Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

A Fiber-Optic Borehole Seismic Vector and Acoustic Sensor System for Geothermal Site Characterization and Monitoring

Björn N.P. Paulsson, Jon A. Thornburg and Ruiqing He

Paulsson, Inc., 16543 Arminta Street, Van Nuys, CA 91406-1745

E-mail: bjorn.paulsson@paulsson.com

Keywords: High-temperature, Fiber-optic, Long-array, Large-aperture, Borehole-seismic, Vector-sensors, Acoustic-sensors.

ABSTRACT

Seismic techniques are the dominant geophysical techniques for the characterization of subsurface structures and stratigraphy. The seismic techniques also dominate the monitoring and mapping of reservoir injection and production processes. Borehole seismology, of all the seismic techniques, despite its current shortcomings, has been shown to provide the highest resolution characterization and most precise monitoring results because it generates higher signal to noise ratio and higher frequency data than surface seismic techniques.

The operational environments for borehole seismic instruments are however much more demanding than for surface seismic instruments making both the instruments and the installation much more expensive. The current state-of-the-art borehole seismic instruments have not been robust enough for long term monitoring compounding the problems with expensive instruments and installations. Furthermore, they have also not been able to record the large bandwidth data available in boreholes or having the sensitivity allowing them to record small high frequency micro seismic events with high vector fidelity.

To reliably achieve high resolution characterization and long term monitoring of Enhanced Geothermal Systems (EGS) sites a new generation of borehole seismic instruments must therefore be developed and deployed.

To address the critical site characterization and monitoring needs for EGS programs, US Department of Energy (DOE) funded Paulsson, Inc. in 2010 to develop a fiber optic based ultra-large bandwidth clamped borehole seismic vector array capable of deploying up to one thousand 3C sensor pods suitable for deployment into ultra-high temperature and high pressure boreholes.

Tests of the fiber optic seismic vector sensors developed on the DOE funding have shown that the new borehole seismic sensor technology is capable of generating outstanding high vector fidelity data with extremely large bandwidth: 0.01 – 6,000 Hz. Field tests have shown that the system can record events at magnitudes much smaller than M-2.6 at frequencies up to 2,000 Hz. The sensors have also proved to be about 100 times more sensitive than the regular coil geophones that are used in borehole seismic systems today. The fiber optic seismic sensors have furthermore been qualified to operate at temperatures over 300°C (572°F). Simultaneously with the fiber optic based seismic 3C vector sensors we are using the lead-in fiber to acquire Distributed Acoustic Sensor (DAS) data from the surface to the bottom of the vector array. While the DAS data is of much lower quality than the vector sensor data it provides a 1 m spatial sampling of the downgoing wavefield which will be used to build the high resolution velocity model which is an essential component in high resolution imaging and monitoring.

1. INTRODUCTION

Effective development of geothermal energy resources is critically dependent on a precise understanding of the complexity of the geologic formations. Successful production of these resources also depends on an accurate monitoring program to understand the dynamic processes of the injection of fluids and of producing the geothermal resources. The complex production processes of geothermal fields will only be understood and managed in detail if robust high-resolution reservoir imaging and monitoring technologies are available to characterize the reservoirs in the early phases of the field development.

High-resolution imaging, including mapping of complex high angle faults and fractures, can only be achieved if large volumes of high quality high frequency borehole seismic data can be recorded and sampled properly both spatially and temporally. 3D VSP P-wave images have shown routinely to have more than twice the spatial resolution than surface seismic images in areas with excellent surface seismic data. In areas with poor to very poor surface seismic data the 3D VSP technique has been proven to still be able to record the high quality P-wave data needed for high resolution P-wave imaging.

High quality Converted Shear wave data are also routinely recorded during borehole seismic acquisition. Images generated using Converted Shear waves, due to their much shorter wavelengths, potentially offer a significant resolution improvement over P-wave images. Shear waves and shear wave images are also providing additional pore-pressure, directional stress, lithologic, stratigraphic, fault and fracture information about the geologic formations surveyed.

If large borehole seismic arrays are deployed and a large number of source points are recorded we will be able to generate 3D borehole seismic images. These 3D borehole seismic P and S wave images will provide high resolution depth images far away from the borehole complementing the currently used reservoir characterization techniques. As a rule, the diameter of the 3D VSP depth images using primary reflections is equal to the image depth – example: at a depth of 5,000 meters the image diameter is 5,000 meters. If secondary reflections, i.e. multiples, are used in the imaging process then the image coverage grows significantly.

The 3D VSP technique can thus produce much higher resolution images than surface seismic techniques and image much larger reservoir volumes than well logging techniques. The 3D VSP technique is thus filling the coverage and resolution gaps between the low resolution but large areal coverage of surface seismic techniques and the high resolution but limited coverage of well logging techniques.

However, in order to effectively monitor injection and production processes, a long high vector fidelity borehole seismic array is needed. A long array is essentially a large aperture seismic antenna which is needed to effectively and precisely map the spatial distribution of natural and induced seismic events. A high vector fidelity array is needed to determine the type of natural or induced seismic events that are being recorded. A correct determination of the vector of the recorded seismic event, from either active or passive seismic sources, is critical to provide input for both 3D imaging and 3D mapping of induced seismic events.

2. THE FIBER OPTIC BOREHOLE SEISMIC TECHNOLOGY

A large aperture 200 3C levels 1,524 m long array with an interpod spacing of 7.62 m (25 ft.) capable of operating at high-temperatures will for the first time allow us to record the large volumes of high quality properly sampled high frequency data needed for high resolution borehole seismic imaging and monitoring of geothermal reservoirs. Following the acquisition of the borehole seismic active source data we will be able to generate high resolution images using advanced imaging techniques such as Reverse Time Migration, Multiples Migration and Interferometric Migration. These images will demonstrate that the ultra-large borehole seismic array is a highly cost effective geothermal reservoir imaging tool.

The borehole seismic images that will be generated using the data recorded with a 200 level 3C array will lower the risk of mislocating new production or injection wells and re-drilling of existing wells into the geothermal reservoirs and will together lead to a greatly improved recovery of the geothermal resources. The improved understanding and delineation of reservoirs will lower the economic risk, allowing for the operation of smaller, more complex and normally marginal geothermal fields. It will also allow for the identification and production of previously unknown geothermal resources in blocks isolated by faulting or stratigraphy.

The fiber optic borehole seismic array that has been developed is capable of monitoring and mapping the injection of fluids into the reservoirs using 3D mapping of micro seismic events. The critical differences between the fiber optic array described in this paper and downhole receiver arrays used in the past include first the aperture; second the spatial sampling and third the sensitivity afforded by the ultra-large 3C all optical array. One will routinely record broad band-width micro seismic data with frequencies up to and over 1,000 Hz, during monitoring of micro seismic events from natural causes or induced fracturing. This is outside the operational frequency range of currently used borehole seismic geophones.

To allow the acquisition of the large volumes of high quality data required for high resolution imaging and monitoring we designed an ultra large borehole seismic array system that can deploy as many as 1,000 3C clamped sensors in deep vertical and horizontal wells. To make this large array possible we designed high temperature fiber optic seismic sensor technology which allows the deployment of 3,000 vector sensors using only limited number of fibers. To deploy all these fiber optic sensors we designed a high strength ultra-robust small diameter drill pipe based deployment system with a built-in active all-metal hydraulic clamping system.

During the design and development phase of the sensor technology, we manufactured a number of fiber optic seismic sensors using several form factors and tested the sensors in our laboratory at different accelerations, different frequencies and at elevated temperatures. After a large number of tests we were able to arrive at a sensor design which provides an outstanding combination of sensor qualities such as sensitivity, vector fidelity, robustness and small size. We have shown that the fiber optic seismic sensors that will be used in the 200 level 3C array are more sensitive, have a lower noise floor, have a broader band width and are more robust than electronic equivalents such as standard geophones and MEMS sensors. These attributes make them excellent choices for the demanding borehole environment. The range of data recorded in a borehole includes low frequency large amplitude data from surface seismic sources and very low amplitude high frequency data from natural and induced micro seismic events.

The drill pipe deployment design allows the receiver array to be deployed in both vertical and horizontal wells which is an operational requirement in geothermal wells since many of the wells drilled for geothermal exploration are highly deviated. The all metal clamping system for the 3C sensor pods uses drill pipe hydraulics as a power source. The fiber optic sensors are operated using light only and manufactured using high temperature fibers. This combination has allowed us to design and manufacturing a receiver array that can operate to temperatures up to 300ºC (572ºF) and at pressures up to 30,000 psi. Because no electronics or electric power will be used in either the hydraulic clamping system or for the fiber optic sensors the borehole seismic fiber optic sensor system is intrinsically safe.

To demonstrate the entire borehole seismic system we built a six level clamped array and tested the array in two wells, one in California and one in Texas, by recording data from both surface and borehole seismic sources. Finally we processed the data from the first two borehole seismic field tests of the new fiber optics seismic sensor system.

The technology that will be used to manufacture the 200 level downhole seismic array has been documented in a Project Final Report submitted by Paulsson, Inc. to RPSEA in December 2013.

The components of the 200 level 3C Fiber Optic Seismic Array include:

1. The Fiber Optic Seismic Sensors
2. The Sensor Pods
3. The Interrogators
4. The Fiber and Fiber tube
5. The Fiber Spool and Operations Dog House
6. The Deployment System
   a. Bottom Assembly
   b. Sensor Pod Housings
   c. Drill Pipe
   d. Top Assembly
   e. Centralizers

2.1 The Fiber Optic Seismic Sensor

The key to the performance of the fiber optic seismic array is the fiber optic seismic vector sensor. The fiber optic seismic sensor system dynamically measures the strain of the fiber between two Fiber Bragg Gratings (FBG), as shown in Figure 1, using an interferometric measurement technique comparing the phase angle between two reflections. It uses a Time Domain Multiplexing (TDM) transmission technique to transmit the dynamic fiber strain information to the interrogation instruments on the surface.

