Introduction

OKEA, together with JV partners Petoro and Neptune Energy, drilled during 2019 an appraisal vertical well offshore Norway, using surface seismic amplitudes to help defining the prospect. The well targeted an extension of the Upper Jurassic Rogn Formation sandstone which forms the main reservoir of the producing Draugen field. To complement planned LWD data, a high-quality rig source VSP survey was required, delivering reliable time-depth-velocity data and corridor stacks, together with measurements of reservoir pressures. An efficient solution was proposed consisting of using a hybrid optical heptacable to record hDVS/DAS VSP data while conveying the formation tester toolstring. This technique of recording seismic-while-logging can potentially save a logging run and precious rig time. A standard wireline VSP was still planned as contingency, in case real time QC of the hDVS data reckoned that not all objectives could be met.

Similar hDVS seismic while-logging operations were run in vertical wells but not always delivering optimal VSP data (Kimura and Galybin, 2017). In this case study, excellent VSP data quality could be recorded and we present some lessons learnt, which can be of interest and benefit to the industry.

Data Acquisition

The hDVS technology enables reducing the VSP operation time by using a hybrid optical heptacable (Varkey et al., 2008) during normal logging operations. The conveyance cable then becomes a seismic instrument able to measure dynamic strain variations along the fiber. The measurement requires the logging cable to be stationary for a few minutes and in contact with the formation. During this period, a seismic source fires several shots to be stacked, while a laser interrogator sends thousands of pulses per second to sample the backscattered light along the optical fiber. With hDVS, the raw optical phase is digitized allowing reprocessing the data with different gauge lengths (Frignet et al., 2014).

During job design, finite element modelling was performed to determine cable coupling to the borehole wall and using cable slacking in detriment of magnetic clamps was recommended. The equipment deployed included a hDVS Tier-3 laser interrogator box, a hybrid optical heptacable with safe working load of 13 klbs and a 3x250in3 G-gun cluster at 2500 psi and 7 m depth controlled by an in-sea digital gun controller. The hDVS acquisition parameters included a gauge length GL=20.4 m, trace spacing DZ=5.1 m and pulse frequency rate PFR=4 kHz. Pre-job OTDR tests showed optical losses less than 0.3 dB/km along the fiber and a total loss of 4.2 dB. The hDVS system automatically determines the end of fiber (EOF) distance channel, which is then matched to the wireline winch depth. The hDVS depth calibration used a single calibration point, the EOF. The cable helical ratio and the speed of light in the fiber allow calculating the depth. Automatic tools were developed that analyze the optical data to first estimate some optical parameters (pulse width and offset) used in the multi-frequency hDVS design, and then detects the apparent EOF and corrects for the optical delays to provide the user with the true EOF location. The EOF depth channel is computed with an accuracy of about one meter.

Figure 1 VSP survey in semisubmersible used Triple G-guns as rig source auto-tuned with an in-sea gun controller, a hybrid optical heptacable to convey a formation tester and the hDVS Tier-3 interrogator box.
The well design was a slim 2-string design with casing shoe set at 1050 mMD, leaving more than 700 m of 8 ½” open hole. While running in hole, the formation tester tool could not reach TD and the data acquisition was conducted from that hanging point on (around 1519 m), some 100 m above target depth. The optical fiber contact to the formation was greatly improved by giving 20 m slack to the hybrid cable and by stacking 45 shots, good data could be recorded in open-hole but not in cased-hole. While pulling out of the hole, the formation tester probe was set at the casing shoe, 30 m of slack given to the cable and 21 shots stacked. Excellent hDVS seismic data could be recorded up to the seabed (Figure 2).

![Figure 2](image.png)

**Figure 2** Field hDVS stacks recorded in open- and cased-hole vertical sections, exhibit clear first arrivals and reflectors. The data gap corresponds to noisy traces removed around casing shoe. The hDVS data was corrected assuming a linear distribution of the cable slack. The results match well the geophone time-depth data.

Remote real-time QC was performed of both optical parameters and seismic data quality and it appeared that the survey objectives were being met. However, due to the inability to reach TD with the formation tester string, as well as remaining uncertainty in data quality in the cased hole section, it was decided to run in with the VSP geophone array string to see if a different tool geometry would allow a descent to targets and TD. The VSP tool has a significantly smaller diameter than the formation testing tool, hence, it might approach the obstruction differently. Unfortunately, the geophone string held up at the same depth, but it resulted nonetheless in a dataset allowing a full comparison with hDVS/DAS data.

