

An Optical Fiber Infrasound Sensor

*Jonathan Berger, Richard Hilt, Eric Husmann,
Scott Nooner, Ruedi Widmer-Schnidrig and Mark Zumberge*

Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California San Diego

Abstract We have designed a new type of infrasonic sensor using optical fibers as distributed sensing elements. The design addresses the limitations of mechanical spatial filters used to average wind-generated, turbulent pressure fluctuations.

We have built two styles of prototype. In the first design of an OFIS (optical fiber infrasound sensor), we rely on the change in optical path that results from an optical fiber's strain-optic coefficient (i.e., the index of refraction is pressure dependent). In the second design, the optical fiber is attached to and strained by a compliant tube, which deforms under pressure. In both types, the optical fiber path length is monitored interferometrically. The second type has proven to have a better signal-to-noise ratio and is currently the primary focus of our developments.

These devices lend themselves to deployment in long, continuous lines, effectively integrating the pressure variations along their lengths. The response over the length of the sensor is governed by the speed of light rather than the speed of sound (as is the case for conventional infrasound filters). Since our sensors can readily be made kilometers long and deployed as spatial filters in arbitrary geometries, they potentially are a significant improvement over conventional systems.

Introduction

The basic specifications of infrasonic monitoring stations for the International Monitoring System of the CTBTO have been established but the ultimate goal of infrasonic monitoring is to maximize the detection capability for signals of interest. The task is to record accurately small changes in ambient air pressure from frequencies of a few hertz to periods of 50 seconds. The measurement of infrasonic signals in this band presents a classical problem of maximizing the signal-to-noise ratio while maintaining some capacity to estimate accurately event azimuth by recording in an array configuration with a spatial separation determined by the wavenumber of interest. The principal source of noise in the frequency band of interest is turbulence in the wind field.

Infrasonic signals are observed from events at all distance ranges, with the dominant period of the signal being a function of source size. Propagation characteristics of acoustic gravity waves in the atmosphere at long-range distances are well known (e.g., Press and Harkrider, 1962), and infrasonic signals have been seen from various large natural events and man-made events. These include great earthquakes (e.g., Mikumo, 1968), explosive volcanoes (Eissler, 1986), atmospheric nuclear explosions (Donn and Ewing, 1962), and smaller conventional explosions (Hedlin *et al.*, 1996).

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Typical variations in wind speed cause pressure variations of hundreds of μbar , while the signals of interest are typically a few μbar or less. This principal component of the noise field is caused by small-scale turbulence, and travels essentially with the wind speed, on the order of a few m/s to a few tens of m/s. Infrasonic signals, on the other hand, travel as acoustic-gravity waves with group velocities around 280-340 m/s, reducing to acoustic pressure waves traveling with the velocity of sound at high frequencies (Press and Harkrider, 1962).

Studies in infrasound detection often center on techniques of noise reduction. Almost all work to date consists of recording pressure at a single point while an attempt is made to force the pressure at that point to be representative of the pressure averaged along a line or over an area. Typically, a series of perforated pipes or permeable hoses are connected to a microphonic sensor. Pressure noise along the pipe's length is partially incoherent while, for pipe lengths less than the wavelength of interest (typically a few hundred meters), the signal is coherent. The aim of the mechanical filter is to add pressure variations at discrete inlets along its length so that the incoherent noise will average away while the signal is enhanced. Conceptually, one can envision the ideal case of many sensors in an array separately recorded and their signals added together electronically.

Significant efforts have gone into the designs of these mechanical filters. One of the more venerable devices is the Daniels filter (Daniels, 1959), which relies on pipes of varying diameter to create a series of acoustic impedance changes with the hope of reducing acoustic reflections in the pipe. Burrige (1971) analyzed this type of "pipe-microbarograph" and similar configurations. When added acoustically in the filter pipe, there exists a phase delay for each element caused by the finite speed of sound. Burrige modeled pipes with varying dimensions, numbers of inlets, and acoustic impedances to find the best compromise of response flattening and attenuation minimization. In all cases, however, the response clearly is a compromise. The difficulty becomes greater as the frequency increases. As Burrige showed, flat response above 0.1 or 1 Hz is not attainable.

