Fiber Optic Geophones for Oil and Gas Field Applications

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Summary
We are presenting a new fiber optic sensor system implemented as a Fiber Optic Geophone (FOG). We are presenting the design and experimental test results for the FOG and compare its performance with regular exploration geophones and geophones used for scientific investigations. We will demonstrate that the new Fiber Optic Geophone (FOG) has a significantly better performance than the current state of the art coil geophones in terms of noise floor, sensitivity and frequency response.

Introduction
In seismic exploration the coil geophone has been the standard sensor for exploration work in the oil and gas industry for over 70 years, Wolf et al. (1938). The coil geophone has been very successful because it combines high performance and a robust design with a reasonable price.

The new fiber optic technology we are presenting has the potential to become the new seismic sensor standard for the geophysical industry because it has a number of positive attributes including a low noise floor, a high sensitivity, extreme robustness and reliability and potentially a low price.

The new fiber optic sensor is in principle a very simple sensor. It uses the dynamic strain of the fiber between two reference points to generate the signal. The sensor element can be configured in a number of different ways. By arranging the strain sensing fiber differently the fiber optic sensor can be configured as a:

1. Distributed strain sensor
2. A fiber optic geophone
3. A fiber optic hydrophone

The Fiber Optic Geophone (FOG) Technology
The FOG system dynamically measures the strain of the fiber between two Fiber Bragg Gratings (FBG) using an interferometric technique and a Time Domain Multiplexing (TDM) technique to transmit the fiber strain information to the recording instruments. A Fiber Bragg Grating is a reflector in the fiber core with a low reflectivity, about 1%, used to separate the sections of fiber into individual sensors allowing recording and analysis of the multiple sensors on a single fiber. A low reflectivity allows most of the light to continue to the next set of FBG's allowing for many FBG's and thus many sensors. A schematic of the FOG system is shown in Figure 1. This combination of fiber optic technologies allows a large number of geophones to be deployed on one fiber while maintaining the performance attributes of the geophones.

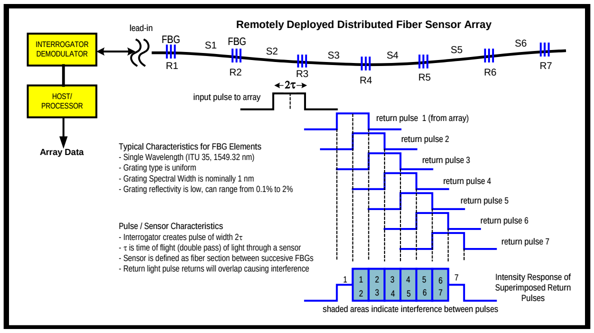

Figure 1. The Fiber Optic Geophone (FOG) system is comprised of three basic integrated building blocks; the Fiber Optic Geophone (FOG); the telemetry cable and the optical interrogator

The FOG is immune to electric and electromagnetic interference, since the system does not require any electronics at the fiber optic sensor end. This design also makes the geophone extremely robust and able to operate in extreme environments such as temperatures up to 300ºC. Even higher temperatures are possible using specialty fibers.

The TDM method interrogates the sensors by sending one light pulse at a time and recording the reflections from the FBG's from each sensor in an array as seen in Figure 1. The strain in the seismic sensor is measured interferometrically by comparing the changes in the relative phase angle between the reflections of the two FBG's bracketing the section of sensing fiber. In the case of a FOG the sensing fiber responds to seismic vibration by dynamically straining the fiber. The fiber optic sensor system can measure strains of the fiber with a resolution smaller than one Ångström (1×10^{-10} m).

The optical system is inherently low noise since it does not pick up electrical noise from any source. The system also uses low noise electronics to convert the optical data into electric digital data. The measured noise floor in the FOG system ranges from about 20 ng/√Hz at 10 HZ to about 5 ng/√Hz as seen in Figure 2. The noise floor from the FOG should be compared with published noise floors from geophones and MEMS sensor, Hons and Stewart, 2009, which is about 1,000 ng/√Hz and the desired noise floor for high resolution seismic systems which is listed as 100 ng/√Hz by Panahi et al., 2006, also shown in Figure 2.

