first break volume 32, February 2014

Distributed Acoustic Sensing – a new tool for seismic applications

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Abstract

Distributed optical fibre sensors are established tools in the energy industry, finding many applications for production optimisation and integrity monitoring. Recently, a new class of instrument, the Distributed Acoustic Sensor (DAS), has been launched which adds seismic imaging to the list of energy industry applications.

In this paper, we describe one such distributed acoustic sensor (named the iDAS) and demonstrate, through a series of lab experiments, the signal quality and performance that can be achieved. We show data which demonstrates the capability of the iDAS to measure the true acoustic signal (amplitude, frequency and phase) at all points along the sensing fibre length. We also compare the iDAS data with data collected from conventional point sensors and detail experiments which validate key performance criteria.

We follow the lab experimental validation of the iDAS with a series of lab and field demonstrations. The lab demonstrations encompass localisation (ranging) of events away from the sensing fibre (for security applications) and acoustic imaging through the formation of a large acoustic camera using a single sensing fibre. The field demonstrations show comparisons of iDAS and geophone measurements in a surface seismic survey and improvements made by stacking shot records from an offshore VSP survey.

Introduction

Distributed optical fibre sensors offer the capability of measuring at thousands of points simultaneously, using a simple, unmodified optical fibre as the sensing element. The most established instrument of this type is the distributed temperature sensor, DTS (Dakin et al., 1985), which is commonly used in downhole applications. Here we describe a new type of distributed sensor, the intelligent distributed acoustic sensor (iDAS), which measures strain changes at all points along the optical fibre at acoustic frequencies. The iDAS (Farhadiroushan et al., 2009) offers a new tool for seismic imaging by allowing the simultaneous acquisition of thousands of sensing channels using just a standard optical fibre as the sensing element. As well as offering unparalleled coverage, the simplicity of the sensing element allows the iDAS to perform seismic measurements without well intervention, or any changes made to the production profile.

The iDAS has been used in many seismic acquisitions to date, encompassing vertical seismic profiling, in both flowing and non-flowing wells, and surface seismic surveys. In this paper, we will describe lab tests which illustrate the validity of the iDAS measurement technique, including results from an iDAS-based acoustic camera. We will then go on to show some examples of field data to illustrate the applicability of the technique in field applications.

Point and distributed sensors

Optical fibre sensors can be generally classified in two groups: point sensors and distributed sensors. Point sensors (e.g., Bostick, 2000) measure at the location of the transducer only, and use an optical fibre cable to transmit light to and from the transducer to a readout unit. Often point sensors are multiplexed such that a number of transducers use the same optical fibre for transmission of the signals to and from the readout unit.

With distributed sensors, on the other hand, the optical fibre itself is the sensing element and there are no additional transducers in the optical path. The readout unit operates according to a radar-style process: a series of pulses are sent into the fibre and the naturally-occurring backscattered light is recorded against time. In doing this, the distributed sensor measures at all points along the fibre. Importantly, the optical fibre is typically standard telecoms fibre and may be, for example, incorporated into a previously-installed telecoms cable or in an existing cable used for communicating to a previously-installed point sensor.

Classically, point sensors have been used where high precision, fast measurements are needed; with distributed sensors favoured where extensive coverage is needed, with a compromise made on either measurement time or resolution/accuracy. This gap has been bridged by this new sensor, which achieves both the precision of a point sensor with

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the wide coverage of a distributed sensor. This system measures the true acoustic signal (amplitude, frequency and phase) at every point along an optical fibre. By using digital signal processing, the acoustic response along the fibre can be combined to enhance the detection sensitivity, thereby exceeding the sensitivity of point sensors, as well as achieving highly directional information, facilitating super resolution imaging.

Distributed disturbance/vibration sensing versus distributed acoustic sensing

Distributed disturbance/vibration fibre-optic sensors (Shatalin et al., 1997) have been used for intrusion detection as they provide vibrational sensitivity together with electromagnetic interference immunity. They have also been introduced into the oil and gas industry in a number of applications. The idea is based on interference effects that are associated with the optical time domain reflectometry (OTDR) signal. A major limitation of such disturbance sensors is that they are incapable of determining the full vector acoustic field – namely the amplitude, frequency and phase – of the incident signal; a necessity for seismic imaging. Measuring the full acoustic field is a much harder technical challenge to overcome but, in doing so, it is possible to achieve high resolution seismic imaging and also make other novel systems, for example a massive acoustic antenna.

There are a number of systems which are generally described as distributed acoustic sensors (DAS). However, unlike the case with the OTDR or DTS, there is no accepted generic architecture for a DAS system. This means that there is a large variation in the fundamental design, and so the performance, of systems marketed as distributed acoustic sensors (for example, the distributed disturbance sensors described above are often described as DAS systems). Here, we mainly focus our discussion on the performance and applicability of the Silixa iDAS unit for seismic applications.