A new approach

Through the use of optical fiber technology we have constructed an infrasound pressure sensor capable of averaging infrasonic signals along km-scale line lengths with an averaging phase-delay governed by the speed of light rather than the speed of sound as is the case with existing infrasonic filters. We have constructed prototype fiber-optic infrasound sensors in our La Jolla labs and deployed a small-scale field version at the University of California San Diego's Piñon Flat Observatory (PFO) in southern California which has been designated in the CTBT as the site of an IMS infrasound monitoring station.

Our new sensor, described here and shown in Figure 1, we call an OFIS (for Optical Fiber Infrasound Sensor). We use a compliant, sealed tube helically wrapped with an optical fiber. As the ambient pressure around the tube changes, its diameter changes in response and strains the optical fiber (this strain is monitored interferometrically). This technique is sensitive to the *integrated* pressure along the tube, and we can build the tube arbitrarily long. The apparent pressure change P inferred from the observed optical path change along a fiber wrapped around a tube of length L is governed by

$$P = (1/L) \int_0^L P(x) dx.$$

Thus pressure variations $P(x)$ (at position x along the tube) having a spatial scale shorter than the total length of the sensor L will be averaged away. An optical fiber is a true, linear, integrator whose incremental step-size is the order of the tube diameter (2.5 cm). Because the phase delay variation along the fiber is governed by the speed of light rather than the speed of sound as in the mechanical filters, the response is flat up to very high frequencies.

To obtain immunity from slight wavelength fluctuations in the laser which illuminates the interferometer, we use an equal-arm Mach-Zender interferometer. In such a device, the difference in the optical path lengths of two identical optical fibers is sensed. We optimize the sensor by configuring the coupling between the optical fibers and the compliant tube such that the signal of interest affects one fiber more than the other while sources of noise have the same effect on both fibers (a.k.a. common mode rejection). For example, the fibers themselves have temperature coefficients, but to a good approximation, both experience the same temperature environment, and—being differential—the interferometer is unaffected. By spacing the wraps of the two fibers as shown in Figure 1, one fiber experiences approximately twice the strain as the other as the tube deforms from pressure changes. The fibers wound close together strengthen one another and hence strain less (for a given pressure difference) than the two isolated fibers.