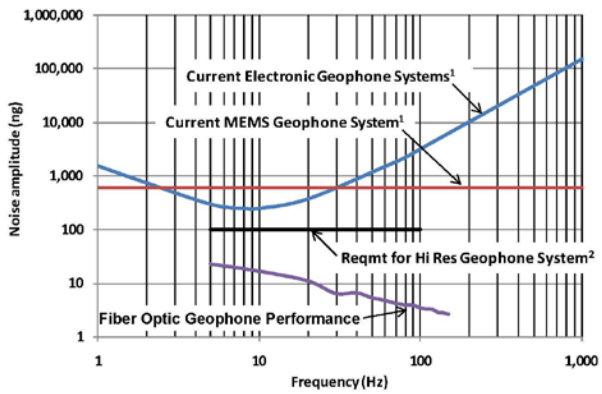

Figure 2. Noise floors for seismic systems.

The pulse width of the interrogating pulses is twice the light round trip transit time between FBG's. For a 20 m length of fiber, i.e. a typical length of sensor fiber in the FOG between FBG's the pulse width is thus 0.2 μsec.

The rate of the phase modulated pulses sent by the interrogator to interrogate the FBG's depends on the overall length of the fiber cable. The maximum pulse rate for the interrogator, which is the optical equivalent of sampling rate for electronic systems, is twice the light transit time in the lead in cable and array because in the TDM interrogation scheme, best performance is achieved if only one pulse travels in the sensor fiber at a time. For a 10 km long fiber the maximum sampling rate is 0.1 ms yielding a Nyquist frequency of 5,000 Hz.

Pulses returned from each FBG contains phase information from preceding adjacent sensor proportional to the fiber strain between two FBG's in the reaction mass spring due to the seismic wave. Upon returning to the interrogator, each pulse is compared to a reference interferometer, generating an intensity pulse in the interrogator, the resulting intensity pulse is converted to an electrical signal and filtered in the analog front end and then digitized. Once digitized, the electrical signal is demodulated - yielding a digital word representative of the instantaneous strain at the sensor. A software demodulation algorithm is then used to ensure a high fidelity output with a low noise floor and large dynamic range. De-multiplexing is accomplished by tracking the pulses in the order received – each from a different sensor. Currently up to 32 geophones can be operated on one fiber without loss of fidelity.

One advantage fiber-optic sensors have over conventional electronic-based sensors is the ability to separate the electronics (preamplifiers, filters, ADC, multiplexing electronics, etc.) from the sensor without any degradation in performance. This removes the electronics from the hostile sensing environment (downhole, ocean bottom, buried, etc.), into a benign, controlled environment where they are accessible for repairs or upgrades. Thus, for permanently installed fiber-optic sensors, only the optical fiber and its associated packaging must be installed permanently. In the case of the new low-cost fiber-optic geophone, this can reduce the cost of the permanently installed equipment.

A large number of fiber-optic channels can be deployed on each fiber, making large channel count system possible in hostile environments such as in boreholes and on ocean floors. The sensor consists of only the fiber making the sensor system robust with a potentially long survival time (as evidenced by deployment of fiber-optic sensors by the US Navy). No electric power needs to be transmitted to the sensor, nor does the fiber-optic sensor generate any electric signal, making the sensor intrinsically safe and immune from EMI/RFI. A high-temperature version of the FOG can be manufactured using commercially available high temperature fiber.

Experimental Results

We tested the FOG in two different environments. The first test was a small refraction type field survey and the second test was in a laboratory. The tests involved comparing the performance of the FOG first with a standard exploration geophone and second with a geophone used for scientific investigations.

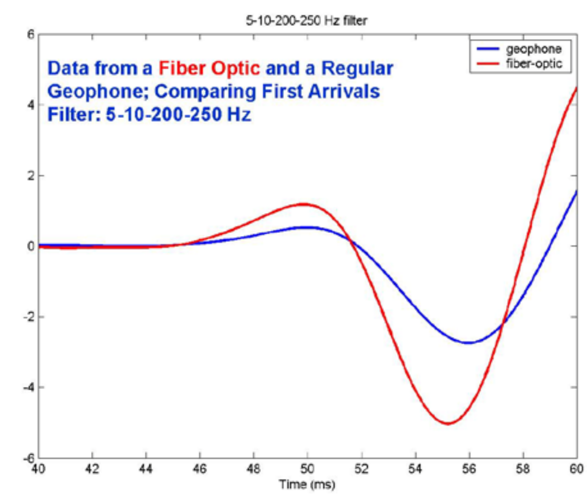

Figure 3. A 20 ms record of the first arrival data from the FOG and a commercial coil geophone from the same seismic source recorded simultaneously.

