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A HIGH PERFORMANCE FIBER OPTIC SEISMIC SENSOR SYSTEM

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ABSTRACT

We are introducing a new fiber optic sensor system implemented as a Fiber Optic Seismic Sensor (FOSS)™ for geophysical imaging and monitoring. We are presenting the design and experimental test results for the fiber optic sensor and comparing its performance with regular exploration geophones and high performance accelerometers. We demonstrate that the new Fiber Optic Seismic Sensor (FOSS)™ has a significantly better performance than the current state-of-the art coil geophones and accelerometers in terms of noise floor, sensitivity, frequency response and high temperature performance. We are also presenting the deployment system that makes it possible to deploy 1,000 (one thousand) downhole 3C seismic sensors in both vertical and horizontal boreholes.

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. About 10 years ago a new seismic sensor was introduced; the Micro Electro Mechanical Systems (MEMS) accelerometer with hopes that it would deliver a game-changing performance improvement. It was thought that the MEMS sensor would record higher fidelity and higher frequency data than the coil geophone. However, the MEMS sensors have proved only to provide similar data to the regular geophone, Hons et al. (2008), so the regular coil geophones are still the sensors of choice for seismic surveys with millions of units manufactured each year.

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 high temperature performance. The novel geophone technology we are presenting is based on technology originally developed for the US Navy. The US Navy has for many decades been one of the largest and one of the most sophisticated users of sensors in its operations worldwide. In particular the US submarine fleet has deployed hydrophone sensors that have been more sophisticated and more advanced than hydrophone sensors used for the geophysical industry for exploration applications.

After more than a decade of development work the US Navy equipped it newest members of its submarine fleet, The Virginia Class submarines, with arrays of 2,700 fiber optic hydrophones mounted on the hulls of the submarines. The primary reason was the requirement for 30+ years of operation without maintenance. The new fiber optic sensors have proved to be much more sensitive and much more reliable than the old piezo-electric and electronic/digital hydrophone system, thus validating the fiber optic sensor choice by the US Navy for its submarines.

The new fiber optic sensor developed for the US Navy is in principle a very simple sensor. It uses the dynamic strain of the fiber between two reference points known as Fiber Bragg Gratings (FBG's) 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 hydrophone
3. A fiber optic accelerometer

This paper will present and discuss the fiber optic accelerometer.

THE FIBER OPTIC SEISMIC SENSOR (FOSS)™ TECHNOLOGY

The FOSS 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 dynamic fiber strain information to the recording instruments. A Fiber Bragg Grating (FBG) 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.

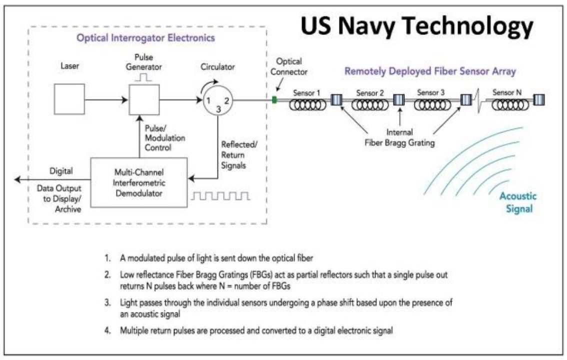

Figure 1. The Fiber Optic Seismic Sensor (FOSS)™ system is comprised of three basic integrated building blocks; the Fiber Optic Seismic Sensor (FOSS)™; the telemetry cable and the optical interrogator. The interrogator technology was first developed by US Navy Research Laboratory (USNRL).

A schematic of the Fiber Optic Seismic Sensor (FOSS)™ system is shown in Figure 1. This combination of fiber optic technologies allows a large number of seismic sensors to be deployed on one fiber while maintaining the high performance attributes of the sensors.

The Fiber Optic Seismic Sensor (FOSS)™ 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 fiber optic seismic sensor extremely robust and able to operate in extreme environments such as temperatures up to and over 300ºC. Even higher temperatures are possible using specialty fibers.

The Time Domain Multiplexing (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 FOSS the sensing fiber responds to seismic vibration by dynamically straining the fiber. The fiber optic sensor system can measure strains in the fiber with a resolution less than one Ångström ($1x10^{-10}$ m).

The optical sensor telemetry system is inherently low noise since it does not pick up electrical noise from any source. The system also uses low noise surface electronics to convert the optical data into electric digital data.

