A new era of borehole measurements for permanent reservoir monitoring

Garth Naldrett[1] explains why Distributed Acoustic Sensing offers new opportunities for VSP measurements, especially where the efficiency of measurements on a permanently installed cable makes borehole acquisition viable.

The year 2020 was one of significant challenge and change. We have seen a global pandemic taking control of our personal lives, the business environment and society in ways we could not have imagined at the start of the year. The immediate impact of global lockdowns and reduction in economic activity was a precipitous decline in the oil price. At the start of the year WTI was trading at more than $63 per barrel, by February initial concerns over limited disruption reduced WTI to $50 per barrel before reaching the now famous negative trading values in April 2020. The response to record low oil prices was rapid cuts in operational budgets and deferred or cancelled Capex. The pandemic also resulted in significant travel restrictions, with countries closing their borders to foreign travel, making international operations increasingly complex to access, undertake and support.

Despite the economic, political, and operational factors Distributed Acoustic Sensing (DAS) VSP operations have not only continued, but 2020 became the busiest year for DAS VSP acquisition against a trend of declining activity in conventional borehole seismic measurements. Multiple installations and surveys have been carried out in most of the major geographical areas in onshore, offshore and deepwater subsea environments. This growth has also been fueled by significant technical advances, broader acceptance, and a wider range of applications. In addition to conventional oil and gas fields DAS borehole seismic measurements have been used for the monitoring stimulation of unconventional reservoirs (Byerley, 2018), enhanced geothermal systems (M. Mondanos, 2019), methane hydrates (Lim T.K., 2020), hard rock mining (Bellefleur, 2020) and CO_2 injection (M. Dean, 2019). In the case of the latter DAS is an important component for measurement, monitoring and verification (MMV) of the containment and conformance of the CO_2 storage. Not only can a DAS VSP monitor the dimensions of a CO_2 plume, but the same fibre-optic installation can also be used to verify wellbore integrity. There are many expectations the industry will use existing subsurface expertise to pivot from hydrocarbon production towards carbon storage, with BP forecasting capture and storage of between 4Gt and 5.5Gt of CO_2 by 2050 (BP, 2020). CO_2 injection monitoring is therefore likely to be a meaningful application for DAS technology.

There has been a significant change in operating behaviour in 2020, some of it related to the pandemic, or at least the pandemic accelerating implementation. The low oil price has placed even greater importance on operational efficiency. While this has resulted in cuts and deferment in seismic campaigns DAS VSPs allow data to be collected with minimal crew on the wellsite, most importantly without rigging up intervention equipment for wells where fibre is already installed. Remote operations have become both an economic necessity and operational requirement due to travel restrictions and the risk or presence of Covid at the work site. Night shifts and back-up support are now often covered by personnel working from home. This not only reduces operational risk, but also lowers the costs associated with travel. While most seismic surveys require mobile sources there are now several installations with permanently installed DAS interrogators as well as multiple permanent seismic sources, such as Surface Orbital Vibrators (SOV) (J. Correa, 2018). This allows time lapse DAS VSP acquisition to take place on demand, entirely remotely, with no crew on site.

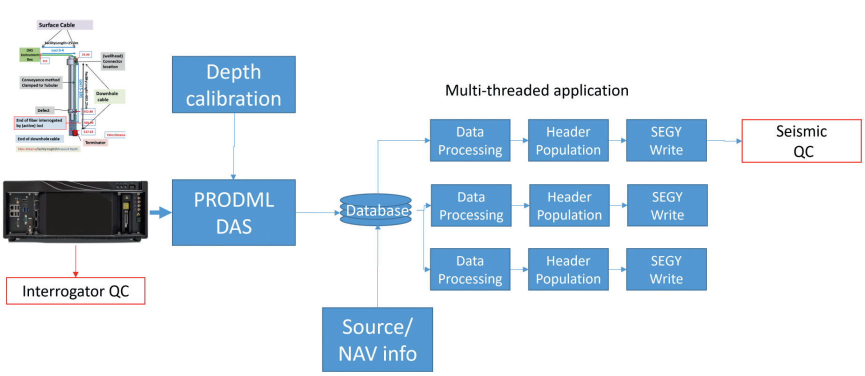

Figure 1 Data workflow for DAS VSP acquisition.