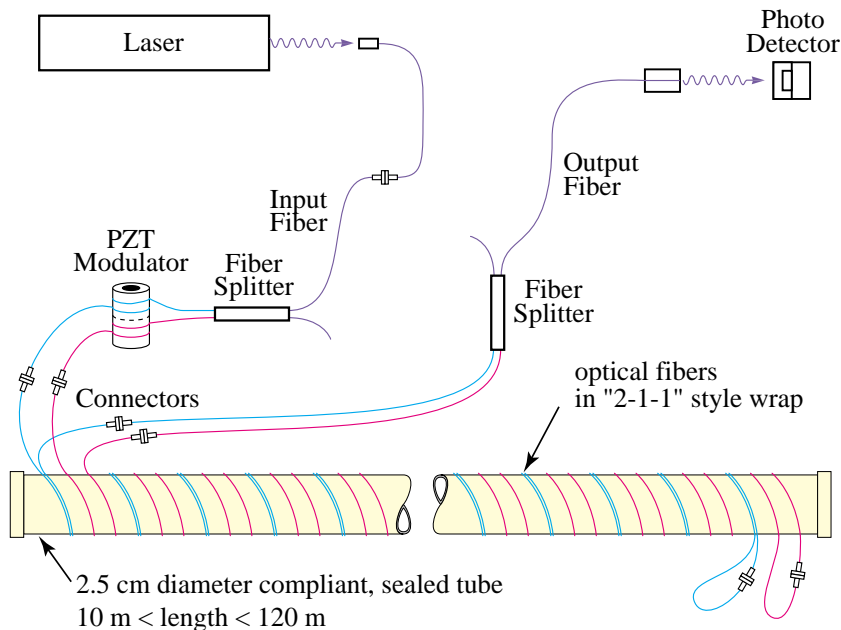


Figure 1. The Optical fiber Infrasound Sensor (OFIS) is constructed from a compliant, sealed tube wrapped with optical fibers to interferometrically sense deformations in the tube caused by pressure fluctuations. The spacing of the optical fiber wraps assures that one of the two fibers experiences greater strain than the other as the tube expands from pressure changes. Other disturbances like temperature and vibration are common to both fibers and hence cancel.

We should mention that our original design did not include a compliant tube, rather we had hoped to rely on an optical fiber's inherent response to pressure changes (via its strain-optic effect). Our plan was to place two optical fibers side-by-side and encase one of them (the

reference fiber) inside a stiff sealed tube to shield it from pressure fluctuations. Early experiments revealed, however, that strains in the loose fibers caused noise larger than the small pressure signals we hoped to detect. This led us to the compliant tube as a means of increasing the pressure-induced strain in the fiber. We further found that it was necessary to constrain the reference arm fiber on the same compliant tube to avoid these same strains that occur along a loose fiber. After finding that this style of wrapping (which we have dubbed a 2-1-1 style) appears to be the most favorable of those we have tried, we built a machine to wrap fibers with this spacing (repeat length is 5.4 cm) on continuous lengths of tubing.

Lab experiments

We experimented with dozens of materials and winding configurations before settling on the type of device shown in Figure 1. This uses silicon tubing having 25 mm outside diameter and 3 mm wall thickness. The optical fibers are tight buffered (900 μm diameter) Corning SMF28 illuminated with a 1310 nm DFB diode laser. Standard optical fiber splitters are used to separate the light into the two arms and re-combine them into a detector where the interference fringes are formed. A piezo-electric cylinder modulates the optical path length difference at 250 kHz and a phase sensitive detector extracts a second fringe signal in quadrature to the direct one. These two analog signals are recorded at 500 Hz and the optical phase (which is proportional to strain and, hence, to pressure) is calculated in post-processing. The sensitivity is empirically determined by noting the interferometer's response to a known pressure difference instilled by pumping air into the inside of the tube. This coefficient, expressed in optical phase shift per μbar of pressure difference per meter of tubing is typically around 0.05 radian $\mu\text{bar}^{-1} \text{m}^{-1}$ for the dimensions listed above.

The sensors are evaluated with spectral analysis. A pair of identical sensors is constructed and ambient pressure fluctuations are recorded with the two lying side-by-side. We assume that self-noise in each instrument is not correlated with the other and that pressure variations are common to both. Power spectral densities of each sensor and the coherency are computed. The incoherent portion of the recording is taken as noise (the incoherent spectrum is the spectrum of the difference between the two time series).

We performed a test of two 10-m-long sensors recording ambient pressure fluctuations in our lab. We put the two fiber-wrapped tubes in a wooden box (20 cm by 40 cm in cross section) lined with woven fiberglass insulation 9 cm thick. Figure 2 is an example of results. Figure 2a shows the time series of each; Figure 2b shows their individual spectra and the spectrum of the difference (or the self-noise). On the bottom of 2b is a graph of the coherency. Clearly the self-noise in these sensors is very low and their ability to detect sub- μbar pressure signals in the band of interest (0.02 Hz to 20 Hz) is promising.

Field experiments

Our first test of these sensors in a more practical environment took place at Piñon Flat Observatory, the University of California's geophysical test site located 180 km northeast of San Diego. We built a 120-m-long wooden enclosure (with vent holes to allow infrasonic pressure variations to be freely passed) identical to the short one used in our lab experiment and placed it along the ground surface. We assembled four 30-m-long segments of the sensor tube with connectorized terminations of the optical fibers to facilitate either linking the segments in series or operating them individually.