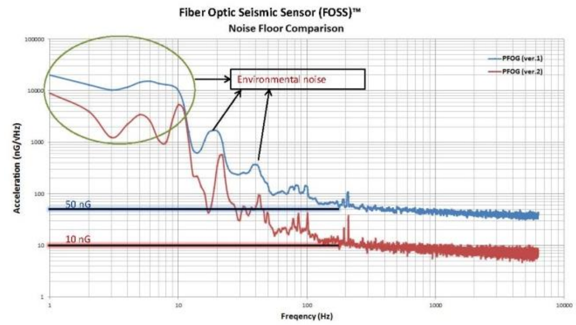

Figure 2. Noise floors for the Paulsson Fiber Optic Seismic Sensor System. The blue curve was the initial noise floor of the system when it was first assembled. After noise source and noise reduction analysis the current noise floor is shown in the red curve.

When the fiber optic seismic sensor system was first turned on, the noise floor at frequencies above 120 Hz was measured to be 50 ng/√Hz. At frequencies below 120 Hz the noise floor was affected by environmental noise. After several months of noise

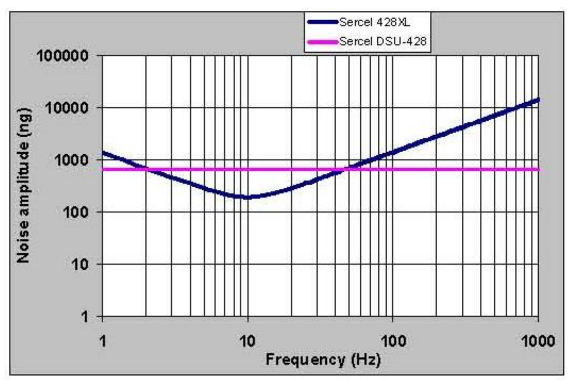

Figure 3. From Hons and Stewart, (2009). Figure 1. Modeled noise floor of a geophone and DSU recorded with the Sercel 428XL system, based published specifications of the DSU-428, the 428XL recording system and the SM24 geophone element.

source analysis and changes to the system the system noise was reduced by 80%. The measured noise floor in the fiber optic seismic sensor system now ranges from about 50 ng/√Hz at 20 HZ to about 10 ng/√Hz at frequencies over 120 Hz, as seen in Figure 2. Further improvements of the electronics will extend the 10 ng/√Hz noise floor to 10 Hz and even below 10 Hz. The current test facility is next to a busy airport with signification environmental low frequency noise, as seen in Figure 2. The noise floor from the fiber optic sensor should be compared with published noise floors from coil geophones and MEMS sensor, (Hons and Stewart, 2009), which is about 1,000 ng/√Hz (see Figure 3 from the Hons and Stewart, (2009) paper). The desired noise floor for high resolution seismic systems is listed as 100 ng/√Hz by Panahi et al. (2006).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, the 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.

For the fiber optic seismic sensor we are using a pulse width of the interrogating pulses of twice the light round trip transit time between FBG's. For a 20 m length of fiber between the FBG's, i.e. a typical length of sensor fiber in the FOSS between the FBG's, and a refractive index of the glass of 1.5, the pulse width is thus 0.2 μsec.

Pulses returned from each FBG contains phase information from preceding adjacent sensors proportional to the fiber strain between two FBG's on each side of the fiber wound around the mandrel as a result of the acceleration of the mandrel due to the passing 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, thus yielding a digital word representative of the instantaneous fiber 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. A large number of fiber-optic channels can be deployed on each fiber, making a large channel count system possible in hostile environments such as in boreholes and on ocean floors. Currently up to 32 fiber optic seismic sensors 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.), to a benign, controlled environment where they are accessible for repairs or upgrades. Thus, for permanently installed fiber optic seismic sensors, only the optical fiber, the mandrel and its associated packaging must be installed permanently. In the case of the new Fiber Optic Seismic Sensor this will significantly increase the robustness of the permanently installed sensors.

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 FOSS is manufactured using commercially available high temperature polyamide coated fiber.

EXPERIMENTAL RESULTS

We tested the Fiber Optic Seismic Sensor (FOSS)™ using a dynamic test system, developed by scientists and engineers at Paulsson, Inc., which has the shaker head installed in an environmental chamber capable of extreme high and low temperatures. Figure 4 illustrates the layout of the dynamic test system.