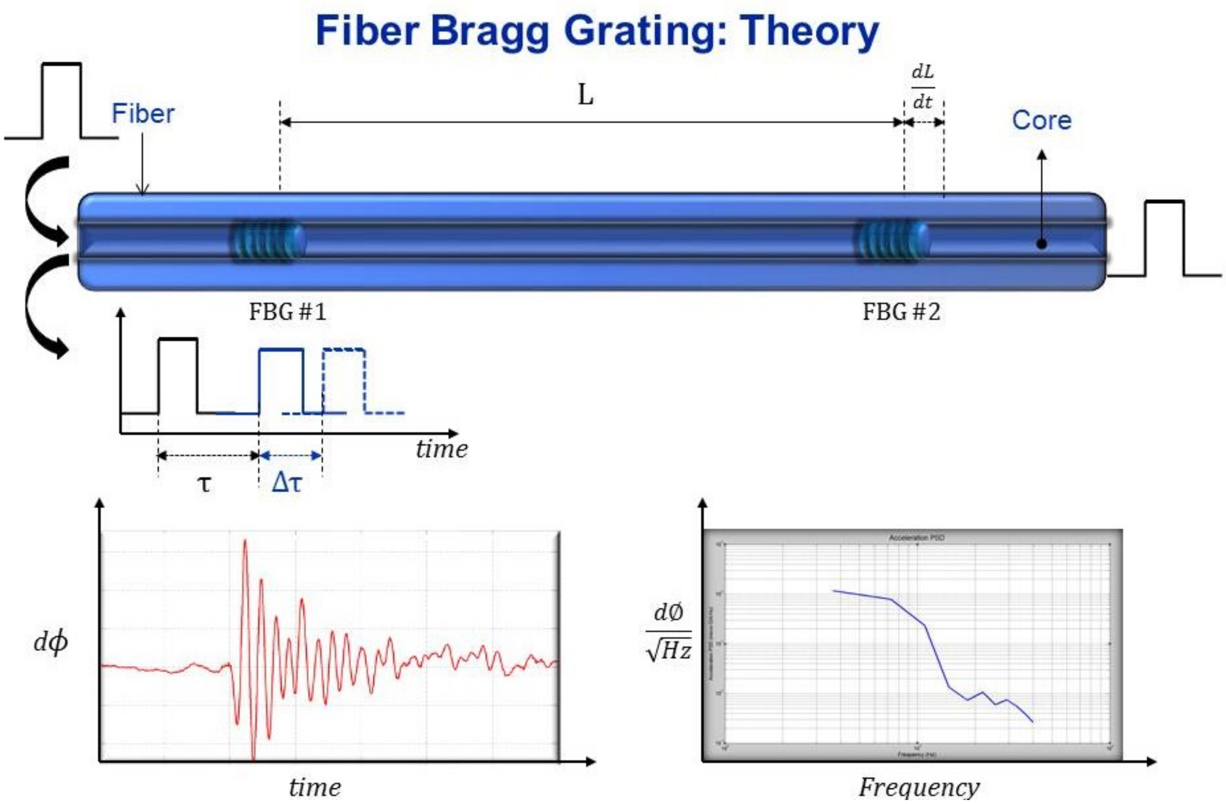

Figure 1. The fiber between a pair of Fiber Bragg Gratings (FBG's) respond to changing pressure, temperature and to seismic waves using interferometric measurements between two FBG's. While the pressures and temperatures are static and only slowly varying the seismic data is dynamic, which allow high quality seismic data to be recorded even as the temperature is changing.

A Fiber Bragg Grating (FBG) is a reflector in the fiber core generated by etching the core with an ultraviolet laser. The FBGs typically have a low reflectivity and is 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 fiber optic seismic sensor system is shown in Figure 1. This use 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 Time Domain Multiplexing (TDM) method interrogates the sensors by sending one light pulse at a time and recording the reflections from the two FBG's that make up each sensor in an array as seen in Figure 1. One can measure strain using a single FBG. A single FBG sensor is however not sensitive enough for high quality seismic measurements. A much better approach for demanding seismic applications is to use pairs of FBG's and use the coiled fiber between the FBG's as the sensor. 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 coiled sensing fiber. In the case of a fiber optic seismic sensor the sensing fiber responds to seismic vibration by dynamically straining the fiber as shown in Figure 2. The fiber optic seismic sensor is immune to electric and electromagnetic

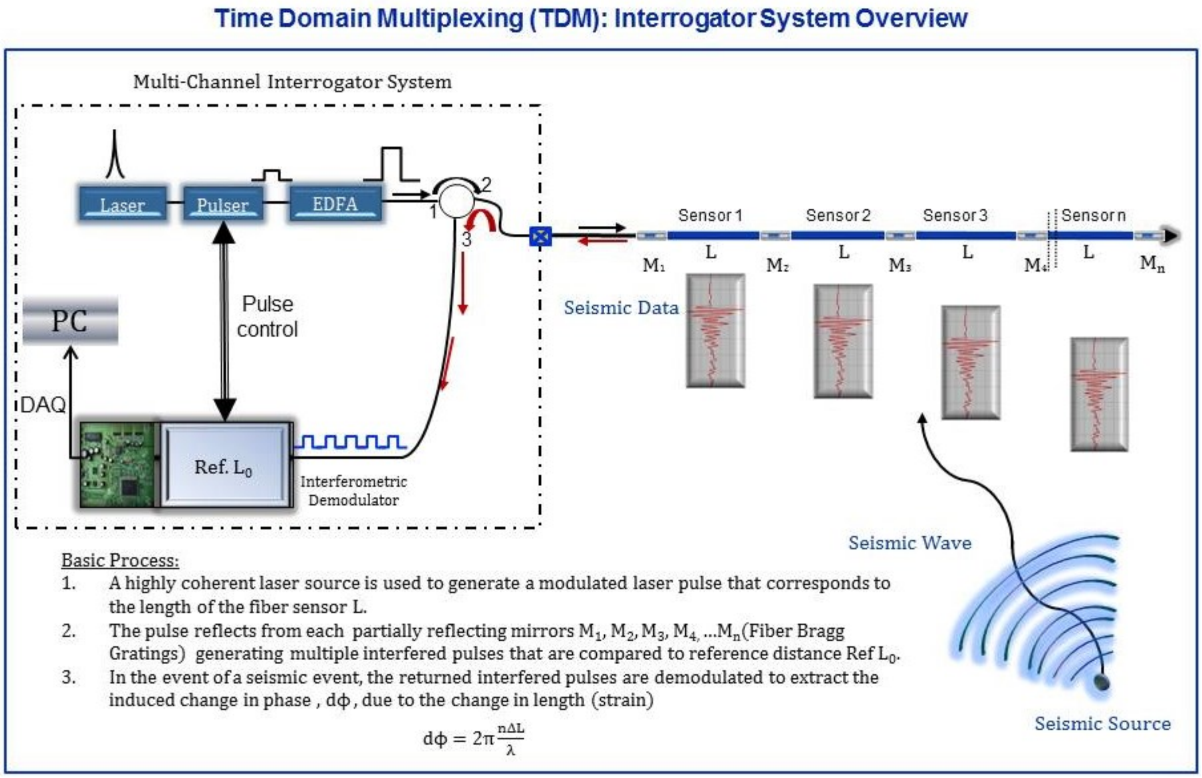

Figure 2. The Optical Interrogator system. The fiber optic seismic sensor system is comprised of three basic integrated building blocks; the fiber optic seismic sensor, the telemetry cable and the Optical Interrogator. The interrogator technology was first developed by US Navy Research Laboratory (USNRL).

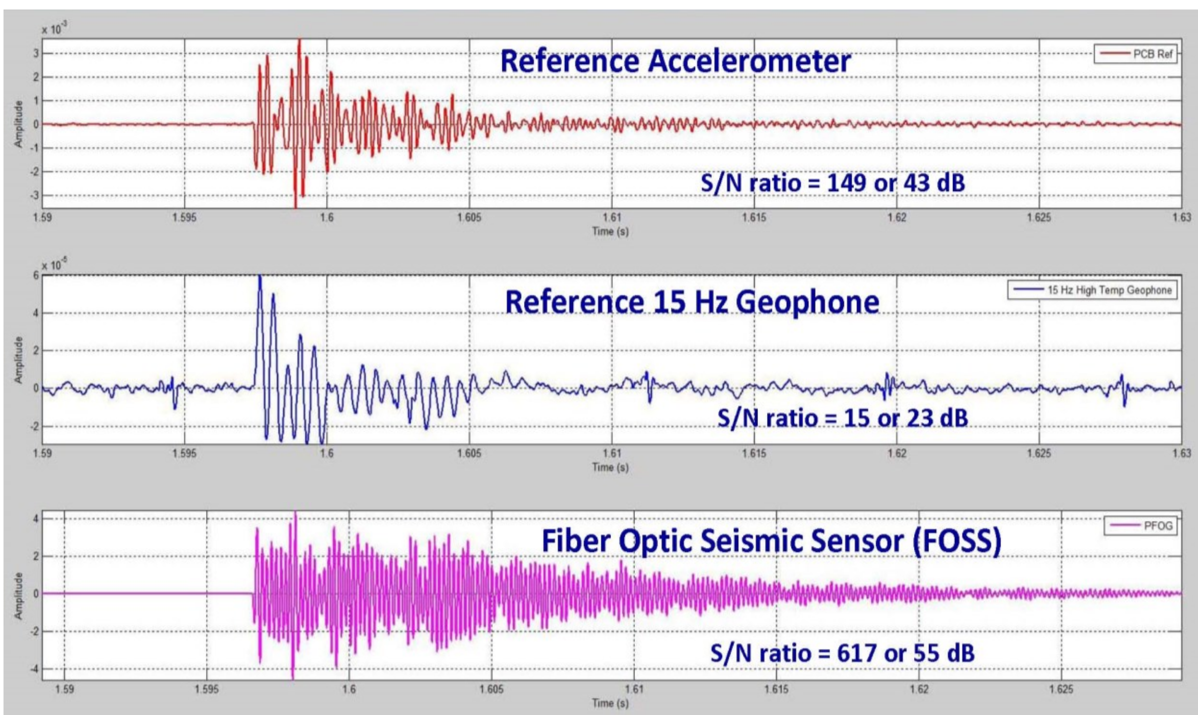

Figure 3. Test results from a tap test performed in the laboratory. Three seismic traces recorded simultaneously from a single tap test. The three sensors are a reference accelerometer (top), a 15 Hz coil geophone (middle) and the Paulsson Fiber Optic Seismic Sensor (FOSS)™ (bottom). Band pass filter applied: 5 – 2,500 Hz

