Introduction

A combined DAS-1C on hybrid wireline (4 conductors plus multiple single mode fibres) with 4 traditional 3-C geophone sensors at the bottom was used to acquire a zero offset VSP survey at the Avalon test site facility in Cornwall, Rosemanowes quarry using a seismic vibrator. This was compared with a wireline run from our early prototype development of our Avalon 3-C optical system in the same well for benchmarking (Figure 1). Our test site comprises multiple deep deviated wells with 9 5/8" casing, wells drilled in the 70s as part of the UK Hot Dry Rock Geothermal Energy Research program and is used to test and validate our downhole tools within a controlled environment as part of the R&D program. The wells are water filled in a granite environment.
Multiple DAS partners were invited to participate to the DAS turkey shoot and record independently the DAS data part alongside with ASL recording the 3-C data simultaneously with exact same recording downhole conditions.
The reference downhole antenna is our 3-component geophones array with 4 levels run on wireline from 2000m MD to surface and only a couple of discrete depths were available from the 3C optical system at 1000m MD which was used as benchmark for the comparative and quantitative analysis and leverage the learnings on the ongoing mechanical tool design and optical sensor pack.
The acquired active data enabled many quantitative comparisons between DAS, traditional wireline 3-C geophones borehole seismic data used as reference dataset and our newly developed 3-C optical system fully passive without any downhole electronics. These comparisons allowed the relative merits of cable-deployed DAS systems and 3-C vector sensors to be evaluated using a defined data analysis workflow. In this paper we describe our findings in terms of SNR, frequency responses, vector fidelity, sensitivity, and comment on the current state of DAS technology and 3-C optical point sensors versus 3-C geophones.

Method

The following were quantitatively evaluated to compare DAS measurements versus 3-C point sensor geophones/fibre optic accelerometers and relative performance with the different DAS partners (Figure 2):

- Coupling quality, continuity and consistency in the downhole antenna covering the logged interval of the well.
- Evaluation of direct P-wave Signal-to-Noise Ratio (SNR)
- Evaluation of various optical settings to check impact of Signal-to-Noise Ratio (SNR)
- Evaluation of down S-wave and downgoing tube waves Signal-to-Noise Ratio (SNR)
- Octave decomposition with associated SNRs
- Spatio-temporal down sampling tests
- Depth calibration and registration with Z geophone
- DAS interrogators system noise floor and optical denoising
- Waveforms comparison (angular response, repeatability)
- Time-depth curves, first arrival amplitudes and smoothed interval velocity
- Hodogram analysis for the 3C geophone and fibre optic sensors

For absolute comparisons with geophone data, DAS integration from strain rate to velocity was performed and spatio-temporal resampling applied to match geophone data. Additionally, SNR improvement via common shot stacking (CSG) and common Receiver Gather (CRG) stacking were evaluated.

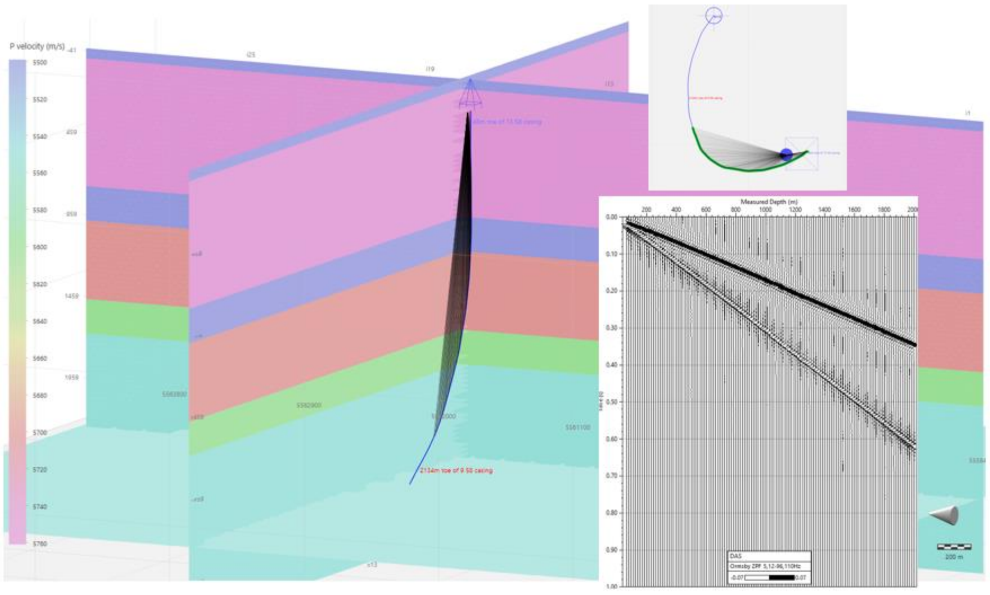

Figure 1 *Zero offset VSP geometry. 3D view and map view of direct P-arrivals. Bottom right show 2.5D ray traced filtered synthetic direct P and P&S arrivals on vertical component only (DAS amplitudes).*

