Copenhagen '12

Y004

Vertical Seismic Profiling Using a Fibre-optic Cable as a Distributed Acoustic Sensor

D. Miller* (Silixa Ltd), T. Parker (Silixa Ltd), S. Kashikar (Silixa Ltd), M. Todorov (Silixa Ltd) & T. Bostick (Weatherford)

SUMMARY

Introduction

Light in an optical fibre travels at about 0.2 m/nsec. That means that a 10-nanosecond pulse of light occupies about 2 metres in the fibre as it propagates and that each 10 nanoseconds of time in the optical echo-response can be associated with reflections coming from a 1-meter portion of the fibre. By generating a fresh pulse every 100 μsec and continuously processing the returned optical signal, one can, in principle, interrogate each meter of a 10 km fibre at a 10 kHz sample rate. Local changes in the optical backscatter due to changes in the environment of the fibre can thus become the basis for using the fibre as a continuous array of sensors. In particular, when components of the local acoustic field are coupled by friction or pressure to local strain on the fibre, the fibre can become a distributed acoustic array with thousands of channels and nearly continuous sampling in both space and time.

Recent advances in opto-electronics and associated signal processing (Farhadiroushan et al, 2009) have enabled the development of a commercial distributed acoustic sensor (DAS) that actualizes much of this potential. Unlike disturbance sensors, (Shatalin, 1998), the DAS measures the strain on the fibre to characterise the full acoustic signal. Unlike systems relying on discrete optical sensors (Bostick, 2000; Hornby et al, 2005; Keul et al, 2005; Hornby et al, 2008) the distributed system does not rely upon manufactured sensors and is not limited by a need for multiple fibres or optical multiplexing to avoid optical crosstalk between interferometers.

We report here on an initial field test of the Silixa DAS.

Devine DAS Field Test

In March 2010 a test was conducted at the University of Texas EGL Devine Test Site near San Antonio, Texas. A detailed description of the site may be found at www.beg.utexas.edu/indassoc/egl/devine/index.htm. It is a 100 acre field laboratory that has been used for a variety of studies conducted in and between three 900 m deep wells (e.g. Raikes, 1991; Miller et al., 1992; Yardley and Crampin, 1993; Bostick, 2000). The Wilson #2 well used in this test was completed with a steel 10 3/4" (0.273 m) surface casing to 592 ft (180 m) and a 7" (0.177 m) fibreglass casing to 3062' (933 m). Both strings of casing were cemented to the surface and are reported to be in excellent condition. Borehole inclination is reported to be within 1° of vertical for the entire length of the well, with a cumulative top-to-bottom lateral displacement of 43' (13 m).

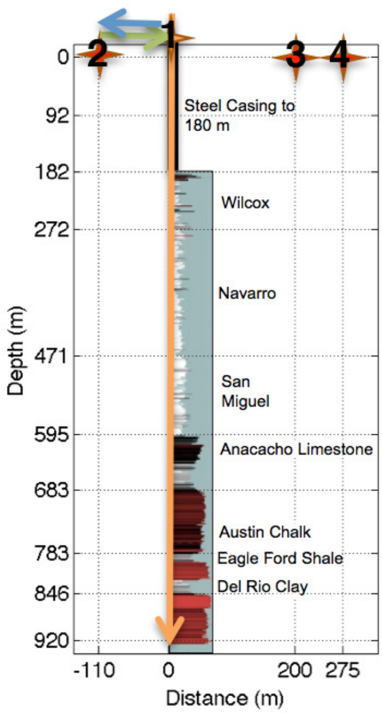


***Figure 1** Survey geometry with formation tops.*

The DAS system is designed to be used with a wide variety of optical cables. For the test at Devine, two distinct cables were used: A Weatherford ¼-inch diameter optical cable designed for permanent downhole deployment was run to near the bottom of the Wilson #2 well as shown in Figure 1. The cable consisted of three fibres, two single mode and one multimode. An optical splice connected the borehole cable to a second standard telecommunication cable laid on the surface from the Wilson #2 well to pass close to the Wilson #4 well 100 m away and back to a DAS acquisition system close to the #2 well. A single Mertz M18 Vibroseis unit successively occupied four positions along a NW-SE line parallel to the line that connects the Devine boreholes. The positions, indicated by numbered stars in Figure 1, were respectively 10 m, 100 m, 200 m, and 275 m from the wellhead, with position 2 offset to the northwest while positions 3 and 4 were offset to the southeast. Position 1 was offset to the southwest, close to the wellhead. At each position, approximately 100 files were recorded. Half were single pulses and half were 10 sec 10-100 Hz non-linear sweeps. No source synchronization or sweep signal was recorded; so all issues related to source timing and signature deconvolution have been solved through analysis of the DAS data only.

