Th H 09

Vertical-Seismic Profiling Using a Hybrid Tool, Combining Three-Component Geophones with DAS Sensors

J. Haldorsen* (READ AS), L. Jahren (READ AS), M. Milenkovic (READ AS), T. Hilton (READ AS)

Summary

We introduce a VSP tool combining three-component geophones with Distributed Acoustic Sensing to the surface for optimum image resolution near the target with a maximized lateral image aperture. However, combining VSP measurements made by geophones with DAS data, it is important to realize the difference between a DAS sensor and a three-component geophone, and also between a DAS sensor and a single-axis geophone. We explore these differences in order to create an optimum VSP image.

Introduction

Using sources on the surface and receivers close to the formation structure of interest, Vertical Seismic Profiling (VSP) data are expected to give formation images of greater detail and resolution, compared to surface-seismic data. A receiver close to the target will record the wave field incident on the target, and - a little time later - the wave field scattered off the target. Measuring both the source and scattered fields close to the target should reduce wave-field ambiguities, as well as more independence from detailed knowledge of the formation between the source and the receivers. However, the spatial extent of formation image from VSP data is much smaller than from comparable surface-seismic data. To increase the image aperture, it is desirable to combine receivers that are close to the object with receivers that are further away. Adding the requirement from general wave-field measurements that one should have at-least two measurements per wavelength of the highest useable frequency of acoustic energy (for compressional waves, this typically corresponds to a wave length of about 30 m or 100 ft), one ends up wanting to deploy a rather large number of receivers. With the deepest receiver at a depth of, e.g., 5100 m, instrumenting the well to the surface would require 340 three-component (3C) receivers at 15 m spacing.

A typical recording system used for acquiring VSP data has the capacity of around 120 individual channels. Using these channels three at the time (for 3C recording), one would be limited to 40 levels. A large-scale VSP data set may require around 30000 source firings. Using a shot-point interval of 50 m, the total sailing length of the source vessel is around 810 Nautical miles. If the source vessel can operate at 5 knots, this typical survey would take a full week of un-interrupted operations to complete, while the source vessel fires one shot every 20 s. Doing this survey with 40-level 3C receiver array would require nine settings of this array. If each of these settings is associated with one week of un-interrupted data acquisition the cost in unproductive rig time for doing the survey would be 31 million USD, at rig rates of around 0.5 million USD/day. Taking a more realistic operational efficiency into consideration, this cost, which already is very high, becomes absolutely prohibitive.

As the information from a carefully processed large-scale 3D VSP data set could be used to significantly increase reservoir productivity and enhance the long-term recovery of hydrocarbons, and that such information also could be important for better placement of development wells and injectors, the operator would have to compromise between the desired image aperture, and the cost. On the other hand, acquiring the data with a hybrid system combining 3C sensors for imaging dipping structures near the bottom, with near-continuous Distributed Acoustic Sensing (DAS) to the surface, would allow the complete survey to be done in one single tool setting, and the full survey discussed above could be completed at less than 20% of the rig-time cost. This HybridVSP™ combination is described in the patent by Kjos (2013).

We will look at the characteristics of the DAS data acquired as a part of a recent 3D VSP survey, and consider how the DAS data should be processed for optimal results. Considering that the noise characteristics, tool coupling, and sampling density are very different, we will also discuss how information obtained from DAS data and 3C geophone data could best be combined.

Sensor Arrays

Distributed Acoustic Sensing (DAS)

The emerging DAS technology uses an optical fiber as the sensing element. The technology offers the capability to sample at thousands of measurement points quasi simultaneously, giving a massive acoustic sensor antenna (Farhadiroushan et al., 2009). When a strain perturbation is induced at a section of the fiber, this will result in a change in the phase difference between light returned from either end of that section. So, continually monitoring the phase, amplitude and wavelength of the returned signal, seismic waves interfering with the cable and inducing strain can be monitored from an optical interrogator, which is part of the surface acquisition system.

