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Permanent Reservoir Monitoring using Fiber Optic Technology

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Summary

Fiber optic sensor systems have been under development for many years. We have produced prototype seismic equipment to demonstrate the optical technology. 4C seabed systems, streamers and near field airgun recording are a few of the projects under development. A 4C seabed cable has been successfully demonstrated during field operations in the North Sea. Data collected from the field tests have proven the prototype optical system meets the performance required of the deepwater seismic operation. It is an excellent fit for conventional 4C seismic operations and would also be the preferred solution for permanently installed reservoir monitoring systems. Some of the advantages we expect to realize from an optical system include: no in-sea electronics, improved reliability, lighter weight, significantly reduced deployed system cost and improved operational safety.

Key words: Optical sensor, accelerometer, monitoring, 4D, seafloor.

Introduction

Traditional seismic acquisition hardware relies on sensors that produce an output voltage that is digitized, multiplexed and transmitted up a cable to the recording system. The electronics required to perform this operation are both expensive and unreliable. The passive nature of the optical telemetry system eliminates the need for costly in-sea electronics and the problems associated with them, yielding a system that is more reliable, less expensive and safer to deploy and operate. Optical sensor based systems are beginning to replace the traditional technology in the oil field especially in low channel count high stress environments. The telemetry architecture utilized here provides a system that is expandable beyond the capabilities of current seismic systems.

Optical sensors used in acquiring seismic data are typically constructed from optical interferometers. Many establishments have demonstrated the performance of optical sensors, with the US Naval Research Laboratory leading the technology in the late 70s and early 80s; Giallorenzi (1987) and Dandridge et al (1991). Since then the wide spread availability of fiber optic components and subsystems have helped the optical sensor system evolve into a reality; e.g. Bostick (2000). In this paper we discuss our optical technology and present our forward looking plans for the technology.

Fiber Optic System Architecture

Dense Wavelength Division Multiplexing (DWDM) is utilized in the telemetry scheme to optically power the sensors. An optoelectronic cabinet has been assembled using 10 wavelengths with capability to run 960 sensor or 240 four-component (4C) channels. Multiplexed light is sent into the cable where it is distributed to and from the optical sensors, the light returning from the sensors is then demultiplexed and demodulated. The basics of the system include a phase modulate laser source passing through an interferometer, where stress from the outside world causes a phase shift in the light as it passes through the interferometer. The phase information is extracted from the returning light to output a signal equivalent to the stress input at the sensor. This provides a completely passive in-sea system with no in-sea electronics.

Optical Sensors

We have developed optical sensors for acoustic pressure and shear wave measurements; including an optical hydrophone that has been qualified to operate in 3000 m depths without degradation in performance. The unit was tested to have a scale factor of -140 dB re rad/μPa ±1dB over environmental pressure and temperature. This translates into a noise floor below 1μB. A 3-axis optical accelerometer has become the preferred sensor for shear wave measurement. The 3-axis design measures 30 mm x 50 mm x 75 mm. Like the hydrophone the accelerometer has very good uniformity and performs well. When mounted inside a pressure vessel it is also capable of 3000 m operation.

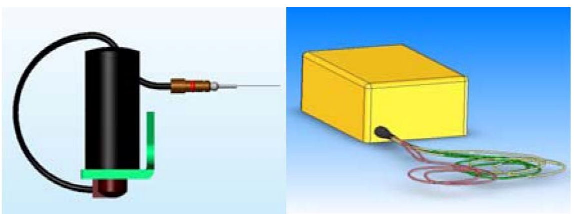

Figure 1. Optical hydrophone and accelerometer.

The Optoelectronic Data Acquisition System

The optoelectronic system generates the optical power for the array and processes the returned optical signals to extract the seismic information. Light returning from the array is routed to a select group of demodulation boards to process the optical data and outputs a 32-bit digital word equal to the seismic data. The data is then sent to a network interface card where it is put into data packets and sent to the recording system over an ATM network. Figure 2 shows the basic optical recording system architecture.

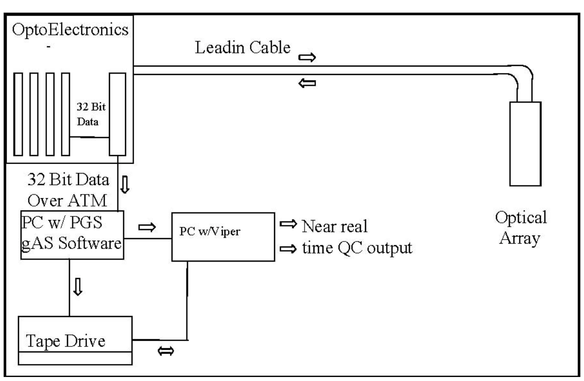

Figure 2. Optoelectronic recording system.

