optical fiber pigtails in protective braided jackets

Flexure springs

FBG

No-slip/no creep fiber connections

Size: 36.5 x 8 x 0.8 mm

*Sensitivity*: ~1.2 με/pm. *Range*: ±2500 με. *Fatigue life*: $10^8$ cycles at ±2000 με. *Temperature limits*: -40C to +120C. *Construction*: Stainless steel frame. Fiberglass-braid-protected fiber pigtails.

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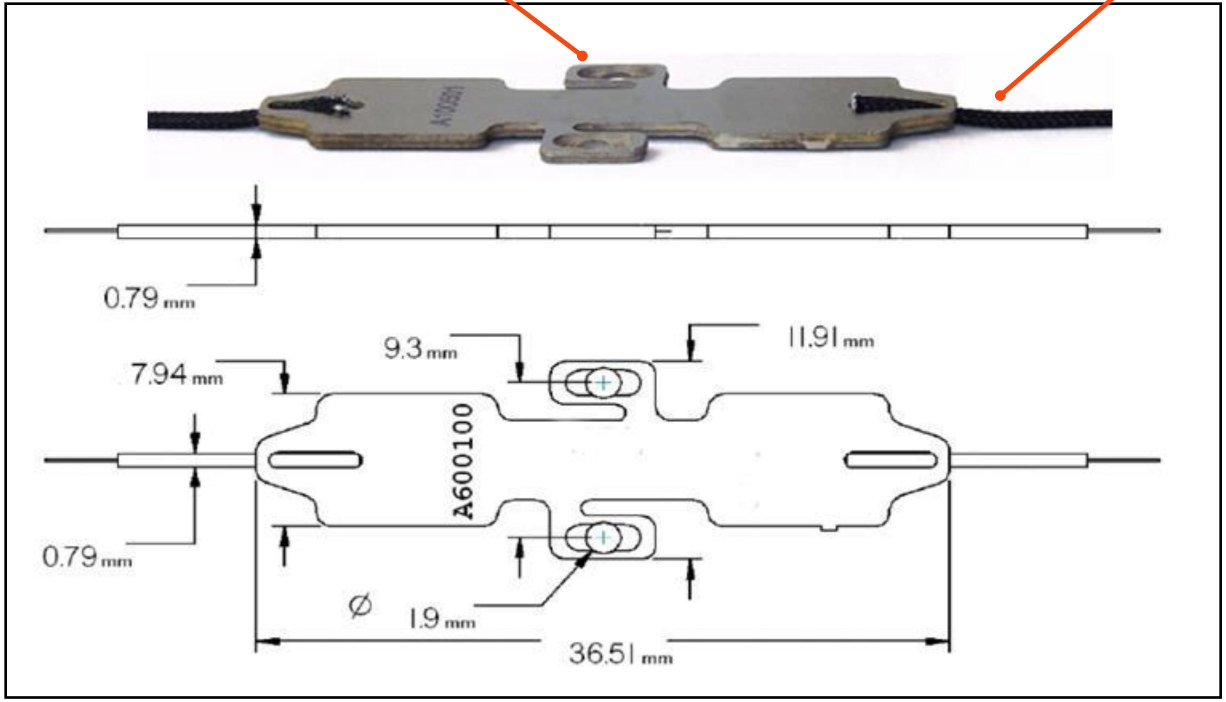
# FBG Sensor Hardware

## Tack-weldable/bondable/screw-mountable FBG temperature sensor

**Screw-mount holes & tack-weld pockets. Weldable with laptop-size, battery-powered welder.**

**Optical fiber in protective braided jacket.**




*Sensitivity:* 28.9 pm/°C. *Temperature range*: -40 to 120°C. *Short-term repeatability* ±0.75°C Drift: ±1.0°C at 50°C and 85% RH. *Construction*: Stainless steel frame. Fiberglass-braid-protected fiber pigtails.

