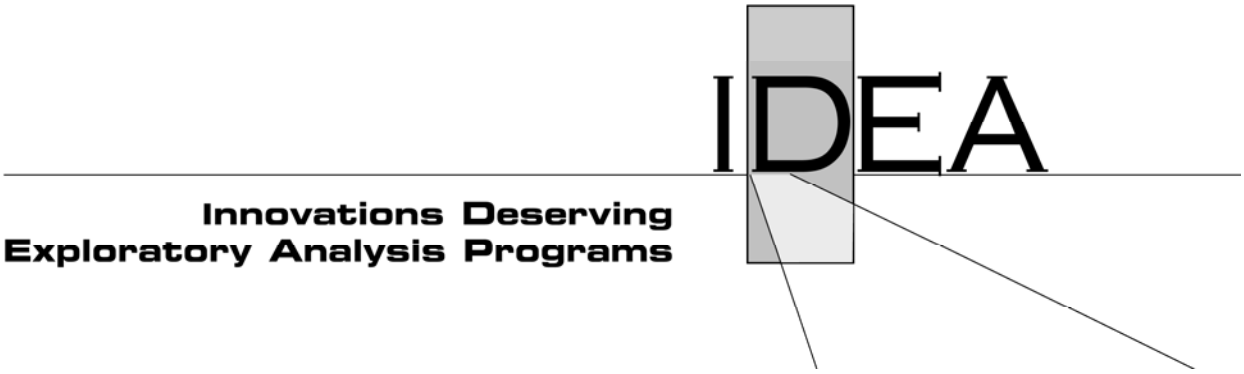

High-Speed Rail IDEA Program

An Investigation into the Use of Buried Fiber Optic Filament to Detect Trains and Broken Rail

Final Report for High-Speed Rail IDEA Project 18

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TRANSPORTATION RESEARCH BOARD
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ABSTRACT

Railroads rely on electric track circuits to perform, among other things, the critical function of broken rail detection. However, track circuitry, which is expensive to maintain, does not detect a substantial percentage of rail breaks in which electrical continuity is maintained. Fiber optic sensing has great potential as a low-cost means of detecting broken rails. This research investigates the feasibility of using coherent optical time-domain reflectometry (C-OTDR) in concert with advanced signal processing techniques and neural networks in buried fiber optic filaments to detect and locate trains and the ballistic event characteristic of rails breaking under stress. An optical transmission through a continuous length of low-loss, telecommunications-grade fiber buried within the right-of-way holds promise for providing an inexpensive, reliable alternative to conventional track circuitry for train presence and broken rail detection. The technology is shown to be sensitive to perturbation in short fiber lengths (50 meters), but using low power coherent OTDR practices to detect polarization shift in long fiber lengths (200 meters) has shown the system to be ineffective due to the accumulation of noise in the fiber.

EXECUTIVE SUMMARY

This project was to investigate the use of fiber optic filaments buried under the track structure to detect rail breaks and train presence. An optical transmission through the filament is used to detect the signature of a short-duration release of energy associated with a rail break, and the signature of a moving train. The premise for the technology is that an externally induced energy wave impinging a buried, single fiber transmitting a coherent light beam will change the polarization angle of the beam where the impingement occurs. The polarization change is part of the backscatter light in the fiber and can be extracted from the returning signal. The approach employs optical time-domain reflectometry in conjunction with advanced signal processing techniques and neural networks. The project team developed a coherent laser system and demonstrated its capability to detect very low energy perturbations on single-mode fiber. Laboratory tests revealed that backscatter is not localized for the event of interest alone, but by all environmental noise along the fiber. The large amount of noise accumulated along the fiber makes the signal of interest, e.g., from a rail break or train, undetectable in fiber lengths in excess of 50 meters. As a result the contractor, Texas Transportation Institute, recommended that the contract be terminated. TTI prepared this final report that documents the work accomplished and the findings.

CHAPTER ONE – INTRODUCTION

IDEA CONCEPT AND PRODUCT

For decades, railroads have relied upon track circuits to perform, among other things, the critical function of detecting broken rail. However, track circuitry, which is expensive to maintain, does not detect a substantial percentage of rail breaks in which electrical continuity is maintained. Fiber optic sensing has great potential as a low-cost means of detecting broken rails. This research proposes to investigate the feasibility of using coherent optical time-domain reflectometry (C-OTDR) in concert with advanced signal processing techniques and neural networks in buried fiber optic filaments to detect and locate trains and the ballistic event characteristic of rails breaking under stress. An optical transmission through a continuous length of low-loss, telecommunications-grade fiber buried within the right-of-way, yet away from track maintenance operations holds promise for providing an inexpensive, reliable alternative to conventional track circuitry for train presence and broken rail detection. The potential implications of this advancement are significant in that buried fiber optic filament is free of the problems associated with the electro-magnetic interference encountered with current track circuits. The objective of this project is a low cost, reliable alternative to conventional track circuits for near real time detection and location of rail break events, as well as detection and location of moving trains on the track that can be commercially developed for application to the railroad to enhance the transition to communications-based train control. The industry movement toward communications-based train control systems and away from track-circuit dependent train control would be greatly enhanced by a viable alternative to the existing approach.

A state-of-the-art coherent laser is used to pulse a buried communications grade optical fiber. Information is extracted from polarization shift in the laser pulse backscatter light to establish

train presence and rail break events as well as the location and time of events. The laser employs coherent continuous wave with a line width of approximately 10 kilohertz. The laser beam is pulsed at 30 nanoseconds width over a 0.1 millisecond period to provide a 2-meter resolution in a 20-kilometer fiber length. The system will recognize a train has stopped by registering the cessation of activity at the last known location.

The system has the potential to continuously monitor train presence, direction and location while monitoring the track structure for rail breaks. Additionally, the system is expected to detect and discriminate between various in-train defects, i.e., flat wheels, dragging equipment, stuck or incomplete released brakes, etc.

BURIED FIBER OPTIC RAIL BREAK DETECTION SENSOR

Rationale

The closed electric track circuit (CETC) is a technology first applied in 1872 and since that time used by the railroad industry for multiple functions in their operations. CETC is primarily used to operate the railroad signal system indicating train occupancy. It is also used for detection of rail breaks, which may cause train derailment. CETC provides a carrier for encoded communications of data transfer and voice traffic and may also be used to locate trains approaching and entering critical safety areas. CETC is currently the operational sensor incorporated in the method to maximize the two way capacity of a single railroad track with passing sidings.

CETC can be simply envisioned as a DC electric current applied to both rails with a relay in the current path at one end of the rails. When train wheels short the applied current through the wheels and axle, the relay coil is released. The released relay provides a means of sensing the train

on the track. A train occupying the track is notified of the operating conditions immediately in front of their location from an illuminated lens or a flag activated by the track circuit.

The railroad industry uses the CETC for many critical operating functions. Through the years so many operating functions have been incorporated into the CETC that now change through the adaptation of new technology is being prevented. Nearly all the operational functions of the CETC can all be replaced by more versatile technologies already in use by the railroads or available to them. All, that is, except a reliable and cost effective means of detecting rail breaks. The CETC system is expensive to install and maintain, approximately $3,000 per mile per year over the 20 year life of the system. Federal regulation requires signal control equipment to be checked by a qualified Signal Maintainer at least once per month to test various components condition and adjust or replace any operationally critical components not complying with the manufacturer's specifications. Given the complexity of today's signal systems, some railroads require Signal Maintainers to be degreed electrical engineers or posses equivalent experience.

The detection of broken rail uses the open circuit characteristic to remove the current from the relay coil. When a rail breaks, the path of electricity is broken. This causes the current in the relay coil to drop, activating the signal light. That a rail has broken is a deduction by the system operator because, he knows there is no train in the area of the activated signal system.

The existing track structure is approaching capacity for the safe operation of the trains moving on the system. Capacity on a single track structure is generally viewed to be the capacity of the structure given an equal distribution of trains in each direction over a twenty four hour period. Many factors govern the capacity of the structure. Some changes to increase capacity require capital investment in the rail structure, while other factors can be managed through

operating practices and policy. These manageable elements affecting capacity will be discussed as appropriate where the buried fiber optic rail break sensor may prove valuable.

Capacity is particularly governed by the method of operation used by the railroad over any particular segment of railroad. Four methods of operation are allowed by Federal regulation for railroads in interchange service. (A new method is being considered and FRA is preparing operating safety requirements and regulations for this potential method of operation.) These are as follows:

1) Train registry, where no train may operate on the railroad until the train currently operating on the railroad completes its operation across the railroad.
2) Track warrant, with or without train signals, where the train is authorized by written warrant to occupy a particular section of the railroad, usually from point A to point B.
3) ABS (absolute block signal) where the train is provided with authority to occupy the railroad from some beginning point to some end point based on signal authority, this system requires authorization to enter the operating portion of the railroad prior to entry.
4) CTC (centralized train control) where the signal itself acts as the authority for the train to move and to occupy the section of railroad between two signals, or the block-of-occupancy.

The limiting control function for capacity of the track structure can be viewed as the minimum non-emergency stopping distance for the longest, fastest, and heaviest train allowed to be operated on the railroad when the block-of-occupancy length plus some arbitrary safety factor distance is set. It follows that no signal-block-of-occupancy may be shorter than the minimum stopping distance.

The CETC exists where a signal system is present. The circuit is also used to detect a separation of the rail to provide broken rail detection. If a rail inadvertently breaks due to stress

build up within the structure, the track circuit continuity is also broken and the signal system will indicate a train is occupying the block-of-occupancy. Certain types of rail breaks may go undetected using the CETC: the compressive fracture is generally not detected, the partial fracture is not detected, and many of the breaks over tie plates go undiscovered until a train derails over the failed piece of track. In 1998 the BNSF railroad experienced nearly 18,000 recorded rail breaks. Approximately 80% of these breaks were detected by the CETC. Of the remaining 3,600 rail breaks, approximately half were detected by track forces during normal work activity. There were 1,700 breaks remaining that were only detected after some damage or train mishap had occurred that was traced back to an undiscovered rail break. The average damage assessment for BNSF 1998 data is nearly $5,000 per derailment, or $8,500,000 for all the broken rail attributable derailments.

The railroad industry and particularly the railroads themselves are seeking means to increase capacity other than to build additional infra-structure. One recognized means of capacity expansion is the so-called PTC (positive train control) method of operating. PTC uses GPS to accurately locate the position of the train on the track structure. Precision location allows trains to operate much closer together while still maintaining a safe stopping distance between trains. Various PTC technologies have been tested and shown to be equivalently reliable with today's safe operating practices. However, there is not an acceptable alternative to detect rail breaks.

Detecting rail breaks (or broken rail) in the PTC operation continues to rely on the use of the CETC. Estimated implementation costs for a high-end PTC strategy for a major railroad corridor of 1,700 miles, operating approximately 70 trains per day, exceeds $300,000,000. This implementation cost does not include any capital or operating expense relief for the CETC, approximately $3,000 per mile or $5,000,000 per year for the CETC alone. No industry endorsed

cost/benefit analysis has been able to show a positive monetary position for the implementation strategy for PTC, because of the continuing cost of CETC maintenance. It is generally recognized by industry insiders that if the cost of the CETC can be eliminated or substantially reduced, PTC investment paybacks will be attractive. The railroad industry is not expected to invest in PTC until an economic and effective means of detecting and revealing rail breaks is available.

Concept Discussion

Laser impulses through a buried fiber optic filament have been shown to be sensitive to perturbation by small quantities of energy. A sponsored TTI Rail Research effort ($75,000 over 18 months) is using a single mode fiber and a coherent laser to demonstrate the buried fiber optic filament capability to detect the disturbance of a rail break. The AAR's Technology Scanning Program is supporting ($30,000 in FY 2000) a related effort to establish train presence in conjunction with rail break detection.