In our first experiment, we compared the records from two 60-m-long sensors operating side-by-side in the test enclosure. Figure 3 shows the results both in the time domain and the frequency domain. Again the two records are highly coherent, although the noise is somewhat higher than seen in our lab. Figure 4 is a similar plot comparing a 120-m-long sensor with a 10-m-long sensor, taken during an especially quiet period. The microbarom peak is coherently seen.

Conclusions

We have designed and tested a new style of infrasonic pressure sensor that can be deployed in lengths up to several km. Tests of the design in the laboratory indicate that the self-noise of the sensor is at least 20 dB below the expected ambient noise level over the band 0.02 to 1 Hz. Side-by-side test of two 60-m prototypes installed in the field show highly coherent noise levels across the band of interest. These sensors are expected to improve significantly the ability to average over wind induced noise and thereby increase the observed signal-to-noise ratio of propagating infrasound signals.

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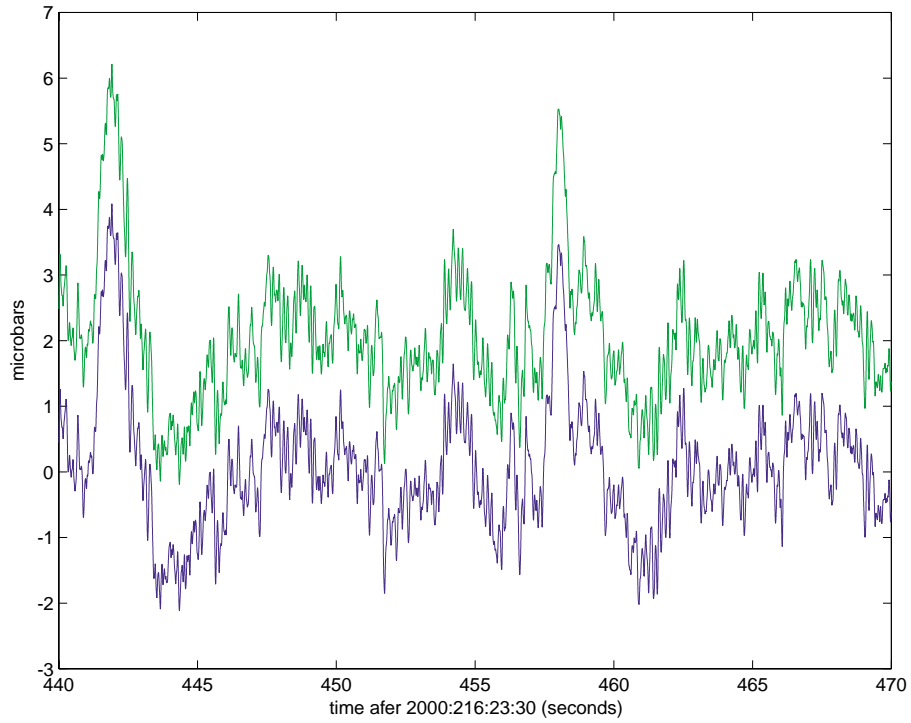


Figure 2a. Pressure variations recorded by two identical 10-m-long OFIS elements placed side-by-side in our basement lab. (The data have been band-pass filtered between 0.1 and 10 Hz).