interference in the borehole, 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 (572ºF). Even higher temperatures are possible using specialty metal coated fibers.

2.2 Laboratory Test of Fiber Optics Seismic Sensor

We undertook an extensive set of tests of fiber optics seismic sensors during the multi-year development process to determine and optimize the sensitivity, vector fidelity, mechanical robustness and ability to operate at high temperatures.

In order to compare and bench-mark the new fiber optic seismic sensors with current state-of-the-art seismic sensors we designed several tests comparing an optical seismic sensor with a standard high temperature geophone and a state-of-the-art piezo-electric accelerometer. After placing the three sensors on a 2 ton granite block we performed a number of simultaneous performance tests of the three sensors. The granite block was isolated from the ground using active noise cancellation equipment to minimize ground noise.

The data from a simultaneous tap test of the three different sensors are shown in Figure 3. This figure shows that the first arrival generated by the fiber optic seismic sensor, third trace from the top in Figure 3, has a faster rise time, indicating a higher frequency response, than the other sensors. It is also clear from these 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 positive peak with the mean amplitude of the pre-arrival data over a 5 millisecond window. The signal/noise ratio for the fiber optic seismic sensor is 617 (55 dB), while the signal/noise ratio for the reference accelerometer is 149 (43 dB). The signal-to-noise ratio for the 15 Hz high temperature borehole geophone is 15 (23 dB) for this particular test. For this 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 signal-to-noise ratio than the state-of-the-art piezo-electric accelerometer. Since this test we have doubled the scale factor for the fiber optic seismic sensor.

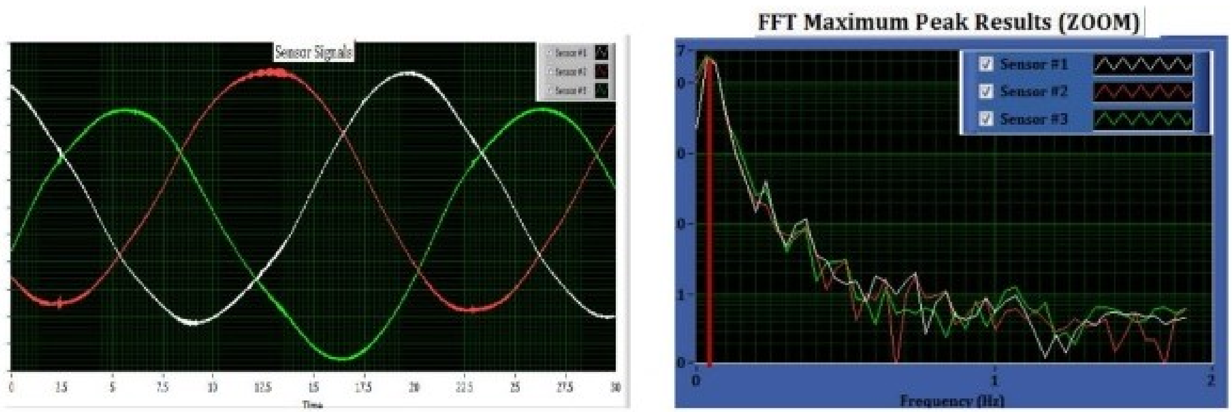

Figure 4. Simultaneous Low frequency test of three Fiber Optic Seismic Sensors at a frequency of 0.03Hz (33 second period). This system can test the sensors from 0.01 Hz – 10 Hz (Period of 100 sec. to 0.1 sec).

We also evaluated the fiber optic seismic sensor in our low frequency test facility that is capable of testing sensors from 0.01 Hz to 10 Hz (Period ranging from 100 seconds to 0.1 seconds). The result from one of the low frequency tests is seen in Figure 4. In this test we were evaluating the performance of the 3C sensors at a frequency of 0.03 Hz (33 second period). 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. The amplitude variation from this range of frequencies is almost flat. This particular test was performed at 25°C. High-temperature, low-frequency tests are planned for the future.

2.3 The Sensor Pods

To protect the sensors from the well environment the fiber optic seismic sensors are placed inside sensor pods capable of withstanding very high pressures. The sensor pods are manufactured using an Inconel alloy. As part of the design and development process we performed extensive modeling of the sensor pod design prior to committing the design to prototype manufacturing. The Finite Difference modeling performed indicates that the sensor pod will be able to withstand an external pressure over 30,000 psi at 200°C.

In order to compare and benchmark the data recorded with the fiber optic seismic sensors as used in the field we mounted 3C fiber optic seismic sensors inside a sensor pod that is 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 fiber optic seismic axial sensor 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 5. The second accelerometer was mounted on the outside of the pod at the position of the radial optical seismic sensor, as illustrated in Figure 5.

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. This set up allowed us to do dynamic testing of the fiber optics sensors and the pod as a system. Figure 5 shows the sensor pod with the 3C sensors during the high-temperature test in

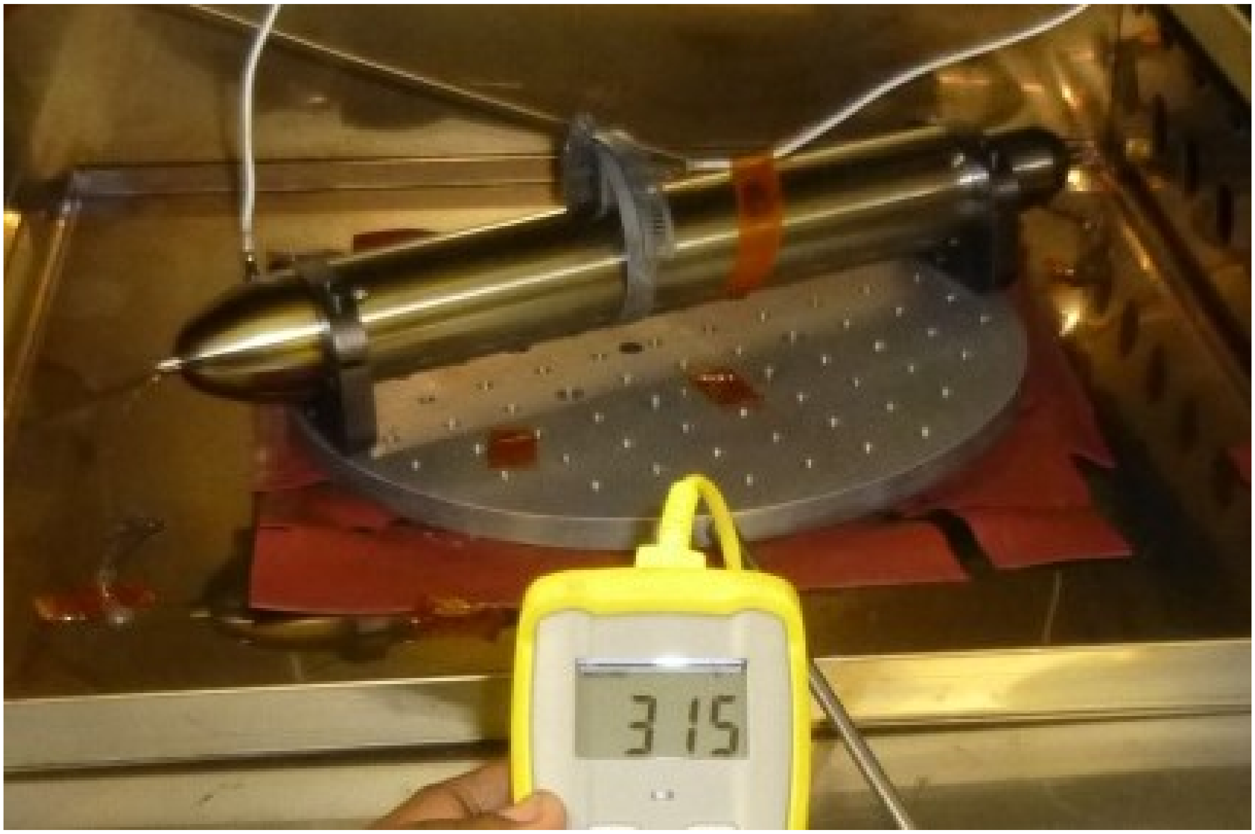

Figure 5. This photo shows the 3C sensor pod inside a high-temperature oven at a measured temperature of 315°C.