The DAS solution is in some respect easy, fast to operate - and it allows for a massively long array. A DAS system can be used to illuminate much larger areas than a standard VSP by taking advantage of the shallow section of the antenna without compromising the benefits of having receivers closer to the target for improved resolution. Thus, DAS "sensors" have been used to speed up VSP acquisition whilst instrumenting the entire well. Offshore rig time is costly, encouraging the development of new methods to reduce the use of rig time. This is particularly important for deep-water operations where daily rig costs are the highest. It appears that the DAS technology can offer the advantage of revealing high-resolution details of the reservoir combined with a large-aperture image, while undershooting or delimiting salt domes, gas layers, or gas chimneys. However, the axial $\cos^2$ directivity of the array (Bona et al., 2017), may in some instances limit the usefulness of the sensor array.

Single-component vs. Multi-component Sensors

A DAS array will only measure the component of the change of strain that is parallel to the fiber, and will thus be insensitive to compressional waves arriving perpendicular to the fiber, and to shear waves propagating both along and perpendicular to the fiber axis, neither of which generate a change in strain along the fiber.

A 3C receiver measures three orthogonal components of particle movement generated by a wave front passing the receiver, with the particle movement caused by a passing compressional wave pointing along the ray in 3D space, back to the scattering point. Combining these measurements with the space-time relationship of a propagating wave described by the wave equation, one may generate complete estimates of components of the wave fields scattered from each spatial point in a reasonably large section of space surrounding the data acquisition site. Compressional and shear waves are associated with particle movements in mutually orthogonal directions, and with a single-component sensor, one may have good recordings of either the shear or the compressional components from a given scattering point, but not of both, and one cannot make inference from a relationship between propagation direction of the wave and the polarization of the induced particle movement. One can get decent images from vertical-components-only data, provided the geology is nearly flat and the fiber axis vertical - in which case the reflection must be from a point in the vertical plane through both source and receiver. This is the product delivered by many contractors, possibly contributing resolution, but only little structural information. To get good measurements of both compressional and shear, one would need a 3C sensor that simultaneously measures particle movements in all three spatial directions.

For a measured total travel time, the scattering point could be any point on a 3D isochron surface, composed of all points in 3D space representing equal total travel time along rays from the source via a scattering point to the receiver. In a constant-velocity medium, the isochron surfaces are ellipsoids with the source and the receiver at its focal points. Knowledge of the propagation direction at the receiver of the incoming, scattered wave field, reduces the number of possible scattering locations to two points at the intersection of the ray along this direction with the isochron surface on opposite sides of the receiver (a "180°" ambiguity). To find information about the direction of the incoming ray, you need at-least one 3C receiver. To resolve the "180°" and the "P/S" ambiguities, one would need multiple 3C receivers. A technique for imaging steep structures, involving reverse-time extrapolation of vector wave fields measured by 3C sensors, is described by Haldorsen et al. (2013).

Field Data

Figure 1 shows a close-up view in the common-shot domain of a "singular-spike" noise event. The noise has a sharp onset and a limited temporal duration. The spikes appear to be most significant within a 15m long spatial window, with some shadow beyond this. It is tempting to assume that this noise is originating in a single, band-limited spike in the raw data sampled at 0.25m. If such spikes are not properly removed, one can easily imagine how the spatial smoothing smear this over an interval related to the DAS "gauge length" when the data are spatially re-sampled to 2 m. The figure also shows data recorded by the same DAS sensor over nearly four early loops around shooting spiral for the 3D data. The high-energy spike noise is seen to occur at random times at this display of common-receiver data.