TTI's program has been reviewed with BNSF's Assistant Vice President, Signal Engineering, Mr. Dennis Boll. Mr. Boll was enthusiastic regarding the potential for this program to allow the BNSF to implement PTC by providing a means of rail break detection at a low implementation cost, estimated at $1,700 per mile. Additionally, Mr. Boll offered to install a 20 mile test section of the system as soon as TTI is comfortable with the systems readiness for field evaluation.

Background Technology

The sensor system will be sensitive to a wide range of inputs from sources in addition to the ballistic impulse measured when a rail breaks under stress. Trains themselves, flat wheels, maintenance of way equipment and even animals will likely give rise to detectable signals. This research uses an advanced signal processing technique called Wavelet analysis to recognize the

unique energy inputs characteristic to trains. Wavelet analysis is a newly developed mathematical tool that has found many applications in digital signal processing. It has been hailed as one of the most important scientific breakthroughs in this century.

Wavelets come in different scales (i.e., different sizes), and they also come in different types. All types of wavelets are finite energy signals (or functions) and each wavelet with its integer translates from a basis set for signal representation. Since each wavelet is a finite energy signal, it is either a signal with finite time duration or with a fast decay such that it can be truncated with minimum error. Contrasting with the Fourier representation that uses infinite duration functions (sine and cosine functions), the wavelet representation seeks to use finite duration wavelet functions. Since natural or man-made signals are finite duration (transient) in nature, it is natural to use wavelets at different scales to represent these signals.

Rail break Detection

The distributed fiber optic sensor is a new technology which could make a major contribution to improving broken rail detection. The optical losses in modern fibers are sufficiently low (< 0.2 dB/km) that a distance of 60 kilometers or more (30 km in each direction) might be covered with a single sensor. A buried fiber would not only detect a rail break, but would also determine the location along the rail line where the energy release occurred.

The distributed sensor envisioned here would be configured as a coherent-optical time-domain reflectometer (C-OTDR) using light polarization shift detection. OTDR equipment is widely used in the telecommunications industry to locate breaks in fiber optic cables. A schematic illustration of a conventional OTDR system is shown in Figure 1. In such a system, light pulses from a semiconductor laser are injected into one end of the fiber, and the reflected light from the fiber produced by Rayleigh back scattering is monitored with a photo detector. Rayleigh scatter is the result of an imperfect refractive index for the material (glass fiber) the light is passing through. Nearly all the light moves forward in a straight line. But, because of the imperfect refractive index of the glass fiber, small amounts of the light are scattered in all directions. Rayleigh backscatter

only accounts for the portion of the scatter that moves in the reverse direction in the media. Discontinuities in the plot of reflected power vs. time indicates the presence and location of breaks or localized sources of attenuation in the fiber. However, conventional OTDR is not nearly sensitive enough to either pressure or acoustic waves to be used in broken rail sensing.

An optically coherent OTDR which makes use of interference between light waves will be needed to achieve the sensitivity required for a practical broken rail sensor system. One configuration for a coherent OTDR (C-OTDR) is illustrated schematically in Figure 2. As with conventional OTDR's, light pulses from a laser are injected into one end of the fiber, and the reflected backscatter light from a disturbance to the fiber is monitored with a photo detector. In contrast to the conventional OTDR, however, the C-OTDR utilizes a light source with a high degree of spectral purity. The polarization shift vs. kilometer plot for the C-OTDR is produced by interference of Rayleigh back scattered light from different parts of the fiber as a light pulse propagates through it. Because the phase relations between the interfering waves are random, any particular trace of reflected power vs. time will have the appearance of noise or a constant polarization shift with distance over the known time of the wave speed in the fiber. However, a localized perturbation in the fiber which alters the optical path length will lead to a change in the C-OTDR response as a localized polarization shift at the point of activity with a corresponding time bin.

Thus, the distributed C-OTDR sensor will consist of a long fiber cable laid along the rail line. For the deployment, we envision a small-diameter (. 1/3") fiber cable buried to a depth of 1' to 2'. The fiber acts as an acoustic wave sensor; that is, the acoustic wave (sound) from the event of interest (a rail breaking) propagates through the soil and causes a change in the

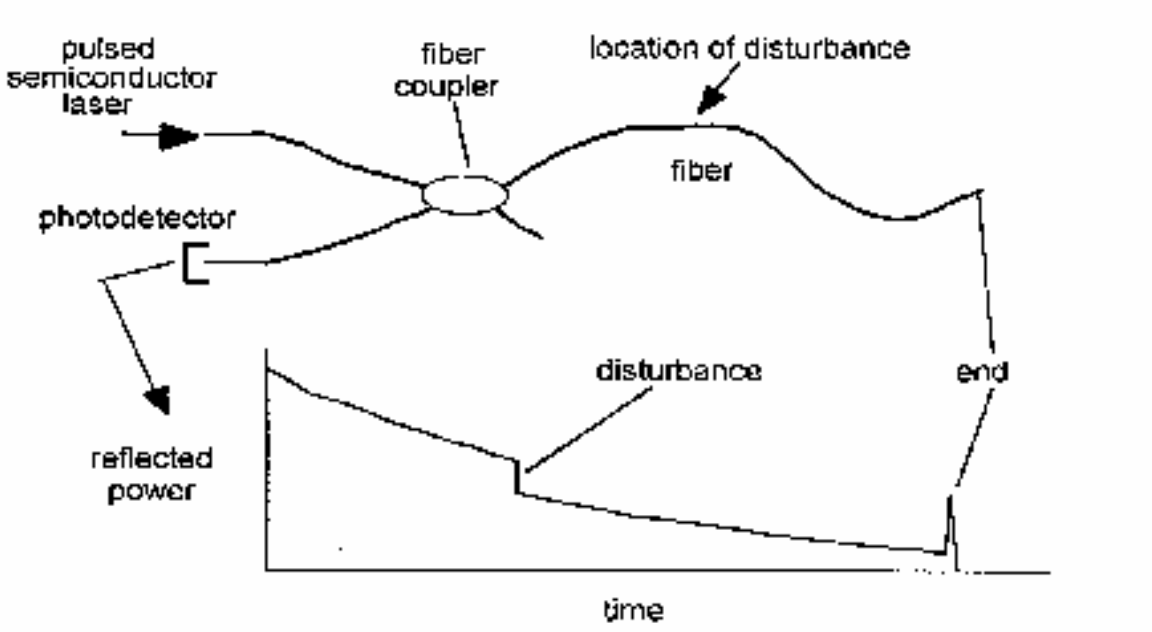

FIGURE 1. Illustration of a Conventional OTDR System.

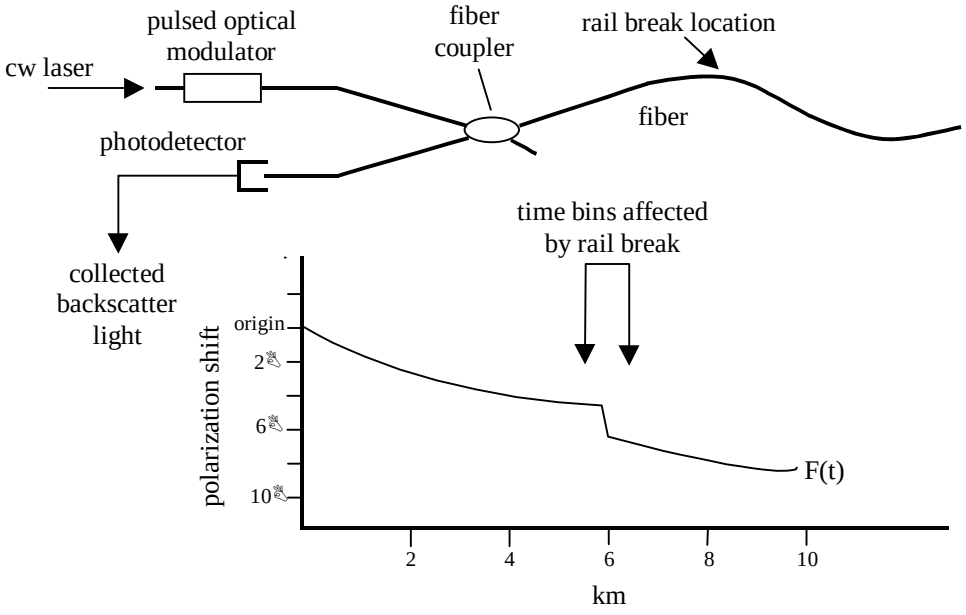

FIGURE 2. Schematic Illustration of a Coherent OTDR System.

phase of light wave propagating in the fiber. The photo detector=s analog output signal is digitized and processed in a time-resolved manner, as in pulsed-radar signal processing. Changes in the shift in polarity of the backscatter light in a particular time bin or set of adjacent time bins indicate the presence of a rail break at the distance corresponding to the time bin in which the signal first appears. Further processing of the data will minimize false-alarm rates; e.g., by using wavelet analysis to distinguish the class of events of interest from the signal signature of passing trains, high-rail vehicles, track work, humans, animals, or environmental effects such as thunder.

Development Work

The current sponsored work has proven the concept that an optical fiber being pulsed with a laser beam when perturbed will have a resulting change in the characteristic of the backscatter light in the fiber. In this application a shift in the polarization of the backscatter light has been shown to occur. The signal has been successfully captured and digitized for computational analysis. The digitized signal has not been successfully characterized and described to date. The principal difficulty in characterizing and describing the captured signal is a coupling loss encountered with the laboratory laser. It is expected that a laser built specifically for this application will significantly reduce the coupling loss. Coupling light loss continues to be the principal topic of investigation for the laser team, principally interested in focusing the light into the fiber at the connection point. The additional work required to finalize the proof of concept system prior to a commercially viable, market-ready product is described below.

In conjunction with the ongoing work in the buried fiber optic sensor, we are proposing to accelerate our ability to field test as soon as practicable. In order to accomplish this, the following activities need to be conducted.

CHAPTER TWO – EXPERIMENTAL SYSTEM

EQUIPMENT

Power Supply:

- Kepco Power Supply – MPS 620M, base power for laser.
- Automotive battery – 12 volt, power supply stabilization.
    - Shumacher Battery Charger – SE-520MA, constant charger for automotive battery.
- Melles Griott – Series 200, Diode Laser Driver, stabilized current regulator for laser.
- Hewlett-Packard – 6218B, mA power supply for New Focus photo detectors.
- Wavetek – Model 188, 4mHz Sweep/Function (waveform) Generator.
- General Radio – Model 1340, pulse generator.
- Audio speaker – 2" round permanent magnet type.

Laser and Fiber:

- 1.33 μm coherent laser – external cavity ring laser amplifying mechanism.
- Uniphase optical modulator – Model S5130-001228, 2.5 Gigabit/second optical intensity modulator.
- Newport – F – POL – IL, optical polarizer.
- New Focus – 2 each; IR DC 125MHz Low Noise Source Photo Receiver, photo detector to convert captured light signal into analog dc power for computer analysis.
- 10 kilometer length of single mode communication grade optical fiber.

Test Equipment:

- Hewlett-Packard – Spectrum Analyzer.
    - Model 8557A, 0.01 – 350 MHz spectrum analyzer.
    - Model 853A, spectrum analyzer display.

- Tektonix – Model 2205 Oscilloscope, two channel with internal trigger capability.
- Fiber Instrument Sales – Model F1851HHCATV, optical intensity meter.
- Pentium computer with onboard analog to digital board to digitize signal and high frequency (up to 50 MHz sampling rate) data acquisition board to control data capture.
- Software program – Labview.