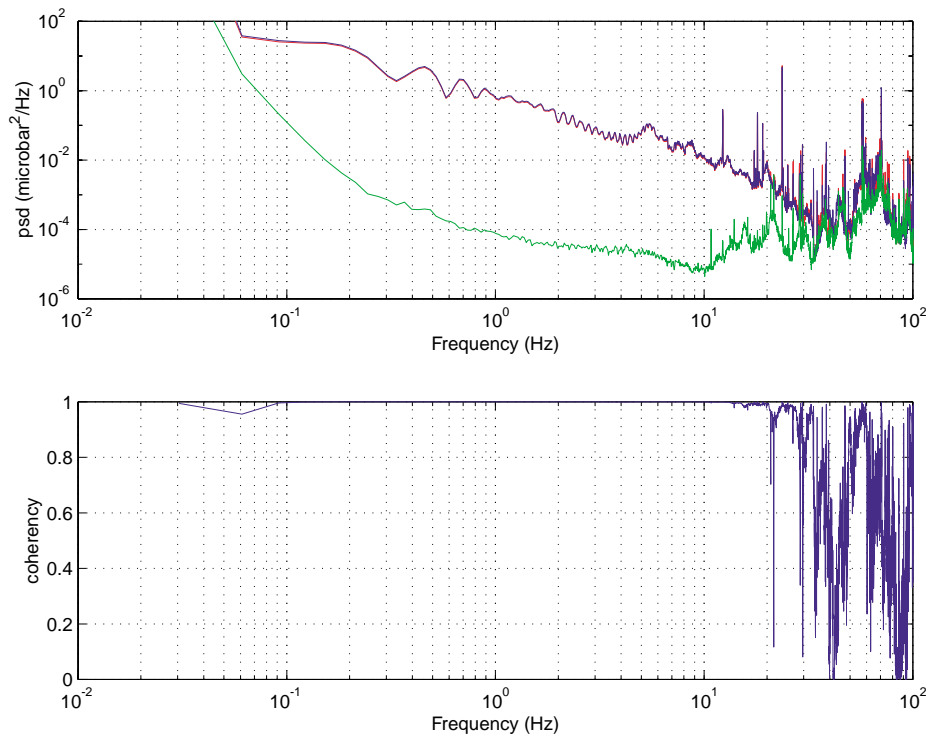


Figure 2b. Spectra taken from longer versions of the records shown in Figure 2a. The red and blue plots are the spectra of the individual records, the green plot is the incoherent noise (since they're nearly identical, it's difficult to see much of the red trace).

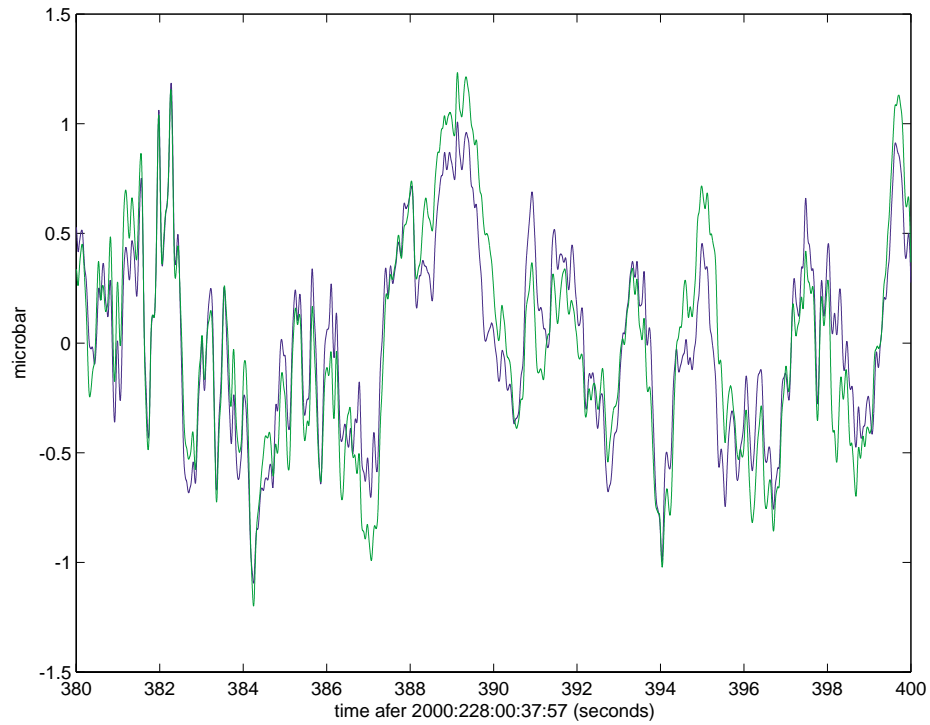


Figure 3a. Pressure variations recorded by two identical 60-m-long OFIS elements placed side-by-side at Piñon Flat Observatory. (The data have been band-pass filtered between 0.1 and 10 Hz).