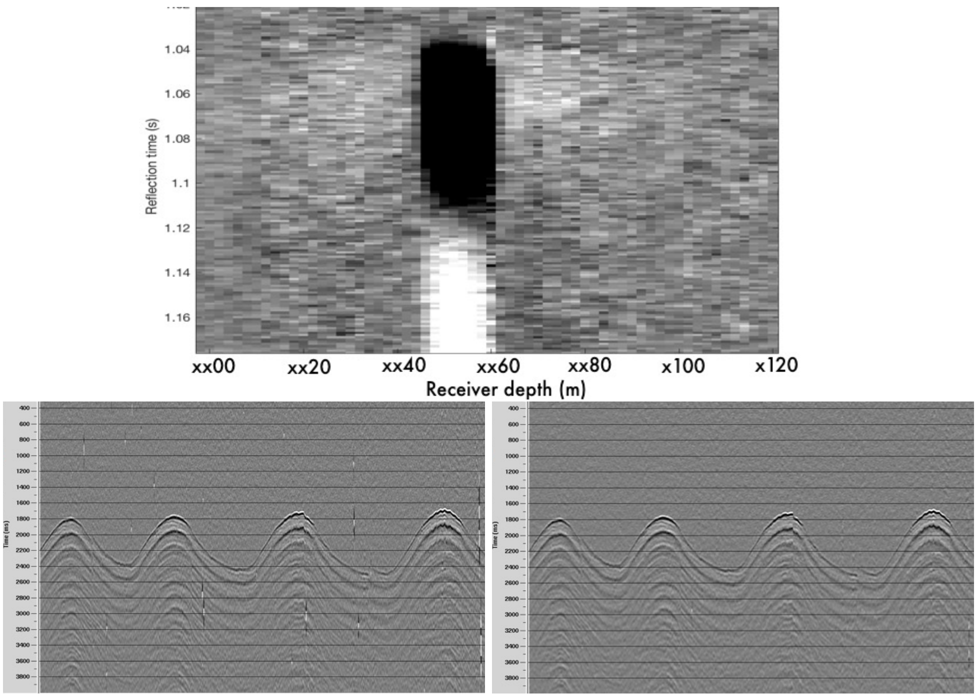

Figure 1 *On top, a close-up view in the common-shot domain of a "singular-spike" noise event. The noise has a sharp onset and a limited temporal duration and appear to be most significant within a 15 m long spatial window, with some shadow beyond this. In the lower left display, we show data recorded by the same DAS sensor over almost four early loops around the shooting spiral for a 3D data set. The high-energy spike noise is seen to occur at random times at a given receiver, and can easily be removed by applying a short spatial filter in the common-receiver domain - as is demonstrated on the display on the lower right.*

Being coherent over 10-15 traces in the common-shot domain, in the common-receiver domain the "singular-spike" noise occurs on a single, isolated trace and is therefore easily removed in this domain by a short spatial median filter. The figure also shows the same data, after applying a three-trace median filter, demonstrating that most of the spikes are gone.

Figures 2 shows DAS data from the 1.4 km deeper section of the well, for a shot recorded about half-way into the 3D survey, when the shooting vessel was close to the rig. Every 20-30 m (10-15 traces), there appears to be a group of channels with a somewhat different response, indicating a non-uniform coupling of the optical fiber in the armored wireline cable to the formation. This may be related to the well being near-vertical, giving quite low gravitational/frictional coupling between the braided wireline cable and the well casing. The figure also shows the well inclination as a function of depth over the same interval of the well. Shallower than 4200 m, the well appears to be nearly perfectly vertical with an inclination of 0.1° or less. The consistency of the DAS data improves when the well inclination exceeds about 1° near the bottom of the section. The improvement in the quality of the DAS data below 4200 m is confirmed by the deconvolved section. Despite the lower fidelity of the data, reflected up-going waves are clearly visible throughout the entire depth range displayed. One should keep in mind that because of the 7.5-fold increase in number of records with DAS data over the 3C data (2 m vs. 15 m), the noise in images from the DAS compared to geophone data should improve by a factor of at-least 2.7 from the stacking done in the migration process.