We will show here that using the new measurement technique embodied in the iDAS, we can use the full acoustic field to accurately stack repetitive seismic signals with a precision to allow seismic imaging. We will also show examples of beamforming to accurately determine the distance of an acoustic event from the sensing fibre. This beamforming capability has been used by the authors to form an acoustic camera and, in security applications, to determine the distance of a possible intruder from the sensing cable. We will start, however, by explaining the measurement principle behind the iDAS and demonstrating the key performance characteristics of the system.

The iDAS technology

The iDAS measures using the same underlying principle as that of the DTS and OTDR. Here, a pulse of light is sent into the optical fibre and, through scattering in the glass, a small amount of the incident light is scattered back towards the sensing unit. The iDAS, however, is capable of determining, from this scattered light, a component which indicates changes in the local axial strain along the fibre. By recording the time of arrival of this returning light, the iDAS can determine the position at which each component of the returning light was generated. As this backscattered light is generated all along the fibre, the system so builds up a profile of the backscattered light, and hence a dynamic profile of the strain, all along the fibre. By repeatedly firing pulses into the fibre, the changes in strain can be determined at acoustic speeds, and so, provided the system has sufficient sensitivity, the acoustic signal can be measured all along the fibre.

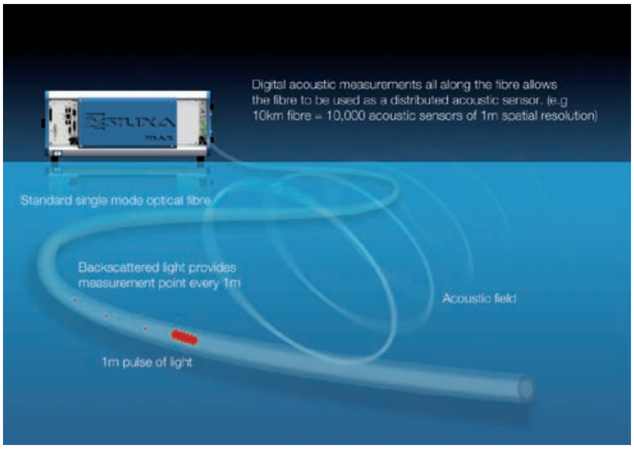


Figure 1 *iDAS principle of operation.*

In the following sections, we demonstrate some of the key performance characteristics of the iDAS unit.

Signal fidelity

The technically most challenging aspect of the iDAS design specification is the ability to faithfully record the acoustic signal, rather than merely record an approximation of the signal.

The signal fidelity can be determined by subjecting a section of the fibre to a known signal, the most convenient being a sine wave. The iDAS acoustic signal and the FFT of this signal can then be used to calculate the degree of any harmonic distortion. Additionally, the intermodulation distortion response can be tested by subjecting the sensing fibre to two tones simultaneously. Comparisons with conventional sensors indicate that harmonic distortions are generally limited by the acoustic source (a 30mm diameter loudspeaker was used to generate the data shown in Figures 2 and 3) rather than the iDAS sensing mechanisms.

The iDAS optical arrangement means that it inherently exhibits no measurable acoustic crosstalk between sensing channels. This fact can be readily demonstrated by applying a large signal at any point along the fibre and observing that this is not seen at any other point.

Acoustic sampling range

In the simplest iDAS implementation, the acoustic sampling rate depends upon the round trip time of the optical pulse

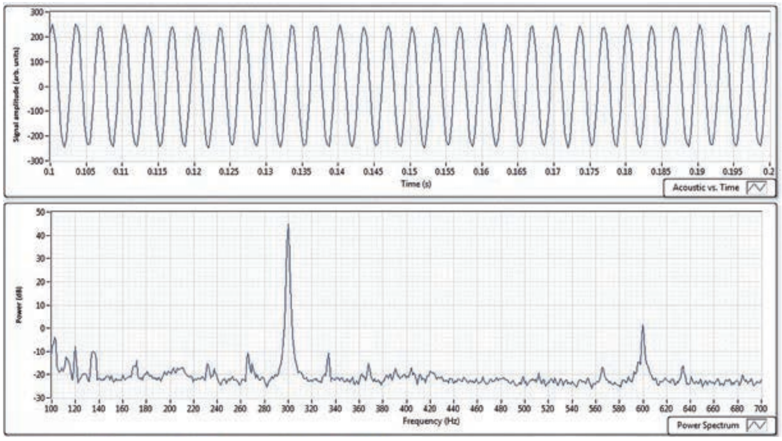


Figure 2 *iDAS time-amplitude and power spectrum from a single measurement point with 50 kHz sampling, for a 300 Hz sine wave excitation. The –45 dB level harmonic distortion is expected to be dominated by the source response rather than the sensor response.*