EXTERNAL CAVITY RING LASER

A narrow linewidth laser light source is used in the coherent detection technique for this distributed sensor. The design of the sensor is to be for a fiber length of 10 kilometers (km). This system will use the Rayleigh backscatter property in the fiber as the measurand. The linewidth for the laser needed to operate in a 10 km fiber is obtained by evaluating the coherence length equation

$$\Delta f = c / L_c$$

where c is the speed of light in a vacuum, L_c is the coherence length (the fiber length desired) and Δf is the spectral width (line width) of the laser needed to operate with the 10 km fiber.

$$\Delta f = c / L_c = 3 \times 10^8 \text{ m/s} / 10 \times 10^3 \text{ m} = 30{,}000 \text{ Hz}$$

The external cavity ring semiconductor laser is a suitable laser for producing the required 30 kHz. linewidth needed for this application. Figure 3 illustrates the layout of the laser system we use conforming to the needs of an external cavity ring laser system.

This system supplies a single longitudinal mode continuous wave (CW) output spectrum with the laser diode operating at 1.33 μm wavelength. The diode facet has low reflectivity at both ends because the mounting position is tilted to the light. The wavelength is selected by the diffracting grating which is mounted on a pair of piezoelectric transducers (PZT's) that control the gratings position. The possibility of having a standing wave is eliminated by the inclusion and placement of a Faraday Rotator, two half-wave plates and a pair of polarized beam splitters. An optical filter selectively further reduces out of specification line width.

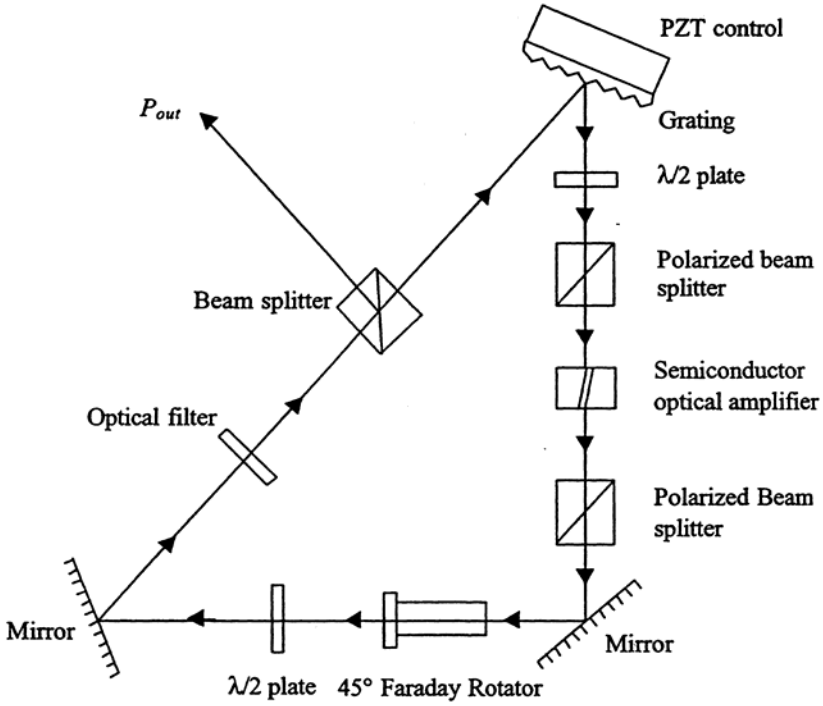

FIGURE 3. External Cavity Semiconductor Ring Laser.

DISTRIBUTED OPTICAL FIBER SENSOR SYSTEM

Sensitivity Test Equipment Arrangement

The test configuration for the apparatus to establish basic sensitivity is shown in Figure 4. The initial work established the working laser and its coupling into the single mode communications grade optical fiber. The apparatus as configured is similar to the traditional optical time domain reflectometery (OTDR). A FiberPort OFR, miniature micro-positioner located inside the laser box is used to couple the free beam of the laser to the optical fiber. An external polarization controller is required to provide correct laser light polarization for the discreet optical modulator. The external modulator is chosen to provide short light pulses without affecting the laser coherence. The optical 50% - 50% coupling splits the available entering light in two paths that connects the oriented-modulated laser light to both a reference and sensing optical fiber path. The reference path is the short length and is terminated with a gold reflecting mirror. The sensing path is much longer, as long as 200 meters for the sensitivity tests. Additionally, the sensing path has several coils (3 – 4 wraps) wound near the end to increase perturbation sensitivity. The coils are attached with adhesive tape to the 2" round audio speaker used to perturb the fiber. At the end of the sensing fiber another gold reflecting mirror is attached. The optical fiber used is single-mode communications grade fiber to obtain maximum sensitivity.

In operation, the laser light is pulsed by the external modulator and fed into the fiber coupler. The two light paths pass through their respective fibers to be reflected by the mirrors. The reflected pulse from the sensing path is phase-modulated. The reflected light beams are then recombined in the coupler. The reflected signals being combined in the optical coupler will interfere with each other either constructively or destructively, depending on their relative phase difference. The combined beam is then directed to the New Focus IR DC detector for conversion to an analog electrical signal. This signal is then displayed on the monitoring oscilloscope and collected by the computer data gathering system for subsequent analysis. Additionally, note that in this test condition, the basis energy state is always above zero, both

when no light is being supplied from the laser into the fiber (the CW bias reference power, P_b) and when the modulator is in an on state supplying light into the coupler (the pulse power, P_0).

Distributed Sensor Test Equipment Arrangement

The distributed fiber sensor equipment arrangement is illustrated in Figure 5. The principal difference between this equipment arrangement and the arrangement for the sensitivity tests is the addition of two more optical couplers. By adding the couplers in their indicated locations a reduction in noise is achieved. The major drawback to adding these couplers is a substantial reduction in signal power at the detector. The signal noise is reduced because the modulated light does not have the positive energy state of the CW bias as in the sensitivity test arrangement. In this equipment arrangement the reference light source comes directly from the unmodulated laser resulting in a stronger CW bias reference power. Further noise reduction is achieved by using angle tip ends (APC) on the open unused legs of the two new couplers. APC ends reduce reflection back into the fiber which is picked up in the coupler. The perturbation is applied to a more central segment of the fiber in this arrangement as opposed to the end of the fiber in the sensitivity tests.

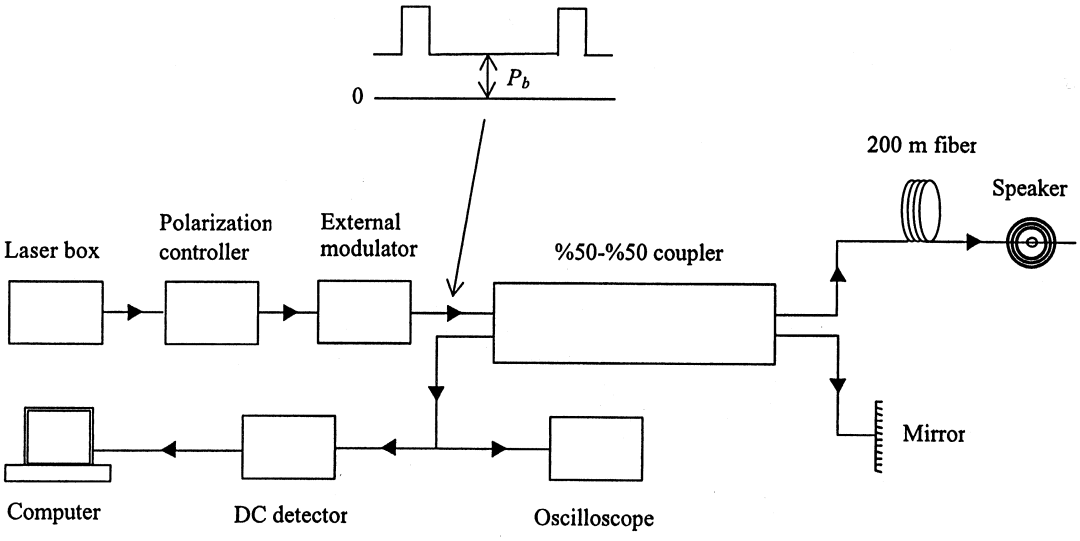

FIGURE 4. System sensitivity experimental

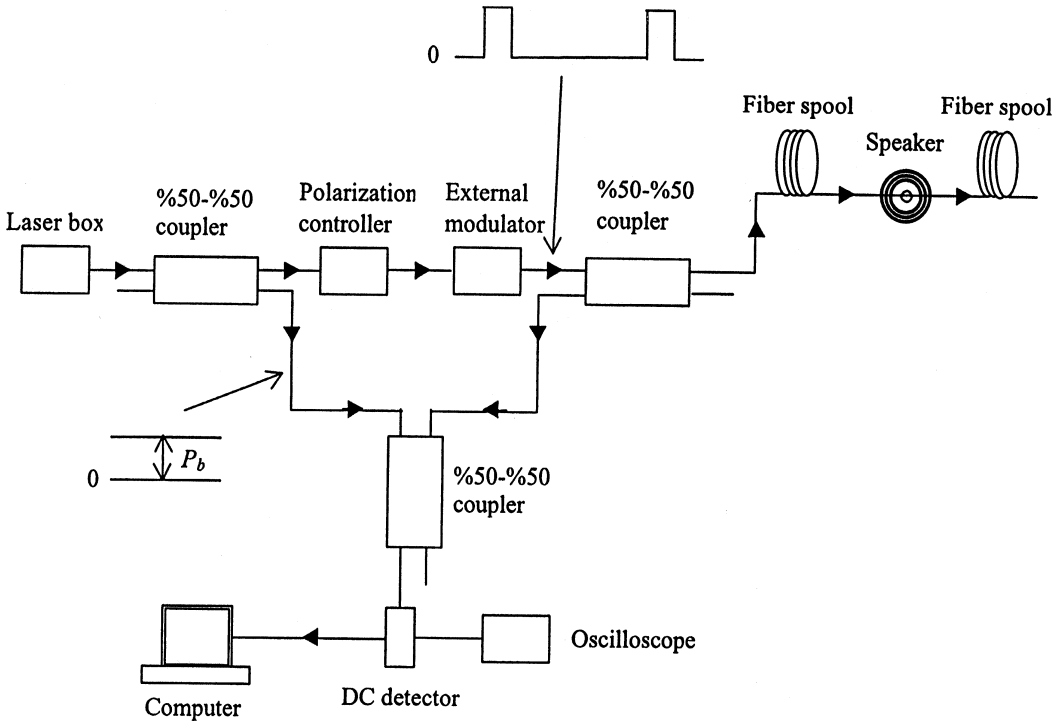

FIGURE 5. Arrangement of equipment for distributed sensor test.

CHAPTER THREE – SIGNAL PROCESSING

To obtain high localized data resolution, a data acquisition board capable of sampling up to 50 MHz was used. The Uniphase modulator provides for a laser pulse width of one tenth of a microsecond (1×10^{-7} second), allowing the A/D board at its highest sampling/capture rate of 50 MHz to capture the signal. The time interval between laser pulses is several microseconds, which provides adequate duration to avoid overlapping the reflected pulse with a new input pulse. The 50 MHz A/D board sampling rate allows a data set of 64 data points to be collected during an event.

The sensitivity test requires capturing the reflected phase-modulated pulse from the end of the sensing fiber path. The interface of the data collecting program with a set of the collected data is illustrated in Figure 6. By analyzing the change in the amplitude the frequency of the perturbation is determined.

For the distributed sensor arrangement, the data for the Rayleigh backscatter light at every point along the fiber must be captured. Analyzing the data should produce the scattering decay curve represented in Figure 7. Detecting an abrupt change along the Rayleigh scattering decay curve indicates a perturbation and its location along the fiber.