The optoelectronic cabinet with 960 channel capability was assembled in cardfiles, were each cardfile contains four laser boards (2 lasers each), 6 demodulators, one clock reference generator and a network interface card. This is one wavelengths worth of processing or 96 optical channels. Figure 3 shows the cardfile up close and the reduced channel count rack used to test our seabed system. Adding an additional cardfile means you add another 96 channels worth of capability. The optoelectronic system fabricated includes ten cardfiles. Only four cardfiles were used in the reduced channel rack.

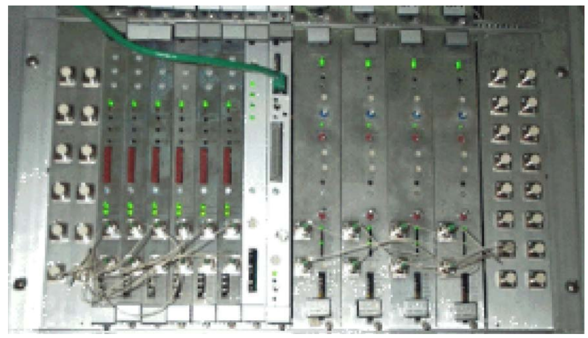

Figure 3. Optoelectronic system cardfile and rack.

Seabed array cable

An array was designed to be used by a 4C exploration crew, being continuously deployed and retrieved in deepwater applications. A steel armored optical cable with the optical fibers inside gel filled stainless steel tubes was used in the construction. A 4C sensor pad was attached to the optical cable every 25 m, the optical fibers in the cable were extracted and fusion spliced to the sensors in the pad. A protective cover and bending strain relief was attached to the entire assembly. 2400 m of array cable plus 4 km of leadin cable were assembled. Mechanical stress test proved the cable assemble can be deployed and retrieved thousands of times without damage to the optical fiber over loads that exceed deepwater deployments of 3000 m. Figure 4 shows the sensor pad assembly.

Figure 4. Sensor pad assembly showing a side view of geophone housing on sensor pad base (upper), and an end-on photo of the protective housing shows a hydrophone mounted in the pad (lower).

Field testing

The field test of the Seabed array (Figure 5) was performed onboard the Bergen Surveyor. The optical array was deployed parallel to the PGS FOURcE seabed cable in 300 m of water, 20 miles NW of Marstein, in the Norwegian Trench. The arrays separation was 50 m and the location of the arrays was monitored using external acoustic transponders. The following two figures show the optical array during the checkout and deployment stages. The data was acquired while the gun boat traveled along the arrays firing every 25 m and again while traversing perpendicular across the center of the arrays.

Figure 5. Optical seabed array being prepared in the warehouse (upper), on a deployment reel (lower left), and during deployed (lower right).

The data shows excellent correlation with that of the electrical system. Figure 6 is a comparison of the hydrophones in the arrays. The data presented shows the corresponding 96 hydrophone channels for the electrical and optical arrays for the same shot in common shot-gathers and the averaged signals from a hydrophone channel, the red trace is the electrical channel and green optical. The low frequency spike seen in the optical channel isn't present in the electrical data because of the roll off filter used in the electrical acquisition system. Finally, the noise response from the two systems is shown. Figure 7 provides the same data for the vertical geophones.

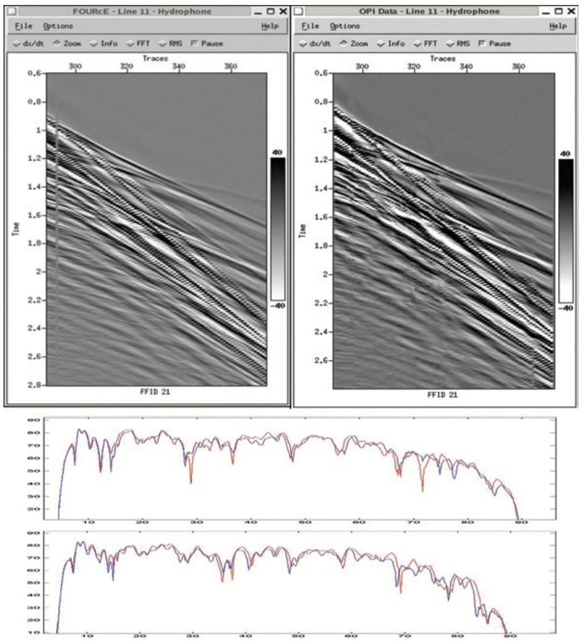

Figure 6. Comparison of electrical vs. optical hydrophones: (upper left) shot gather for 96 electrical channels, (upper right) shot gather for 96 optical channels, (lower) two superimposed amplitude spectra for two of the channels from the FOURcE electrical cable compared to two optical channels.