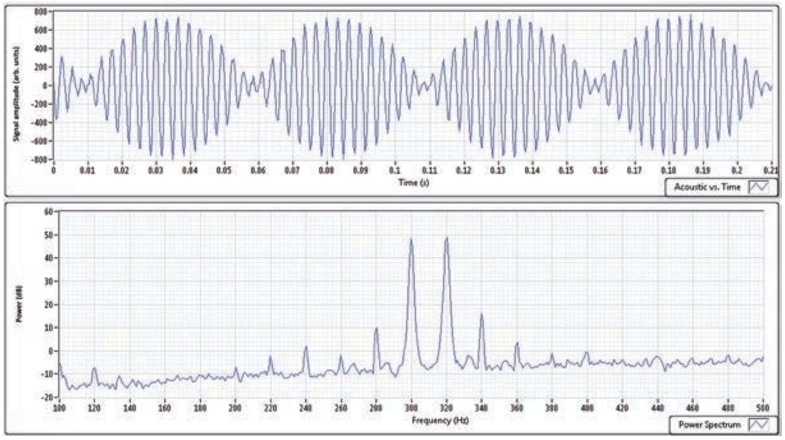


Figure 3 *iDAS time-amplitude and power spectrum from a single measurement point excited simultaneously by tones at 300 Hz and 320 Hz. The –30 dB side bands are expected to be mostly attributed to the performance of the audio amplifier/speaker used to excite the fibre.*

in the fibre. This is because, to avoid crosstalk, there should only be one propagating pulse in the fibre at any one time. The speed of light in glass is around 200,000,000 m/s, which means the maximum acoustic sampling rate is approximately 10 kHz for a 10 km fibre (or alternatively 100 kHz for 1 km fibre or 1 kHz for 100 km fibre).

Note, the requirement to have a maximum of one pulse in the fibre at any one time is not a fundamental limit and it is possible to increase the sampling rate by interleaving the light from multiple lasers with different wavelengths (a common telecoms technique). In this case, it is possible to achieve higher acoustic sampling rates than those indicated above.

Acoustic bandwidth

The acoustic bandwidth of the iDAS system is usually in practice limited by the physics of the transmission of the acoustic signal from the source through the formation and into the sensing fibre rather than a function of the iDAS sensing mechanism itself. Frequencies of as low as 8 mHz (over a 2-minute period) have been measured (the lowest we can reliably generate), though we do not see any reason why frequencies lower than this could also be detected. We have also measured frequencies as high as 49.5 kHz (for a 1 km length of fibre with 100 kHz sampling). Again, we do not see a physical reason for not achieving higher frequencies, other than the Nyquist limit of the sampling rate used.

Dynamic range

The dynamic range of the iDAS can be demonstrated in an elegant experiment where a weight is attached to a 2 m length of fibre which is then extended and released. The fibre then acts as a spring, exhibiting damped simple harmonic motion, while the iDAS measures the dynamic strain in the fibre.

In the example shown here, we extended the fibre 10 mm (0.5% strain) before releasing. The harmonic motion is clearly accurately captured, as compared to a reference accelerometer. We tested this using a maximum 10 mm extension (close to the breaking strain of the fibre) and measured continuously until where the signal is lost in the system noise, below a 10 nm extension. In this way, we have demonstrated a 120 dB dynamic range for low frequency acoustic energy, with a strain sensitivity of better than 5 nanostrain (here measured for a 4 Hz signal).