Results and Interpretation

Figure 2 shows raw DAS data from a single file recorded when the source pulsed at position 1. The horizontal axis is recording time in milliseconds and the vertical axis is channel index. Each channel corresponds to 1.024 m of fibre with the index increasing with distance from the DAS unit. Channels 1-90 are spooled near the acquisition unit. Channels 91-160 are on the ground, with channel index increasing away from the source, as indicated by the blue arrows in Figures 1 and 2. Refracted compressional waves and coupled shear and Rayleigh waves, with travel time increasing with increasing channel index can be seen at these channels in Figure 2. Channels 160-256 retrace the positions of channels 91-160 in the opposite direction as indicated by green arrows in Figures 1 and 2.

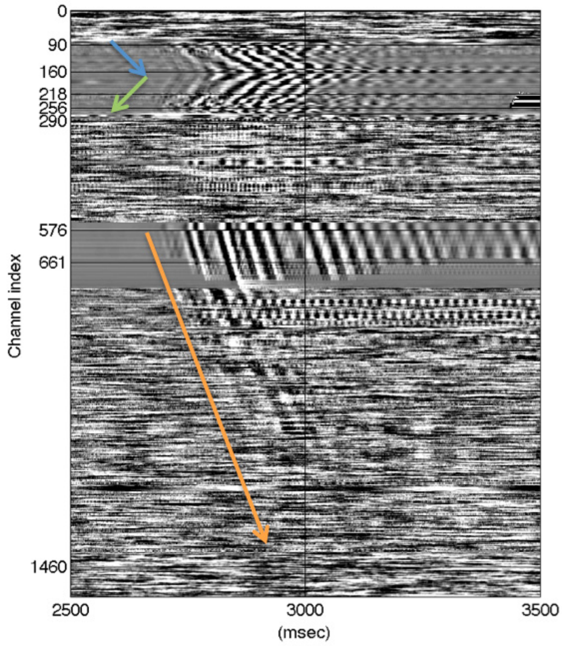


Figure 2 *Trace-normalized raw data from a single vibrator pulse at source position 1.*

The optical splice between cable types is at channel 290. Channels 290-569 are spooled on the logging truck and channel 576 is at the sheave wheel just above the wellhead. The cable is centred in the open wellhead at the surface. Channels 576-1500 are in the borehole. High-amplitude signal is visible in channels 576-730 propagating downward at 4.1 km/sec. This signal, which is generated at the wellhead by high-amplitude ground roll, is similar to signal that has been observed in other borehole tests and is interpreted as extensional vibration of the optical cable where static friction between the cable and borehole wall is negligible or has been overcome by strong motion. A Distributed Temperature Sensing (DTS) record from the deployed cable indicated that the water level in the well was approximately 24 m below the wellhead.

Because the DAS opto-electronics capture both amplitude and phase of the scattered optical signal, the DAS system is able to produce output data that is linearly related to the strain amplitude of the fibre core over a broad dynamic range. This, in turn, means that the DAS data can be processed with methods that were developed for other linear transducers such as accelerometers, geophones and hydrophones. In particular, it means that the signal-to-noise ratio in DAS data can be improved using coherent stacking, correlation and deconvolution.

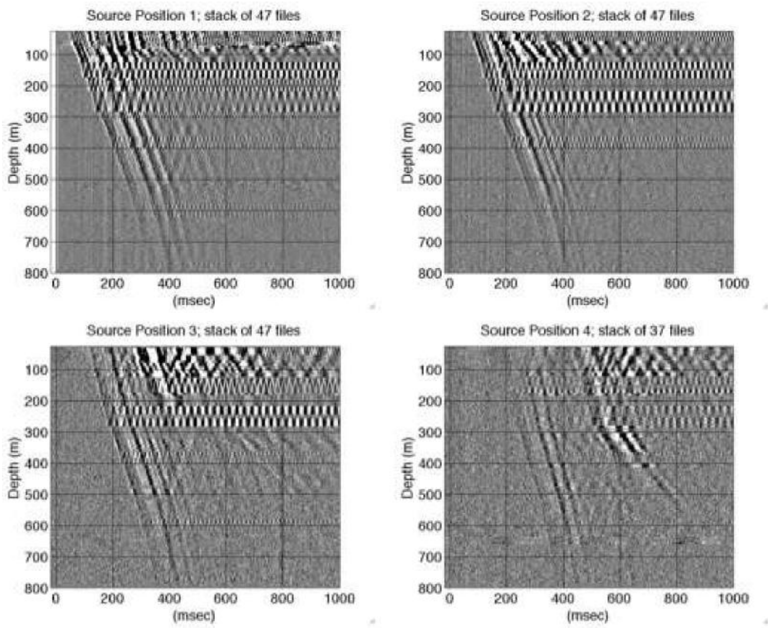
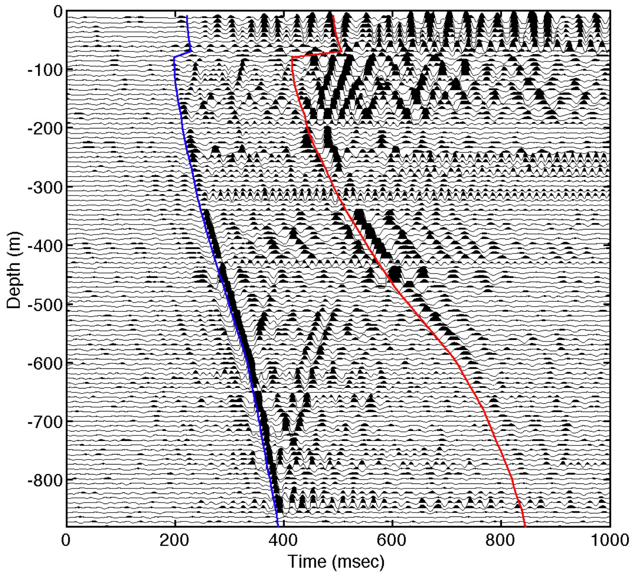


