Vertical Seismic Profiling Using Distributed Acoustic Sensing in a Hydrofrac Treatment Well
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SUMMARY

Distributed Acoustic Sensing (DAS) is a Fiber Optic (FO) cable based technology which is gaining importance for VSP surveys, especially for time-lapse monitoring of reservoirs. DAS offers advantages over geophones but it also poses unique challenges: receiver depth uncertainty and low signal-to-noise ratio. Here, we present an analysis of a VSP acquisition where the FO cable was installed in a treatment well for monitoring a multi-stage hydraulic fracture treatment in the same well. We describe methods for depth calibration and discuss various sources of noise and a processing flow to enhance the signal-to-noise ratio. Large spike noise, most likely from the DAS acquisition system, appears to be a major source of noise in the raw DAS data, but can be removed with careful processing. Other sources of noise include temperature fluctuations in the well and optical noise. The field trial showed that excellent quality VSP data can be recorded in a hydro-frac treatment well.

INTRODUCTION

A new technique for acquiring VSP surveys, Distributed Acoustic Sensing (DAS), is gaining importance to replace geophones as seismic sensors in the borehole. Several field trials conducted recently in onshore wells (Mestayer et al., 2011, 2012; Miller et al., 2012) as well as offshore wells (Mateeva et al., 2013a) demonstrate that DAS is an usable technology for VSP. In an extreme deviation from what would be possible with geophones, we describe a field trial to test DAS VSP in a treatment well with the objective to monitor hydraulic fracturing. Previous attempts to monitor hydraulic fracturing (Wills et al., 1992; Fehler and Pearson, 1984) were limited by the observations from a near-by monitoring well. DAS in the treatment well would allow us to make seismic measurements within the stimulated zone without requiring a separate monitoring well (Wills et al., 2012).

A typical DAS system (see Figure 1) is comprised of a Coherent Optical Time Domain Interferometer, commonly referred to as a light-box or Interrogator unit at the surface connected to a fiber optical cable installed in the well. The system is analogous to an array of geophones placed along the entire length of the fiber. The interrogator unit emits short laser pulses into the fiber and analyzes the Rayleigh-scattering to probe the strain along the fiber. As the pulse travels along the fiber, part of the energy is back-scattered by the microscopic defects in the fiber and then it propagates back to the surface. Though the amplitude and phase of the back-scattered signal at a location in the fiber is random, the change in phase-lag between two locations at two times is proportional to the strain in that section of the fiber (Hartog et al., 2013). Hartog et al. (2013) describes different systems to estimate the phase-lag, either by using a single pulse or a pair of pulses with slightly different frequencies separated in time. The two-way travel-time of the back-scattered signal corresponds to the location of the ‘receiver’ in the fiber. The distance over which the phase-lag is estimated at each receiver is called the ‘gauge-length’ and is usually fixed prior to the acquisition. Larger gauge-length corresponds to better signal-to-noise ratio but poorer spatial resolution and vice-versa. The fiber is either hung against the borehole wall, installed on the tubing or cemented outside the casing. When installed on the tubing or cemented outside the casing, it can be used as a permanent monitoring device.

DAS seismic acquisition has several advantages over acquisition with geophones. DAS data can be acquired over the entire well at one instant while geophones are mostly deployed in short arrays and so covering a significant part of the well requires several string moves. Thus geophones are not ideally suited to instantaneous measurements (as we require for hydrofrac monitoring). Geophones require invasive and error-prone deployment and often cannot be deployed at all (for example, in a treatment well or at an offshore platform). FO cables are easier to deploy and are often permanent and installed for other monitoring purposes (like Distributed Temperature Sensing). DAS is considered a game changer for downhole seismic acquisition and, for some operations that could not be done without DAS, a game maker. It is simple to acquire DAS from multiple wells simultaneously (Mateeva et al., 2013b). For geophones, the same functionality would require multiple copies of most of the equipment (geophone array, wireline truck, recording instruments) and would, in most cases, be impractical and prohibitively expensive.

Current FO cables used for DAS have limitations: they are more sensitive to strain along the length of the fiber and not to strain perpendicular to the fiber (broadside to the fiber). As a result, DAS is more sensitive to P-waves and less sen-

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sitive to shear waves when propagation direction is parallel to the fiber. DAS has also an uncertainty in receiver depths. Strain measurements from back-scattered energy are associated with a certain depth along the fiber based on the arrival time of the back-scattered energy, assuming a certain velocity of light in the fiber. The optical length (along the fiber) can be larger than the measured depth along the well due to ‘overstuff’, where the fiber length is made longer than the cable length to prevent snapping when stretched. This leads to uncertainty in the optical length and depth errors that grow with depth. In addition, the length of the cable above the wellhead is not always accurately known. Another well-known issue with DAS is the lower signal-to-noise ratio compared to geophones (lower by 40 dB) (Mestayer et al., 2012). This limits the use of DAS in projects with weak signals. Fortunately, the current field trial has adequate signal-to-noise ratio after stacking and it is expected that the future editions of the optical hardware will close the geophone/DAS sensitivity significantly (Mateeva et al., 2013a). In our study, the treatment related operations in the well make the data much noiser and challenging than would be in a regular VSP.

