Field Trials of Distributed Acoustic Sensing for Geophysical Monitoring

J. Mestayer, B. Cox, P. Wills, D. Kiyashchenko, J. Lopez, M. Costello, Shell International E&P Inc.; S. Bourne, G. Ugueto, R. Lupton, G. Solano, Shell Upstream Americas; D. Hill, A, Lewis, QinetiQ OptaSense®*

Summary

Distributed Acoustic Sensing (DAS), a rapidly evolving fiber-optic based technology for permanent in-well and geophysical monitoring, was used to record VSP data in two field trials in Shell assets onshore Canada and USA. Useful in-well velocity data were gathered from the entire length of the well from wellhead to TD (up to 4 km), which compared well with geophone recording and sonic log data. Walk-away VSP data yield images that are nearly equivalent to images from conventional borehole geophones in terms of signal to noise ratio and resolution. Permanently installed fiber-optic infrastructure will enable low-cost non-intrusive geophysical monitoring.

Introduction

Distributed Acoustic Sensing (DAS) is a rapidly maturing fiber-optic technology with numerous applications in geophysical surveillance and in-well monitoring. DAS transforms nearly any fiber-optic cable into a distributed array of acoustic sensors. Often existing cables can be used. To record data requires a specialist Coherent Optical Time Domain Reflectometer (C-OTDR) unit referred to as an "Interrogator Unit" or "IU", which is connected to the existing fiber optic infrastructure. The entire cable can be sampled at a rate of up to 20 kHz. This technology is being developed in a partnership between Shell and OptaSense, a subsidiary of QinetiQ U.K. (Molenaar et.al, 2011).

Fiber optic cables may be installed in vertical and horizontal boreholes, which may be producer, injector, or observation wells. The deployment of multiple fibers in a single cable is routine, and can allow DAS measurements in conjunction with other fiber optic techniques such as Distributed Temperature Sensing (DTS). Fiber optic cables are robust and can survive for years in the down-hole environment. Previously the cost, inconvenience, and risk of well intervention associated with conventional down-hole geophones made in-well geophysical surveillance expensive and often unfeasible. Permanently installed down-hole fiber-optic cables are ideal for low-cost non-intrusive geophysical monitoring. Once the system is installed, no further intervention is required and repeat surveys only require additional seismic source efforts. Often DAS offers the only viable alternative.

Shell's first field trial of DAS for geophysical monitoring occurred in September 2009 in a tight gas development in Canada. This field trial provided proof of concept for DAS as a tool for recording down-hole seismic from active sources. Analysis of this and subsequent datasets highlighted a number of potential applications and research areas which resulted in additional field trials, throughout 2010. Here we discuss the results of two new geophysical field trials carried out in assets in onshore Canada and USA which employed the 2010 version OptaSense DAS Interrogator Unit

DAS Field Trial at Quest CCS Project

The Quest Carbon Capture and Sequestration (CCS) project is intended to capture up to 1.2 mln tones of CO_2 annually from the Scotford Upgrader in Alberta, Canada and deliver it via pipeline to underground storage, significantly reducing the overall carbon footprint of the Athabasca Oil Sands Project (Figure 1). The overall study objective is to test the feasibility of recording VSP data, and DAS data in particular, as a Measurement-Monitoring-Verification (MMV) tool for the Quest CCS Project. In the Quest field trial, carried out in September 2010, several surveillance methods were tested, including repeat Zero-Offset (ZO) VSP's to monitor CO_2 containment, Walk-Away (WA) VSP's to track the CO_2 injection plume, and tube wave monitoring of casing integrity and completion permeability.

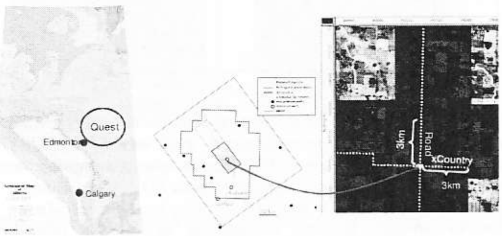

Figure 1- Left: Geological map of Alberta (Canada) indicating the Quest CCS project area. Right: The triangle indicates the vertical well where the DAS cable and geophones were deployed to record the VSP surveys. The dotted lines indicate WAW VSP shot lines.

Figure 1 shows the configuration of the ZO-VSP's and the WA-VSP's (dotted white lines). The WA-VSP's were acquired along N-S and E-W lines. The N-S line was extended 9km to the north to test the feasibility of refraction seismic in this area. A single mode lead-in cable was run from the wellhead to the DAS Interrogator Unit, which was in turn connected to a computer for data visualization and storage. In addition to the Vibroseis controller, this is the only equipment that was required to complete the VSP acquisition.

