Using advanced fibre-optic point sensors at high temperatures to expand downhole deployment use cases

Brett Bunn[1]* and Paul E. Murray[2] present a new fibre-optic sensing system, which consists of a highly configurable suite of 3-component optical point receiver accelerometers for true vector wavefield recording at temperatures and pressures beyond the capability of any electromechanical system.

Introduction

Downhole tools provide essential data required to better understand subsurface conditions. Unlike other geophysical survey methods which must infer depth from some inverse method, downhole tools provide direct depth-dependent measurements that are critical as both primary investigation methods and complementary 'ground truth' measurements to calibrate the larger geophysical reconnaissance surveys that are part of the exploration and development life cycle. This improved knowledge reduces risk and allows operators to make field development decisions with lower costs, fewer dry holes, and better hazard mitigation. The ultimate representation of this kind of geophysical risk management is the reservoir monitoring system—installing sensors and data telemetry equipment on a permanent (or semi-permanent) basis to provide highly repeatable, time-dependent measurements which can be correlated with the production and drilling data to provide real-time subsurface monitoring and surveillance. Just as with reconnaissance surveys, the role for downhole measurements is equally important for long-term monitoring, and building a tool that can survive for months or years in the downhole environment remains a well-understood challenge for equipment manufacturers.

In some downhole environments, 'traditional' electromechanical sensors such as geophones and hydrophones perform adequately over long periods of time. Many companies (including Geospace Technologies) market downhole tools with arrays of these sensors to that end. For other applications, the downhole environment quickly turns hostile for sensors that work reliably in relatively benign environments. Operators are increasingly drilling deeper where temperatures and pressures increase to the point that no traditional sensor can survive long enough to provide more than a single set of reliable measurements. It is also not simply a matter of the sensors themselves surviving the duration; the sensitive electronic components in the downhole data acquisition and telemetry systems required to bring those measurements to the surface cannot withstand the pressure, temperature, and chemical hazards any better.

As we look towards the future of cleaner energy production on this planet, geophysical methods are now being tasked to manage risk in new markets beyond oil and gas exploration, and the hostile environments for our geophysical sensors are simply multiplying. When one considers the requirements of performing continuous, reliable subsurface monitoring for a geothermal energy production facility or a carbon capture, utilization, and storage (CCUS) reservoir, we see the problem. The hostility of the environments the market demands our sensors must work within will only increase going forward.

Operators that have attempted to use traditional downhole tools in these harsher environments now have given us a compendium on their usable lifetime in extremis (refs. 3-8). An early alternative with an equally large body of documentation is the use of fibre-optic distributed acoustic sensing (DAS) technology (Hill, 2017). The results of DAS experiments are decidedly mixed at best; while the fibre itself can survive in scenarios where electromechanical systems fail, the data suffer from inadequate coupling, low resolution, poor signal-to-noise ratio, and lack of directionality (i.e., the vector nature of the wavefield is lost). While proponents of DAS technology assert that it is a simple matter to convert the measurement of optical phase in these systems to strain (and therefore to particle motion and wave propagation), there are several assumptions about both the nature of a distributed sensor and the methods by which these systems attempt to interrogate specific sections of fibre that complicate the issue. Electromechanical sensors that are small relative to the wavelength of interest can easily be treated as point receivers, and the methods for calibrating the output of a point receiver to an exciting seismic (or acoustic) wavefield are well known to those skilled in the art. For distributed sensors, this is decidedly more complicated, and for some embodiments of DAS-type systems, impossible to truly calibrate sensors for the rapidly varying conditions as may occur in a dynamic borehole environment.

This is a serious complication because the standard for high-fidelity 4D petrophysical characterisation for a reservoir has been set using high figure of merit multi-component point receiv-

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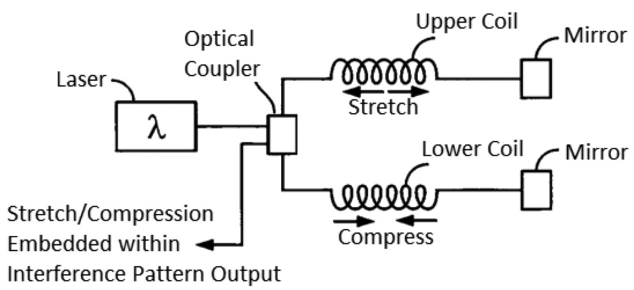

Figure 1 A diagram of the optical interferometer of the type used in the Insight downhole system.

ers with high vector fidelity. To see the subtle changes in seismic wavefields that arise from changes in the subsurface conditions, we need the calibrated output and accuracy of traditional sensors with the additional requirement that the sensors can survive in all deployment environments for decades.