# Response of FBG Strain Sensor

## Temperature response

More generally, the FBG sensor responds to temperature as well as strain:

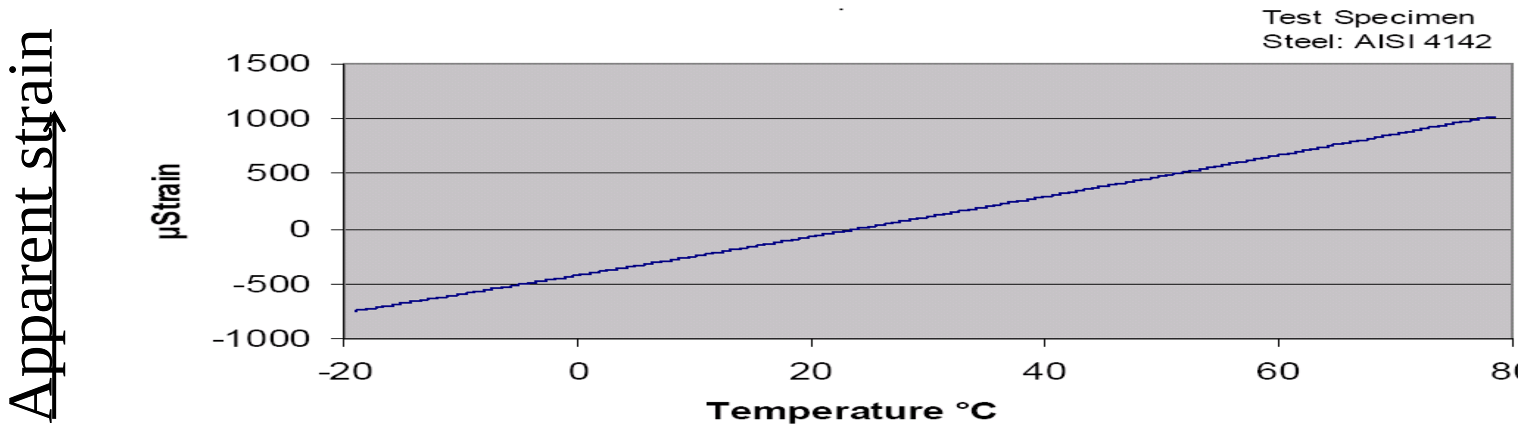
$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg}} = F_G\varepsilon + F_G\Delta T\alpha_{Substrate\ Expansion} + \Delta T\alpha_{Refractive\ Index\ Change}$$

Response to *force-induced strain*, ε — the desired variable. ($F_G$ is the gauge factor.)

Response to *true thermal strain* caused by substrate expansion — assuming that the substrate CTE (Coefficient of Thermal Expansion) exceeds the fiber CTE.

Response to *apparent thermal strain.* Cause: change of refractive index ($n_d$) with temperature. Recall that $\lambda_{Bragg} = 2 \cdot n_d \cdot \Lambda$.

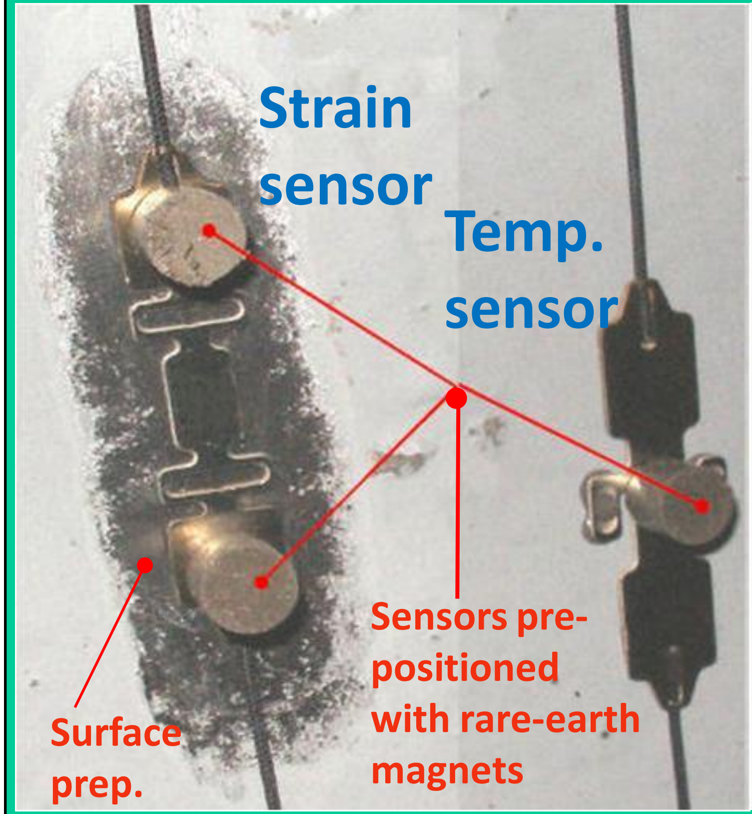
The curve below—for an unstrained FBG strain sensor mounted on steel—illustrates the need for temperature compensation:



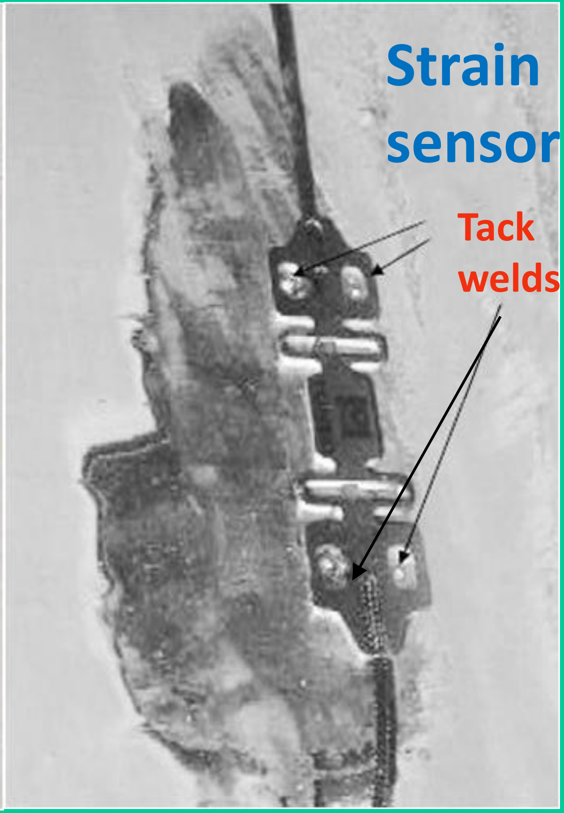
# FBG Sensor Hardware

Tack-weldable/bondable FBG strain and temperature sensors: structural installation