In the following sections we describe the field experiment utilizing DAS to record signal from Vibroseis sources before, during and after stimulation in a multi-stage fracturing operation. We first look at removal of a significant noise source - strong seismic spikes on uncorrelated data that created unacceptable noise upon correlation. We then describe the depth calibration process. Next, we summarize the processing workflow and present the VSP gathers before and after stimulation.

**FIELD TRIAL**

![Well Completion Schematic](image)

Figure 2: Well completion schematic. The green tick marks indicate the stages that have time-lapse DAS VSP data.

The field trial featured DAS VSP monitoring of hydraulic fracturing in a treatment well in a Shell-owned gas field. The vertical well is drilled in fluvial deposits from the Cretaceous period. The time-lapse survey was a near offset VSP using Vibroseis as sources and DAS as receivers. There were three source locations, each with two Vibroseis trucks placed bumper-to-bumper. The Vibroseis sources were activated sequentially for each location, with 32 sweeps, of 16s/4s sweep/listen times per location. The frequency of the sweep signal varied linearly with time with a bandwidth of 6-80 Hz. The FO cable was installed on the production tubing of the well and was cemented within the zone of interest (see Figure 2). DAS receivers were spaced 8 m apart along the cable with a gauge-length of 40 m. The DAS data were acquired with the ‘ODH3’ interrogator unit of Optasense, at 20 kHz sampling rate* and then band-pass filtered to a band of 2 Hz to 500 Hz followed by down-sampling to 1 ms. Seismic data were collected before, during and after stimulation of 8 of the total 19 stages.

**SPIKE NOISE**

Figure 3(a) shows an example of the down-sampled raw-data and Figure 3(b) shows the raw-data correlated with the Vibroseis sweep signal. The receivers in the figures are numbered increasing with depth. Notice that the raw and correlated data contain noise that appears as horizontal stripes (e.g. appears on all receivers at a given time). This is a common observation in DAS data and is linked to time-variant optical noise that occurs equally on all receivers. In addition, we see ringing (vertical stripes) at certain receivers in the correlated data, especially in the receivers right above the plug of the stimulated stage (located at receiver # 432). The data are less noisy below the plug. The ringing masks the wave-field and renders time-lapse interpretation impossible. It is linked to spike-like noise in the uncorrelated data.

![Figure 3](image)

Figure 3: (a) Raw-data (b) Correlated Data. The receivers are numbered increasingly from the top of the well. The data presented here were collected after stimulation of a stage. Note different time scales in (a) and (b): raw-data are 20 seconds long while the correlated data are 4 seconds long.

The spikes in the uncorrelated data are large in amplitude ranging in size up to 900 times the background signal level. These spikes spread out to the entire time record as ringing noise when raw-data are correlated with Vibroseis sweep signal. We observe spikes in data collected before and after stimulation. However, the incidence of the spikes is higher in the deeper section of the well, above the plug of the stage being stimulated, and just after stimulation. It is unclear whether the spikes are caused by large fiber strain or whether some other mechanism, such as problems with the optical hardware, is responsible. Figure 4(a) shows spikes extracted from data at different receivers and from different shot gathers aligned at their peaks. We see that the normalized spikes (see Figure 4(b)) are

* DAS data are purely digital and have no analogue of an anti-alias filter. The optical system tends to generate white noise up to high frequencies and this noise aliases into the seismic band. So it is of interest to sample at the highest frequency possible and than bandpass and resample. The highest DAS sample frequency is determined by the requirement that only one light signal can be in the fiber at any time.
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all similar and decay to pre-spike level within about 150 ms. The spike is steep but doesn’t occur over a single time sample - it builds up to the peak, which doesn’t support the idea of sudden cycle skipping due to large strain. We did not observe any correlation between the height of the peak and the time it took to reach the peak value. We observed similar spike noise in some laboratory data too, even when the cable is not exposed to any external stimulus. The spikes in the laboratory have the same temporal shape as the field data after amplitude normalization. Finally, spike noise was observed in downhole data at some other wells, at all depths, despite the fact that well data are generally very quiet.

**Spike removal:** Spikes are identified by processing one trace at a time. All the data points larger than an amplitude cut-off are identified as points on the spikes and are set to zero. The amplitude cut-off for each trace is set a scale factor times the median of the absolute values of all the data on the trace. Once the spikes are filtered, 32 successive sweeps were median-stacked at a given receiver. Taking a median further suppresses the remnant spikes and considerably improves the data quality. Note that the use of Vibroseis data limited the spikes to a small portion of any given shot signal, which made the spike elimination much more robust.