Figure 4. The dynamic test station for the Fiber Optic Seismic Sensors (FOSS). This test station can test the sensor at both low and high temperatures.

We tested the Fiber Optic Seismic Sensors (FOSS)™ at frequencies ranging from 0.01 Hz to 4,000 Hz, at temperatures ranging from 25°C to 320°C and at various accelerations. The first tests used our high frequency shaker system. We used sweeps from 5 Hz – 4,000 Hz at an acceleration of 600 μG to characterize the properties of the fiber optic seismic sensors. To compare and benchmark our Fiber Optic Seismic Sensor (FOSS)™ system we did simultaneous testing of the FOSS with a standard 15 Hz coil geophone and two high performance piezo electric accelerometer.

We installed the four sensors on the shaker head inside the oven and attached them to our data acquisition system which is capable of simultaneous recording of all four sensors as shown in Figure 5.

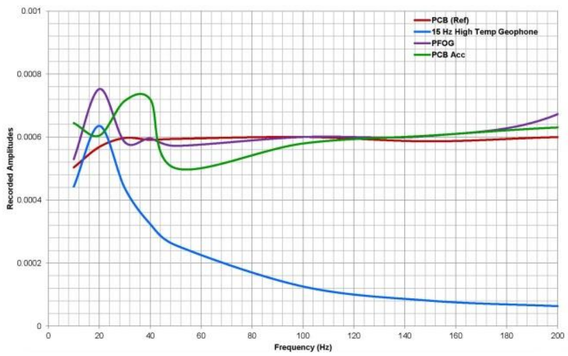

Figure 5. Results from a 10 – 200 Hz sensor test using a shaker at a fixed acceleration of 600 µG in an oven at 25°C with the test system shown in Figure 4. Four sensors were mounted on the shaker head. The four sensors included one reference accelerometer, one 15 Hz geophone, one Fiber Optic Seismic Sensor (FOSS)™ and a second piezo-electric accelerometer.

We first tested the sensors at 25°C in the frequency band 5 – 4,000 Hz, followed by a 200°C test using the same frequency band. The 10 – 200 Hz 600 µG test at 25°C is shown in Figure 5. The red curve is the piezo-electric feedback accelerometer data from 10 – 200 Hz. This accelerometer kept the shaker at 600 µG over the test frequency band of 5 – 4,000 Hz, using a feedback loop system. The blue curve is the amplitude output from the regular 15 Hz geophone from 10 – 200 Hz. The green curve is from the second piezo-electric accelerometer. The purple curve is the amplitude output as function of frequency for the Fiber Optic Seismic Sensor (FOSS)™ test from 10 to 200 Hz. The test results from the 200°C tests are virtually identical to those at 25°C, showing that our fiber optic seismic sensor is stable with temperature.

Both the 25°C and the 200°C tests showed that the standard coil geophone lost most of its amplitude output at 100 Hz, while the accelerometers, both the fiber optic and the piezo- electric retained the amplitude over the entire test frequency band of 5 – 4,000 Hz.

The performance tests with the shaker were followed by tap tests of the sensors. We placed the three sensors in close proximity to each other on the top of the granite block seen in Figure 4. To isolate the test system from environmental noise the granite block was placed on active vibration isolation pads. The first tap test was performed at an ambient temperature of about 25°C. The tests involved comparing the performance of the FOSS with a standard exploration 15 Hz coil geophone and a high performance accelerometer.

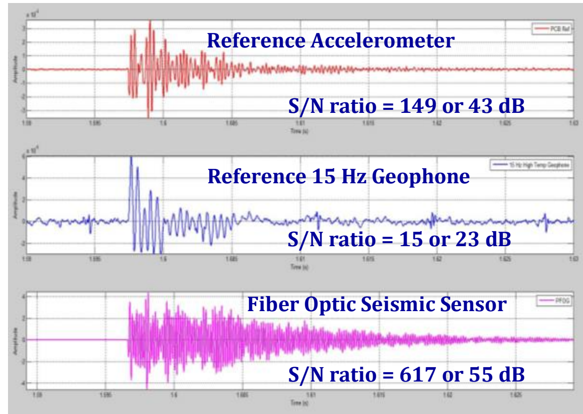

Figure 6. Seismic traces from simultaneous tap test of a reference accelerometer (top), a 15 Hz coil geophone (middle) and the Paulsson Fiber Optic Seismic Sensor (FOSS)™ (bottom). Band pass filter applied: 5 – 2,500 Hz