In the right panel in Figure 2, we show that the liner slack correction applied to hDVS depths greatly improves the match with the geophone array time-depth curve. Finite-element modelling of cable behavior might further improve these corrections.

**Data Analyses**

Time picking of hDVS data in this job had an accuracy of the order of 0.5 ms while geophone data of the order of 0.25 ms. The resulting interval velocities have an overall good match (Figure 3). Travel time smooth inversion techniques (Lizarralde and Swift, 1999) are recommended to handle DAS densely spaced data and produce stable interval velocity profiles.

The hDVS VSP useable frequency bandwidth in this survey is 4-80 Hz while for the geophone array it is 4-130Hz (Figure 3). Converting the hDVS moving average strain data (over a gauge length) to velocity would boost the high frequencies but the useable signal remains below 80 Hz. The observed difference is in part due to the different coupling: cable slacking used in the case of hDVS on hybrid cable and an active strong anchoring force in the case of the geophone array. Despite of the hDVS data
on hybrid cable having enough bandwidth to meet the VSP objectives, there are still key differences in SNR between the two techniques.

The hDVS and geophone VSP data were processed with similar standard workflows, which include geometrical spreading corrections, median filter wavefield separation, deterministic deconvolution of upgoing by downgoing and corridor stacking. The hDVS/DAS sensor polarity needs to be taken in account, as it does not flip the polarity of downgoing and upgoing waves as a geophone does. In Figure 3 we show in a transposed VSP display, the zero-phase 4-80 Hz deconvolved upgoing waves for geophones and hDVS surveys. In this type of display, the most accurate data lies in the center making it easier to compare different upgoing datasets.

The match between hDVS and geophone results is very good in this vertical well, with more than one kilometer of high-quality lookahead VSP reflection data originating from rocks far below the deepest sensor. In Figure 4, a synthetic seismogram produced from LWD sonic and density logs and the two VSP corridor stacks, are overlaid on PSTM surface seismic data. The good quality of the well to seismic ties is evident. Both corridor stacks match with the surface seismic data far below the deepest sensor measurements, which is also remarkable.

![Figure 3 Geophones and hDVS velocities (left), native hDVS moving average strain spectra and geophone spectra in dB (middle) and respective upgoing waves (right). The native hDVS data was not converted to velocity, but anchored geophones clearly have higher frequencies (red=0 dB, green=−40 dB). Upgoing waves deconvolved over 4-80 Hz are displayed as Transposed VSPs, where the most accurate data is in the center.](image)

**Conclusions**

In this case study, a VSP was recorded in a deep-water vertical well using hDVS/DAS technology run on a hybrid optical heptacable during logging operations with a formation tester. Excellent VSP data quality could be recorded up to seabed, over 4-80 Hz bandwidth, providing accurate well to seismic tie and over 1 km of quality look-ahead reflection data. This solution not only brings data acquisition efficiency, but it is also intrinsically safer because no additional equipment is deployed in the well. The hDVS data quality met the survey objectives, but during operation uncertainty remained on data quality in the cased section of the borehole. Partly, to ensure data acquisition and, partly, due to the inability to reach TD with the formation tester string, it was decided to run the geophone array to see if a different tool geometry would allow a deeper descent and acquire VSP data in the cased hole section. Unfortunately, the toolstring held up at the same depth but positively this resulted in a dataset allowing a full comparison with hDVS data. The results compared very satisfactorily.
The lessons learnt in this case study can be of interest and a benefit to the industry in a time when the pressure on the Operators is high to reduce cost. Such cost-effective solutions may help geoscientists overcome internal resistance towards the cost associated with recording VSPs and revive their use by allowing the measurements to be performed simultaneously with essential wireline logging such as formation testing.

![Figure 4 Seismic to well tie in showing hDVS and Geophone corridor stacks over 4-80Hz and 35Hz Ricker synthetic. LWD density log available over only deeper 200 m may. An excellent match VSP is observed with the PSTM surface seismic., with over 1 km of quality lookahead data.](image)

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**References**