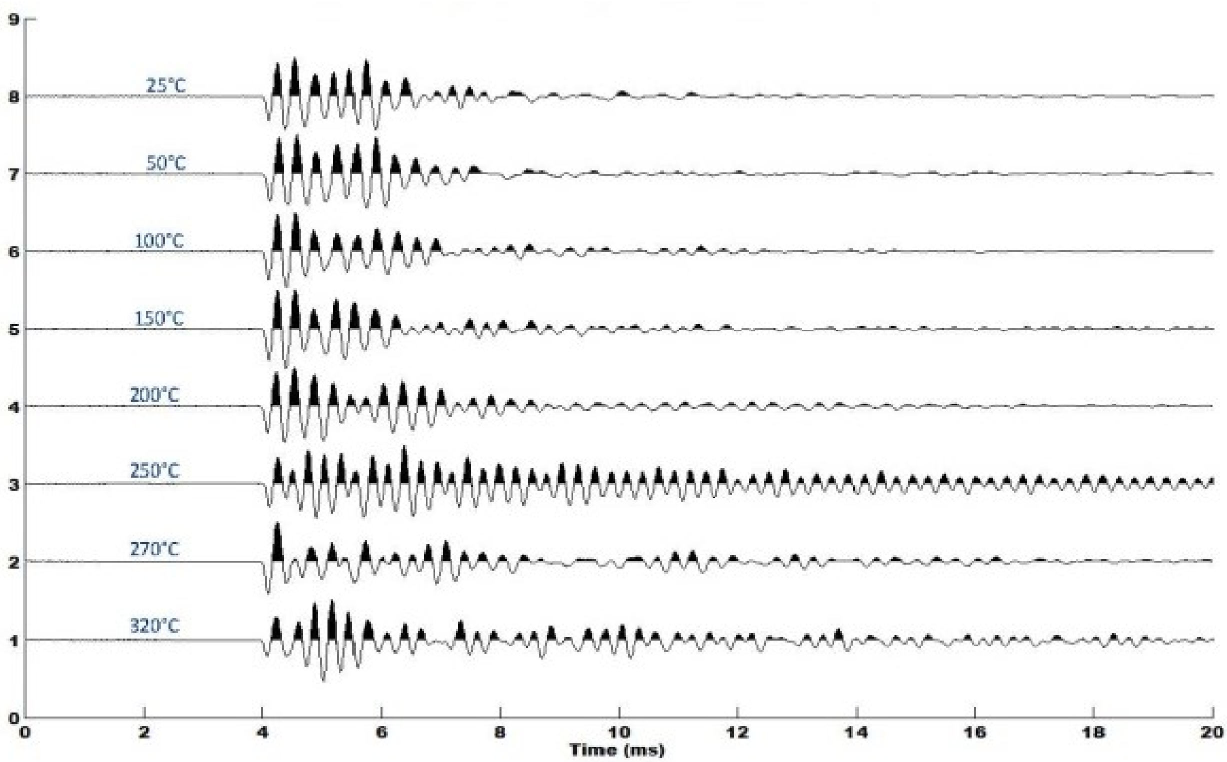

Figure 6. 20 Millisecond Data Record from a Tap Test Recorded on a Radial Fiber Optic Seismic Sensor installed in a 3C Sensor Pod at Temperatures Ranging from 25°C to 320°C.

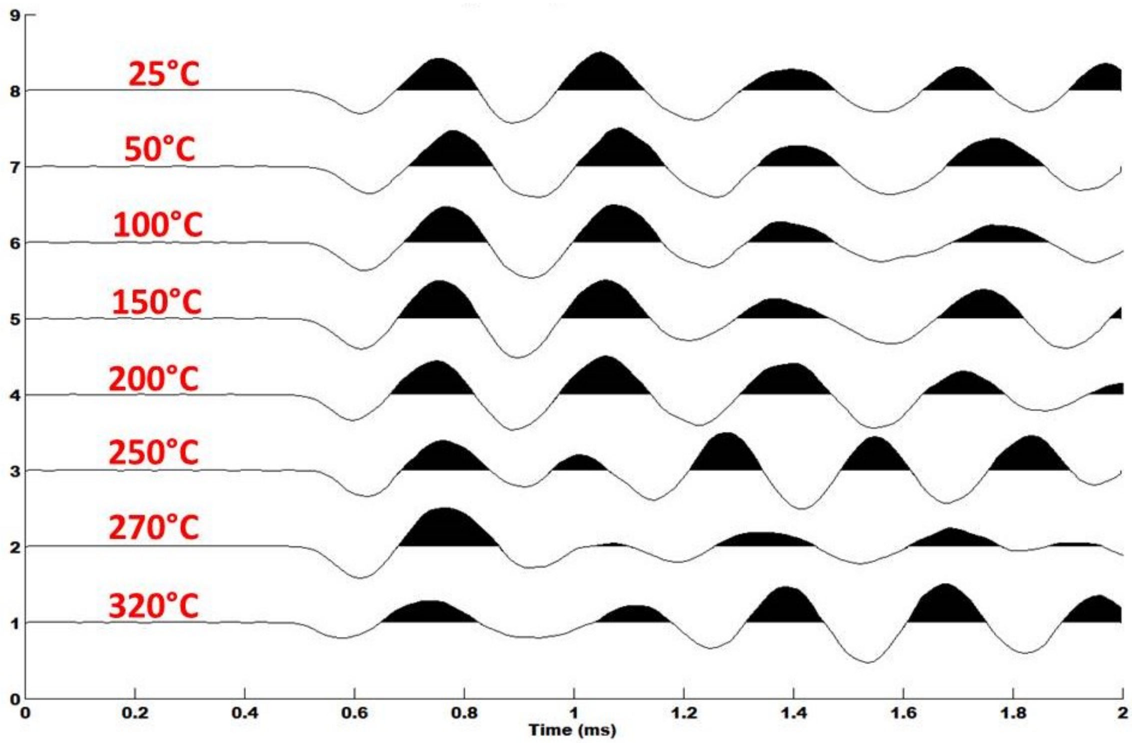

Figure 7. Two millisecond data Record from a Tap Test Recorded on a Radial Fiber Optic Seismic Sensor installed in a 3C Sensor Pod at Temperatures Ranging from 25°C to 320°C. The 3C sensor pod can be seen in figure 5.

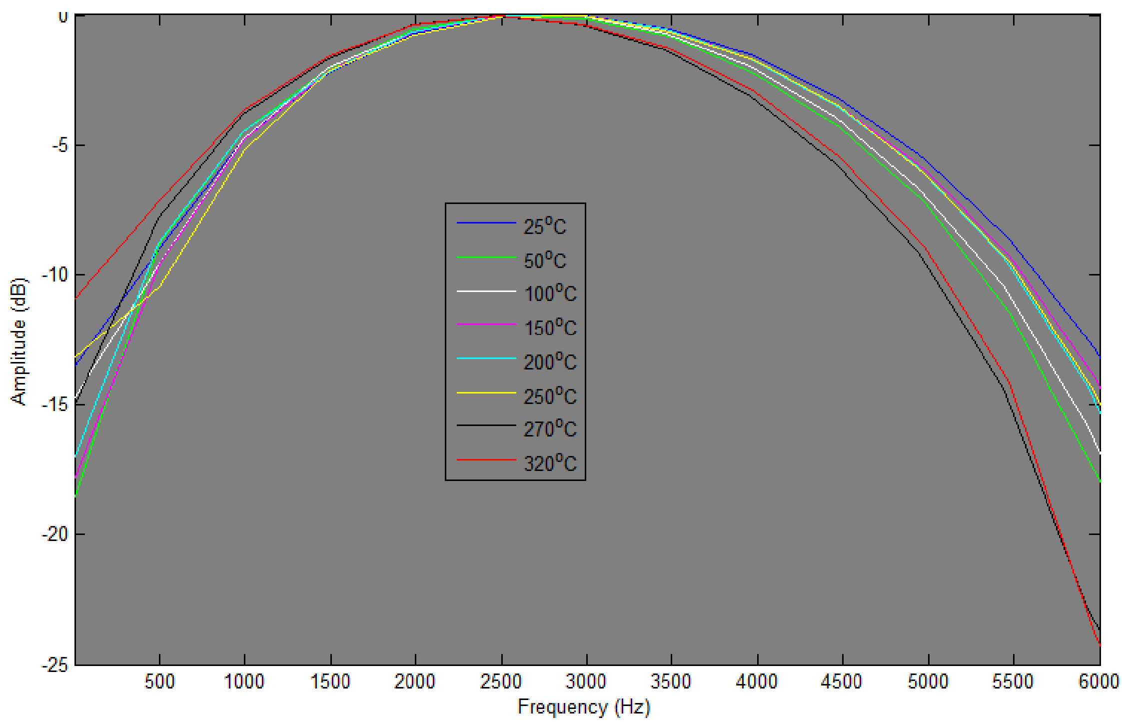

Figure 8. Eight Spectra of the Two Millisecond waveforms generated by Tap Testing data from Figure 7. The Spectra Demonstrate a High Quality Broad Band Signal from close to 0 Hz to about 6,000 Hz.

an 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 during the last tap test.

We started the tap test sequence at a room temperature of 25°C followed by increasing the temperature in a number of steps, as shown in Figure 6. 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 equilibrated temperature. Each temperature step took approximately two hours. We performed the final test after the sensor pod with the three fiber optic sensors had been in the oven for 54 hours at 320°C. In Figure 6, we show 20 millisecond 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 to the data displayed.