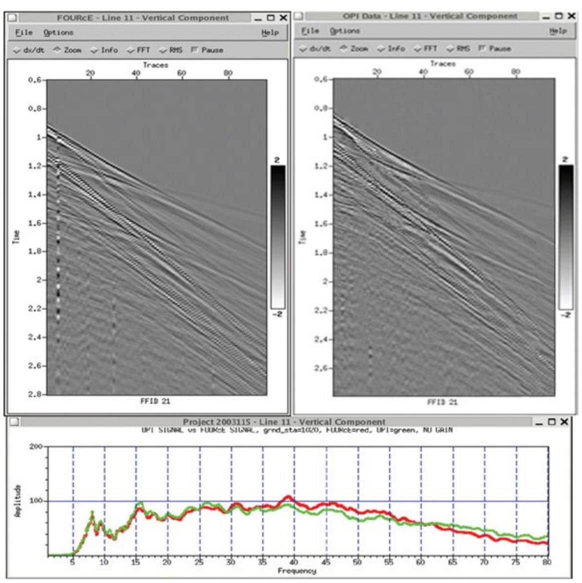

Figure 7. Electrical vertical geophones compared to optical vertical geophones: (upper left) FOURcE electrical shot gather, (upper right) optical shot gather, and (lower) superimposed average amplitude spectra for electrical (red) vs. optical (green) output.

Figure 8 is a noise comparison of the hydrophones and geophone group summed over an 8 second shot record.

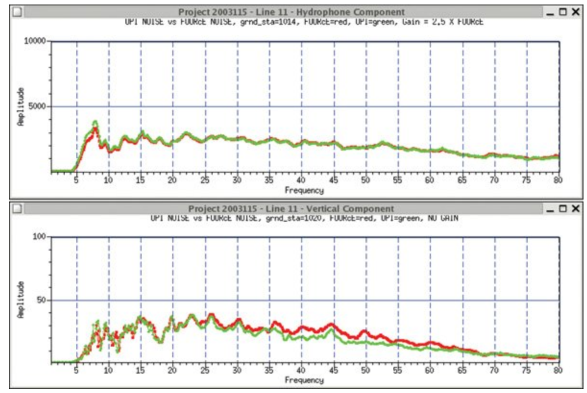

Figure 8. Superimposed amplitude spectra for electrical (red) and optical (green) noise data: hydropohone (upper) and geophone (lower).

Near-field airgun recording

With the proven robustness and survivability of the optical system, we have recently integrated the optical hydrophone into a cable and attached to an airgun array to record the near-field signature of the gun array. The optical system has the added advantage of not being susceptible to the switching solenoids and electrical transients created when the airguns are fired.

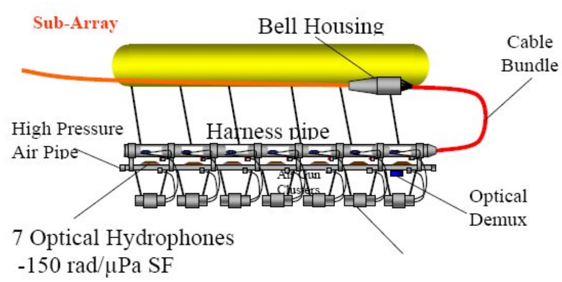

Figure 9. Near field airgun recording system.

Optical streamer

We have also developed the optical telemetry and connectors to support 12 km streamer operations. In addition, we have performed vessel handling and tow tests to validate the optical system performance while under tow in a typical seismic operation. The technology developed will be used in the development of a reduced diameter optical streamer for prototype field testing in 2006.

Figure10. Near-field hydrophone.

Conclusions

We have successfully demonstrated prototype optical seismic hardware. A DWDM telemetry system allows for the expandability to lengths greater than 12 km with channel counts in excess of 2000 per cable. The optical system has been tested along side conventional cable technology with comparable results. Data collected from the field tests have proven the prototype optical system meets or exceeds the performance required of the deepwater seabed systems. The optical technology offers the advantages of no in-sea electronics, improved reliability, lighter weight, significantly reduced deployed system cost and improved operational safety. Fiber optics is an excellent fit for seismic operations and a preferred solution for permanently installed reservoir monitoring systems.

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References

Bostick (2000)

Dandridge et al (1991)

Giallorenzi (1987)