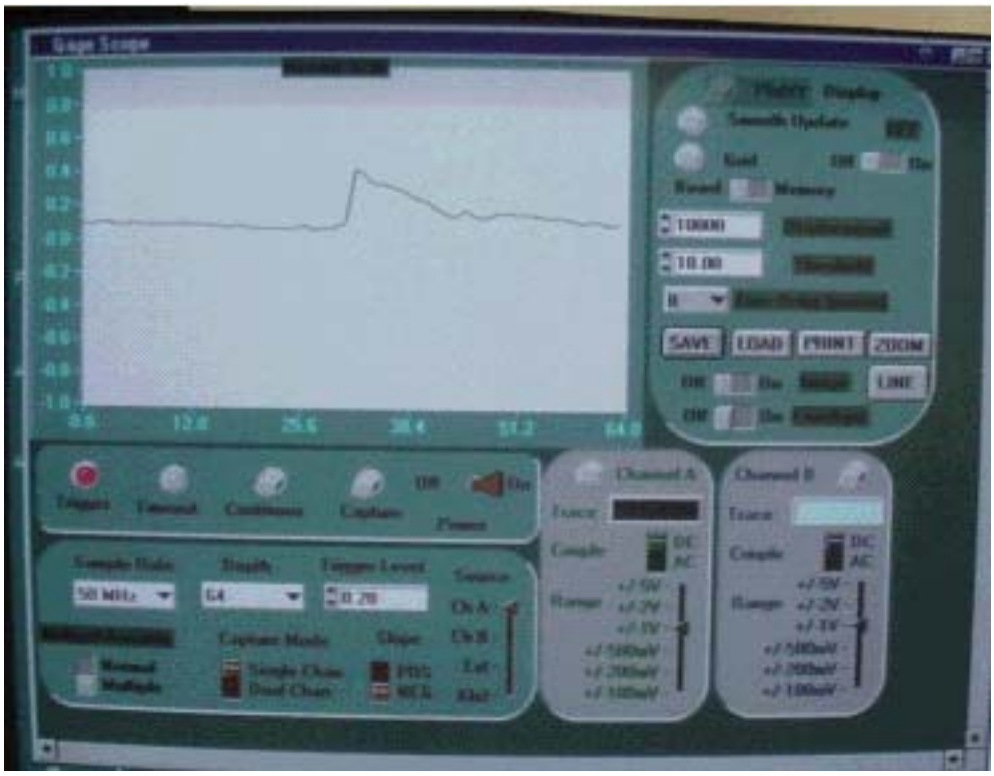

FIGURE 6. Data Acquisition Program Interface with a set of Data Displayed.

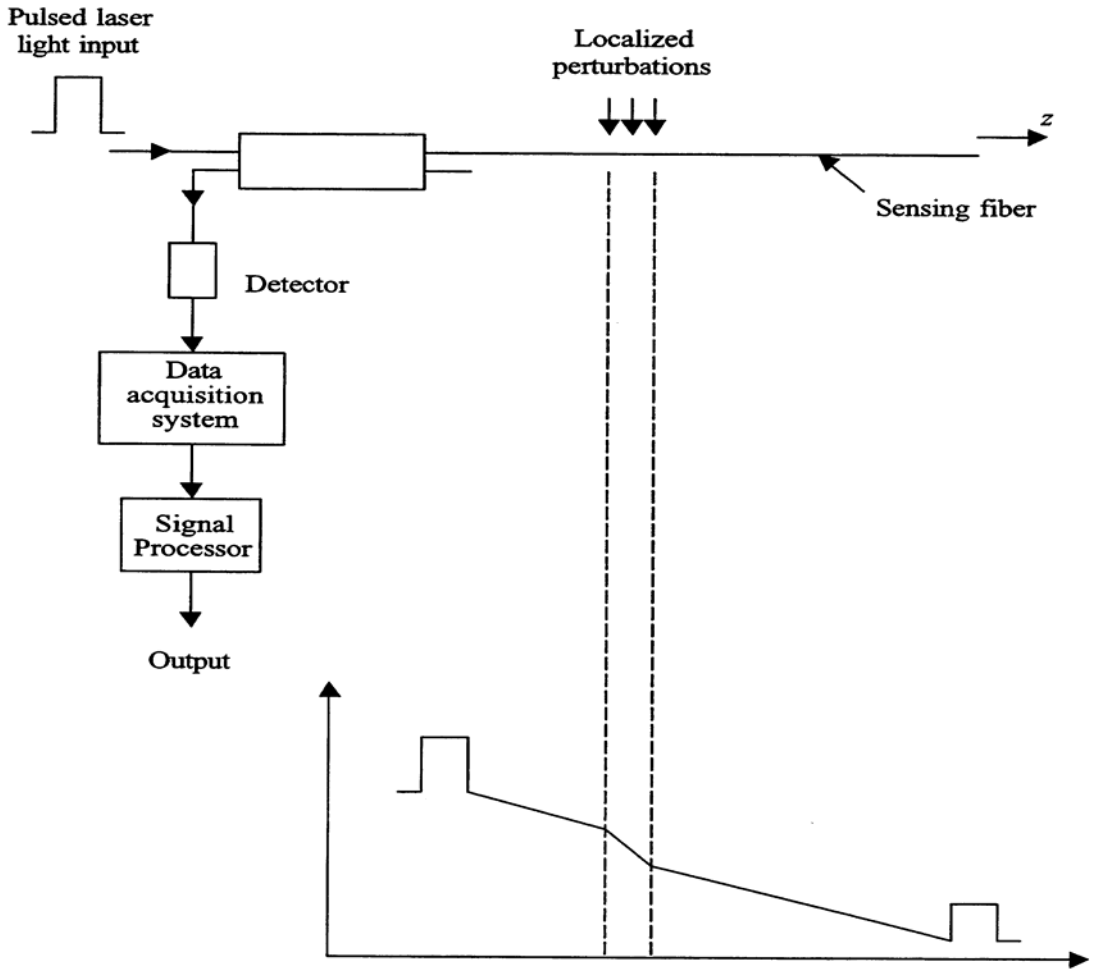

FIGURE 7. Rayleigh Backscatter Decay with Perturbation.

CHAPTER FOUR – EXPERIMENTAL RESULTS AND DISCUSSION

External-cavity ring laser

The external cavity ring laser effectively reduces linewidth of the semiconductor laser. A spectrum analyzer is used to measure the linewidth of the semiconductor laser. The result is illustrated in Figure 8.

The center portion of the curve, a smooth spike, is not an actual part of the signal but is a part of the method to interpret the remainder of the signal. The remainder of the curve represents the actual spectrum of the laser light. The analyzer settings of 10 dB/division and 200 kHz/division allow evaluation of the laser line width being displayed. The line width here is half-amplitude, corresponding to a 3 dB loss, or approximately 150 kHz. The capability of the external cavity ring laser is to produce a line width as narrow as 30 kHz, however external environment, noise, etc. causes mechanical shift in the components which changes the line width. The 150 kHz line width used in the sensitivity tests corresponds to a 2 km coherent length of fiber. Since the sensitivity test only uses a 200 meter fiber length, the line width is sufficient to produce reliable data.

A production laser for this technology to be used in the field would be capable of long stable operation.

Sensitivity Test

Working with the equipment arrangement in Figure 3, the sensor sensitivity is tested. The results of the test shows the sensor is very sensitive to external perturbation. Perturbations of 2 kHz, 3 kHz, and 4 kHz were applied to the apparatus. At least 5 sets of data were captured for each frequency value. Signal analysis using discrete wavelet transform (DWT) for 5 level decomposition demonstrated that data produced consistent results. Figures 9 and 10 display the

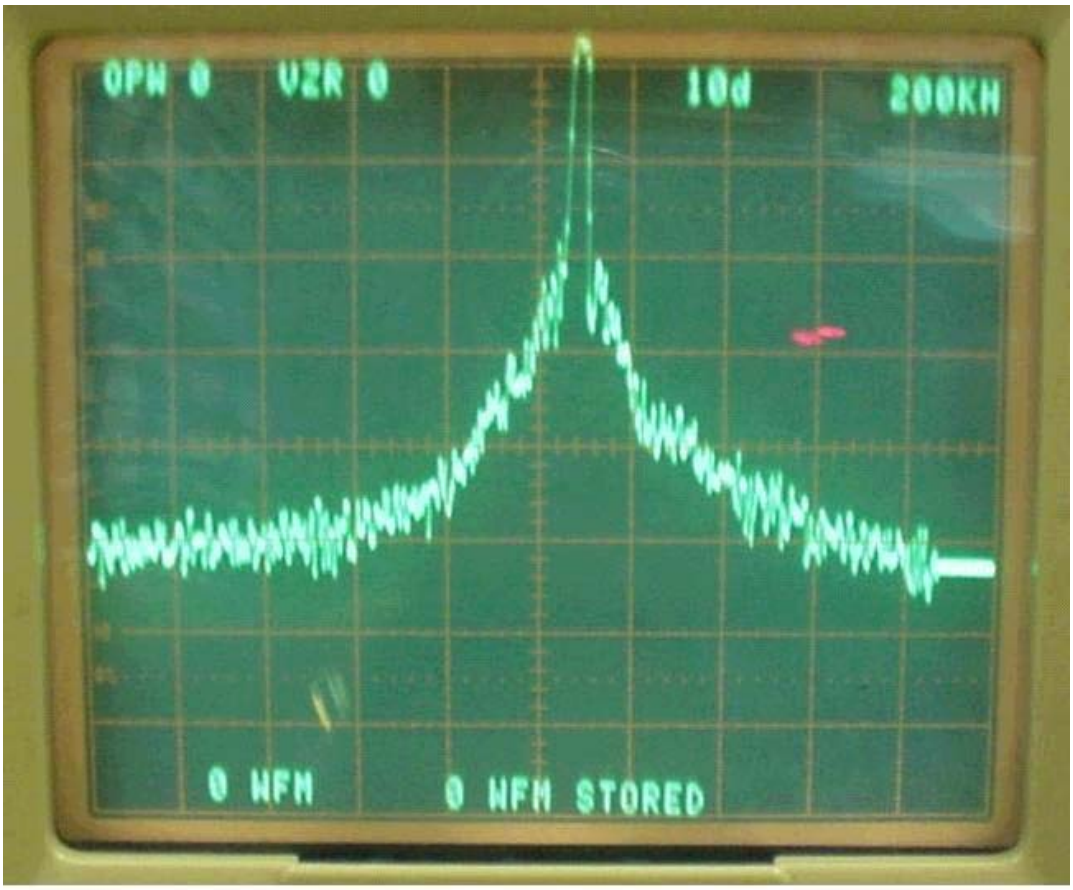

FIGURE 8. The linewidth of the laser as displayed in the spectrum analyzer.

results of the 2 kHz and 3 kHz perturbations respectively. The left column is the wavelet coefficients and least resolution scaling coefficients. The right column is the corresponding fast Fourier transforms (FFT) of the same data. The original signal is displayed at the top of the respective figure and the reconstructed signal is displayed at the bottom of that figure which verifies the decomposition process is correct. Each point in the original data set corresponds to an average value for the amplitude of one reflected pulse. The reconstructed signal is the summation of the DWT coefficients ($a_4 + w_4 + w_3 + w_2 + w_1 + w_0$).

The frequency properties of the perturbations are clearly shown by the second level wavelet coefficients w_1. Some low frequency noise and its harmonics are shown by coefficients w_3 and w_4 at higher resolution. Given the high amplitude of the spectral response we conclude these are from the laser rather than noise generated from the fiber. In order to verify this conclusion, several data sets were taken with no induced perturbation. The analysis of one set of this data is provided in Figure 11. In this Figure the behavior of coefficients w_3 and w_4 are nearly the same as in Figures 9 and 10. However, the spectra of the coefficients w_0, w_1, and w_2 bands are much flatter, indicating the laser has some low frequency (~ 500 Hz) noise.