![Figure 4: (a) Selected spikes from different traces and shot gathers aligned about the peak. (b) Spikes in figure 4(a) normalized by their amplitude.](image)

**DC BIAS**

![Figure 5: (a) DC level as a function of time-of-day during stage 9. DC level is related to the activity in the well and depends on the phase of stimulation: A) Pre-stimulation B) Pressure testing C) Stimulation D) Flow-back. (b) Integrated DC level qualitatively matches the temperature measurements using DTS.](image)

After spike removal, a DC bias on DAS traces was noticed even though, ideally, we expect the signal from the vibroseis truck and the random noise to have zero mean and thus there should be no such bias†. In Figure 5(a), the DC level (mean of trace at each receiver: one number per receiver) for each shot-gather (vibroseis sweep) is plotted at the time when the shot was collected. The figure shows the variation of DC Level with the receiver location and time of day, before, during and after stimulation of Stage 9. The color indicates the amplitude of the DC level and is shown white when no data were collected.

The DC level is approximately zero throughout the well during the pre-stimulation phase. However, in the remaining three phases the DC level varies above the plug (shallower receivers) and is zero below the plug. DC level variation is clearly correlated with the activity in the well and when integrated with respect to time of day, the integrated DC level followed the temperature in the well measured using Distributed Temperature Sensing (see Figure 5(b)). Temperature causes long-period strain in DAS fiber, especially in treatment wells where temperature may change up to 50°C. DTS estimates temperature from the temperature dependent Raman-scattering of the laser pulse in the FO cable and is not affected by the strain in the fiber.

**DEPTH CALIBRATION**

Depth calibration is an important issue for DAS, both for regular VSP and time-lapse measurements. For time-lapse interpretation of hydrofrac monitoring, accurate depths are required to correlate data with well operations. We calibrated the receiver depths using two independent methods: 1) Tube-wave reflection at plug: Tube-waves are waves guided by the borehole fluid that travel along the well and have a linear moveout. We use tube-waves generated from perforation shots fired before stimulation of each stage to identify plug locations. The plug acts as a barrier to the downward propagating tube-wave and reflects it back up (see Figure 6(a)). 2) DC level jump at base of perforations: We have shown that the DC level correlates with the temperature fluctuation in the well. As a result DC level after stimulation has a finite negative value above the lowest perforation and jumps to zero below the lowest perforation (see Figure 6(b)). In general, the plug was within a few feet of the bottom perforation and we refer to both with the generic term ‘plug’. The goal of both depth calibration methods is to identify the fiber channel that corresponds to a known depth in the well (plug) at each stage and assign the known depth to the fiber channel. The depth of the plug is known within couple of feet from the wire-line measurements during plug placement. Both tube-wave reflection and DC level jump are smeared over 5 receivers (about a gauge-length) since DAS averages strain over a gauge-length. We take the middle receiver as the plug location. The plug locations from the two independent methods matched within a receiver.

**PROCESSING FLOW**

The processing work-flow is summarized in Figure 7. As we mentioned earlier, we first remove the spikes from the down-

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† In addition, Optasense applied a bandpass filter to retain data only between 2 Hz to 500 Hz. We don’t know how the observed low frequency energy survives the filter.
Figure 6: (a) Shot-gather of Optasense raw-data collected during the perforation shot of stage #9 shows tube-wave generation. (b) DC level jump across the plug in the field data. The lower figure in (b) is a zoomed in to show the DC level jump across the plug.

Figure 7: Processing Flow

- raw data (downsampled to 1 kHz)
- remove spikes & clip noise
- apply zero-phase bandpass filter (4-8-90-110 Hz)
- apply median filter to remove optical noise
- median-stack the sweeps
- correlate with sweep signal
- apply FX-Decon filter

Figure 8: (a) Pre-stimulation Stack, (b) Post-stimulation Stack before processing. (c) Pre-stimulation Stack, (d) Post-stimulation Stack after processing.

CONCLUSIONS

The field trial showed that excellent quality VSP data can be recorded in a hydrofrac treatment well. We showed that DAS receiver depth can be reliably calibrated using either tube-wave reflections or DAS DC bias. The major sources of noise appear to be spike-like noise probably due to optical hardware difficulties, that is accentuated under noisy conditions. However, a simple spike-removal algorithm does an excellent job of removing the spikes, partly because of the long raw records obtained with a single vibroseis sweep. DAS data may be contaminated by strain due to temperature fluctuations and results in DC bias, but this does not affect the final seismic records and actually is useful in calibrating channel depths. Treatment well data, given its high quality, shows promise for time-lapse monitoring of hydraulic fracturing.

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