*Prep & Placement*




*Welding*

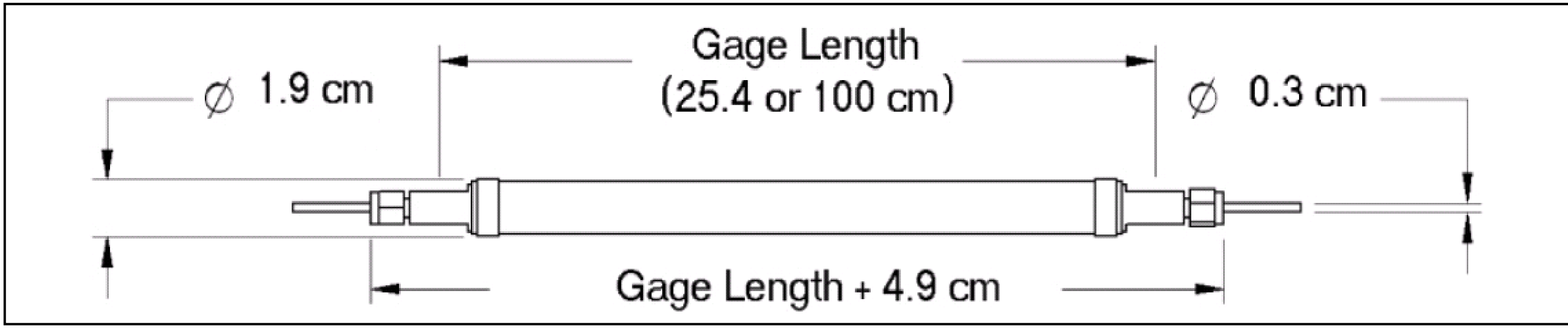



*Connection & Encapsulation*

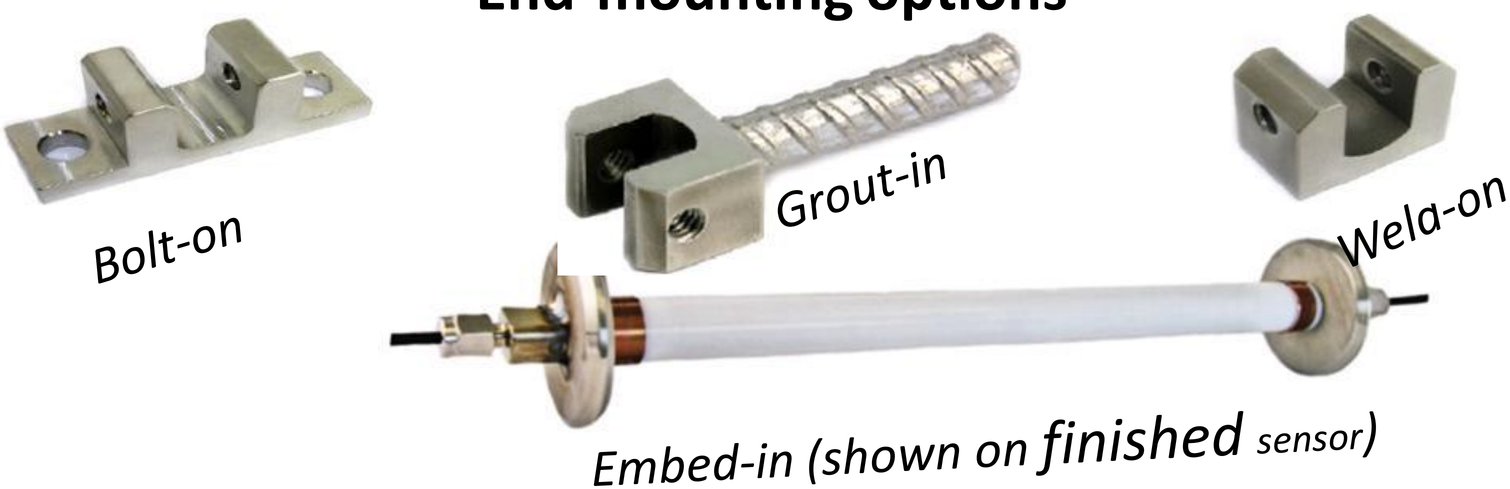
- Short pigtails get spliced to ***armored*** fiber-optic cables.
- Sensor, pigtails, splices, and ends of armored cable get environmentally sealed together with stainless-steel over-patch.

# FBG Sensor Hardware

## Multi-mountable, environmentally sealed FBG strain sensor




**End-mounting options**




Sensitivity: ~1$\mu\varepsilon$. *Accuracy*: 0.5%. Range: 2500 $\mu\varepsilon$. *Connection*: Armored cable. *Environmental* : Stainless steel & Teflon envelope; especially suited for wet environments. T*emp. limits*: - 40C to +80C. Built-in T-compensation FBG.

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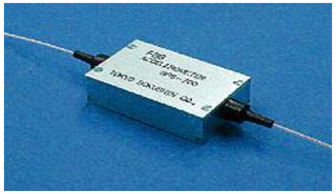
# FBG Sensor Hardware


Accelerometer


Strain meter

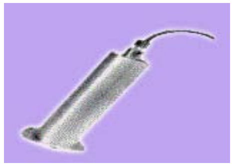

Pressure meter


Incline meter


Relative Displacement Meter


Temperature


Fissurometer

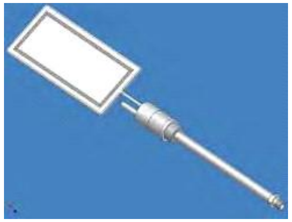

Ocean bottom seismometer


Water Detection


Land Slide Detection


Gas and Humidity


Pressure for Oil Drilling


Load Cell

# FBG Sensor Instrumentation

## High speed fixed-location FBG interrogator

- Sampling rate as fast as 2000 Hz—with each scan referenced to a stable, zero-temperature-coefficient wavelength standard
- 80 nm standard range (1510 to 1590 nm); 160 nm optional range
- For multiplexed monitoring of 4 fibers—*16 fibers with expansion module*, each fiber potentially containing ≥40 FBGs


