Surface seismic with DAS: looking deep and shallow at the same time

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Summary

Unlike conventional point sensors, Distributed Acoustic Sensing (DAS) has unique features allowing us to record multiple datasets with variable acquisition parameters set inside the recording box, while using one continuous recording cable and a single round of shooting. We reveal how these distinct features allow DAS to deliver multi-scale data and have the capability to focus on both the near surface and deeper targets simultaneously. We present synthetic and field examples of "deep" and "shallow" DAS surveys and demonstrate their effectiveness. The new capabilities of surface seismic with DAS technology comprise a sensing revolution that addresses long-standing near-surface issues in land seismic without compromising the deeper imaging.

Introduction

Seismic acquisition on land has long been driven by a perceived need to increase the channel count and thus trace density. These improvements are expected to enable better sampling of low-velocity noise and lead to cleaner images. This logic has driven seismic acquisition geometry from 'heavy and sparse' to 'light and dense', i.e. away from large groups towards finer spatial sampling with much lighter source and receiver field arrays and ultimately to point-source, point-receiver configurations (May, 2016). The tradeoff here is purely economic since the ideal acquisition geometry of 'heavy and dense' is simply too expensive with conventional sensors. This leads to compromises, since 'dense' still means much coarser sampling than is typically used between individual sensors within field arrays and as such 'light and dense' is far from being a supervolume that would allow replicating of arbitrary field arrays. As a consequence, processing of densely acquired seismic data becomes a significant challenge. One school of thought is to keep increasing point-source and point-receiver density as a brute-force answer to geophysical challenges, while letting processing struggle with massive volumes of data with low signal-to-noise (SNR). Another school of thought is that perhaps a certain minimum SNR quality should be set for pre-stack data beyond which the geophysical value of massive data is questionable. After all – theoretically one can acquire data with weaker point sources and not so sensitive sensors – but such data cannot be processed with reasonable computer resources and turnaround time.

With conventional sensors almost every acquisition decision needs to be made upfront leading to inevitable compromises. What if there could be an alternative system that can give you the flexibility to acquire 'heavy and sparse' and 'light and dense' data at the same time? Or acquire 'heavy and dense' in an economic way? This may sound too good to be true, but we think we may be on the verge of achieving this vision.

Surface seismic with DAS

Distributed Acoustic Sensing (DAS) is a way to record seismic data using an optical fiber as a seismic sensor (Mestayer et al., 2011; Parker et al., 2014; Dean et al., 2017). Figure 1 shows a 2D image acquired with DAS in Saudi Arabia (Bakulin et al., 2017). Since regular fiber-optic cables are mostly sensitive to deformation along the fiber axis, this DAS image was produced with only 300 DAS channels from the vertical portions of the fiber in six shallow holes (0-140 m, Figure 2a) and not from the intervening horizontal sections (Figure 2bc). The resulting image matched legacy 2D surface seismic acquired with surface geophone arrays (Figure 1). Cables placed in horizontal trenches at the surface (Figure 2b) recorded data similar to horizontal geophone. However, with novel omnidirectional cables already in existence (Yavuz et al., 2016) and new versions being developed, we are able to record reflection data with DAS similar to surface seismic using horizontal fiber optic cables. Cable deployed inside trenches and vertical holes are well coupled (Figure 2) and other deployment methods are under development. Therefore, all components exist to enable surface seismic acquisition using DAS. Here we focus on the geophysical value proposition of surface seismic with DAS: what

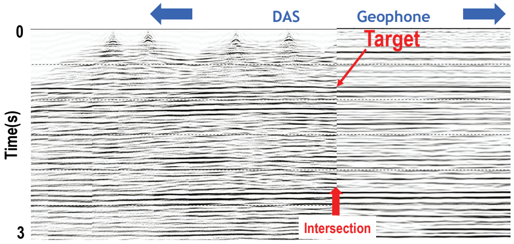

Figure 1. Comparison of seismic images obtained with land DAS (left) and geophones (right).

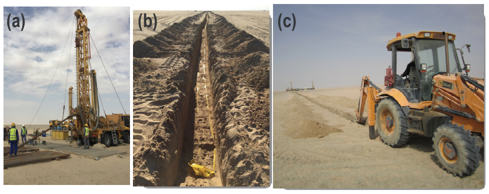

Figure 2. Cable deployment methods in vertical holes (a) and horizontal trenches (b,c).