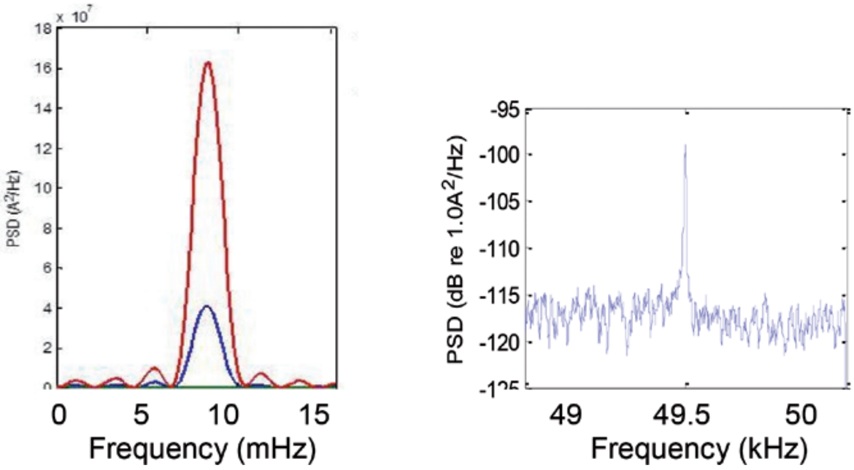


Figure 4 *Demonstration of iDAS frequency measurements from 8 mHz to 49.5 kHz*

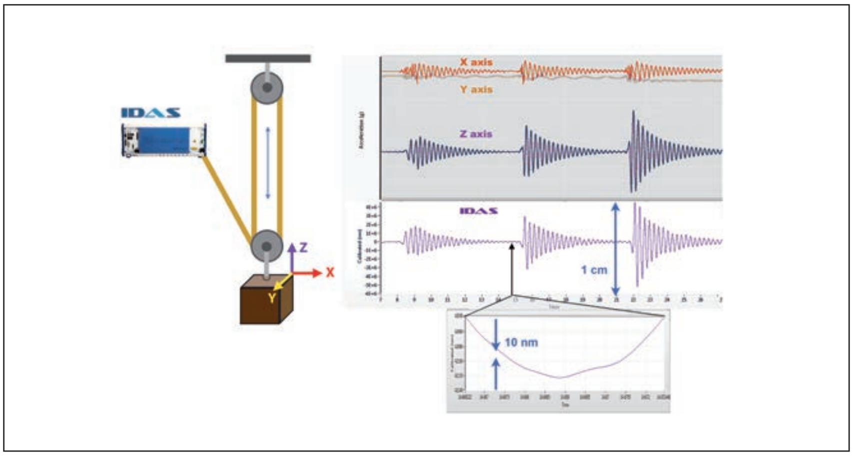


Figure 5 *Demonstration of iDAS low frequency dynamic range of 120 dB. The figure compares the response of a tri-axial accelerometer to the iDAS-measured strain. There is an excellent match between the z-axis accelerometer and the iDAS response, with the iDAS measuring from 10 mm extension (0.5% strain) to 10 nm extension (5 nanostrain).*

Spatial resolution

The length of the optical pulse used to interrogate the fibre is an important factor in determining the spatial resolution of the sensing system; for example a pulse of 10 ns duration provides averaging over a 1 m length of fibre. Provided the optoelectronics bandwidth is sufficiently fast, this will then translate into a spatial resolution of 1 m. A factor related to the spatial resolution is the sampling resolution (the distance between consecutive sampling points), which is a term often incorrectly used interchangeably with the term spatial resolution.

The iDAS allows a spatial resolution of between 1 m to 10 m, with a sampling resolution to as fine as 25 cm possible. There is usually a quadratic trade-off between the signal-to-noise ratio (SNR) and the spatial resolution, dz, such that SNR $\propto (dz)^2$. In addition, achieving a fine spatial resolution requires the use of high-speed electronics and high-speed data processing capabilities which add to the complexity of the system design.

Measurement range

Two factors govern the maximum achievable sensing range: the optical losses along the fibre and the number of sampling points which can be processed in the system. The iDAS uses the optimum optical wavelength for losses, around 1550 nm, which allows a single system to achieve a range of up to 40 km with good signal-to-noise ratio. By adding optical amplifiers (a common component in optical communications systems) we have shown 80 km range with negligible signal-to-noise degradation.

Figure 6 shows the measurement of an acoustic signal incident upon a region at the beginning and end of an 82 km fibre. In this plot, we observe the sinusoidal stimuli at the two positions with the correct amplitude, frequency and phase response, with no appreciable degradation of signal-to-noise over the 82 km length. This opens up the possibility of creating a massive surface array, all simultaneously interrogated by a single sensing unit.

The current iDAS hardware can process more than 40,000 sensing points simultaneously. This means, a single iDAS can sample more than 40 km with 1 m sampling or, with the addition of amplifiers, 80 km with 2 m sampling.

Lab comparison with conventional sensors

We have conducted a variety of experiments to validate the performance of the iDAS against that of conventional sensors. The example in Figure 7 shows a typical lab validation test we have conducted. Here, we compare the iDAS measurement along a fibre, helically-wrapped around a Perspex water-filled tube with a measurement from a hydrophone placed in the water. The acoustic excitation is caused by air bubbling into the bottom of the tube. Figure 7 shows a typical signature from both the hydrophone and the iDAS.

As can be seen, there is a similar performance from both sensors (considering that there is some 50 Hz mains pickup in the hydrophone signal and that, as the hydrophone is measuring at a point in the tube and the iDAS is measuring the average hoop strain of the tube wall, there are some differences in respective signals being measured).

Beamforming with iDAS

The iDAS technology offers the possibility of forming a massive acoustic camera/telescope suitable for seismic appli. Achieving a high signal-to-noise-ratio with fine spatial resolution is extremely important and, as shown above, we have achieved a good signal quality for fibre lengths up to 82 km using a bidirectional erbium doped fibre amplifier (EDFA) chain. In principle, we see no reason why the EDFA chain cannot be increased to extend the range up to the 320 km achieved in ODTR systems (Kim et al., 2001), and so form a massive sensing array.

Distributed vibrational sensors (e.g., Shatalin et al., 1997 and Juarez et al., 2007) can locate sources near a cable but cannot detect the phase of acoustic field and so cannot determine, among other things, the distance of the source from the cable. The results reported here from the iDAS, which is the true analogue to a synchronised microphonic array, can be used for beamforming (the phase-shifted addition of acoustic fields measured at different sensing points). This allows us to find the position of acoustic sources relative to the cable, and selectively listen to different points in the acoustic field. We currently use this technique in security applications to distinguish more imminent threats from lessermore distant ones and therefore reduce false alarms considerably (e.g., construction work 20 m away from a perimeter is not a threat while digging few metres away is) . We foresee a similar use in microseismic and fracture monitoring applications where we can estimate the position of the source as well as the speed of sound in the ground by measuring the emitted signals at different locations along the fibre.