To verify the sensor has detected the perturbation to the fiber, the experiment was repeated using a 4 kHz frequency with the fiber attached to the speaker and with the fiber detached from the speaker. The power to the speaker remained constant. The expected results of this experiment are that the decrease in signal amplitude when the fiber is unattached from the speaker will be large, in the order of 75% reduction. However the decrease in amplitude is only 50%, which suggests the fiber is susceptible to atmospheric and environmental noise build-up. The data analysis is provided in Figure 12.

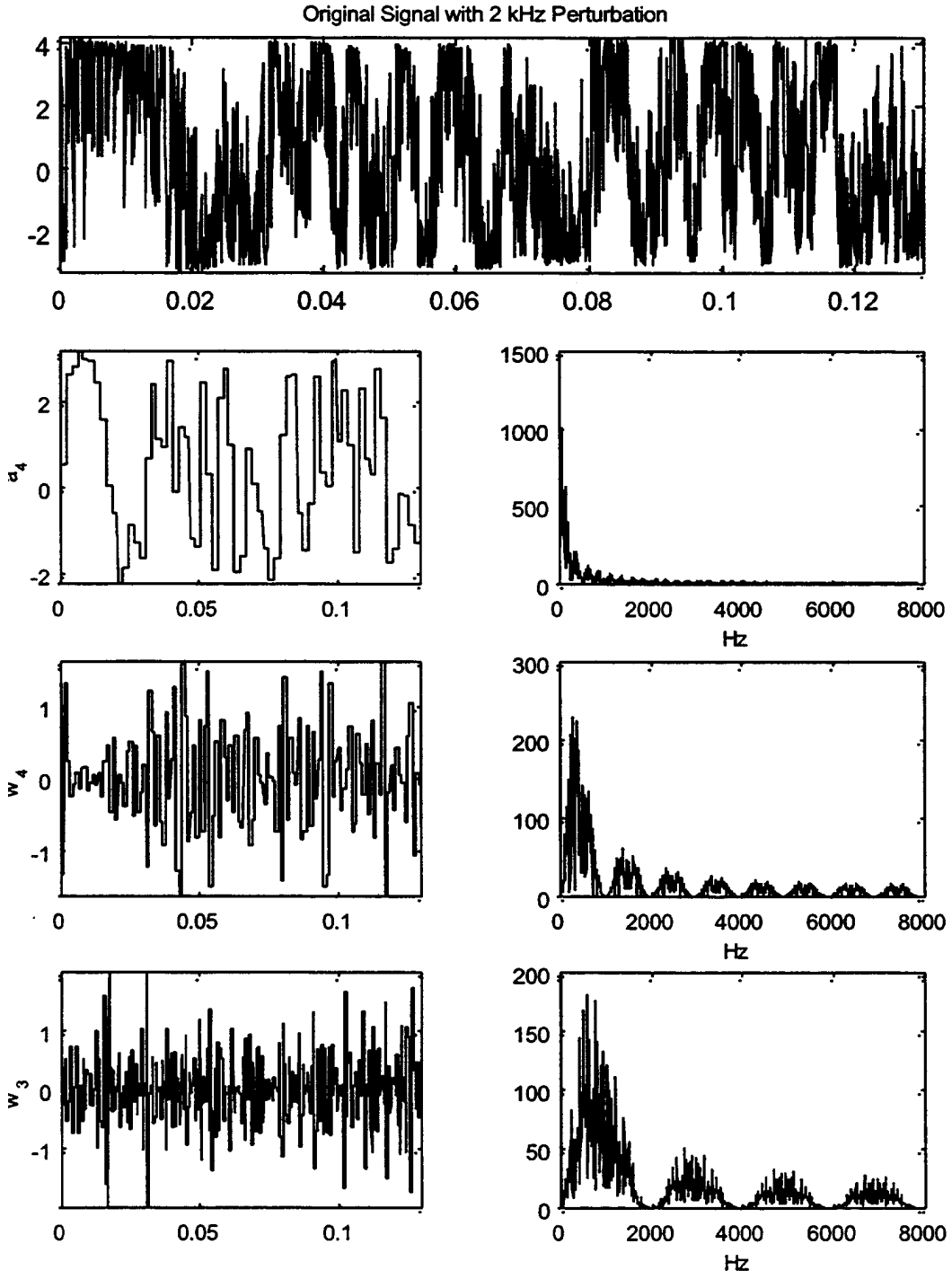

FIGURE 9. The DWT coefficients and their FFTs of 2kHz perturbation.

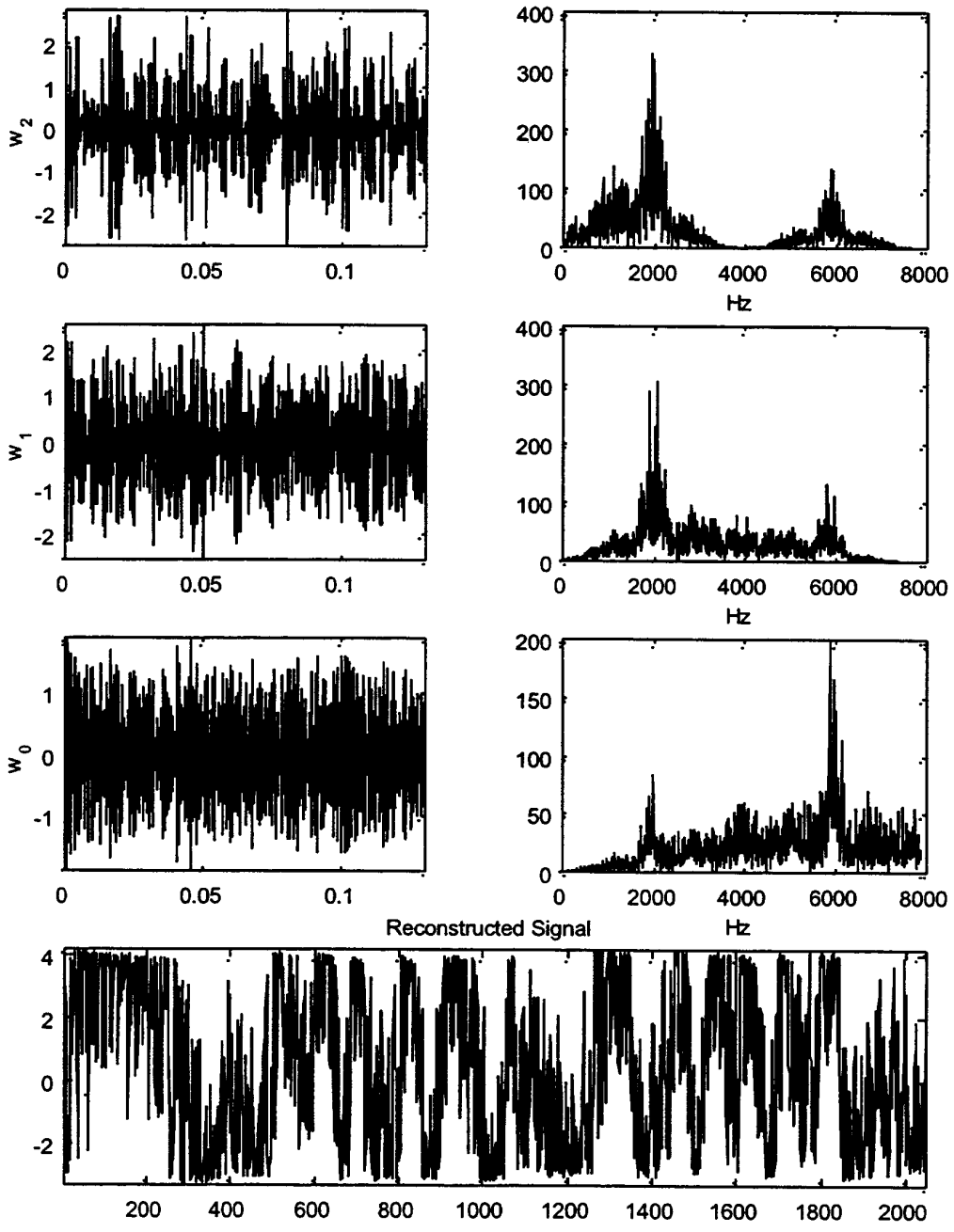

FIGURE 9. Continued.

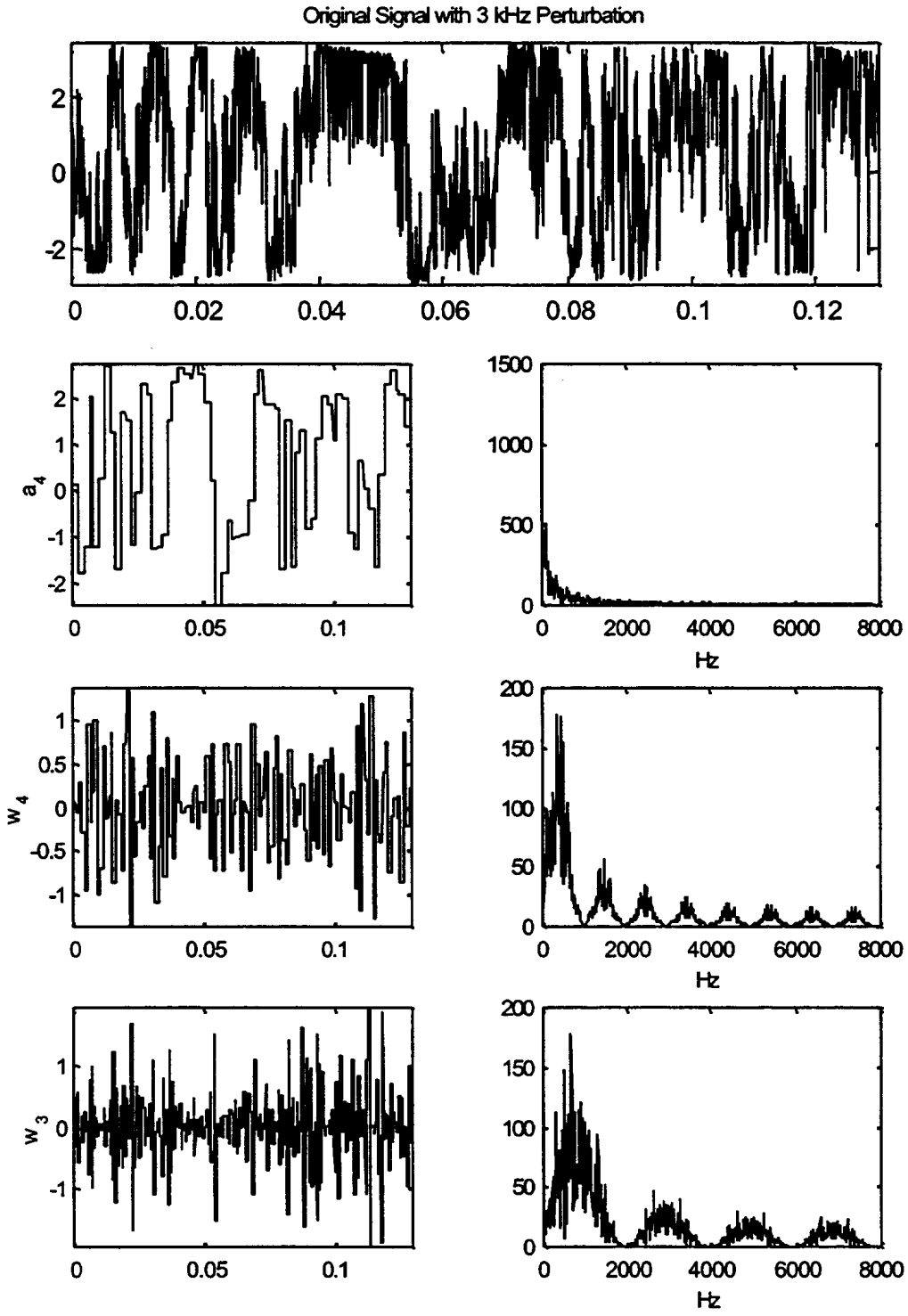

Figure 10. The DWT coefficients and their FFTs for the 3 kHz perturbation.