The small scale field survey used a 50 lb mass dropped from a height of 5 ft as the seismic source. In figure 3 the first arrivals are shown for both the FOG and the commercial coil geophone band pass filtered with a 5-10-200-250 Hz filter. The FOG first arrival has a faster rise time indicating a higher frequency response. This figure shows that the FOG and the regular coil geophone have the same phase response to the energy from the source making the FOG effectively a geophone measuring velocity.

In figure 4 we show 180 ms of the data filtered with 5-10-200-250 Hz band pass filter. The FOG waveform is in phase with the regular geophone but shows additional events. An example of the higher frequency is the doublet at 80 msec. The performance test included a repeatability study where data were concurrently recorded using both the Fiber Optic Geophone and the regular coil geophone. The repeatability study was done by dropping a 50 lb (22.5 kg) weight onto the ground five times from a height of 5 ft (1.5 m) and recording the data independently for each drop of the weight. The test shows that the repeatability of the FOG is excellent. The repeatability of the standard coil geophone was similarly excellent validating the test of the FOG.

We analyzed the spectral content of the data shown in Figure 4. The spectra of the FOG and the regular geophone are shown in Figure 5. The figure shows that the spectrum of the FOG is flatter between 20 and 100 Hz. At 100 Hz the FOG amplitude spectrum is only down by only 10 dB relative to its peak amplitude as compared with the amplitude spectrum from the regular geophone which is down by about 25 dB from its peak at 100 Hz.

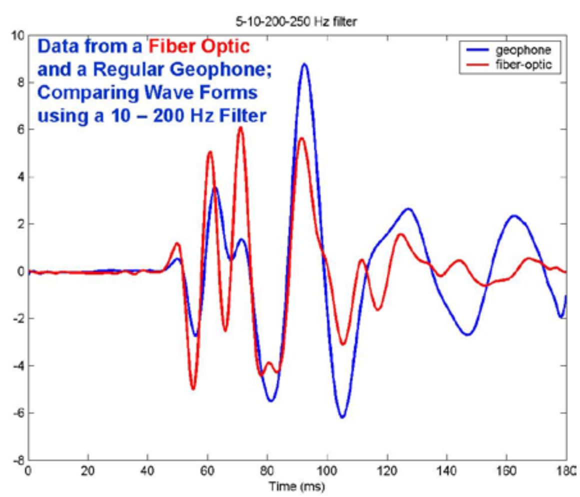

Figure 4. A 180 msec record of the same data as shown in Figure 3. The data from the two sensors is recorded with the same source effort. The FOG is in phase with the regular geophone but records a higher frequency record.

The second test of the FOG was performed by Lawrence Berkeley National Laboratory. This test was comparing the FOG with a Teledyne Geotech S-13 science grade geophone. The FOG and the Teledyne sensors were placed on a heavy granite slab during the test. The test was performed in a noisy lab environment.

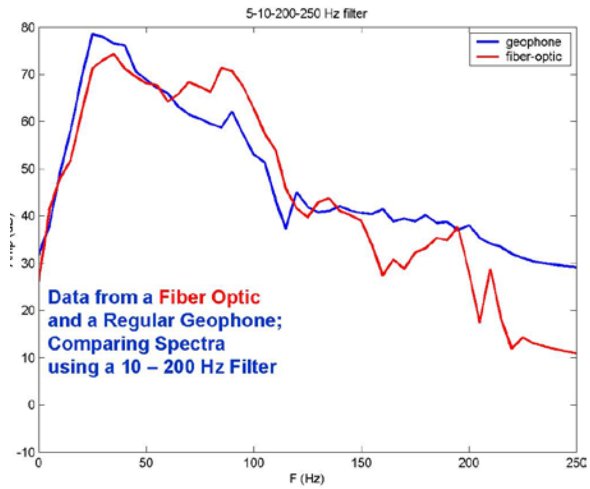

Figure 5. Spectra of the FOG and regular geophone data shown in Figure 4. Note the flatter spectrum for the FOG.