A cost function is computed over possible distances and speeds to estimate the distance of the source simultaneously with the speed of sound through the medium between the source and the fibre. This cost function is the beam-steered beamfomer output, in that it searches for the range which results in the maximum average energy across all sensing points; it generates a focused spot on the source location (Chen et al., 2002). The cost function gives a maximum at both the correct source location and the speed of sound. Figure 8(a) shows the measured signal of the iDAS as a response to digging 5 m from the fibre. Figure 8b shows the computed cost function as a function of the distance and the speed of sound. In this case, a distance of 5 m and speed of sound of around 215 m/s are found to maximize the cost function.

Acoustic camera

In the example above, the cable was deployed as a simple linear array. A more powerful arrangement is made by forming the fibre into a two-dimensional array, such as a grid or a spiral (Figure 9), or, even better, in a three-

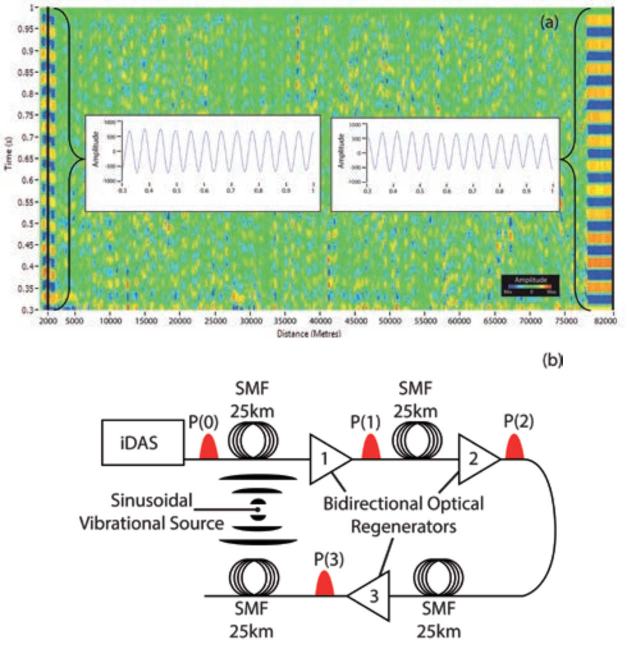


Figure 6 *Accurate signal recovery, with the correct phase response and negligible SNR reduction, at the beginning and end of an 82 km fibre. (a) iDAS signal; (b) optical arrangement used.*

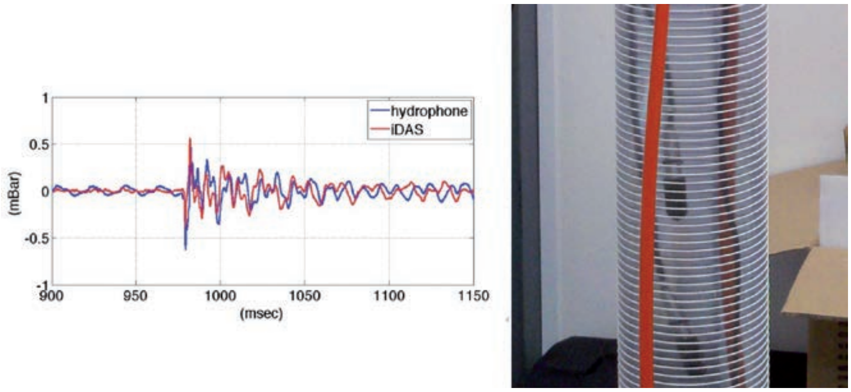


Figure 7 *Hydrophone and iDAS response for the generation of a single air bubble within a water-filled Perspex tube. The hydrophone is in the tube, around which the iDAS fibre is wrapped.*