The phase of the DAS recording is very stable, the first arrivals are strong to TD (2km), and strong reflections can be observed (Figure 2). Overall the ZO DAS recording is very comparable to the ZO geophone recording.

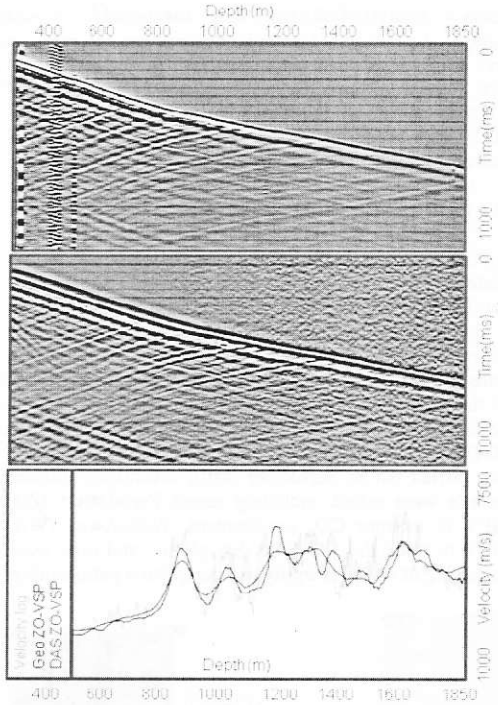

Figure 2 - Top: ZO VSP recorded using a geophone array (at 7.5m spacing, moved 3 times to cover entire well). Middle: ZO VSP recorded using the DAS array (10m channel spacing, covering the entire well). AGC has been applied to both ZO-VSP recordings. The red lines indicate the first arrival picks used for calculating velocities profiles. Bottom: Comparison of velocity profiles obtained using DAS ZO-VSP (red), Geophone ZO-VSP (blue), and the velocity log (green).

DAS has clear advantages over conventional geophones when it comes to deployment. Not only is DAS permanently installed, so no well intervention is required, but DAS records the entire well with a single shot, while geophone acquisition often requires multiple tool settings (three at Quest) to cover the entire depth range of the well. As a result shots need to be fired multiple times in the same place, potentially limiting the continuity and repeatability of the data.

The recorded DAS/geophone ZO-VSP's can be used to extract velocity profiles along the well, which could help to monitor CO_2 containment. Using the derivative in depth of the picked first arrival times (Figure 2) we obtain velocity profiles, shown in the bottom panel of Figure 2. The DAS velocities (red) correspond well with the geophone velocities (blue) and the sonic log (green). Note that the geophone velocity profile shows some erroneous deviation around 1200m, which is caused by the discontinuity between the three geophone array settings.

To quantify the fidelity of the DAS system, a signal-to-noise ratio (SNR) analysis was performed on the ZO data in four time windows: 1) signal shallow, 2) noise shallow, 3) signal deep, 4) noise deep (see Figure 3). From this we can observe that the signal in the DAS and geophone datasets are comparable when the spectra are normalized. For the geophones the noise floor is most likely ambient (well) noise, while the noise floor in DAS is likely to be inherent to the instrument and is roughly constant with depth. The DAS signal decreases with depth and falls below the noise floor at some point. A drawback of the geophone acquisition is that there is an amplitude difference (in both signal and noise) between shallow and deep geophone placements.

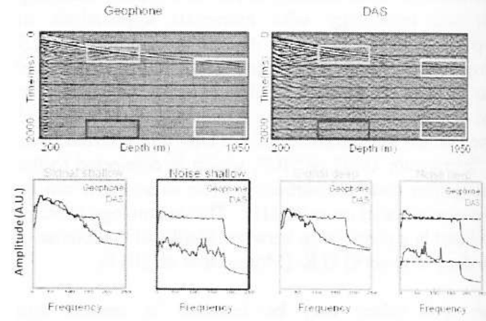

Figure 3- Top: Geophone and DAS data and the windows used for SNR analysis. Bottom: Scaled frequency spectra for geophone (blue) and DAS (red) data for the indicated windows.

The recorded WA-VSP datasets comprised 126 levels at 15m for the geophones (two tool settings) and 177 channels at 10m for DAS. The full wave-fields were migrated resulting in the images shown in Figure 4. The DAS image is very comparable with the image obtained from the geophone data. Although the 2010 DAS Interrogator Unit has a higher noise floor than the conventional geophone recording, the signal to noise ratio of the image is very similar after the migration since most of the incoherent noise has been stacked out. The impact of this result is dramatic since it shows that DAS technology can yield a useful VSP result despite the fact that there is still significant scope for further improvement in the DAS optoelectronics and fiber-optic cable design.