In Figure 7 we show a two millisecond window including the first arrival of the data shown in Figure 6. The data is very consistent. When we analyze the spectral content of the laboratory tap test data we find high quality broad band seismic energy within the -15 dB points at ~1Hz and at ~ 6,000 Hz as shown in Figure 8. The broad band data together with the sensitivity and the high temperature capability of the sensor makes the fiber optic seismic sensors ideal for micro seismic monitoring of fluid injection and detection and mapping while fracturing geothermal reservoirs.

3. THE INTERROGATOR

The main components of the system electronics include an optical interrogator and an optical data format to SEGY converter. The interrogator electronics contains all the optical components including lasers, light splitters, modulators, circulators, compensators, Erbium Doped Fiber Amplifiers (EDFAs), amplifiers and A/D converters. A simple schematics of the electronics is shown in Figure 2. The system electronics used for the prototype fiber optics sensors can be seen in Figure 9.

As shown in Figure 9 the field electronics have been mounted into field racks that protect the electronics both during shipment and operations. The field rack mounting allows an efficient and safe set up of the system in the field. An integral part of the electronics is an online real time translator optical data to SEGY data. This will allow real time field processing of the data which is a critical capability of an efficient borehole seismic system.

Figure 9. Optical Interrogator for Paulsson OpticSeis™ system.

4. THE FIBER AND FIBER TUBE

The fiber used in the fiber optic seismic system is an 80 µm polyimide coated fiber that is capable of operating at 350°C. Our current interrogator can operate 50 channels per fiber so the 200 level 3C array, which operates 600 channels, requires 12 fibers, not counting the spares. We will include 4 spare fibers for the vector sensors as well as fibers for DTS and DAS acquisition simultaneously with the acquisition of the vector data. We will use pure silica core fiber in the system to minimize darkening due to hydrogen. All the fibers for the vector sensors and the DTS and DAS sensors will be placed in a Fiber-In-Metal-Tube (FIMT) manufactured using an Inconel alloy. The FIMT will be placed in a 0.25" tube also manufactured using an Inconel alloy. This tube will extend from the surface to the first pod and between all the pods. This tubing will be welded to the pods using an automated orbital welding technique. This will allow us to eliminate any connectors in the system design making the overall system extremely robust.

5. THE FIBER SPOOL AND OPERATIONS DOG HOUSE

The tubing containing the fibers will be spooled onto an electro-hydraulic spool that is shown in Figure 10. The spool is placed in a specially designed 20 ft. container that is equipped with side doors for easy access of the spool holding the tubing with fiber and the fiber optic sensor pods. The 20 ft. container also houses the operator's room, aka "dog house" that is placed next to the spool. The 20 ft. shipping container will protect the spool with the fiber tube and sensors as well as the electronics during shipments of the system.

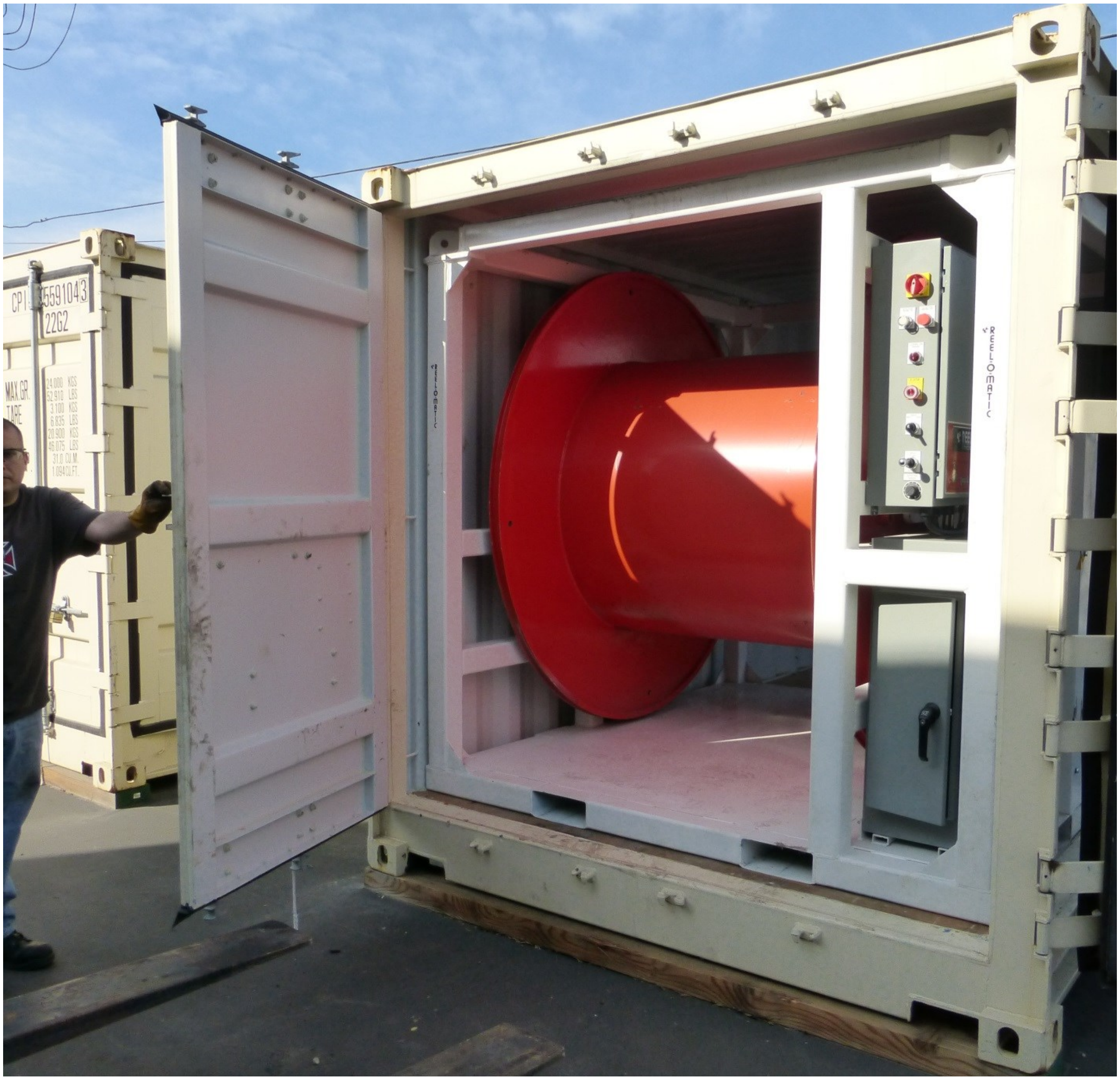

Figure 10. The electro-hydraulic spool especially developed for the tube containing the fiber optic fibers.

6. THE DEPLOYMENT SYSTEM

To deploy the 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 an S135 steel which is also used for offshore drilling operations. The system design and the quality of the steel used for the system allow us to deploy the borehole seismic array to a drilled depth of 30,000 ft. in both vertical and horizontal boreholes.

We have destructively tested and evaluated the drill pipe used for the developed system and measured an axial strength of about 145,000 lbs. before exceeding the elastic to plastic yield point. The projected weight of the entire borehole system is about 5.4 lbs./ft. With a 20% safety margin the maximum weight we can use during the deployment of the borehole seismic system is 116,000 lbs. Using the measured strength of the drill pipe, the weight of the system and a common safety margin of 20% we can deploy a 200 level system to a drilled depth of about 21,730 ft. To deploy deeper than 21,730 ft. we will use a tapered string with heavier wall drill pipe when the load exceeds 116,000 lbs. We have designed such a pipe with the same OD but with a thicker wall capable to hold a weight of 220,000 lbs.

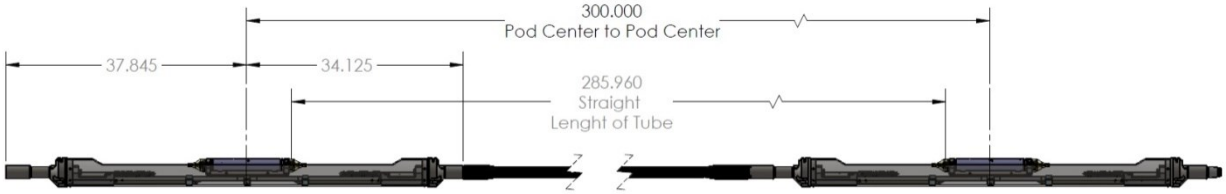

Figure 11. Two sensor pod housings showing a 300" (25 ft., 7.62 m) c/c pod spacing. The sensor pod housings serve several functions; One is to protect the fiber optic sensor pods during the deployment; Second is to house the clamping mechanism; Third, the sensor pod housing is big enough so it can also hold other sensors and functions.