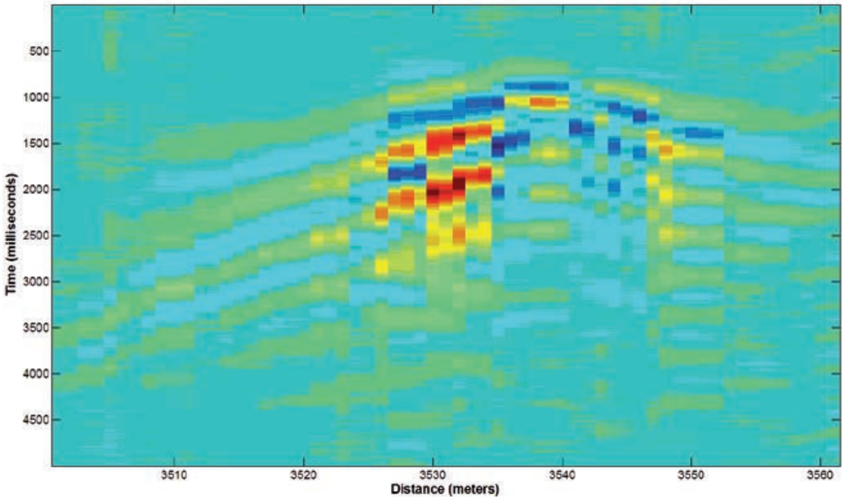


Figure 8a *iDAS measured signal of digging 5 m away from the fibre.*

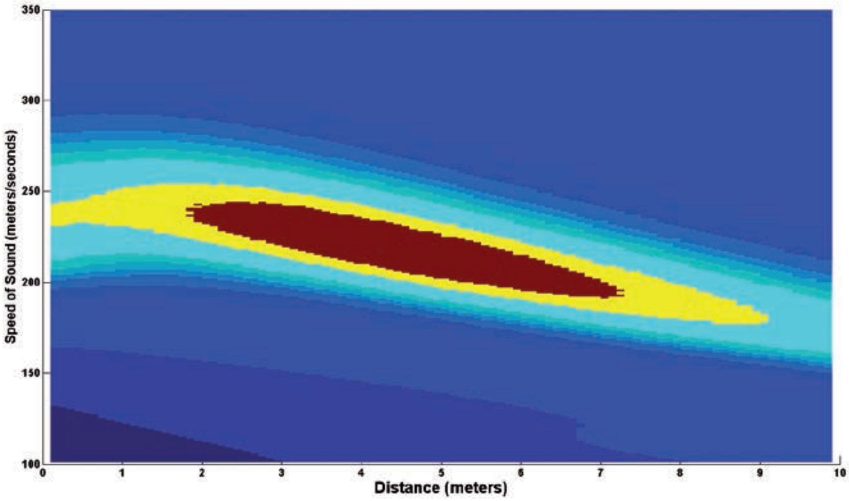


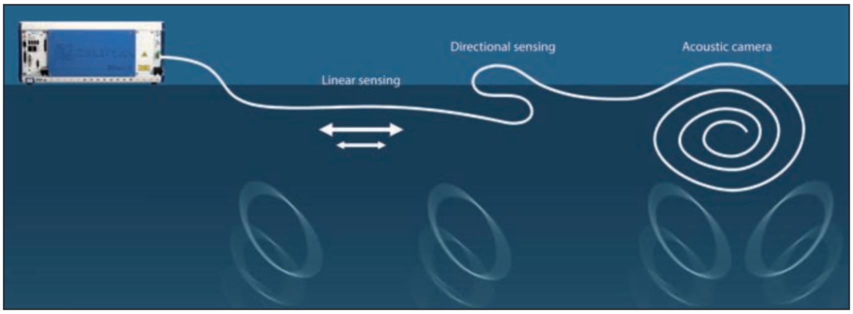
Figure 8b *The computed cost function to estimate the distance and the speed of sound.*

dimensional array, such as may be formed by running the cable through a 2D surface array and down a series of boreholes. Note, in all cases, the array may be formed of a single, flexible optical cable. It should be noted, however, that as the iDAS works by accurately measuring the axial strain on the core of the sensing fibre, there is significant scope for improving the sensitivity and directionality of the system through appropriate design of the sensing cable. For example, it is possible to incorporate design elements as used in optical hydrophone and/or directional accelerometer arrays and, with the appropriate wavelength choice, to even measure directly on existing arrays.

Here, we show the feasibility of forming an acoustic camera using a 2D grid array of optical fibre, arranged in coils and laid on the ground, with a moving source held by an experimenter (Figure 10a). Using the multiple signal classification (MUSIC) algorithm (Schmidt, 1986), the calculated sound field can be displayed (Figure 10b) as a function of elevation and azimuth. Further processing (particle filtering, Arulampalam, 2002) is then used to track the movement of each of the detected sound sources (shown as the black dots in Figure 10b).

Forming a large, high density beamforming array requires a long length of optical fibre. For example, an array of

Figure 9 *Examples of arrays formed with a single fibre cable.*



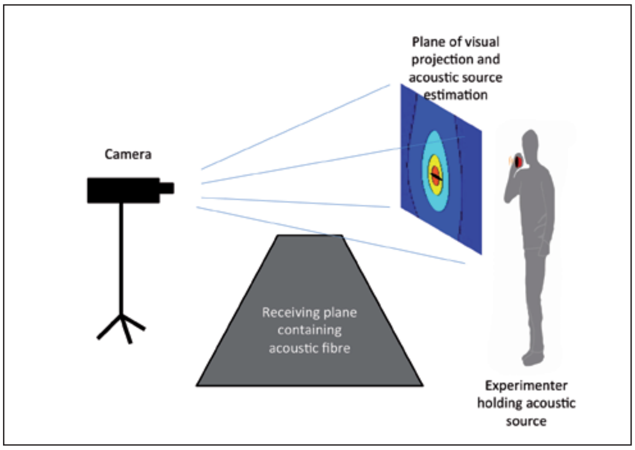


Figure 10a *Acoustic camera experimental layout.*

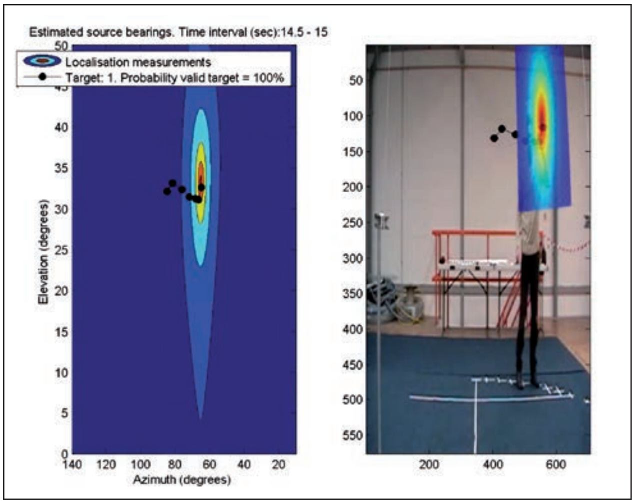


Figure 10b *Calculated acoustic image and superposition of acoustic image on photograph of experimenter.*