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The remote capability has been enabled through Edge computing. Due to the high data volumes, typically 2TB per well per day for seismic acquisition, a lot of crew time had previously been spent on the movement and management of large data sets. In 2017 Silixa trialled Edge computing for offshore seismic acquisition. This involved placing a high-performance edge server on the platform, running multi-threaded applications for the real-time processing of seismic data sets. Several tasks were automated, such as spatial diversity stacking, depth calibration, shot extraction, SEGY conversion, SEGY header population and data QC. This significantly reduced the field engineer's workload, as well as the volumes of deliverable data. Processed SEGY files were created offshore rather than moving high volumes of raw data DAS data to shore for conversion. As the DAS and edge server are accessible through the operators' network these activities could now be performed from shore. As the applications are multi-threaded it is possible to simultaneously process high-resolution data, to be used for imaging, at the same time as smaller lower-resolution data sets to be transmitted for real time onshore QC. This automation is especially important as the number of wells on the platform being simultaneously monitored is increasing.

Subsea monitoring

Successful case studies shown on land and platform installations naturally created interest in deploying DAS technology in subsea wells. The combination of reduced availability of data from subsea fields and a more complex environment creates a strong argument for permanent monitoring systems. Some of the environmental complexities include source multiples, ambient and source generated noise and geological challenges. These are all areas where DAS VSP acquisition can offer advantages of conventional streamer or surface acquisition systems and provide higher-resolution images (van Gestel J-P, 2019).

Previous publications (Naldrett G, 2020) have described how, by using engineered fibre with high reflection, the DAS interrogator can be mounted remotely, at the surface facility. The first installation of an engineered fiber for ultra-deepwater subsea DAS VSP acquisition took place in 2020 (G. Naldrett, 2020). Future installations and 3D VSP acquisitions are planned for 2021 and beyond, offering a game-changing technology for subsea fields which typically suffer from a lack of data.

These systems allow up to 10dB of one-way optical loss between the interrogator and the well. This is equivalent to 50 km of fibre distance, but the range is substantially reduced by subsea connectors having high optical losses. A typical wellhead feed-through system involves about 3dB of optical loss (equivalent to a range reduction of 15 km). The umbilical from the surface may also have several connections, effectively reducing the range even further.

To extend the range and performance of the Subsea DAS interrogator further enhancements have been introduced. These include the use of signal amplification from surface, enhancement of the optical path in the umbilicals and optical signal conditioning, routing and amplification subsea. This has allowed us to demonstrate operation with more than 25dB of one-way loss between the interrogator and subsea well. This increases the range to more than 125 km and makes almost all subsea wells and tie backs accessible from a surface-mounted interrogator while still maintaining a good signal-to-noise ratio.

Subsea systems are carefully engineered and tested such that the entire system of interrogator, umbilical, connectors, and engineering of the fibre can operate together to achieve the application requirement(s). The implementation requires interaction between multi-disciplinary teams consisting of geoscientists, petroleum engineers, completion engineers, subsea engineers, facilities teams and information security and technology. The engineering, planning, project management and operational execution are all vital for ensuring a successful outcome.

Not only has DAS VSP shown promise for offshore and subsea monitoring, but there is an immediate application using existing subsea cables for active and passive DAS surface seismic monitoring. In 2019 BP (Zhan G, 2020) showed the potential for active DAS surveys on the BP Atlantis field, where a DAS interrogator was connected to fibres in an umbilical originally installed for communications purposes. Despite their relative age there was no degradation in the fibres and the umbilicals were able to detect active sources more than 25 km from the umbilicals. Although at the time of publication BP had not yet performed any imaging using these data sets, it did confirm reflected waves were present, offering the potential for use in reservoir imaging. As the umbilicals extend to the surface there are potential applications for better understanding water velocity and free surface multiples by the direct measurement of these waves. Given DAS applications in subsea wells would require fibres in the umbilicals, we see these have been used for increasing the extent of the image when acquiring subsea DAS VSP data.