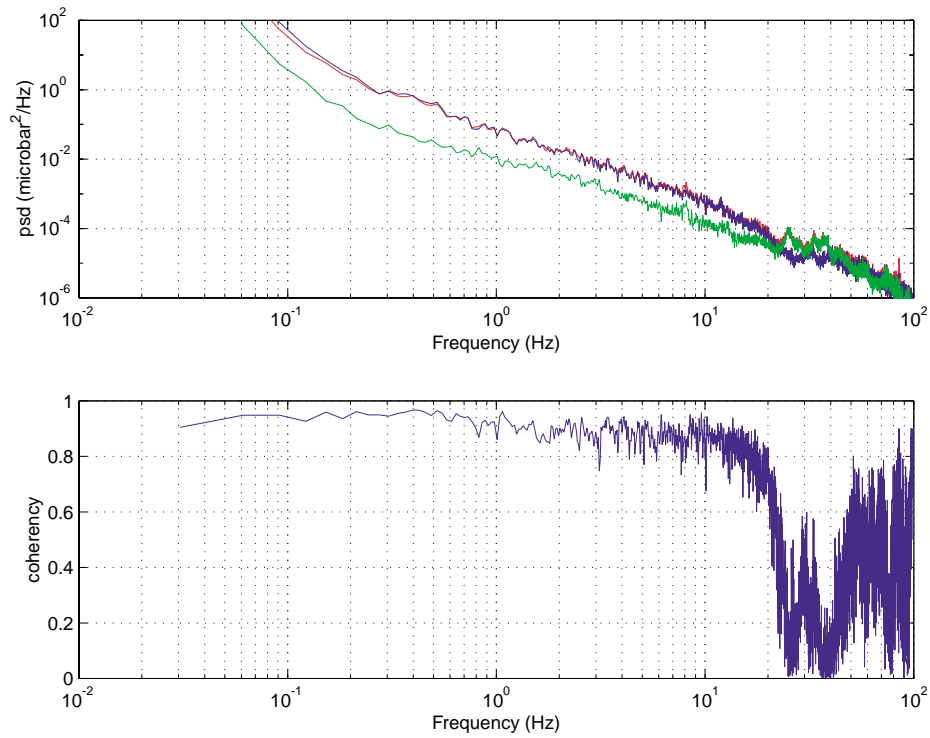


Figure 3b. Spectra taken from the 60-m sensors during operation in the field. The red and blue traces are the spectra of the individual records, the green plot is the incoherent noise.