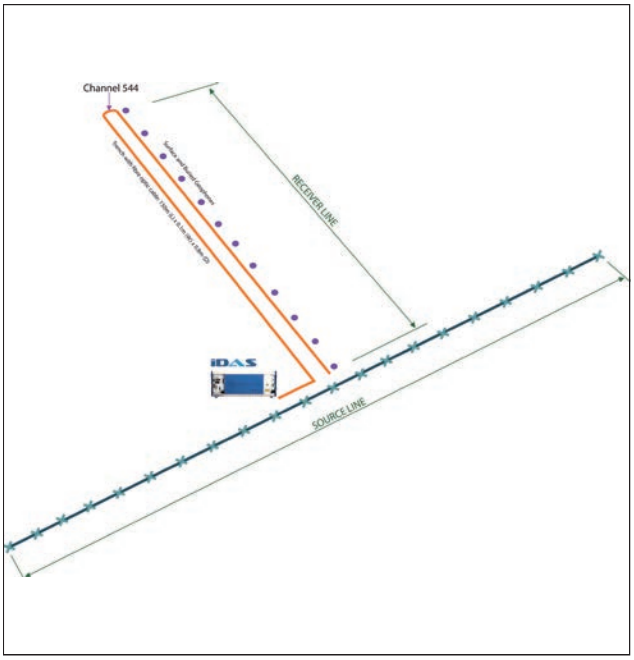


Figure 11 *iDAS surface seismic survey geometry.*

1 km x 1 km, formed of a single cable deployed in parallel lines, 20 m apart will require around 53 km of fibre cable. The challenge is to retain sufficiently high signal-to-noise ratio, and signal quality, over these extended ranges, particularly while retaining the fine spatial resolution typically needed for many applications. However, as shown above, we have demonstrated using an amplifier chain to extend the range of an iDAS unit to 82 km, while maintaining high signal quality.

Example surface seismic

The iDAS has been used for a large variety of seismic acquisitions, and a selection of representative data, demonstrating validation of key iDAS features, is shown here. Figure 12 shows data from a surface seismic trial (Daley et al., 2013) where the fibre path is symmetrical around channel 544, such that the signal received from the left and right hand side of the plot should be identical. In this example, the fibre cable was buried in a trench at a depth of 0.8 m (the cable was looped back upon itself to create the symmetry just mentioned) and the source was a 720 kg weight drop (see Figure 11).

The degree to which the iDAS signal is repeatable can be demonstrated by directly comparing the signal from two geographically co-located channels (Figure 13), which are at different points along the fibre path. As can be seen, the two signals show good agreement in amplitude and delay.

In the same survey, a comparison was made between the iDAS measurement along a buried cable and those from a set of surface and buried geophones.

Figure 14 shows iDAS data averaged over 1 m, 4 m 16 m and 64 m (taking into account time delays for the arrival) and compares this to data from a buried geophone and surface geophone, for a common receiver gather. The figure shows that the iDAS and geophones show similar SNR at near offsets, when the iDAS data is averaged over 4 m to 16 m. As the receiver and sources lines are orthogonal, the directivity of the fibre sensing mechanism, for the simple linear cable used, becomes more apparent for larger offsets (e.g., Madsen et al., 2012).

Example VSP in flowing well

With the signal fidelity demonstrated by the iDAS, it is expected that the SNR will improve with stacking of repeat-

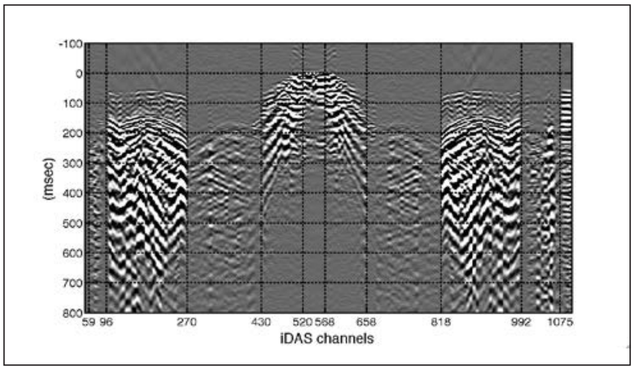


Figure 12 *iDAS data from a buried fibre laid in a symmetrical path with the symmetry point at channel 544.*

ed shots. This is demonstrated in the dataset presented in Figure 15. Here, an airgun was used as the excitation source, deployed beneath an offshore platform. Repeat shots were acquired both while the well, a water injector, was flowing and while the well was shut in. The sensing cable was deployed within the production tubing; significantly better coupling and acoustic SNR would be achieved if the cable was cemented behind the casing.