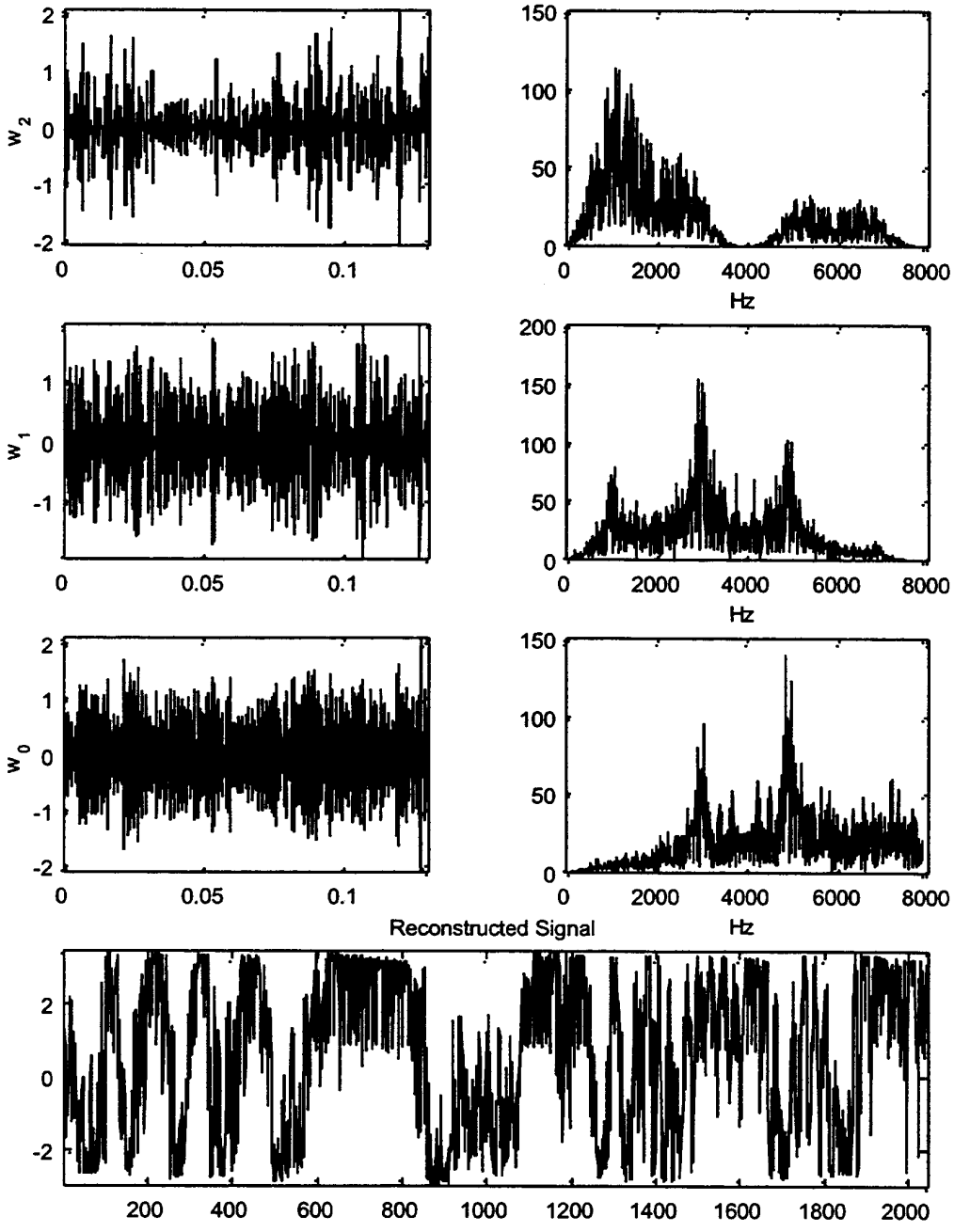

FIGURE 10. Continued.

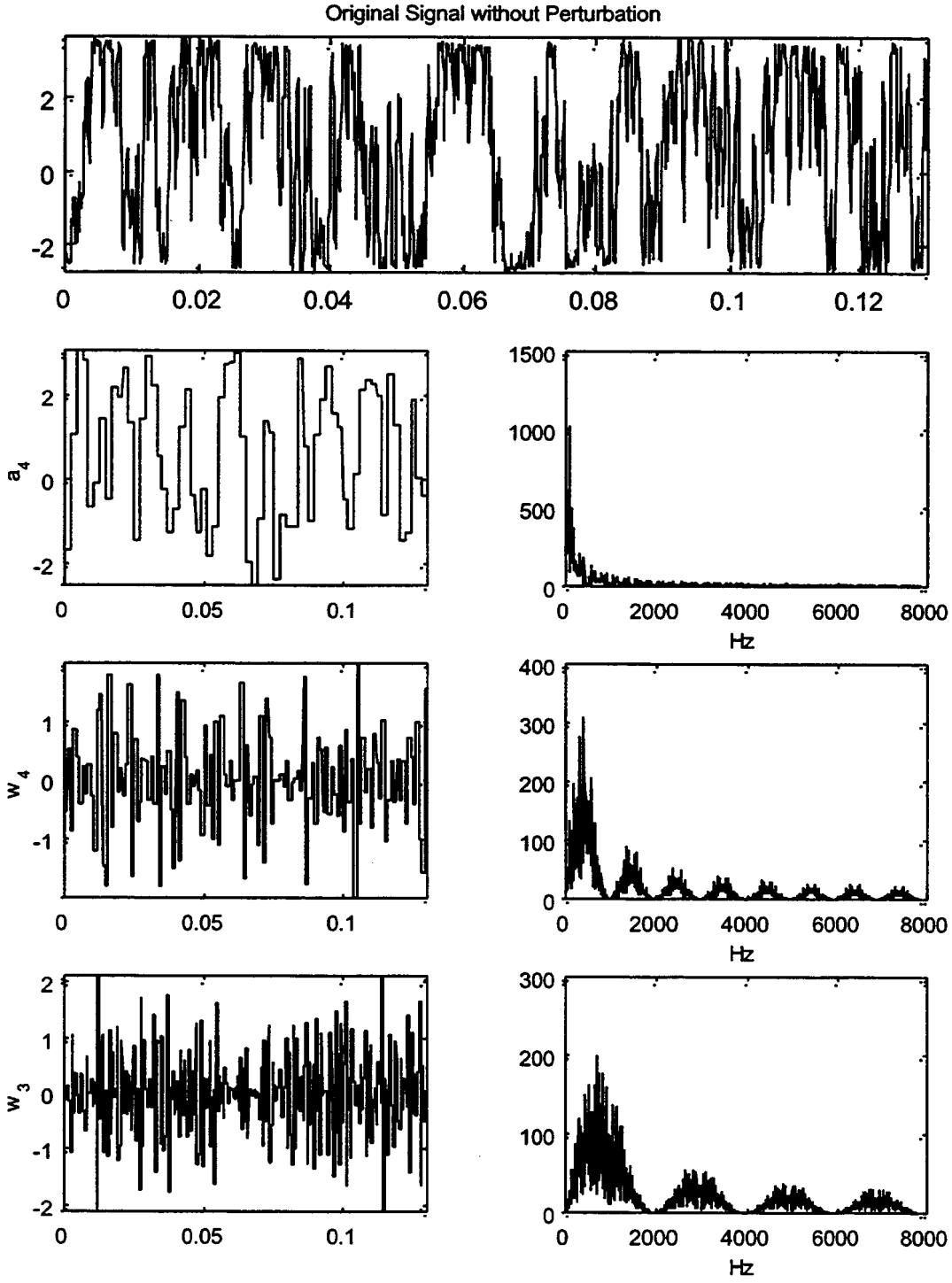

FIGURE 11. The DWT coefficients and their FFTs without perturbation.

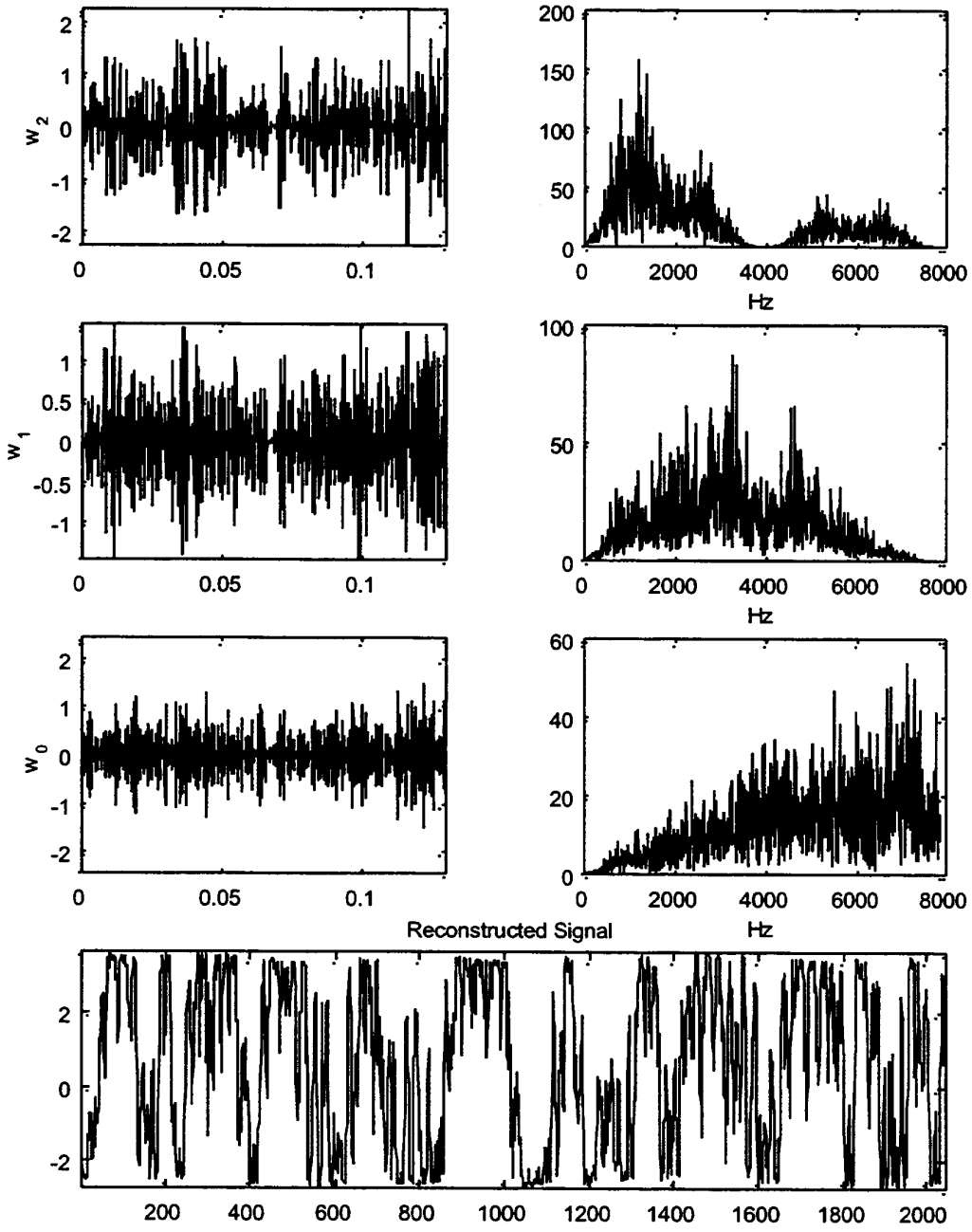

FIGURE 11. Continued.