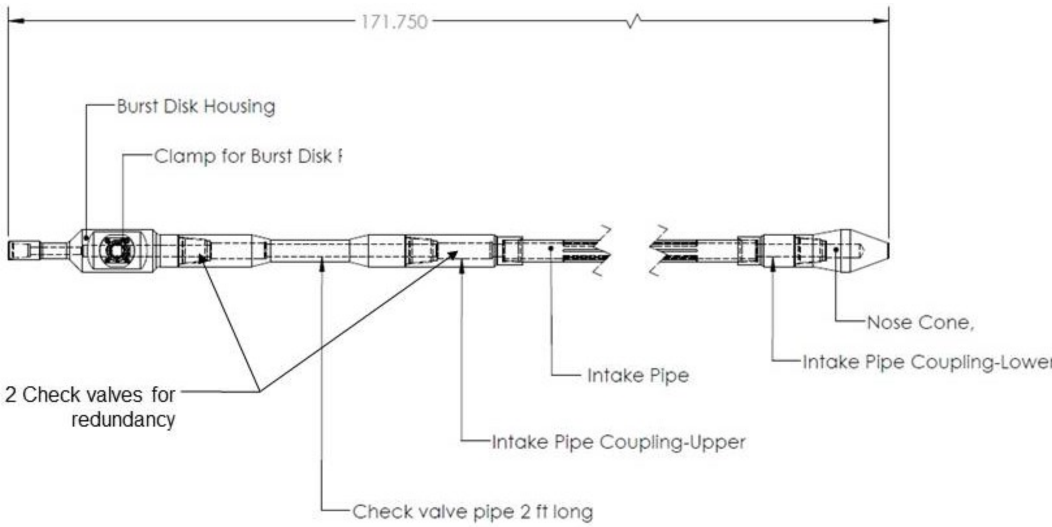

Figure 12. Bottom assembly of the array. The bottom assembly includes the nose cone, the intake pipe, two check valves and a burst-disk/cross-over assembly. The bottom assembly controls the inflow of well fluids into the system. The check valves allow fluid to enter the drill pipe and prevent back flow when the system is pressured up. The burst disk assembly prevents the system from being pulled wet after a survey by allowing a bypass of the check valves after the burst pressure is exceeded.

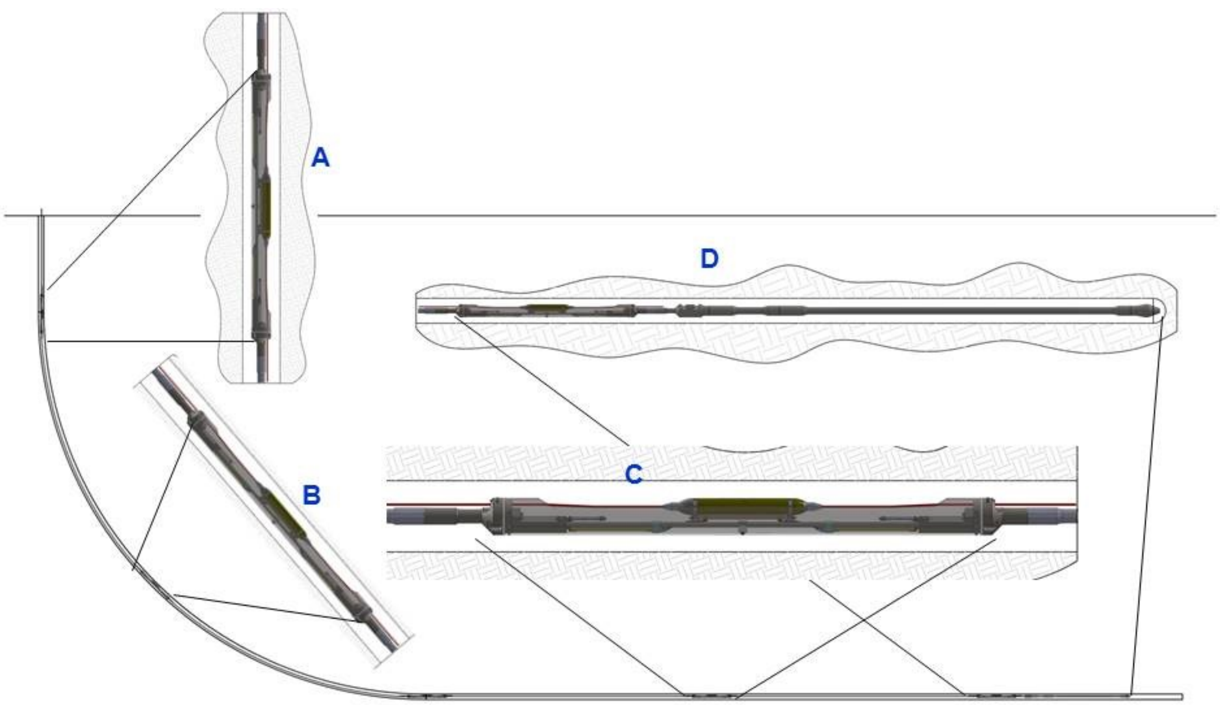

Figure 13. Fiber optic seismic redeployable array deployed into a well which starts vertical but is deviated to horizontal

Using the same assumptions as for the thinner wall tubing we can deploy the system until we reach a weight of 80% of 220,000 lbs. or 176,000 lbs. allowing us to deploy a 200 level system to a drilled depth of 30,000 ft.

The clamping function for the sensor pods in the tool string is using an all-metal hydraulic actuator. This actuator is powered using pipe hydraulics controlled from the surface so the system does not use electric power in the tool for clamping purposes. A fiber optic downhole seismic sensor and a pipe hydraulics based clamping system are in combination thus intrinsically safe since no electric power is used for either the sensor or the clamping system.

The deployment system consists of four sets of components:

1. Sensor pod housings as seen in Figure 11
2. Drill pipe as spacers between the sensor pod housings as seen in Figure 11. The drill pipe provides the means to deploy and suspend the sensor array in both vertical or horizontal wells
3. Bottom assembly as seen in Figure 12. The bottom assembly consists of:
    - A Nose cone.
    - A Fluid Intake section - lower coupler.
    - A Fluid Intake section.
    - A Fluid Intake section - upper coupler and holder for check valve.
        - A Check valve holder.
    - A Burst disk – cross over assembly.
4. Top assembly consisting of
    - A 36” drill pipe pup joint. The drill pipe pup joint is capped at upper end and equipped with a number of ports to supply fluid to pressurize the drill pipe to actuate the clamping mechanisms.
    - Pressure gauges.
    - Valves to supply the fluid to the drill pipe.
    - Valves to release the clamping pressure as needed.

Figure 14. The drill pipe and the sensor pod housings used for the fiber optic seismic sensor system test survey.

Figure 15. The deployment system and the pod with fiber optic sensor used for a field survey.

Figure 16. One of the sensor pod housings with the fiber optic sensor pod attached prior to lowering the assembly into the well.

The Sensor Pod Housing and Pod seismic Tool A in Figure 13 is shown in the vertical part of the well. Tool B is shown in the 45 degree part of the well and Tool C in the horizontal section of the well. Tool D, in the horizontal section of the well shows the last sensor pod housing and pod linked with the bottom assembly. The bottom assembly is a combination of fluid-take-in section, check valves and burst disk assemblies. This section is required for the safe operation of the clamping system for the 3C fiber optic seismic sensor pods.

Prior to deployment into the well the entire fiber optic seismic sensor deployment system is laid out in front of the well. In Figure 14 from the left, are shown the 19' long drill pipe joints, seven sensor pod housings and one bottom assembly. Proper accounting of the correct number of drill pipe joints is critical for deploying the 3C clamped sensors to the correct depth. The system is partially preassembled on the ground near the well to speed up the deployment of the system. We estimate that the deployment speed for the system, after the crew is trained, is about 1,000 ft. per hour

After the sensor pod has been attached to the sensor pod housing, as shown in Figure 15 the assembly is ready to be lowered into the well. The fully assembled sensor pod housing shown in Figure 15 shows the pod with the 3C fiber optic seismic sensors attached to the sensor pod housing which includes a drill pipe deployed and operated clamping mechanism. This clamping mechanism can be seen behind the sensor pod labeled "OpticSeis™ 3C"

After attaching the pod to the sensor pod housing the assembly is lifted up to clear it from the well head and the slips. Figure 16 shows a sensor pod housing suspended by a joint of drill pipe which is held by the workover rig. Below the sensor pod housing is the string of drill pipe and the sensor pod housings previously deployed into the well. The sensor pod housing has a number of functions. It is part of the structural backbone of the deployment system, it protects the sensor pod during the deployment into the well and it also contains the clamping mechanism.

7. FIELD DATA SAMPLE

7.1 Seismic Vector Sensor Data

The second survey with the prototype system was a comprehensive survey testing the response of the fiber optics seismic sensors using both surface and downhole seismic sources. The data that will be shown in this paper is from one of the very small TNT charges that were shot in a well 1,100 ft. from the receiver well with the Paulsson fiber optic seismic sensor array. The source was set off at a depth of 300 ft. while the receivers were placed at a depth of about 800 ft. The straight line distance between the source and the receiver are thus about 1,200 ft.

The data displayed in Figures 17 to 20 and Table 1 is from a shot of 0.65 gram (650 milligram) of TNT (string shot) with the TNT wrapped around a steel pole lowered into the well. Using this technique more than 90% of the effective energy is coupled into tube waves and consequently less than 10% is transmitted into seismic body waves. In Figure 18 we display data from three of the six pods post rotation of the data displayed without AGC. The reason for only displaying data from three of the pods is that these three pods all had the latest generation, at that time, fiber optic seismic sensor. The other three pods had an earlier version of the fiber optic sensors which were not as sensitive. Since the survey in 2013 we have made the sensors even more responsive so the new system should perform even better than the sensors used in 2013.

The hodograms shown in Figure 17 are from the analysis of the three pre-rotation components in the lowermost pod in the array. The 3D hodograms show that the system has very good vector fidelity. The hodograms points to the known source location of the small explosive charge.

The data displayed in Figure 18 are from the 3C pods and the 3C data had been rotated to the principal component for each pod. Sensor 3 is the principal component. The straight line distance between the source point and the receiver location was about 1,200 ft. The Three 3C Pods, Post-Rotation (Depth 800 – 900 ft., Filter: 80-100-1500-2000 Hz). Using frequency analysis we found that the - 25 dB point was at 2,000 Hz as seen in Figure 19.