Fibre enhancement

Although often overlooked, the downhole fibre is an integral part of the monitoring system and should go through the same design rigour as the interrogator. Until recently standard single mode fibres have typically been used for DAS acquisition. While they provide low loss, they also provide limited reflection or scattering of the Rayleigh light on which DAS depends. The amount of scattering also varies in space and time along the fibre length. This can create an issue for some designs of interrogator and manifests itself as a varying SNR along the length of fibre, often referred to as fading.

To improve the signal-to-noise ratio (SNR) DAS manufacturers have investigated techniques to improve the reflection within

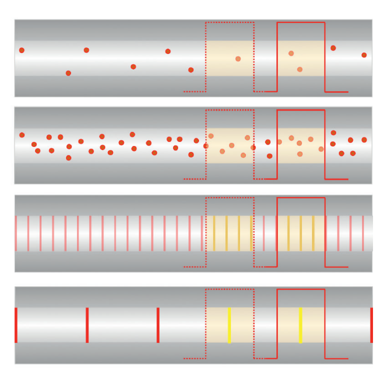

Figure 2 Optical scatterers in standard, enhanced and engineered fibres.

the fibre, and therefore provide more optical power to the DAS interrogator. Three types of enhancement are typically considered and are often commonly referred to as Enhanced Backscatter Fibre (EBF) or engineered fibres. The three types of enhancement are highly doped fibres, continuously enhanced fibres and engineered fibres. While the highly doped fibres create more reflection, they also significantly increase the loss and are therefore normally only suitable for short lengths, if at all. Continuous enhanced fibre provides more signal, with lower loss than doped fibres, but with no control over the phase relationship coming from multiple scatterers and therefore limiting how effective they are at improving the DAS SNR. With engineered fibres the location and reflectivity are accurately controlled and matched to the DAS interrogator. Each fibre can be designed and optimized along its length for the application requirement, be it seismic acquisition, well integrity monitoring or production profiling. These factors can be tuned for the expected wavelengths and spatial resolution of the monitoring system, offering a 20dB improvement of the SNR compared to standard single mode fibres.

The changes described above take place in the core of the fibre, within a typical diameter of 9um. The rest of the fibre is unaffected and can be run in a standard downhole cable of the type shown in Figure 3. The cables normally have a square outer polymer encapsulation of 11 mm, inside of which there is a ¼-inch stainless steel tube providing pressure isolation and mechanical protection to the fibres in the centre. Drilling and completion teams are very familiar with deploying this style of cable on the tubing string as they closely resemble existing electrical and hydraulic lines used for safety valves, chemical injection and downhole gauges.

Figure 3 Downhole cable with engineered fibres, standard single mode and multimode fibres.

Fibre Longevity

While the SNR improvements are a key parameter for successful seismic acquisition, for permanent installations it is also vital to ensure these improvements do not affect the reliability and longevity of the fibre. There have been many reports regarding hydrogen darkening in downhole fibres over the past 20 years (Wallace, 2004). Hydrogen darkening occurs when free hydrogen atoms physically bond with $Si0_2$ glass compound, forming H_2 and hydroxyl (OH) peaks at 1240nm and 1385nm optical wavelengths respectively. These attenuation peaks can occur within a matter of hours, increasing loss by many dB/km and effectively rendering the glass 'dark' to the DAS interrogator. Potential hydrogen