The data from the simultaneous tap test of the three sensors is shown in Figure 6. The first arrival for the fiber optic seismic sensor has a faster rise time, indicating a higher frequency response. It is also clear from this data that the Fiber Optic Seismic Sensor has the highest signal/noise ratio. We calculated the signal-to-noise ratio by dividing the amplitude of the second peak with the mean amplitude of the pre-arrival data over a 5 ms window. The signal/noise ratio for the fiber optic seismic sensor is 617 (55 dB), the signal/noise ratio for the reference accelerometer is 149 (43 dB). The signal-to-noise ratio for the 15 Hz geophone is 15 (23 dB) for this particular test. The fiber optic seismic sensor thus has a 41 times larger signal-to-noise ratio than the regular coil geophone and a four times larger ratio than the piezo-electric accelerometer.

We also tested our Fiber Optic Seismic Sensor (FOSS)™ in our low frequency shaker system that is capable of shaking our sensor from 0.01 Hz to 10 Hz.

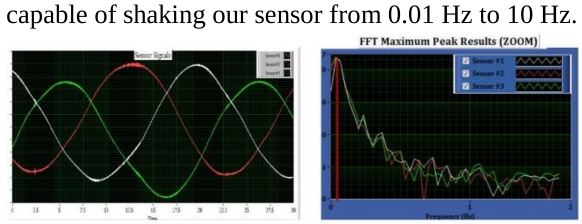

Figure 7. Simultaneous Low frequency test of three Fiber Optic Seismic Sensors at a frequency of 0.03Hz (33 second period). This system can test the sensors from 0.01 Hz – 10 Hz.

The result from one of the low frequency tests is seen in Figure 7. In this test we were shaking the 3C sensors at a frequency of 0.03 Hz (33 second period). This particular test was performed at 25°C. High-temperature, low-frequency tests are planned for the future.

We made a number of low frequency tests of the fiber optic seismic sensor. In one of the test series we tested the fiber optic sensor from 0.03 Hz to 0.9 Hz as seen in Figure 8. The amplitude variation from this range of frequencies is shown in Figure 8. The graph in Figure 8 shows that the amplitude response from this set of tests is almost flat.

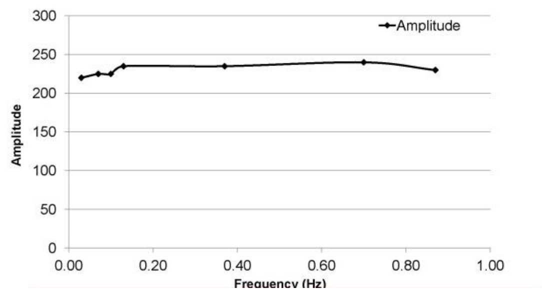

Figure 8. Amplitude variation of low frequency test of Fiber Optic Seismic Sensor (FOSS)™ at frequencies 0.03 – 0.9 Hz (33 – 1.1 second period).

In order compare and benchmark the data from the Fiber Optic Seismic Sensor (FOSS)™ we mounted 3C FOSS sensors inside the sensor pod that will be used for the borehole seismic systems. We then attached high temperature piezo-electric accelerometers to the pod to generate comparative data. One external piezo-electric accelerometer was mounted parallel with the FOSS axial accelerometer near the left end of the sensor pod. The cable going to this accelerometer is seen at the left end of the fiber optic seismic sensor pod in Figure 9. The second accelerometer was mounted on the outside of the pod at the position of the radial optical seismic sensor, as illustrated in Figure 9.

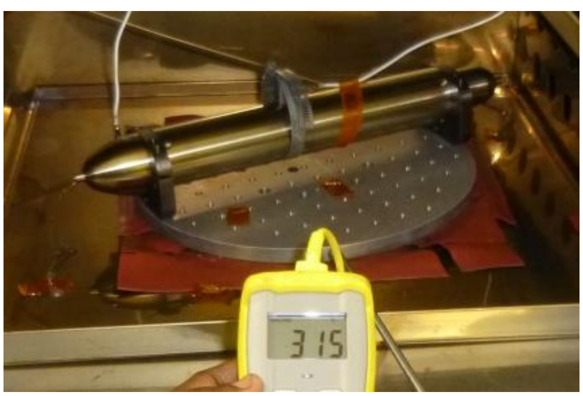

Figure 9. This photo shows the 3C sensor pod inside a high-temperature oven.