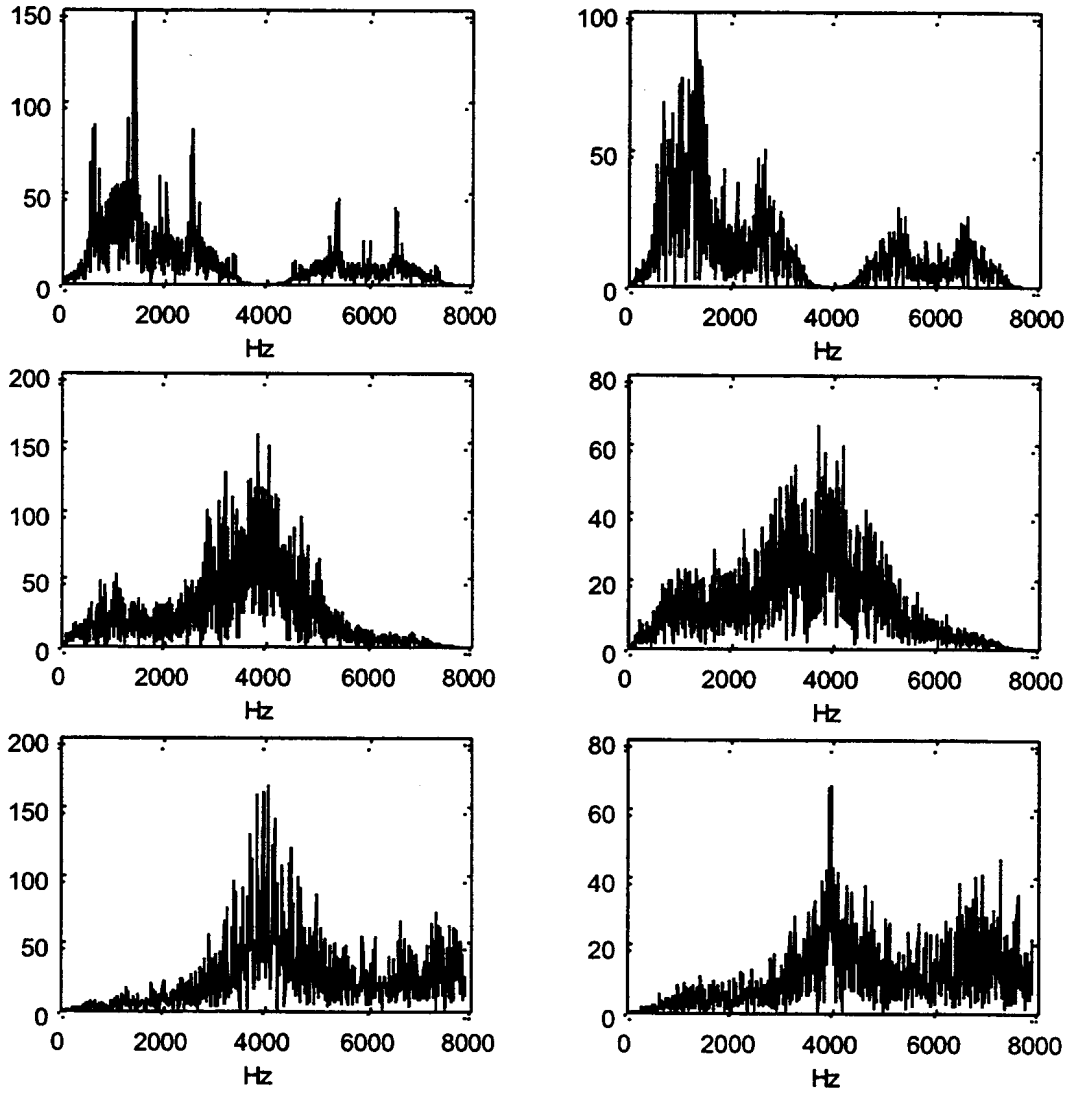

FIGURE 12. The FFTs of DWT coefficients with the fiber end attached to the speaker in the left column and unattached in the right column.

Distributed Sensor Test

Working with the equipment arrangement in Figure 4, the distributed sensor is tested. The test is designed to view the Rayleigh backscatter decay curve as depicted in Figure 7. The decay curve could not be depicted in the tests. The noise level in the 200 meter fiber proved to be so high that it covers the Rayleigh backscatter decay curve. Additionally, the input power of the laser used in the experiments is low at only 200 mw. The actual power reaching the sensor path fiber is at best 20 mw due to the various devices required to carryout this configuration. Due to budget constraints, a higher power laser is not available for use. The resultant signal is shown in Figure 13.

System Noise Experiments

In order to study the noise problem of the sensor system, three additional experiments have been conducted:

1. The system with a 200 meter sensing arm.
2. The system with a 2 meter sensing arm.
3. The system with a 200 meter sensing arm in an isolation box.

The isolation box provides sound proofing and an isothermal environment for the fiber.
The objective of these experiments is twofold. First, how the fiber length affects the noise level in the system is determined. Second, the performance of the isolation box is determined.

These experiments were conducted at night in order to minimize the influence of external building environmental noises. There was no talking or walking in the vicinity of the apparatus during the experiments to prevent sound and air flow in the environment.

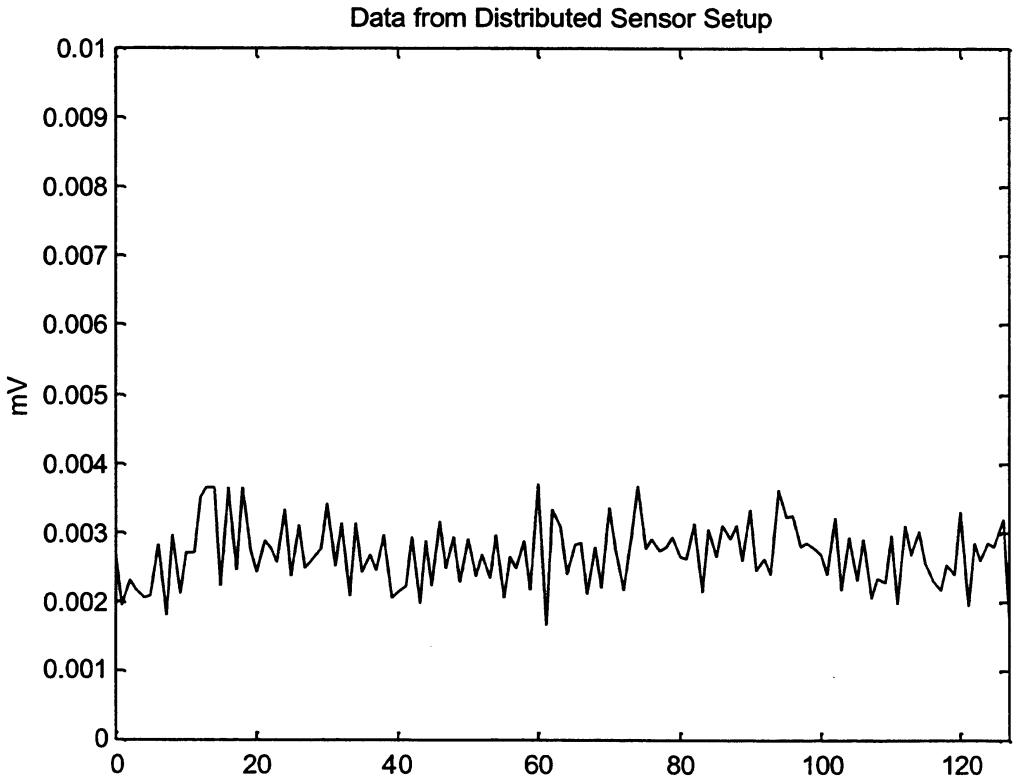

FIGURE 13. A data set plot from the distributed sensor test.

The optical signal is converted into an analog electrical signal at the detector. The computer has a data acquisition board with a fast (50 MHz maximum sampling rate) A/D converter for digital data collection. Although we expected the signal noise to be located in the very low frequency range, data was collected using eight different sampling rates: 1 kHz, 10 kHz, 100 kHz, 500 kHz, 1 MHz, 10 MHz, 25 MHz, and 50 MHz, in order to cover a broad range of possible noise frequencies. For each sampling rate, five data files were saved. Each data file contains fifteen sets of continuous data. Each set of data has 16,000 samples of the signal.

Analysis of the data files for the different sampling rates produced the same result and shows that the signal noise is located in low frequency range (< 3 kHz), as expected. The 10 kHz sampling rate data files were chosen as a representative example. Using this sampling rate, the length of one data set (16 k) is sufficient to capture the signal noise with several Hz frequencies.

To analyze the signal noise, we averaged a total of 75 data sets and performed a Fourier transform (FT) to plot the noise distribution in frequency domain. From Parseval's relation:

$$E_x = \int_{-\infty}^{+\infty} |\, x(t)\,|^2 \; dt = \int_{-\infty}^{+\infty} |\, X(F)\,|^2 \; dF,$$

we know that the amplitude of the Fourier transform also reflects the signal power at this frequency. The amplitudes of the FT's are directly compared for the three different experiments: the 200 m long arm without isolation, the 200 m long arm with isolation, and the 2 m long arm without isolation. The plot of the average data for the 10 kHz sampling rate and their FT plots are shown in the following Figures, 14, 15, and 16.

Comparing Figure 14 with Figure 15, illustrates the signal noise level is much smaller in the system with 2 m sensing arm than the noise in the system with 200 m sensing arm. The signal noise in the 200 meter long sensing arm is about 45 times larger than the signal noise in the 2 meter long arm. It is shown that the length of fiber can greatly affect the noise level in the system.

Comparing Figure 14 with Figure 16, it is observed the signal noise level was reduced approximately 60% by using the isolation box to prevent sound and temperature fluctuation. The performance of this box is limited because the sound wave still can enter the box. Sound can be transmitted though the material, which is 1 inch thick acrylic plate, and enter the box to perturb the fiber. Thinner plate should be able to improve the performance but may not stand the pressure caused by vacuum.

The tests indicate the isolation of the fiber from rapid environmental changes or fluctuations reduces the background signal noise in the system. The buried fiber along the Union Pacific track also represents an isolation type fiber system. The buried fiber may further reduce undesired external environmental influence and should be tested.