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advantages it may offer over conventional acquisition with point sensors and whether it can enable new geophysical solutions that are currently out of reach.

Value proposition of surface seismic with DAS

To grasp the geophysical implications we have to fully understand this new DAS sensor as it is very distinct from any other sensor we use. DAS measures dynamic strain using two reference pulses of light propagating along an optical fiber (Figure 3). Those pulses interact with natural imperfections of the fiber and strain is inferred from the measured phase lag between backscattered signal at the front and end of the gauge length (Dean et al., 2017). Gauge length (G) and pulse width (L) are two fundamental parameters of DAS acquisition. In essence, using G creates a seismic array with aperture equal to G and infinitely small spacing between elements (Bakku, 2015). Pulse width also acts as an array. Average strain recorded by DAS channel can be related to the point strain using the following equation:

$$R = \frac{\sin(\frac{k_x G}{2})}{\frac{k_x G}{2}} \frac{\sin(\frac{k_x L}{2})}{\frac{k_x L}{2}} \tag{1}$$

where G and L are gauge length and pulse width respectively, whereas k_x is wavenumber projection along the cable. We use this equation as a simple proxy to relate point-sensor acquisition with geophones and distributed fiber optic cables. We immediately recognize filter response of two arrays with apertures of G and L and infinitely small spacing between elements. The amplitude response of a DAS "sensor" is shown in Figure 4. In practice G > L and for simplicity we focus on the effect of the gauge length as a dominant factor. Recording DAS data with small G is similar to a single-sensor or small geophone group and indeed is usually characterized by low S/N ratio typical of land single-sensor data. Likewise, recording with large G is akin to a large geophone group and results in higher SNR due to summation of the signal and suppression of the low-velocity noise. In practice, G can vary from 1 to 100 m or more. For conventional geophone acquisition, one has to decide on geophone sampling ahead of time. In the 'heavy and sparse' acquisition setup we place point sensors very close (1-5 m) to create arrays in the field and output only one trace from each array with improved SNR. In the 'light and dense' scenario, we place single sensors at a spacing of 10 m or more, which is usually too large for conventional array forming, thus generating lower SNR data that needs more processing effort. The beauty of DAS acquisition is that the sensing cable is always the same, whereas all acquisition parameters are set in the recording box (interrogator). For example, sensor spacing can be anything starting from 0.25 m (Parker et al., 2014). Indeed, since light propagates continuously through all parts of the fiber, one can estimate interferometric phase lags at any desired location. Therefore, we obtain a measurement system unthinkable from the perspective of point geophone sensors (Figure 3). That is we can have small G (point sensors) at sub-meter spacing ('light and dense') and large G (effectively large geophone groups) at sub-meter spacing, or any combination of the two. All of this can be achieved with a single measuring fiber, and with a single interrogator box using the same source excitation. While any other intermediate combination or "DAS acquisition geometry" can be generated, let us single out two specific geometries of most immediate use:

1) "Shallow" acquisition with small G and super-dense spacing to characterize the near surface that is critical for land seismic ('light and dense');
2) "Deep" acquisition with large G and moderate spacing which would be proxy for conventional data targeting deep reflections and requiring good SNR for weak signal ('heavy and sparse').

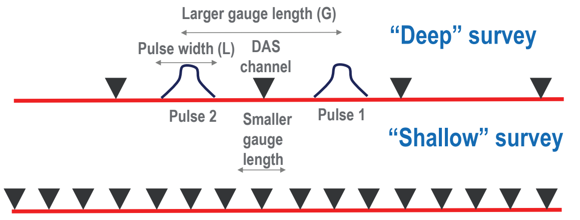

Figure 3. Schematic of measuring dynamic strain using two reference pulses of light propagating along an optical DAS fiber. Top and bottom figures show two different acquisition schemes that can be simultaneously recorded with DAS on a single fiber cable.

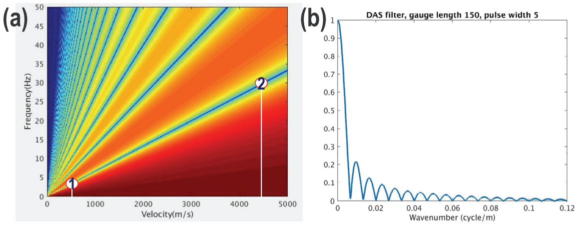

Figure 4. Amplitude response of the DAS sensor filter (1) as a function of wavenumber showing how point strain is averaged to produce final response by distributed DAS sensor.