A series of tap tests were performed by tapping the outside of the fiber optic seismic sensor pod at an extended range of temperatures to evaluate the performance of the fiber optic sensor while mounted inside the sensor pod, thus dynamically testing the sensor and the pod as a system.

Figure 9 shows the geophone pod with the 3C sensors during the high-temperature test in the oven. The digital thermometer shows a temperature of 315°C on the base plate. A temperature reading on the pod itself showed a temperature of 320°C at the last tap test.

We started the tap test sequence at a room temperature of 25°C followed by increasing temperatures, as shown in Figure 10. For each new temperature, care was taken to make the seismic tap test measurement after the oven, the sensor pod and the fixtures reached their respective temperature equilibrium. Each temperature step took approximately two hours. For the final test at 320°C we performed the test after the sensor pod with the three sensors had been in the oven for 54 hours.

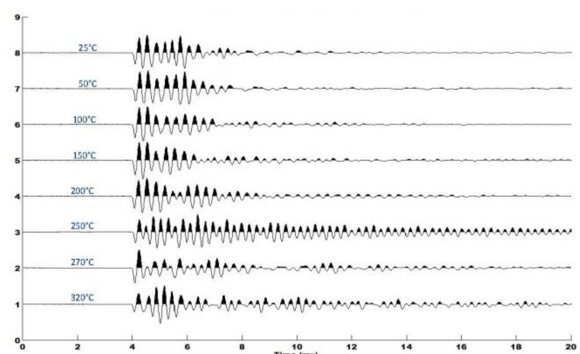

Figure 10. Tap test 20 ms data recorded on a Radial Fiber Optic Seismic Sensor (FOSS)™ installed in a 3C sensor pod at temperatures ranging from 25°C to 320°C.

In Figure 10 are indicated 20 ms records from eight different tap tests at eight different temperatures ranging from 25°C to 320°C. The data is very consistent considering manual taps were used by two different engineers. The first engineer did the tap tests from 25°C to 200°C and the second engineer the tap tests from 250°C to 320°C. No filtering was applied so the data contain energy from below 10 Hz to 4,000 Hz.

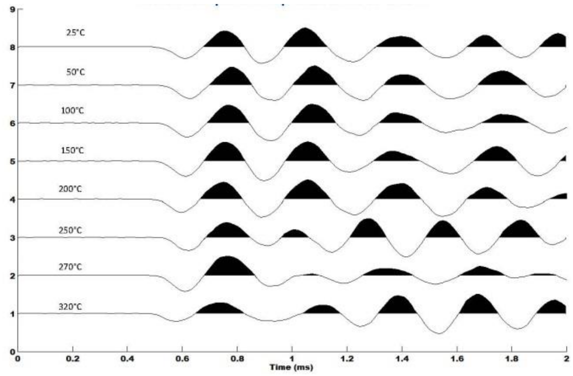

Figure 11. Tap test 2 ms data recorded on a Radial Fiber Optic Seismic Sensor (FOSS)™ installed in a 3C sensor pod at temperatures ranging from 25°C to 320°C. The 3C sensor pod can be seen in figure 9.

In Figure 11 we show a 2 ms window including the first arrival of the data shown in Figure 10. Once again, the data is very consistent, especially considering that the tap test data is generated by manual taps by two different engineers.

DEPLOYMENT SYSTEM

To deploy our fiber optic seismic sensors Paulsson, Inc. designed and manufactured a deployment system that is based on small diameter high strength drill pipe. The seismic deployment system is manufactured using the same type of steel as used for offshore drilling to assure that the system can be deployed to a drilled depth of 30,000 ft in both vertical and horizontal boreholes.

Figure 12a. The Sensor Pod installed into a Sensor Pod Housing.

Figure 12b. The 3C Fiber Optic Seismic Sensor (FOSS)™ packaged into a 16" long and 2" in diameter pod which is a pressure vessel capable of operating at an external pressure of 30,000 psi and an ambient temperature of 320°C (608°F).