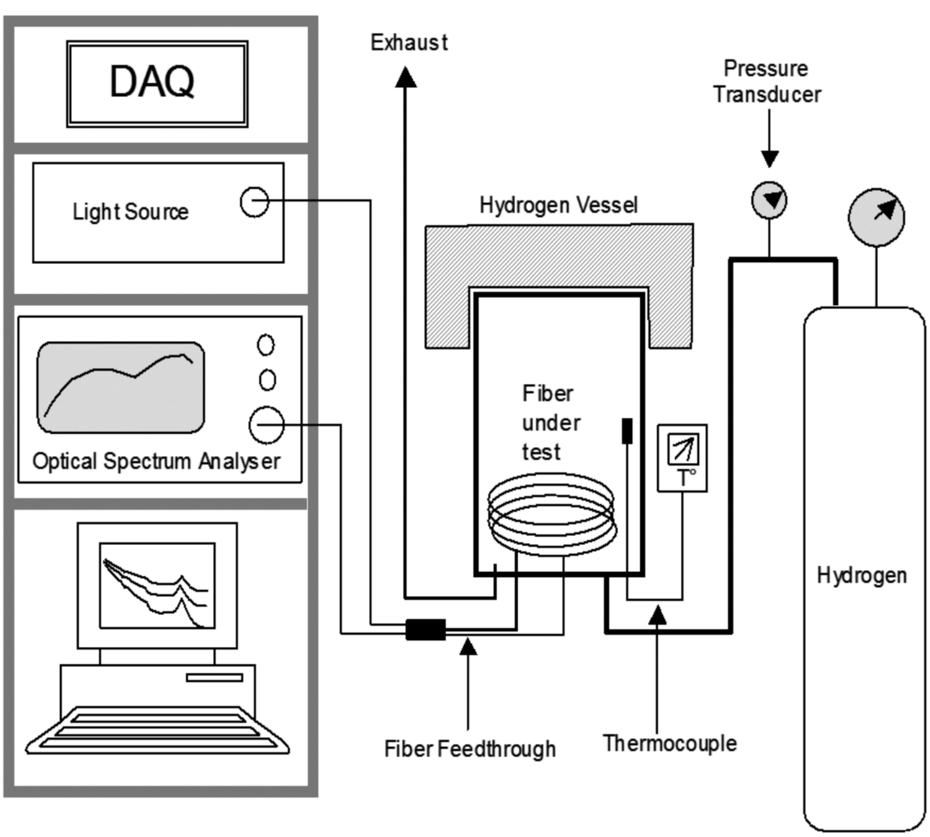

Figure 4 Hydrogen vessel set-up for fibre testing, as defined by Seafom standards (Seafom, 2013).

sources include corrosion, hydrogen traps within the stainless-steel layers of the cable, as well as the reservoir and wellbore environment. While mitigation is possible, such as use of hydrogen scavenging gels and metal barriers within the cable, it is impossible to entirely remove the hydrogen. For this reason, it is important to ensure any enhanced or engineered fibre has at least the same resistance to hydrogen as specialty fibres developed for oilfield use. The methods employed for protection are normally proprietary, involving either glass chemistry, hermetic barriers, or a combination of these two. To ensure suitability, fibres can be tested according to oilfield industry standards (Seafom, 2013). This is a highly accelerated lifetime test (HALT) where the fibre being tested is exposed to high concentrations of hydrogen at representative wellbore temperatures for periods of days or weeks. An example of a successful test is shown in Figure 5, where there is no change in optical loss at the wavelength of interest (1550nm as shown by the red arrow). Figure 6 shows a fibre that has failed the same test, with losses increasing after 250 hours and finishing with a 2.8dB increase in loss at the wavelength of interest.

Opportunities

While the primary application for installing a permanent reservoir monitoring system might be seismic acquisition, the same Distributed Fibre Optic (DFO) system can create additional value through supplementary applications such as leak detection, artificial lift optimization, out of zone injection (OOZI), sand detection, stimulation monitoring and flow profiling. A recent paper on the BP Clair field in the North Sea (Sadigov T, 2020) discusses the benefits of co-interpretation of DFO-derived inflow data with seismic data. The inflow data was able to correlate flow with a