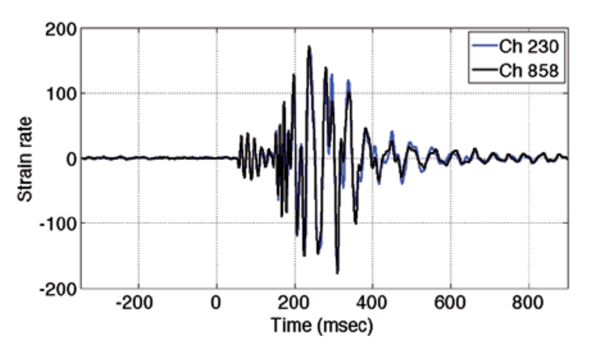


Figure 13 *iDAS data from channels 230 and 858. As expected, the data accurately overlays.*

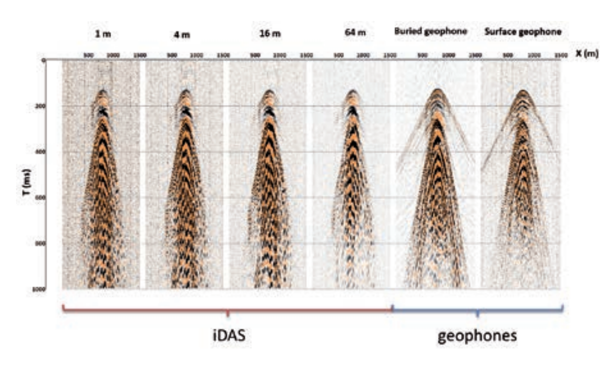


Figure 14 *iDAS data, with different amounts of spatial averaging, compared to buried and surface geophone data.*

The data shows that, in both cases, stacking improves the SNR, as should be expected. The shut-in dataset is significantly cleaner than that from the flowing dataset, due to the flow signal generated in the latter case. Note though that this flow signal is also useful in that it was used to calculate the flow profile in the well using the Doppler shift of the up-going and down-going flow noise (see for example Johannessen et al., 2012 for a description of the processing used for flow measurements).

The data quality is such that it is possible to pick out the first arrival in the flowing well whereas it is sufficient to perform imaging in the shut in well. Note though that the data shown here is unprocessed and it is expected that advanced processing techniques may be used to remove the flow signal and so clean up the flowing well dataset.

Conclusions

The intelligent Distributed Acoustic Sensors offer a versatile new tool for high-resolution acoustic sensing and imaging, such as through the formation of a massive acoustic camera/telescope. The new technology can be used for surface, seabed and downhole measurements. We have shown validation measurements for the techniques used and recent examples field measurements demonstrating the applicability of using the iDAS technology in the field.

The use of the iDAS in downhole applications allows a continuum of benefits extending to flow profiling and condition monitoring, all using the same optical fibre cable.

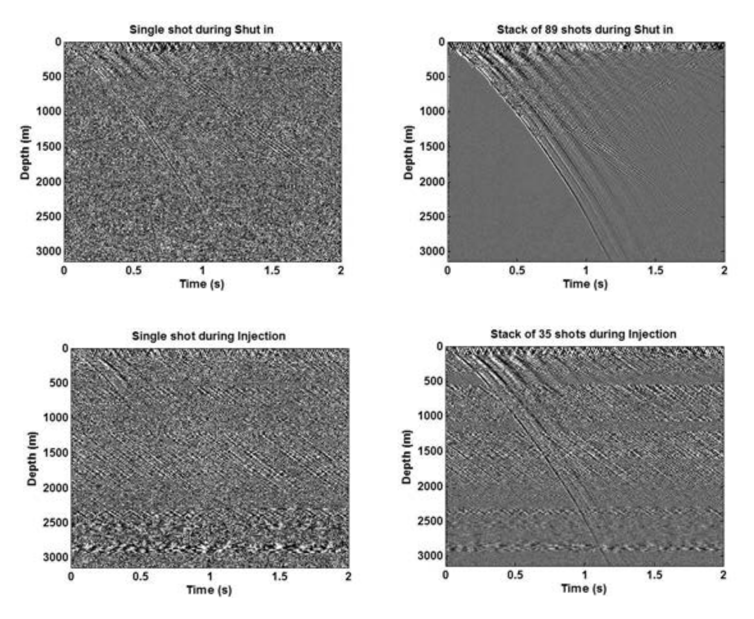


Figure 15 *VSP data from a flowing and shut-in offshore water injector well. The data shows improvements in SNR with stacking as expected, with the shut-in data cleaner than the flowing data.*

Acknowledgments

The authors would like to thank Roman Pevzner and Valeriya Shulakova of CO2CRC, Curtin University and Thomas M. Daley, Barry M. Freifeld, Jonathan Ajo-Franklin and Shan Dou, of the Lawrence Berkeley National Laboratory for the use of the raw and processed surface seismic data, and field geometry presented. The authors would also like to acknowledge the significant contributions from their colleagues at Silixa in the preparation of this paper.

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Received 21 May 2013; accepted 18 December 2013.
doi: 10.3997/1365-2397.2013034