We seek to address these challenging complications with fibre-optic point receivers. To accomplish this, Geospace Technologies developed the Insight™ by OptoSeis® downhole fibre optic sensing system, which consists of a highly configurable suite of 3-component optical point receiver accelerometers for true vector wavefield recording at temperatures and pressures beyond the capability of any electromechanical system. We have recently completed a field demonstration of this system and provide a brief introduction to the technology and our field test results which demonstrate fitness for the proposed applications.

Fibre optic point sensors past and present

The fibre optic accelerometer as point receiver is a mature technology that has been used for decades but has only been used in exploration seismology since the early 2010s. Notably, OptoSeis developed the world's first deep-water reservoir monitoring system for the Jubarte field in 2012 (Thedy, 2013, Seth, 2013) using these types of sensors. Those optical accelerometers, like those in the Insight systems, are a variant of the Michelson interferometer first used in the Michelson-Morley experiments of 1887. As particle motion causes each leg of the interferometer to change length with opposite polarity, a laser interrogator directly and continuously extracts optical interference phase of the interferometer, within the demodulator and delivers real time particle motion to the data acquisition system (Figure 1). Optical interference phase is filtered to the desired bandwidth and scaled to acceleration units with ultra-high dynamic range and a high degree of linearity, meaning the resulting measurements are repeatable even as the environment around the accelerometer (temperature, pressure, etc.) changes. The data acquisition itself is time-continuous, i.e., the optical data recorded from each sensor are from individual signals which are then digitised. The same types of sensors were also deployed in high density, high channel-count 3D land systems (with 1C sensors) by OptoSeis. It is this combined experience with multi-component subsea sensors and land systems that created the enabling technologies for this downhole system.

The Insight system is an all-optical monitoring solution with no electronic components in either the downhole components or telemetry cabling. The laser interrogator/data acquisition system can be anywhere from adjacent to the borehole to tens of kilometres away in a remote location depending on the use case. The sensors themselves are discrete 3-component fibre-optic accelerometers designed for slimhole tools to accommodate any sized wellbore and borehole deviations. The number of sensor stations and spacings are highly configurable, allowing users to simultaneously acquire hundreds of multi-level, real-time continuous 3-component measurements of the vector wavefield.

The downhole components of the Insight system are rated to operate for years at temperatures up to 150ºC with a maximum pressure rating of 20,000 psi. Since there are no electronic components throughout the telemetry, this system has the added advantage of being immune to electromagnetic interference (EMI) as either an EMI source or receiver.

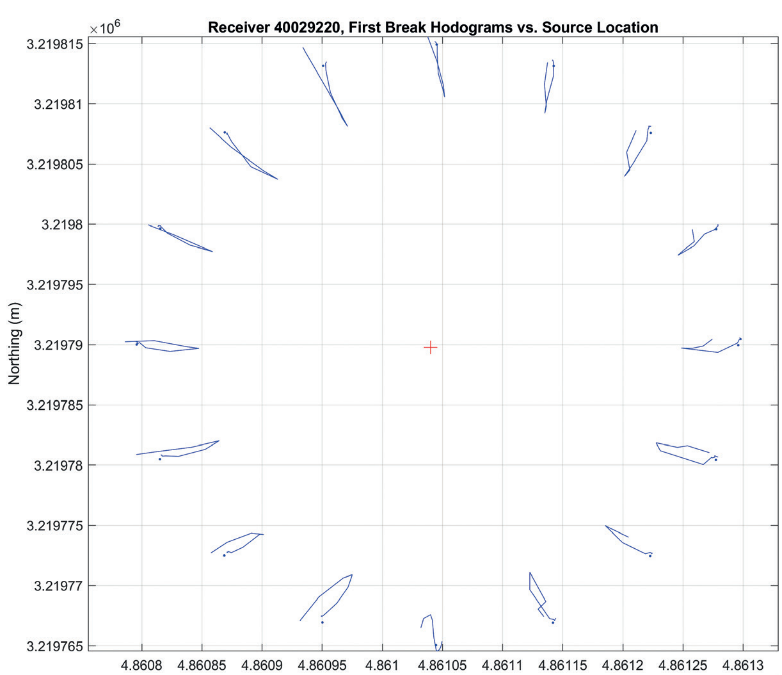

Figure 2 Hodograms of the X-Y plane projection of the direct arrival waveforms from the circle of sources onto a single 3-C sensor station. The data have been rotated from the Galperin configuration to an orthogonal basis for display and interpretation.