We have analyzed in details one of the traces recorded by the fiber optic seismic sensors from the small TNT charge. This trace is shown in Figure 20. This figure shows the high quality seismic record generated by a very small explosive charge set off in a well about 1,200 ft. (366 m) away. All the sensor amplitude acceleration transfer functions have been calibrated so we can map the optical output amplitude into absolute acceleration as documented in Table 1. We analyzed the data recorded from the small TNT charge and compared the data with earthquakes. We calculated that the 0.65 gram of uncoupled TNT in a fluid filled well is equivalent of an earthquake with magnitude M-2.6. Small earthquakes do not only have low energy they also generate mostly high frequency seismic data so any sensor that is deployed to monitor small micro seismic events must not only be sensitive but also be able to record high frequencies.

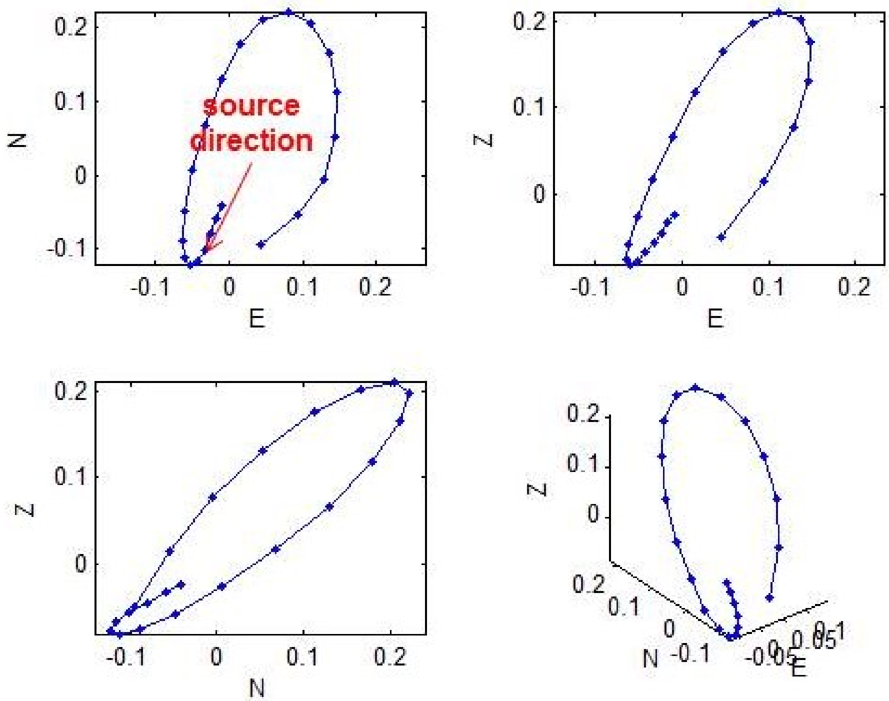

Figure 17. Hodogram analysis of the lowermost pod in the OpticSeis® array. The hodogram shows good 3D vector fidelity. The hodogram points towards the known source point location.

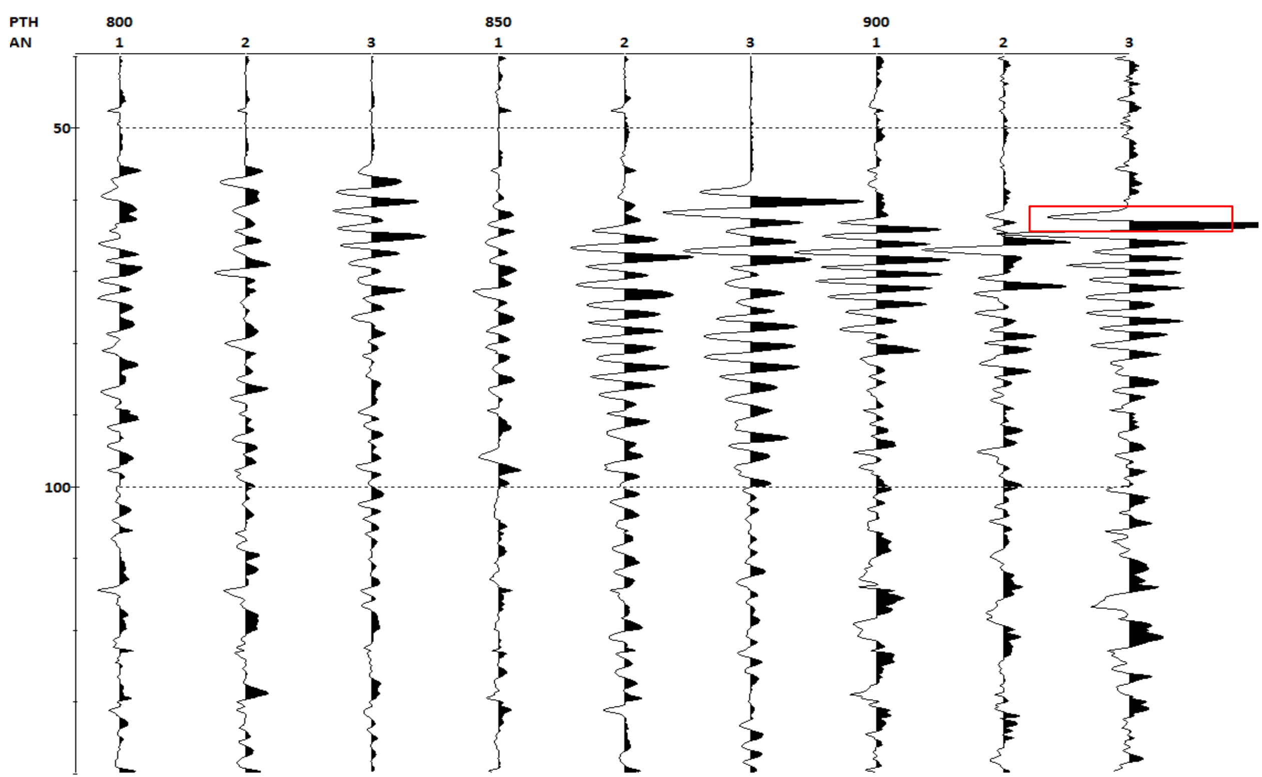

Figure 18. A string shot of 0.65 gram TNT @ 1,200 ft.: Three 3C Pods, Post-Rotation (Depth 800 – 900 ft., Filter: 80-100-1500-2000 Hz) No AGC applied. Sensors 3 are the principal components pointing to the source.

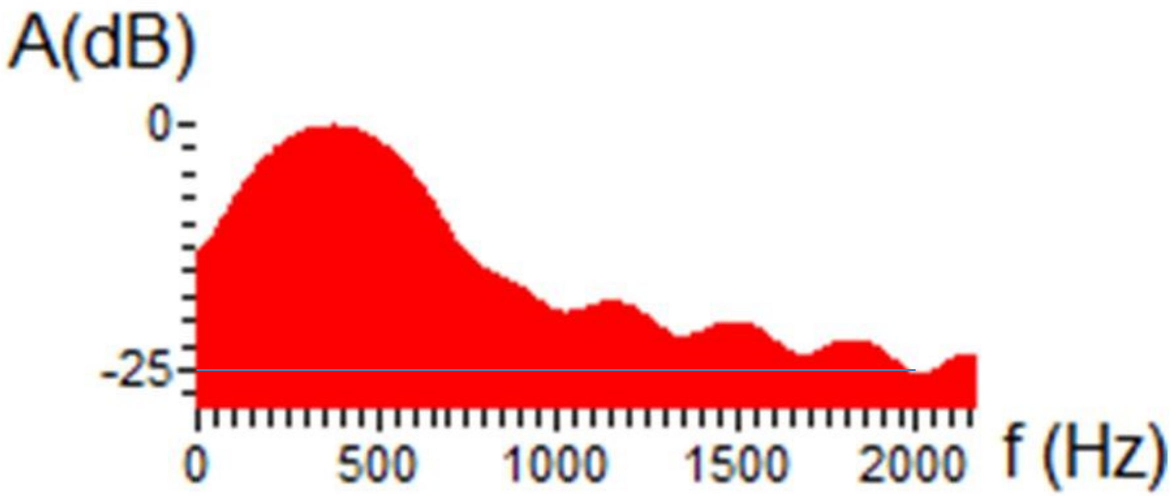

Figure 19. Frequency spectrum of the first arrival wavelet inside the rectangle in Figure 18 generated by the 0.65 gram shot of TNT at a distance of 1,200 ft. between the source and the receivers. The -25dB point is at 2,000 Hz.