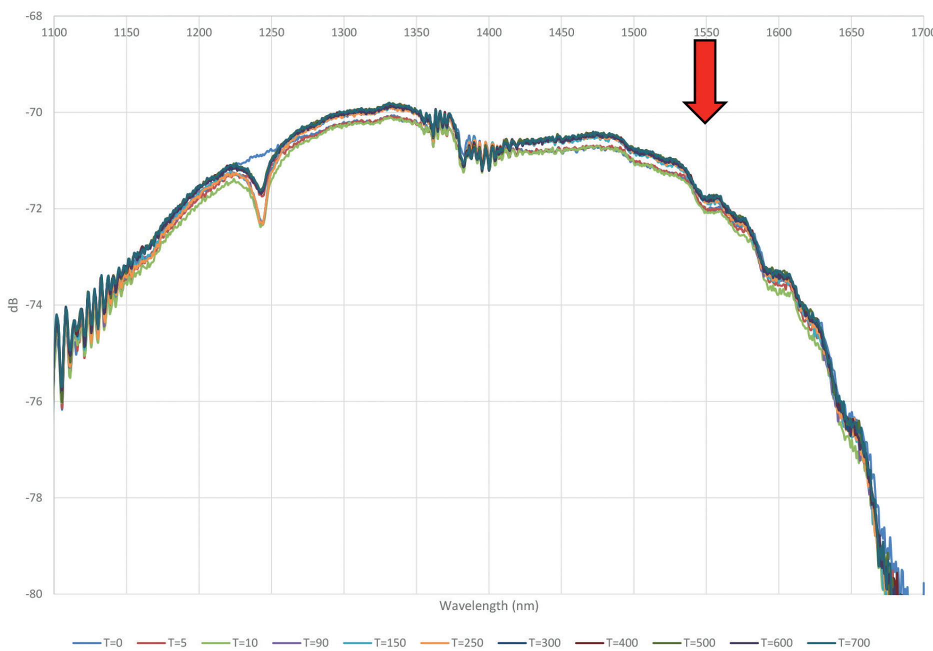

Figure 5 Constellation(TM) engineered fibre after 700 hours of accelerated testing.

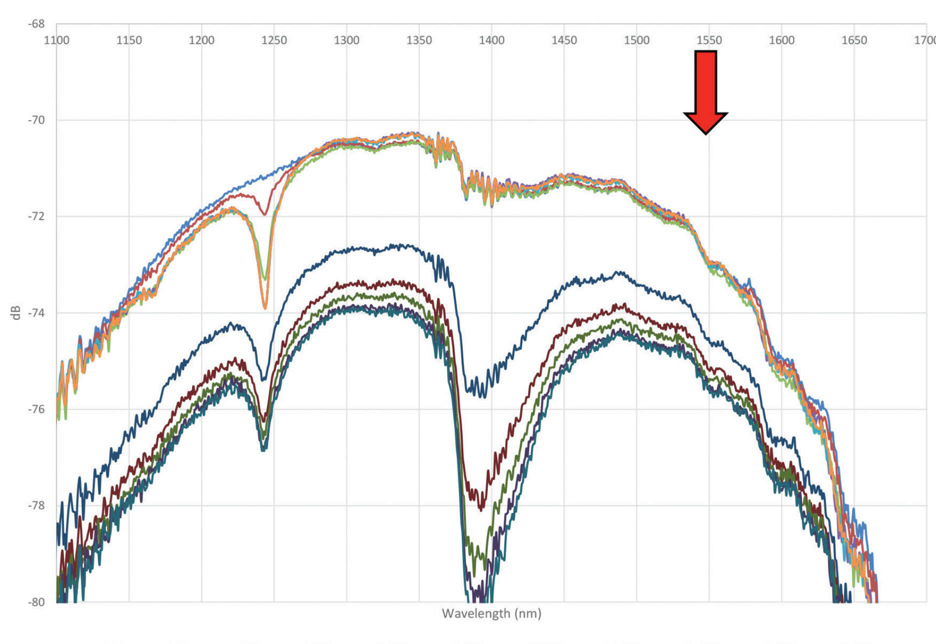

Figure 6 Standard fibre demonstrating high loss after 250 hours of testing.

seismic fault. The inflow data allows a higher spatial and temporal resolution of flow in the near wellbore region than is possible with 4D seismic but combing the inflow data with the far field information from 4D seismic data offers the best solution for effective reservoir management. The recent success of fibre-optic downhole wet connect systems will undoubtably allow more opportunities to merge seismic and inflow technologies and interpretations.

Conclusions

Distributed Acoustic Sensing offers new opportunities for VSP measurements, especially where the efficiency of measurements on a permanently installed cable makes borehole acquisition viable. The ability to perform repeat measurement at low cost is especially attractive where time lapse monitoring of injection or production can improve reservoir monitoring. The remote monitoring capabilities, enabled by Edge computing, are leading to significant reductions overall in acquisition costs. Engineered fibres offer the opportunity to significantly increase the signal-to-noise ratio by providing more optical signal, but the impact of fibre lifetime needs to be considered as part of the selection process.

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