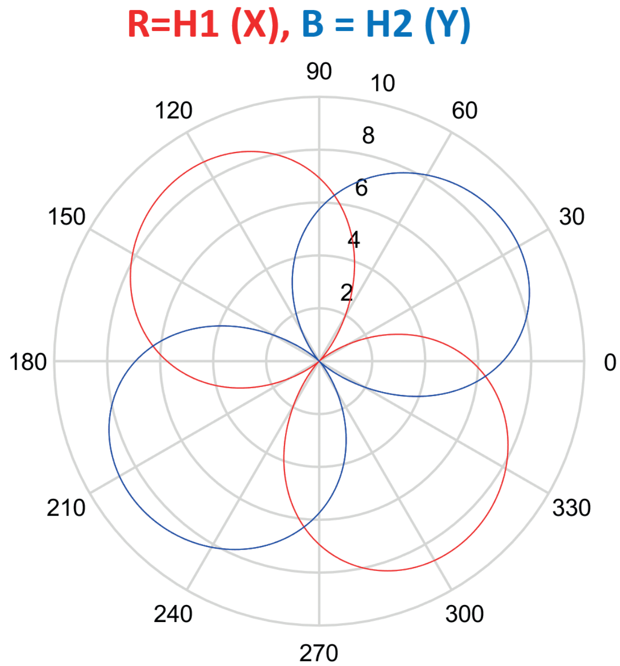

Figure 3 Semblance analysis revealing the underlying radiation patterns of the rotated sensors. From the dipole radiation patterns we can see the sensors within this station are behaving as independent sensors that are mechanically coupled to the environment and not interfering with each other.

With this combination of data acquisition features and survivability characteristics, we believe this tool is suitable for use in active source VSP surveys, 4D time lapse monitoring of P- and S-wave behaviour related to changes in subsurface stress conditions, microseismic (passive) recording of induced seismicity, check shot surveys, and cross-well tomography in a variety of conditions and depths previously unavailable to geophysicists.

New markets and relative cost

It bears repeating that while the use cases for downhole seismic measurements in oil and gas development are well known to the working geophysicist, the emerging new energy markets are creating opportunities to apply these technologies to new problems with similar limitations. CO_2 injection wells utilise high pressures and temperatures; the hostile environments of both natural and purpose-built closed-loop geothermal systems are self-evident. The primary design challenge for tools to work in these applications will be their ability to survive at duration in those environments. Now, fibre-optic solutions represent the state of the art.

It will also be pointed out there is a significant cost difference between DAS and discrete sensor fibre-optic systems (or between DAS and traditional multicomponent VSP tools). If the resulting data are too noisy, do not measure the directional nature of the wavefield, or cannot discriminate seismicity from other environmental changes, the authors suggest these represent real opportunity costs which must be factored into any evaluation of a geophysical tool that is being proposed to mitigate their E&P risks.

Field test results of the fibre-optic 3C downhole tool

In the Spring of 2023, Geospace performed a field test of the Insight tool at the Devine Test Site in near Devine, Texas, operated by the Bureau of Economic Geology, University of Texas at Austin. In this test, we deployed a five-level, 3-component downhole testing tool with magnetic collar clamps on each receiver station down a 1,417-metre steel-cased well. During this field test, we acquired two suites of data to examine different aspects of the sensors' performance in a real-world setting. One suite of data was acquired using a circle of near-offset source points arranged in 22.5-degree increments around the wellbore. The second suite of data was acquired as a walkaway VSP with shot points at regular spacings along a radial line in a constant azimuth from the wellbore. We acquired both using an accelerated weight drop source.