The sensor pod and the 6 ft long sensor pod housing are shown in Figure 12a. The sensor pod holds the three component fiber optic sensors. The 3C Fiber Optic Seismic Sensor (FOSS)™ discussed in this paper has been packaged into a pod that is capable of withstanding an external pressure of 30,000 psi, allowing for deployment in the deepest wells in the Gulf of Mexico. This sensor pod is shown in Figures 9 and 12. The sensor pod housing serves several functions. It serves to protect the sensor pod and the tubing containing the fibers during the deployment stage. It also contains the clamping mechanism to clamp the sensor pod to the borehole wall. The sensor pod housing also dampens the tube waves traveling in the borehole, thus increasing the signal-to-noise ratio of the recorded borehole seismic data. The sensor pod housing is also designed to deploy a ¼" tube for a Distributed Temperature Sensor system (DTS) simultaneously with the FOSS system.

During deployment in a well, the pipe is filled with the well fluid through a filter and through a check valve. When the deployment is complete the drill pipe is thus filled with fluid of the same density as is present outside the pipe, so the pressure gradient is the same inside and outside the deployment system drill pipe. The fluid inside the tubing is used to actuate the all-metal clamping mechanism used to clamp the sensor pods to the borehole wall. The pod clamping is achieved by applying an additional differential pressure on the fluid inside the tubing to yield a clamp force to weight ratio exceeding 10 for the sensor pod, thus providing for outstanding coupling and vector fidelity.

FIELD TEST

Figure 13. Showing the Fiber Optic Seismic Sensor array during deployment.

We completed the manufacturing of a prototype five level 3C borehole seismic array incorporating our high temperature Fiber Optic Seismic Sensors (FOSS®) into our high pressure sensor pods and our deployment system. We mounted the borehole seismic array onto a large spool and tested the completed five level array at our assembly facility prior to moving the array and the associated deployment equipment to the field. We mobilized the borehole seismic system to a test well located in Long Beach, CA in November 2012 and conducted a test of the five level array to a depth of about 1,600 ft. Figure 13 shows the array being deployed into a well.

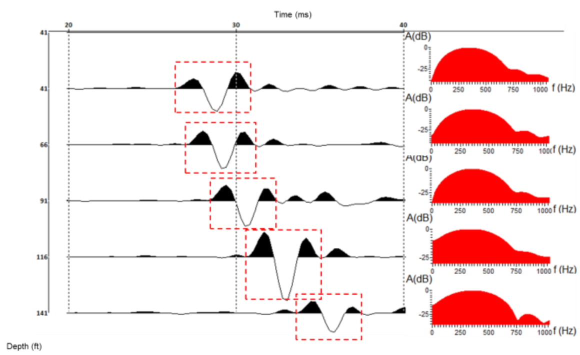

Figure 14. Wave form data and spectra from offset VSP source points

Fiber 14 show the principal component, i.e. rotated to point to the source, of the three component data. The test results showed that we can record high signal to noise ratio high fidelity seismic data at frequencies exceeding 1,000 Hz. The high quality high signal-to-noise ratio data showed that the Paulsson designed and manufactured borehole seismic array works as designed and will be an important geothermal reservoir imaging and monitoring system.

CONCLUSIONS

The Fiber Optic Seismic Sensor (FOSS)™ system discussed in this paper was developed by Paulsson, Inc. in collaboration with Optiphase, Inc. In the first tests the fiber optic seismic sensors have shown superior performance relative to state of the art sensors such as exploration type coil geophones and high performance accelerometers in terms of band width, sensitivity and high temperature performance. The lower noise floor, the flatter spectral response and the higher sensitivity of the new fiber optic seismic sensor will allow for higher resolution imaging and monitoring of small and more subtle reservoir features and recovery processes in all types of reservoirs. The robust design with all electronics placed at the surface will allow the sensors to be deployed at very high temperatures, thus making the sensor a viable sensor for deep high temperature oil and gas wells and for geothermal exploration and production. The new Fiber Optic Seismic Sensor (FOSS)™ represents a breakthrough for the seismic industry and has the potential to challenge the dominance of the regular coil geophone.

SUMMARY

1. The Fiber Optic Seismic Sensor design presented in this paper has proven to be successful in laboratory tests and has the following attributes:

   a. Flat frequency response over a large frequency range
   b. Outstanding low frequency performance
   c. Very high sensitivity
   d. High signal to noise ratio
   e. Outstanding high temperature performance

2. The fiber optic borehole seismic system has proved to be successful in a borehole field tests which validates the design and function of the new borehole seismic technology on a system level. Outstanding signal to noise ratio data was recorded with very large bandwidth.

ACKNOWLEDGMENTS

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