Figure 3 *Stacked data from source pulses.*

Figure 3 shows combined data

from all source pulses at each source location. In each case, representative traces for each file were cross-correlated to determine relative timing, and the multiple files were combined using a diversity stack. A band-limited time-differentiation operator has been applied as well to make the spectral response similar to what would be recorded with an axially oriented geophone. These data are evidently very similar to what would have been recorded by a conventional vertical-component seismic tool. Some ringing due to poor coupling is visible at shallow depths for all positions; and some apparent digitizer cross feed from the strong ground roll is visible for positions 1 and 2, but the dominant signal is clearly due to propagating seismic waves. Note, in particular, the downgoing shear signal in the position 4 data and both the downgoing and upgoing reflected compressional signal visible in all the panels.

The best results were obtained from the recorded Vibroseis sweeps. Time synchronisation and stacking of raw data files were performed as with the pulse data. For each source position, taking advantage of the DAS' nearly continuous spatial sampling, we used a simple Hilbert-transform-based velocity filter (Marzetta et al., 1988) to separate up and down-going signal. Taking advantage of the DAS' high redundancy, we extracted an estimated signature from 150 m of downgoing signal and applied an array-conditioned deconvolution operator (Haldorsen et al., 1994) to the total wavefield. Single-channel notch filters and orthogonal projection operators were used to suppress noise in the poorly coupled channels. Figure 4a shows the result from source position 4, spatially downsampled to an 8 m sampling interval and trace normalized by pre-signal noise level. The blue and red curves superimposed on the display were obtained by raytracing in a model based on published models (Miller et al., 1992; Yardley and Crampin, 1993) and refined to fit these new data. See Yardley and Crampin (1993) Figure 3 for a similar result using a standard borehole tool. Figure 4b shows a migrated image made from the deconvolved upgoing signal from source positions 2-4. See Raikes (1991) Figure 4 for a similar result using a standard borehole tool.



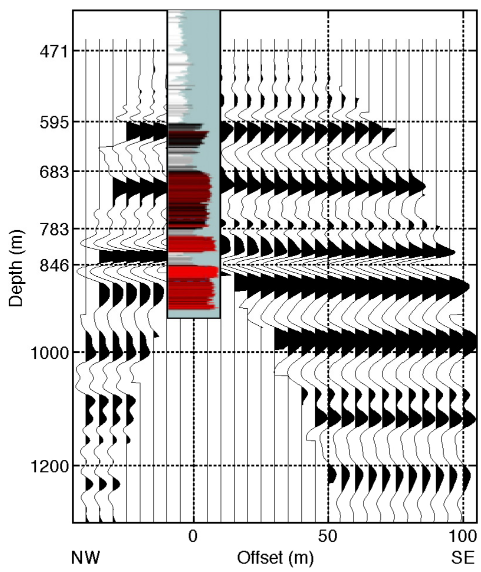


Figure 4 *(a) Deconvolved, stacked data from source sweeps at position 4. (b) Migrated image made from combined deconvolved upgoing data.*

We see no tubewaves in these data. Ground roll-induced tubewaves are not expected due to the water level being sufficiently below the surface. Below the water level, acoustic coupling is a combination of frictional and hydraulic means. The absence of visible tubewaves converted at the bottom of the well indicates that the frictional coupling is dominant. This optical cable is responding more as a vertical strain sensor than as a hydrophone.

Conclusions

These data show clear, coherent seismic signal that is comparable to published results made from data recorded at the same site using standard borehole seismic tools. Stacked data from offset sources, especially at position 4, show both compressional and shear arrivals that agree with elastic modelling and could not be artefacts of processing or misinterpreted coherent noise.

The Silixa DAS system will certainly continue to improve its sensitivity and dynamic range. The DAS technology provides a method for efficiently and effectively deploying a large array of linear sensors in the wellbore. In its present form it appears to be capable of performing commercial check-shot and VSP surveys with a very favourable cost-benefit ratio. In wells with pre-existing optical cables (e.g. with cables used for optical sensing) the DAS system could be tested with no incremental costs of downhole deployment or well intervention.

Optical sensing offers distinct advantages for in-well monitoring. Both discrete and distributed sensors can be deployed without the need for downhole electronics. Given the wide availability of multi-fibre cables, deployments that combine the high sensitivity and high vector-fidelity of discrete optical sensors with the high fold and low cost-per-channel of the DAS system should become increasingly practical.

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