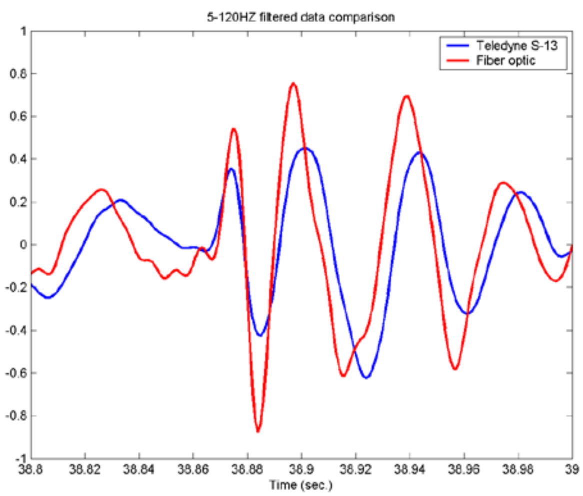

Figure 6. Tap test data recorded on a Fiber Optic Geophone (FOG) and a Geophone used for scientific studies.

The test consisted of continuous recording the FOG and the Teledyne S-13 data onto a 4-channel Tektronics TDM digital oscilloscope. During the continuous records the granite table was tapped several times to generate distinct events. One of the taps can be seen in the 200 ms long record shown in Figure 6. In this figure the blue curve is data from the Teledyne S-13 geophone and the red curve is from the FOG. The peak to peak amplitude of the FOG sensor is about 1.7 while the peak to peak amplitude of the

Fiber Optic Geophones for Oil and Gas Field Applications

Teledyne S-13 sensor is about 1.0. The noise amplitude is about the same on the two sensors. The signal to noise ratio is thus 1.7 times higher for the FOG.

Longer records of the same data from the FOG and the Teledyne S-13 sensor are shown in Figure 7. In this figure the background noise is at the same amplitude level for the two sensors but the signal amplitude of the tap at about 38.85 sec. is about 70% higher for the FOG than for the Teledyne S-13 sensor. There is a different time delay for the two instruments which was not corrected causing an apparent constant phase shift between the two sensors.

In Figure 8 the amplitude spectra are shown for the waveform data shown in Figure 7. The two spectra are normalized to their own maximum amplitudes. The shapes of the two spectra are similar. The Teledyne S-13 sensor has an advantage at low frequencies below 20 Hz. The Teledyne S-13 sensor is a 1 Hz scientific grade geophone equipped with a 5 kg inertial mass. The FOG has an advantage at frequencies over 35 Hz over the Teledyne S-13 geophone in this laboratory test. The FOG data amplitude is about 10 dB higher relative to its peak at frequencies over 50 Hz than the data from the Teledyne S-13 geophone.

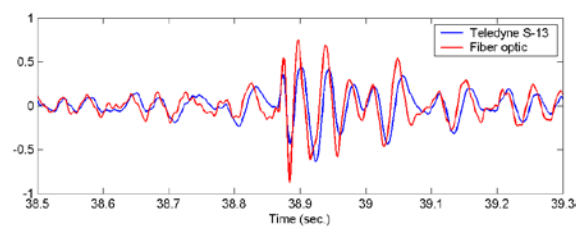

Figure 7. 800 ms wave form data from the Fiber Optic Geophone (FOG) and a Teledyne S-13 science grade geophone.

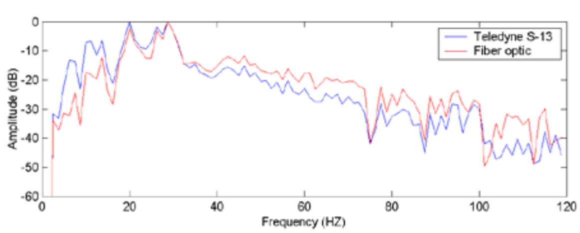

Figure 8. A spectrum of the 800 ms wave form data shown in Figure 7 from the FOG and a Teledyne S-13 science grade geophone.

Conclusions

The Fiber Optic Geophone (FOG) discussed in this paper is a new seismic sensor system and the data presented is the very first data recorded with this new sensor. In the first tests, the FOG has shown that its performance matches or exceeds the performance of both exploration type and scientific grade geophones.

In each of the two comparative tests the FOG was in phase with the coil geophone indicating that the FOG effectively is a velocity sensor.

The lower noise floor, the flatter spectral response and the higher sensitivity of the new FOG will allow for higher resolution imaging and monitoring of small and more subtle reservoir features and recovery processes – especially in carbonate reservoirs where higher frequencies can be recorded. The robust design will also allow the sensors to be deployed at higher temperatures than any existing geophones. The new FOG represents a potential breakthrough for the seismic industry and has the potential to challenge the dominance of the regular coil geophone.

Acknowledgement

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