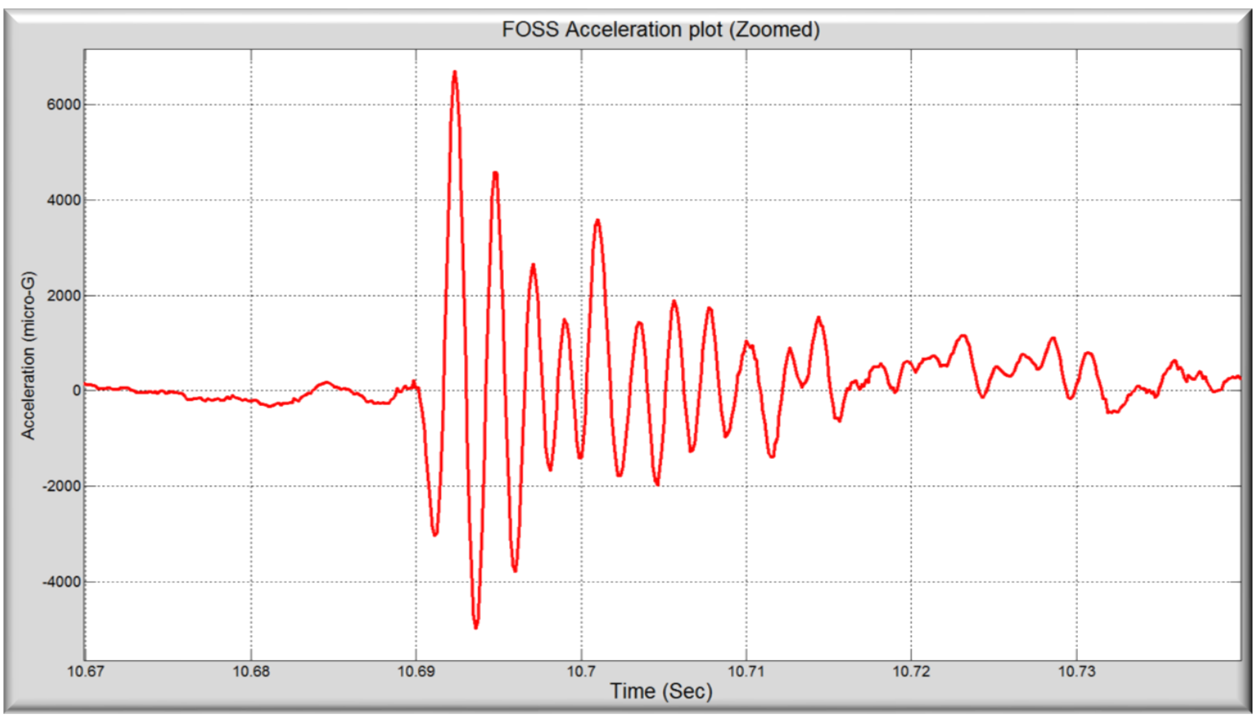

Figure 20. A 3C rotated trace from a small charge equivalent to a M-2.6 micro seismic event recorded on the fiber optic array.

Frequency (Hz)	Acceleration (μg)
600	7.3
700	6.7
800	6.2
900	5.8
1,000	5.5
2,000	2.0

Table 1. The seismic data shown in Figure 20 mapped into absolute acceleration using the calibrated sensor transfer function. Data from 0.65 gram of TNT at a distance of 1,200 ft. (366 m) Assuming 90% of TNT energy go into tube waves = 200 Joules from 0.65 gram of TNT = Magnitude -2.6 (M-2.6)

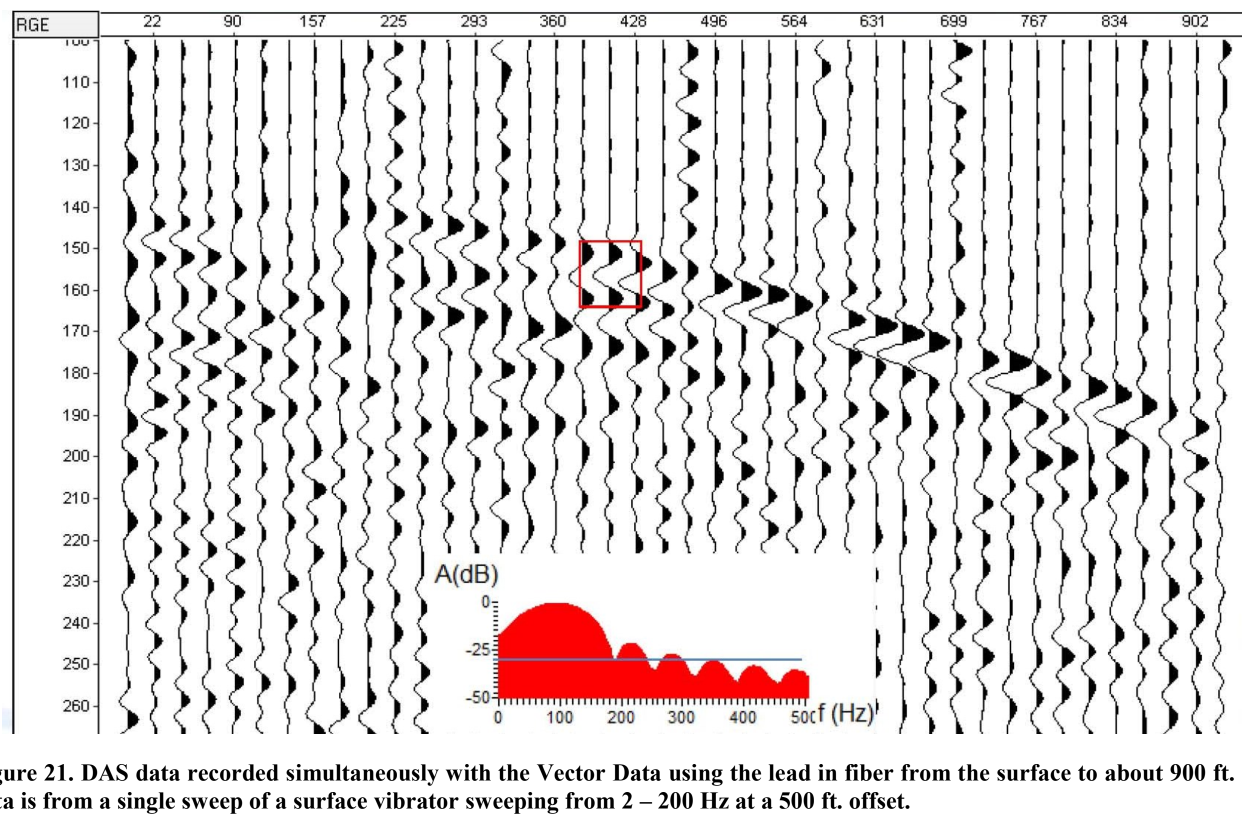

Figure 21. DAS data recorded simultaneously with the Vector Data using the lead in fiber from the surface to about 900 ft. The data is from a single sweep of a surface vibrator sweeping from 2 – 200 Hz at a 500 ft. offset.

7.2 Distributed Acoustic Sensor (DAS) data

The vector sensors using fiber wound around vector mandrels are much more sensitive than DAS. Laboratory tests have shown that the vector sensors are more than three orders of magnitude more sensitive than DAS sensors. However – the DAS data can be useful in estimating the formation velocities by recording the downgoing first arrival from surface seismic sources.

Figure 21 show a sample of DAS data recorded on the Paulsson fiber optic system during a survey. The DAS data was recorded simultaneously with the vector data using one of the lead-in fibers. The DAS data shown in Figure 21 is from a single 2 – 200 Hz sweep with a single vibrator. As can be seen in the spectrum inserted in Figure 21 the DAS data contain the entire spectrum of the vibrator sweep. Note in particular the low frequency performance of the fiber optic seismic sensor. In a similar fashion Distributed Temperature Sensor (DTS) data can also be recorded simultaneously with the vector seismic data using the lead in fibers.

8. CONCLUSIONS

A very sensitive, large bandwidth, high temperature vector fiber optic seismic vector sensor system capable of long term deployment at 30,000 psi and 300°C (572°F) has been developed and integrated into a borehole seismic system.

In the first tests the fiber optic seismic sensors have shown to have superior performance relative to state-of-the-art seismic 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 detailed reservoir characterization and monitoring.

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 exploration and production and for deep high temperature geothermal wells. Removing all the electronics from the hostile well environment will also allow the system to be permanently deployed into wells since the fragile component are all installed in a controlled environment where they can be monitored, repaired and replaced.

The new fiber optic seismic sensor represents a breakthrough for seismic sensor technology and has the potential to challenge the dominance of the regular coil geophone in the most demanding operational environments such as geothermal reservoir imaging and monitoring and for other demanding high temperature and high pressure applications.

The Fiber Optic Seismic Sensor (FOSS)™ design has the following attributes:

- Flat frequency response over a very large frequency range
    - High Frequency performance: Tested to 6,000 Hz.
    - Low frequency performance: Tested to 0.01 Hz (100 second period)
- Very high sensitivity.
- High signal to noise ratio – the latest sensor design generate about 100 times the S/N ratio as compared with geophones
- Outstanding high temperature performance tested to 320°C (608°F)

A deployment system has also been developed and has shown in destructive tests to be strong enough to deploy a 1,000 level 3C borehole seismic array in vertical and horizontal boreholes to a Measured Depth (MD) of 30,000 ft.

Using the developed designs of the sensor and the deployment system a six level Fiber Optic Seismic Sensor (FOSS)™ array was manufactured, assembled and tested in two borehole seismic surveys. Outstanding data from surface seismic and borehole seismic sources were recorded. Outstanding vector fidelity and source to source consistency was demonstrated. One of the sources recorded was a small shot of TNT, which was estimated to be the equivalent of an M-2.6 micro seismic event at a distance of 1,200 ft. The data from this TNT shot was recorded with a S/N ratio of more than 30 and with a frequency range between about 1 to 2,000 Hz.

9. ACKNOWLEDGMENTS

The research discussed in this paper has been supported by the following grants: DOE Contract DE-FE0004522, RPSEA Contract 09121-3700-02 and DOE Contract DE-EE0005509. The support and assistance from these grants made it possible to develop the fiber optic sensor and deployment technology described in this report. The support from Karen Kluger for DE-FE0004522, Bill Head for RPSEA Contract 09121-3700-2 and Bill Vandermeer for DE-EE0005509 is gratefully acknowledged. Without their support this project would not have been successfully concluded. We also gratefully acknowledge the use of the TIRE field test site in Long Beach, California provided by Mike Bruno at GeoMechanics Technologies. This allowed for the first field test of the Fiber Optic Seismic Sensor (FOSS)™ system. We are grateful to ConocoPhillips to sponsor the second test in Pearland, TX and allowing the release of some of the data to RPSEA and DOE.