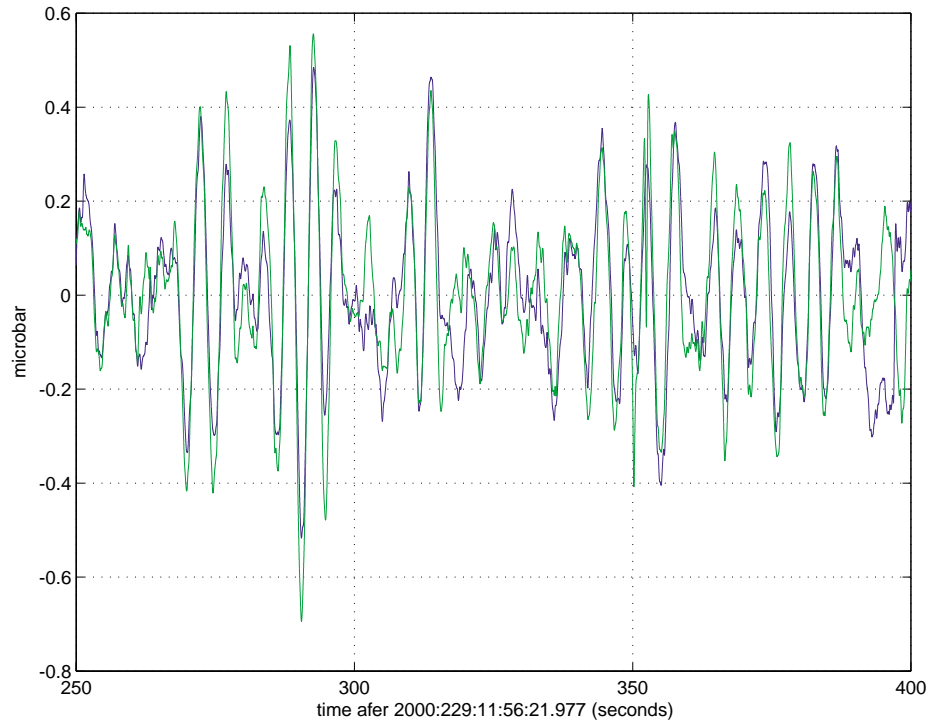


Figure 4a. Pressure variations recorded with a 10-m-long OFIS element placed adjacent to one end of a 120-m-long OFIS element. (As in the other plots, the data have been band-pass filtered between 0.1 and 10 Hz).

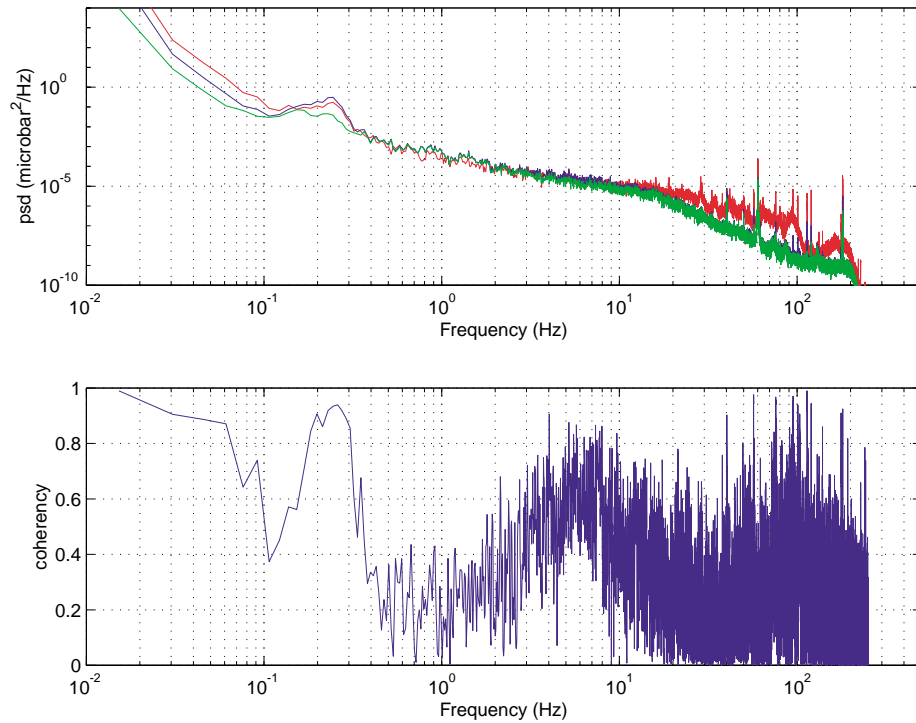


Figure 4b. Spectra taken from the 10-m (red) and 120-m (blue) sensors during operation in the field. The green plot is the incoherent part of the spectrum.

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