The purpose of the circular arrangement was to analyse the vector fidelity of the sensors. In Figure 2, we see a plot of the hodograms of the direct arrival waveform projected onto the horizontal plane after rotating the data from their Galperin in situ configuration to an orthogonal arrangement. Using the

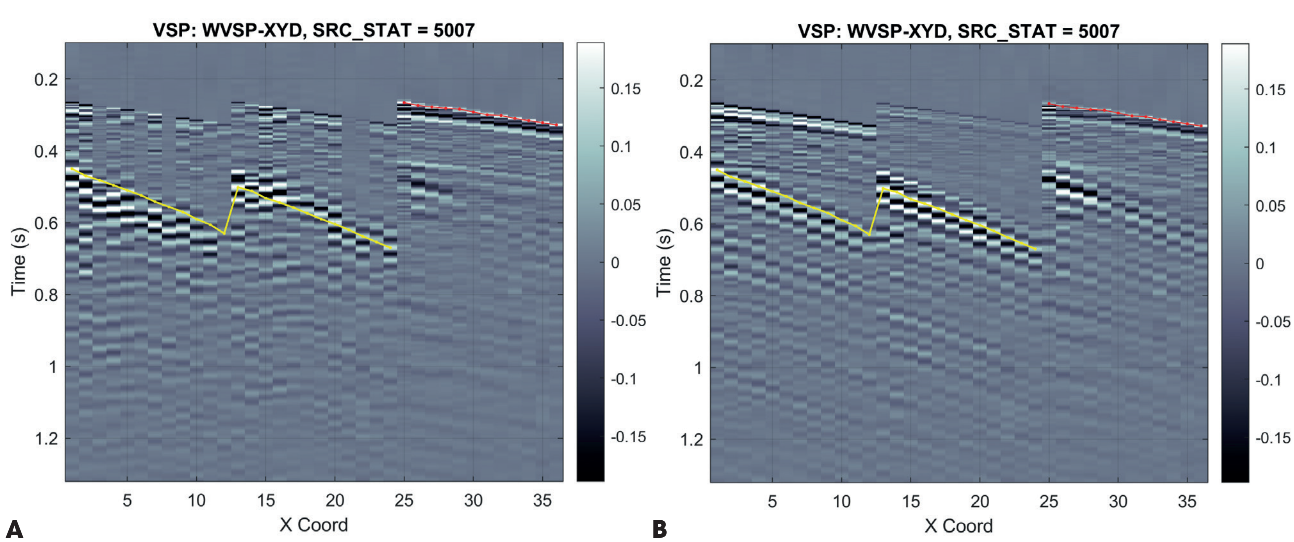

Figure 4 Unrotated data from a mid-distance common source point into the receivers shown in A), and the data rotated to the fast (N68W) and slow directions corresponding to the regional anisotropy in B).

methods of Murray et al. (2016), we rotated the data through the entire circle and computed the semblance at 1-degree increments to recover the actual radiation patterns of the sensors (Figure 3). We interpret these results to show that the individual sensors in each 3C station are well coupled to the environment and are neither mechanically nor optically coupled to each other. The orthogonality of the resulting radiation patterns with deep nulls shows the individual sensors behave as independent dipole sensors.

Examining the data from one of the common offsets of the walkaway VSP (Figure 4), we observe down-going P- and S-waves emanating from the vertical point source. Rotating the data to the known maximum and minimum local stress directions, we can see the S-waves organise into fast and slow components as predicted by the local anisotropy conditions. Localised changes in subsurface fluid pressure conditions can be inferred from these measurable changes in anisotropy. While such vector wavefield measurements are considered de rigueur for electromechanical multi-component sensors, this type of directional wavefield analysis is beyond the capability of current DAS offerings. The ability to measure S-wave polarisation changes will be a key factor in any system used to monitor subsurface fluid movement and changes in stress in either storage or recovery.

Conclusions

The future of borehole seismic data is one that is not suited to the last generation of electromechanical sensors. The demand for better seismic data in more hostile environments will only increase with drilling depth, and the emerging markets of CO_2 sequestration monitoring and geothermal energy will only increase that demand to operate where traditional sensors cannot work. DAS systems may function better in these environments, but they cannot provide vector wavefield information that is critical for VSP surveys, microseismic monitoring and 4D analysis of subsurface stress conditions. Discrete 3-component optical point receiver systems such as the Insight tool offer the best solution to providing the kind of vector wavefield data required to solve the difficult monitoring problems that will dominate the geophysical market for the coming decades in both traditional oil and gas exploration and the emerging markets.

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