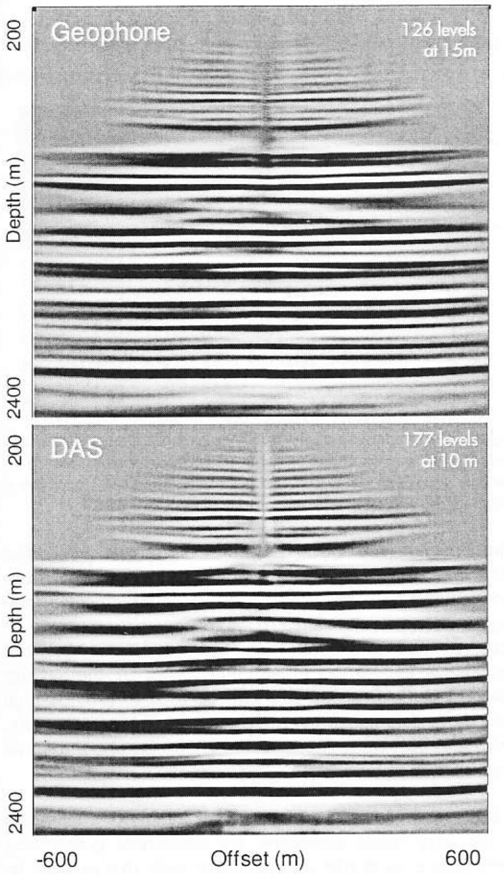

Figure 4 - Walk-away VSP images from conventional geophone data (top) and DAS (bottom).

DAS Field Trial at Pinedale Field

In October and November 2010, a second field trial was completed in the southernmost section of the Pinedale tight gas development in Wyoming, USA. DAS data were acquired during hydraulic fracturing operations of two producers adjacent to the observation well, to evaluate DAS as a tool for micro-seismic monitoring. In addition, a zero offset (ZO) and walk-away VSP were recorded in an observation well, which we will focus on here.

The DAS data were sampled at 10 kHz with a spatial resolution of 10 m. With the cable extending down to a depth of nearly 14,000 ft (4 km), this marks Shell's deepest deployment of a DAS cable to date. To ensure that acceptable signal levels were obtained, a source energy penetration test was performed at the zero-offset point (see Figure 5). Two and four synchronized Vibroseis trucks were employed. With two vibes, the first arrival signal was not observed in the deepest section of the well. However, with the increase to four vibes the signal becomes visible. The signal to noise ratio is much improved after stacking 16 individual sweeps. When 32 sweeps are included, reflections become visible in the data.

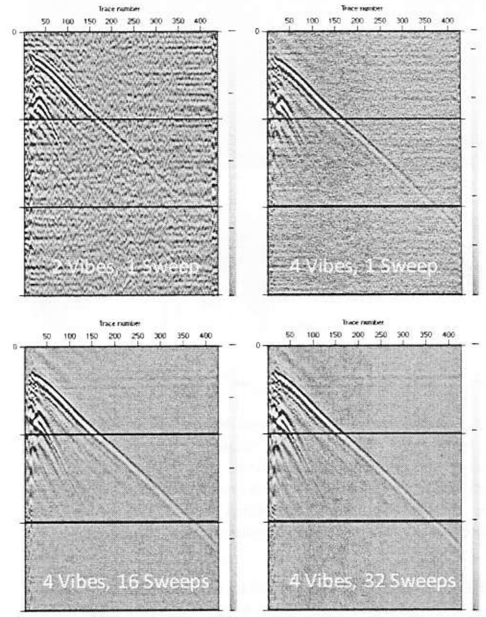

Figure 5 - DAS recordings of zero-offset VSP with varying source energy. Depth range 0 to 4 km.

A comparison of the DAS recordings to the relatively small portion of the well that was also outfitted with geophones is shown in the top panel of Figure 6. Due to the depth of the well, full coverage with the geophone array (46 levels at 15 m spacing) would have required re-positioning multiple times. Even this would not have been adequate at Pinedale, as the shallower portions of the well have a larger casing inner diameter, requiring a change of the geophone clamping mechanism at shallower depths. As observed at Quest, the DAS data is qualitatively very similar to the signal observed on the geophones. The reflections are easier to see on the geophone record. However, the strongest reflection in the DAS record (highlighted with a dashed white line), matches well with the geophone data. It is hoped that further processing will allow additional information to be extracted from the DAS reflections. Interval velocities were computed from the first arrivals picked on both data sets (highlighted in red). The resulting velocities are plotted on the lower panel of Figure 6. The DAS curve (blue) and the geophone curve (black) both correspond well with the available sonic logs.