Imaging with Hybrid VSP Data

Generally, the images obtained from the 42-levels of 3C geophones and the large number of DAS sensors are quite similar and show the same structural features. Because of the different depth in the well, and the difference in directional sensitivity, the emphases are different for the images obtained. The shallower

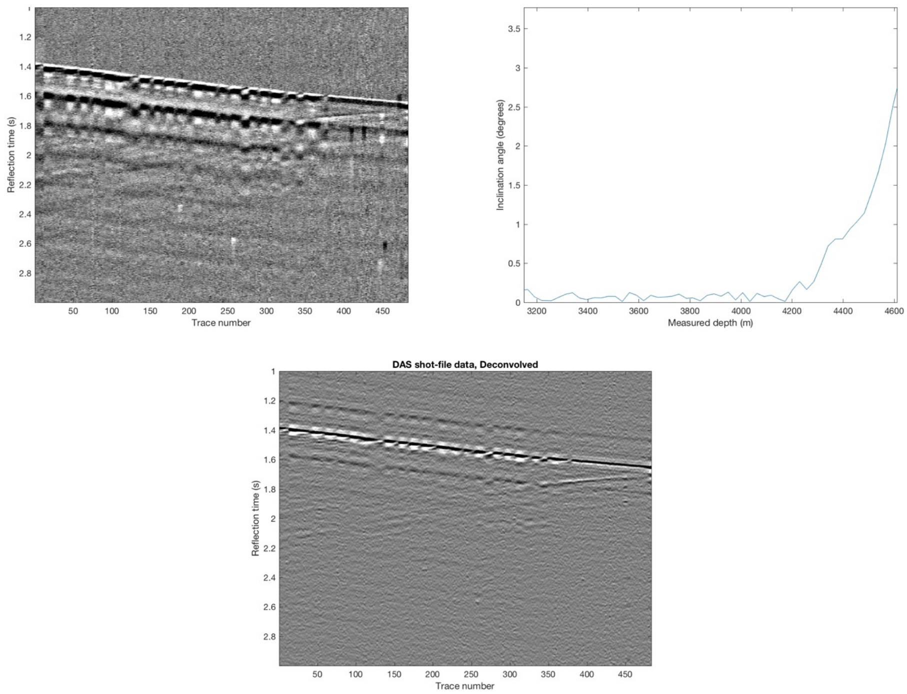

Figure 2 *On the top left, DAS data recorded over the deeper 1.4 km of the optical fiber, for a shot recorded with the shooting vessel close to the rig. On the top right, the inclination for the well, showing a nearly perfectly vertical well, except deeper than 4200 m. Below, the deconvolved DAS data, confirming the improvement in the quality of the DAS data below 4200 m.*

placement of the DAS sensors in the well tends to increase the image aperture over the deeper 3C vector sensors. However, the focused sensitivity of the DAS sensors ($\cos^2\alpha$, where α is the angle between the sensor axis and the particle movement), tends to reduce this aperture.

Conclusions: Lessons Learned

In general, the DAS recordings are noisier than geophone recordings. However, with the 7.5 times denser spatial sampling than 3C geophones, migration stacking will reduce the level of noise by at-least a factor of 2.7 ($= \sqrt{7.5}$). We also saw that deployed inside multiple-layers of un-cemented casing, neither geophones nor DAS sensors give data that suitable for VSP imaging. There appears to be a clear correlation between well inclination and quality of the DAS data. As the inclination rises from less than 0.1° to more than 1°, below a depth of around 4200 m, the DAS measurement shows significantly improved coherency and consistency.

References

Bona, A., T. Dean, J. Correa, R. Pevzner, K.V. Tertyshnikov, L. Van Zaanen, Amplitude and Phase Response of DAS Receivers: 79th EAGE Conference and Exhibition, Extended Abstracts, We A5 13.

Farhadiroushan, M., T. R. Parker, and S. Shatalin, 2009, Method and Apparatus for Optical Sensing: WO2010136810A2.

Haldorsen, J. B. U., T. Hilton, M. Milenkovic, M. C. Schinelli, L. F. Soares, J. E. Lira, A. Zelia, 2013b, Formation Imaging from Three-Component Borehole-Seismic Data Using both Space-time Relations and Wave-Field Polarization: Thirteenth International Congress of the Brazilian Geophysical Society, Rio de Janeiro, Brazil, August 2013.

Kjos, T., 2013, Fiberoptisk og elektrisk seismikksensorkabel for tilegnelse og overføring av informasjon om seismiske hendelser registrert av flere multikomponentgeofoner i et undergrunnsreservoar: Norwegian Patent 335878.