Size:
114 x 234 x 132 mm

# FBG Sensor Instrumentation

Fixed-location computer

- Interrogator-matched industrial grade PC for data logging, manipulation/analysis, and communication:
- One of two available models


Size: 132 x 267 x 135

# FBG Sensor Instrumentation

## Moderate speed portable FBG interrogator

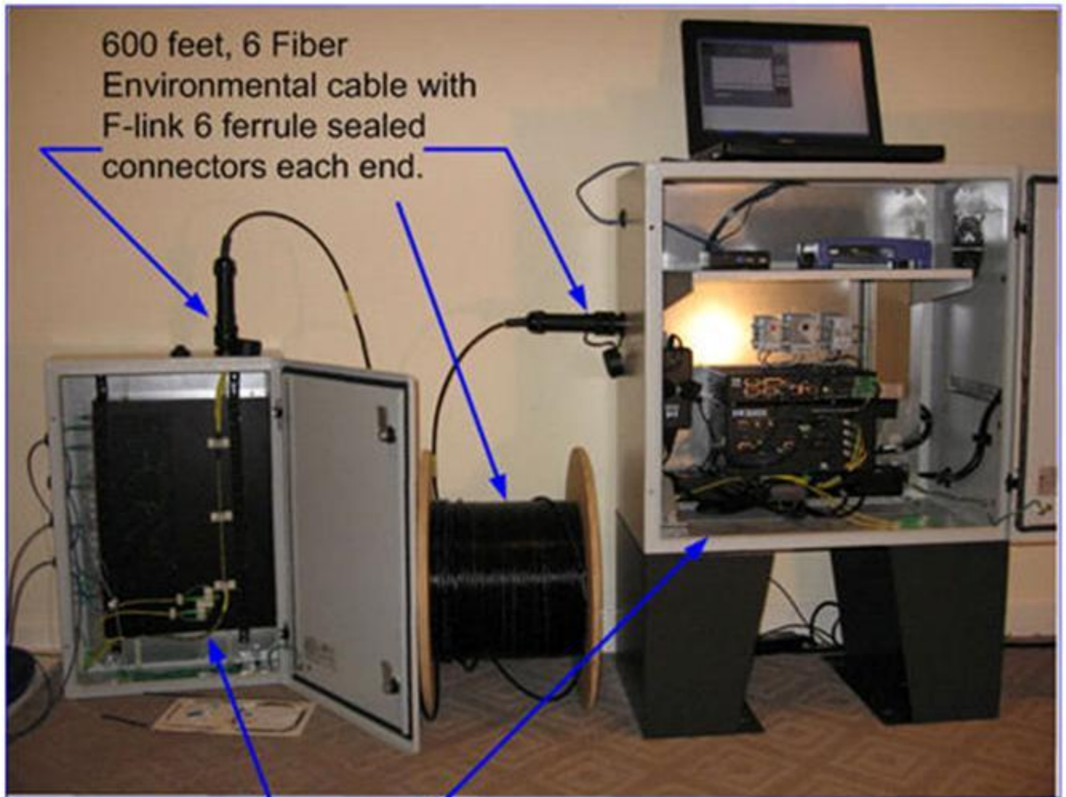
- For sampling as fast as 1 ZHz (faster model available soon)
- For multiplexed monitoring of 1 fiber, potentially containing over a hundred FBGs. Complete with integral monitor and pre-installed software


Size:
360 x 275
x
100 mm

Weight:
7.3 kg
(16 lb)

# FBG Sensor Instrumentation

## Environmentally enclosed *field system* example




**Sm040-016 passive multiplexer for remote cable connections**

**Main control cabinet with sm130 high-speed FBG interrogator, sp130 PC, dual climate control, heat exchanger, internet switch, satellite modem and optical /electrical connections**