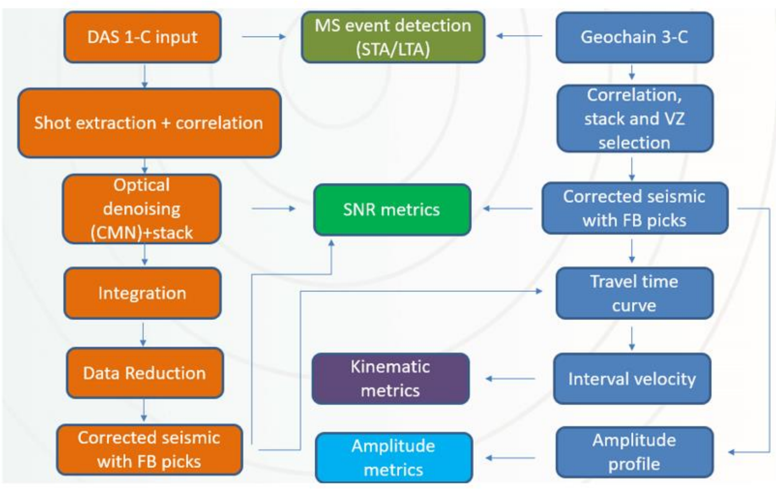

Figure 2 *DAS and 3-C wireline sensors data analysis workflow. The 3-C sensor data is the reference to generate true reference for the quantitative evaluation and comparisons of the DAS VSP data quality.*

Data analysis

The traditional wireline VSP data was of excellent quality and the DAS data was also of good quality over a significant depth interval, although the area of good and consistent coupling was limited to the deviated hole section.
The ZVSP data acquired with both the traditional wireline and DAS methods show good agreement, although the DAS data acquired was originally sampled at 1/1.964/2.04 m using a range of gauge lengths (DAS partner dependent) compared with 15m receiver spacing for the 3-C geophones. Perhaps the biggest difference in the two systems occurs in the vertical sections where the DAS cable appears to be poorly mechanically coupled to the borehole wall even though a small cable slack was tested and applied (Figure 3).
In general, the wireline and DAS data agree well in the deviated well section and the DAS depth calibration (2 points calibration method) is very good (<1m mis-tie). However, there is a clear difference in S/N ratio of around 10-20 dB (Figure 4), which is typical for comparisons between traditional point sensors and DAS data acquired on standard single-mode fibre. Traces recorded by the prototype fibre optic sensors show similar SNR levels compared to the DAS 1-C (Figure 5) in the early stage of our design.

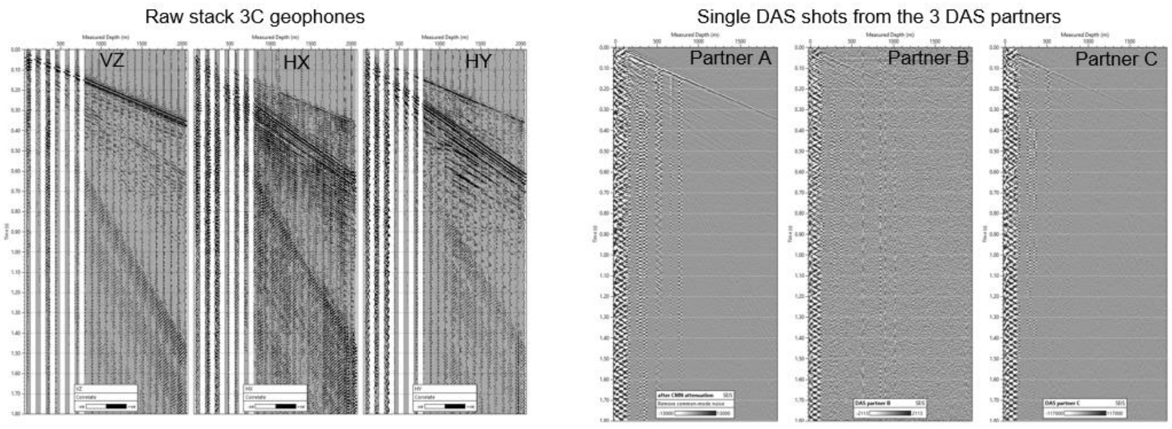

Figure 3 *Left: Raw field 3C data from geophones (VZ/HX/HY components). Right: Single DAS shot from the three different DAS partners.*