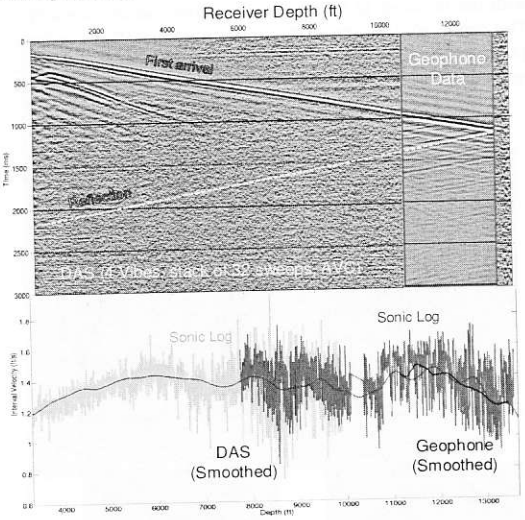

Figure 6 - Top: Zero-offset VSP recorded on DAS, with the first arrival highlighted in red. The relatively small depth range recorded on the conventional geophone array is also shown. The strongest reflector observed is shown with a dashed white line. Bottom: interval velocities calculated from DAS (blue) and geophone (black) data and their comparison with sonic logs.

In an effort to quantify the signal to noise levels in both the DAS and geophone zero-offset VSP data sets, frequency spectra were computed as shown in Figure 7. In the spectra for the deeper section (bottom right), the DAS SNR is lower than the geophone result. This may be the main reason for the very weak sensitivity to reflections seen in Fig. 6 (top). Although a direct comparison between DAS and geophones in the shallow portion of the well wasn't possible, the shallow SNR for DAS was higher than the deep DAS section, with frequency content very similar to the geophone data.

Conclusions and Outlook

DAS down-hole acquisition is inherently simpler than acquisition with geophones in that the entire well is covered with a single shot. With geophone strings, several tool movements are typically required. Single deployment leads to reduced HSE exposure and savings on all expenses related to down-hole acquisition – equipment (source and receiver) rental, staff time and rig time. Acquiring the full well in a single shot (or a stack of single shots) should improve repeatability and hence time-lapse sensitivity.

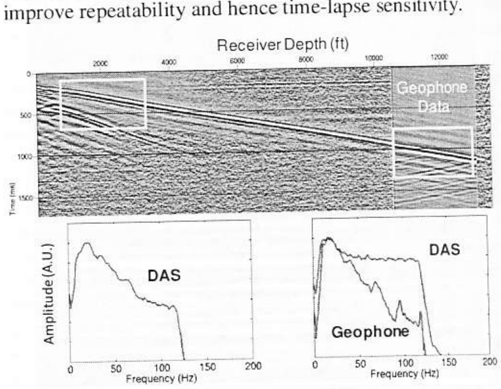

Figure 7 - Comparison of frequency spectra for shallow (left) and deep (right) receiver channels for DAS and geophones. There is no shallow geophone data. The flat portion of the DAS spectrum at depth (right) represents the noise floor of the DAS data.

The Pinedale and Quest examples show that zero-offset DAS check-shots are useful down to 4 km and reflections interpretable to 2 km. With hardware improvements (time-lapse) 3D VSP of shallow-target geometries may be acquired and processed with little difference between geophones and DAS. In addition, some of the savings inherent to DAS acquisition can be used to provide high fold shot stacking, further improving the DAS data quality. DAS may yet realize the vision of a fully instrumented well from surface to total depth.

It is becoming apparent that there are situations where DAS is the only viable alternative for down-hole geophysical surveillance, as in slim-hole wells, or wells that may not be entered without removing the completion equipment, or where long arrays may not be safely deployed (e.g. long horizontal wells). Improved repeatability is likely by using comparatively inexpensive permanently deployed fiber, rather than multiply deployed geophones. Therefore, while it appears that DAS measurements may not yet attain the high fidelity of geophone systems, the low cost, simplicity, and non-intrusiveness of DAS operations may be a "fit-for-purpose" solution for reservoir monitoring applications.

Acknowledgements

Shell Upstream Americas CoE teams for designing and supporting fiber installations; D. Brown for operational coordination at Pinedale; M. Davidson for geophysical operations support; Wasif Syed for supporting the surface fiber installation at Pinedale; Jim Roy, John Holbrook and Stuart Russell for operating the system and recording the data; K. Hornman, B. Duijndam, P. Webster, B. Westwood for technical advice. We thank Shell for permission to publish this paper.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2011 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Molenaar, M. M., D. J. Hill, P. Webster, E. Fidan, and B. Birch, 2011, First downhole application of distributed acoustic sensing (DAS) for hydraulic fracture monitoring and diagnostics: SPE 140561.