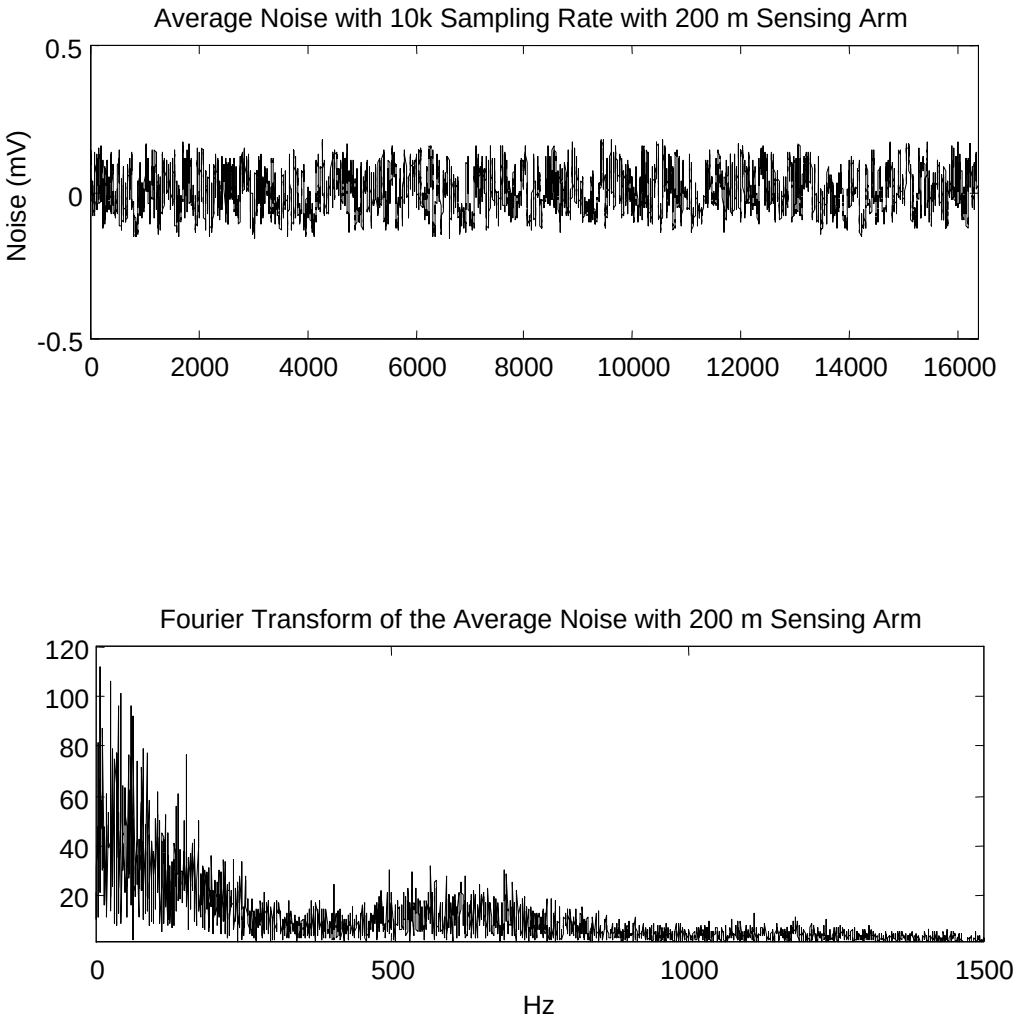

FIGURE 14. Noise and its Fourier transform of the system with 200 m sensing arm.

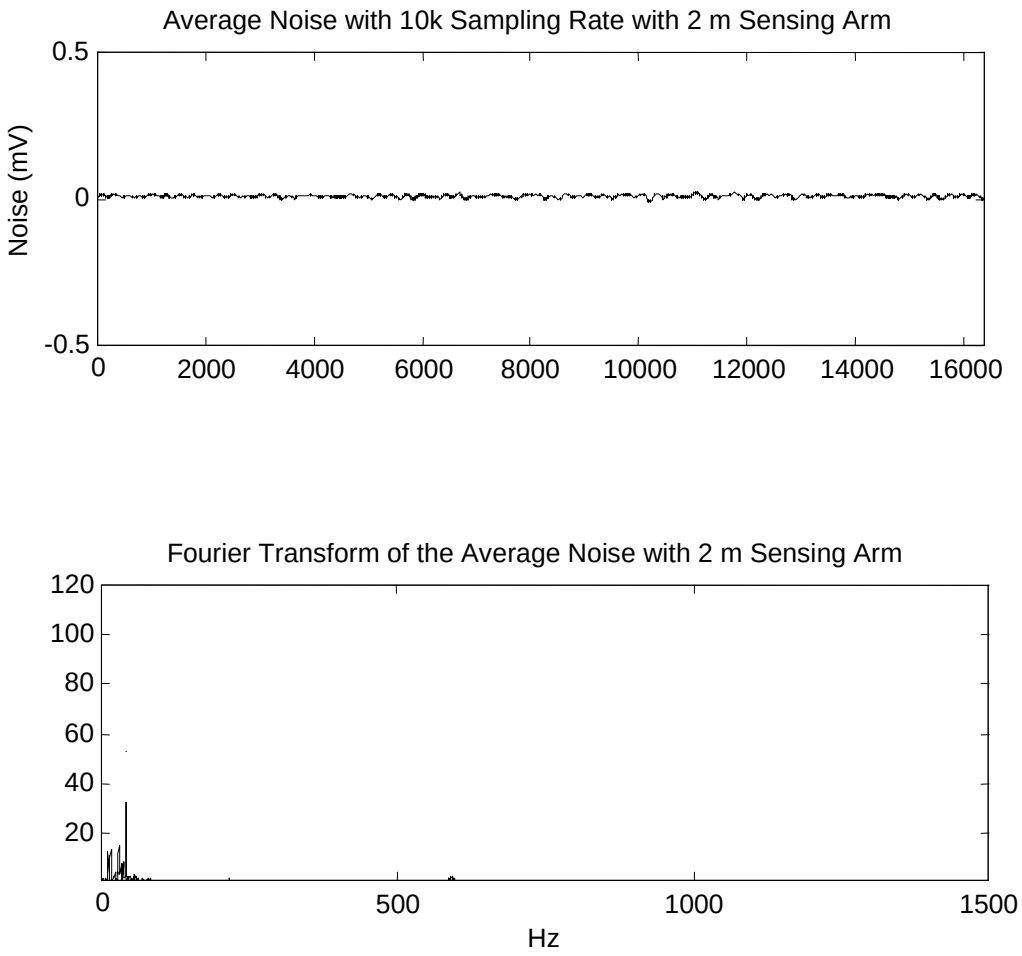

FIGURE 15. Noise and its Fourier transform of the system with 2 m sensing arm.

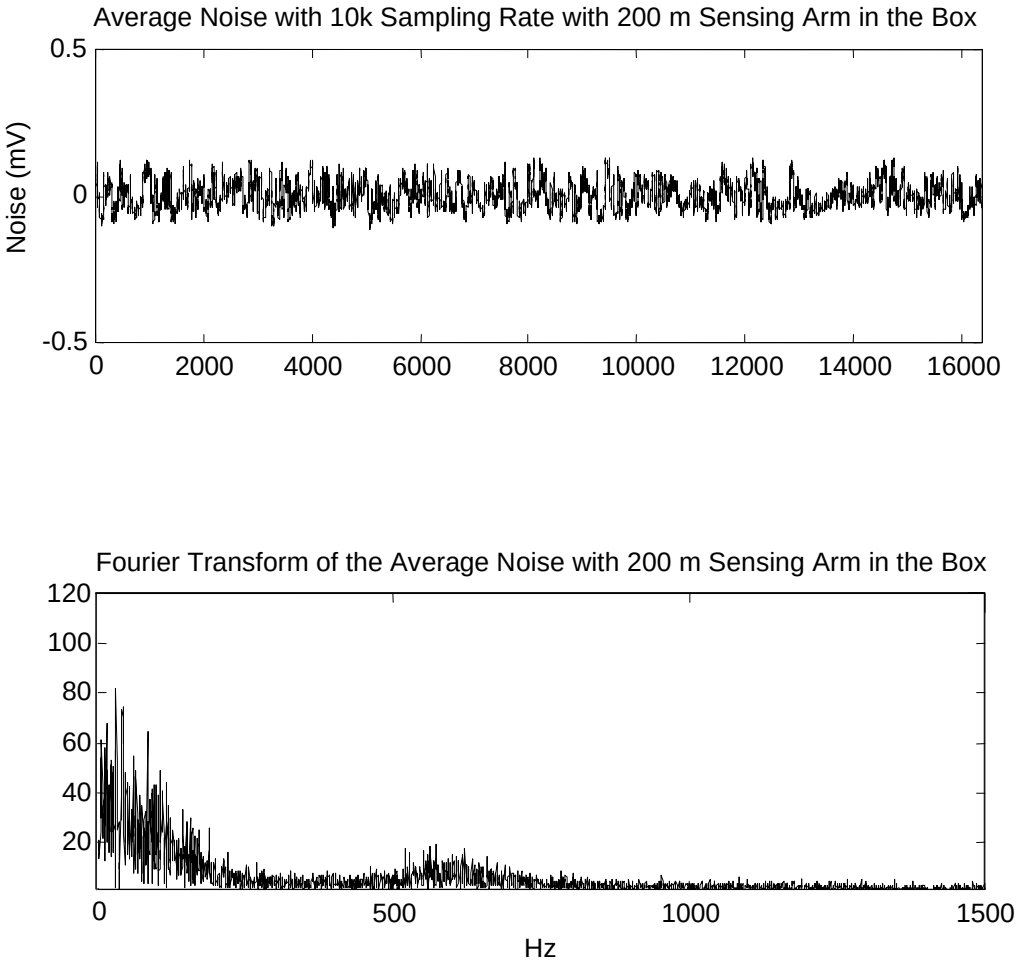

FIGURE 16. Noise and its Fourier transform of the system with 200 m sensing arm in the insulating box.

CHAPTER 5 – CONCLUSION AND RECOMMENDATIONS

The technique of using Rayleigh backscatter decay to detect modulated vibration on a long optical fiber sensor is not proven. We have shown the optical fiber is very sensitive to both mechanical contact perturbation and atmospheric born perturbation. What we have not been able to demonstrate is the ability to detect Rayleigh backscatter in even a moderately long (200 meter) optical fiber. This project has shown that a low power narrow linewidth coherent laser injected into single mode communication grade optical fiber is over powered by the environmental noise impinging it. The reason behind this is the Rayleigh scattering is not localized to the point of highest perturbation, but rather occurs along the continuous fiber and is cumulative at the detector. We conclude the accumulated noise along the fiber exceeds the localized perturbation energy when the fiber exceeds 58 meters. (Under the laser power conditions this research has been able to bring to bear.)

To overcome the limitations caused by the accumulation of noise, Brillouin scattering is recommended to be evaluated for a long distributed fiber sensor system. The Brillouin scattering technique has a clear advantage in that it is affected only at the point where vibration occurs. The intensity of the signal along the signal path will not be affected by noise. Subsequently, perturbation information will be carried by Brillouin scattering strength for detection of localized vibration. The disadvantage of the Brillouin technique is that it requires a higher energy laser. However, the concern for increased laser power may prove to be moot because of the availability of cheap semiconductor lasers and using erbium doped fiber to amplify (EDFA) the light output.

The concept of detecting surface train activity using a remote or buried fiber sensor remains valid. Detection techniques for Brillouin scatter are a current topic of investigation and may hold promise for application in the field of remote sensing in buried fiber. Detection of Rayleigh backscatter in a remotely located sensing fiber using coherent optical time domain

reflectometery (C-OTDR) is a possible technique. C-OTDR has not been demonstrated in a long length (10 to 20 kilometers) of optical fiber. A high power output laser having a very narrow linewidth is required for the C-OTDR technique to be successful in a long fiber length. This type of laser is available commercially, but costs nearly $40,000. Fabry-Perot interferometry is a proven technique and can be demonstrated with currently available equipment for long fiber lengths. The Fabry-Perot interferometery technique does not use light backscatter, instead it uses the well understood light wave theory that provides the basis for interferometers. To effectively detect train activity in a remote buried fiber sensor using Fabry-Perot interferometry only a low cost low power laser (5 to 10 miliwatts of light couple into the fiber) is required for fibers as long as 15 kilometers. Unlike the C-OTDR technologies which use commercial single mode fiber "as is", the Fabry-Perot technique would require that the interferometers be distributed along the length of the fiber. For example, the interferometers might be placed approximately every 800 meters in a 15 kilometer length of fiber.