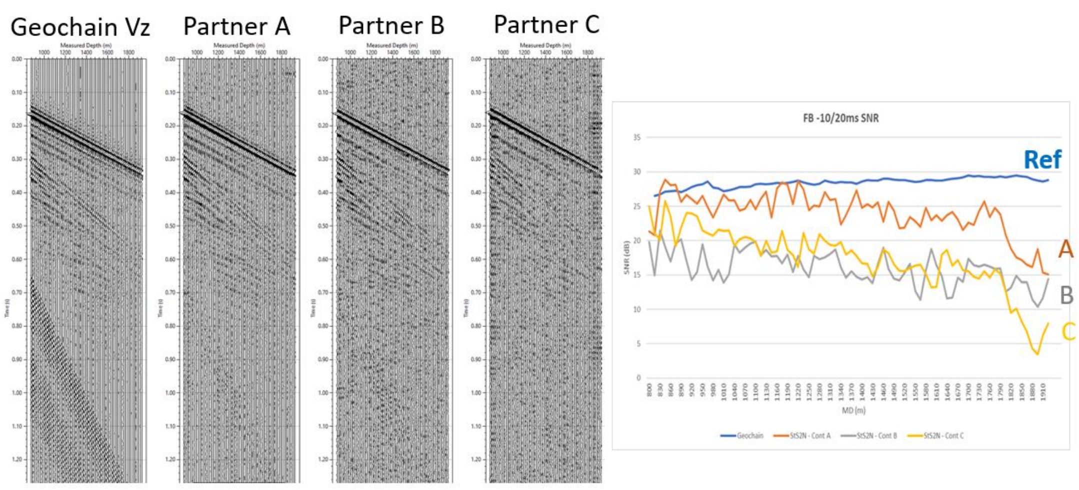

Figure 4 *Left: VZ geophone stacked reference versus DAS for partners A, B and C after pre-processing. Right: First break P-wave SNRs on VZ geophone reference and pre-processed DAS data from the three different DAS partners.*

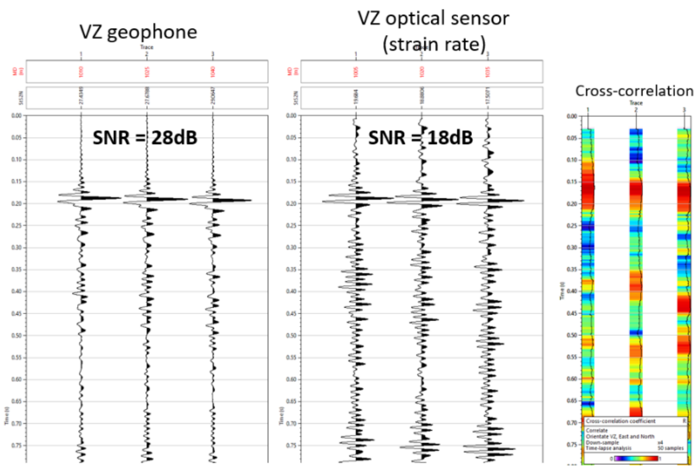

Figure 5 *Left: VZ geophone at three common depths around 1000m MD with optical sensors VZ component (middle) and correlation factor on the right (red is correlation 1 around first arrival at 180ms). SNR from optical sensor is worse than geophone but shows good character match.*

Conclusions

This comparison has demonstrated the quantitative value and relevant metrics (SNR, kinematic and amplitude) of acquiring DAS VSP data in an onshore environment with a hybrid wireline cable-based system. The DAS ZVSP data has been shown to be adequate for basic VSP applications, although the data is still significantly lower quality than traditional geophone data after data conditioning and pre-processing. It has demonstrated that the three DAS partner performances and results are very close, consistent and match very well the geophone data used as reference.
The prototype 3C optical system showed good vertical component response with SNR equivalent to DAS 1-C and lower than our 3-C geophone response. Horizontal components were not included in the analysis at that stage. However, our current laboratory results on vector fidelity of the newly designed slim optical tool have shown excellent results on 3-C vector responses and will be validated with upcoming field trial in our quarry utilizing both vibrator and impulsive airgun source and presented in the near future.
There would be lots of benefits considering the combined hybrid solution for added value between densely sampled DAS receivers and 3-C measurements from the geophones and 3C vector fibre optic sensors. The key issue with any cable-based system is the mechanical coupling of the cable to the casing/borehole wall, limitation to 1-C measurements and lower SNR. Retrievable hybrid systems combining point and distributed sensors could be of value for passive micro seismic monitoring applications (Geothermal, CCUS, etc.…).

Furthermore, those results show consistency in the DAS data quality/fidelity of measurements and robust depth calibration procedures from the three invited DAS partners. It clearly shows continuous improvements in surface DAS interrogators for acoustic measurements, both sensitivity and noise floors have considerably improved over the last few years.
Finally, waveform processing such as denoising/integration and data reduction are key steps to transform and compare DAS data to geophone point sensor for quantitative comparisons. Having access to a reference geophone dataset is helpful in defining data acquisition design, choice of sensing strategy, understanding expectations, and calibrating DAS measurements.

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