Let us demonstrate how these two datasets can address challenges of land seismic acquisition in complex areas using a realistic elastic model inspired by one of our fields. Figure 5 shows a shot gather from a simplified 1D elastic model. This results in very faint reflections covered by thick train of linear noise. For simplicity, here we use a Ricker wavelet with 17 Hz central frequency for both deep reflection and near-surface surveys.

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“Shallow” survey with DAS

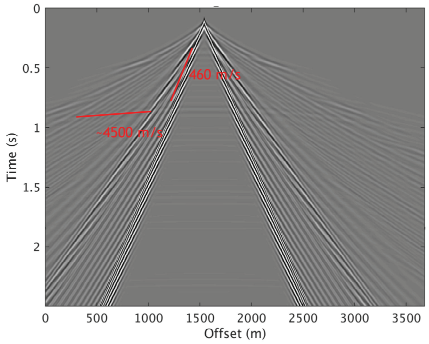

Figure 5. Synthetic shot gather produced by elastic model inspired by onshore field in Saudi Arabia. Vertical force simulates vibrator, whereas vertical geophones are shown at 0.5 sampling.

The objective of the “shallow” survey is to obtain a detailed velocity model for the near surface (usually with lowest velocity) using one of the approaches typically relying on strong signals such as surface waves or early arrivals. Using a small G is a natural selection for large signals and with the goal to preserve low-velocity arrivals. Also, most near-surface methods strongly benefit from dense spatial sampling. For example, one common method to obtain a detailed near-surface model is surface-wave inversion. It relies on picking groundroll dispersion curves and other near-surface modes on velocity-frequency panels, inverting them for a local 1D model, and joining such models at different locations. Using a gauge length of 7 m, pulse width of 3 m and DAS channel spacing of 0.5 m, we obtain undistorted panels (Figure 6a) that are almost identical to single-sensor horizontal geophones at 0.5 m (not shown). Comparing with single-sensor production geophone data spaced at 25 m (Figure 6b), we observe that DAS data has clear advantages of being alias-free and of higher quality from very low to very high frequencies. This means that the entire near surface can be accurately characterized from the deeper (using low frequencies) to shallower (highest frequencies) part without compromising sampling. Production data is aliased starting from 10 to 15 Hz, and in the presence of noise is much harder to pick. It goes without saying that any use of receiver arrays in conventional data would lead to suppression of groundroll signal and smearing of dispersion curves.

Another near-surface technique is so called weathering reflection seismic (WRS) that requires special acquisition of micro-spreads with very dense 1-2 m source spacing in order to pick zero-offset times and moveout velocities for the shallowest near-surface reflectors (Martin et el., 2009). A “Shallow” DAS survey delivers such data without any additional shooting effort. Figure 7 shows a zoomed part of the shot gather similar to Figure 5, but after filtering performed with 0.5 m sampling. Such shallow reflections would be undersampled with conventional production data and would be part of the “reflection blind spot” commonly present on our seismic volumes. A densely sampled DAS “shallow” survey would eliminate this problem and can enable use of shallow reflections and diffractions for building any type of velocity model – from shallow (for statics) to deeper velocity models (for migration from topography).

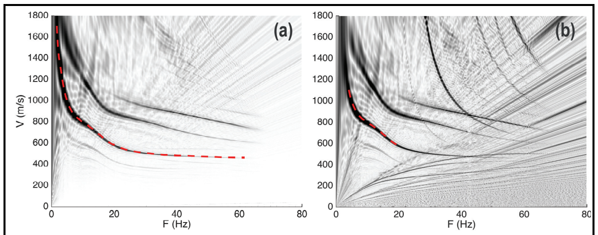

Figure 6. Velocity-frequency panels obtained with (a) densely sampled DAS data sampled at 0.5 m (G=7 m, L=3 m) and (b) single geophones at 25 m.

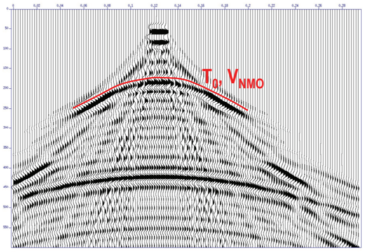

Figure 7. High-resolution shallow reflection unraveled using 0.5 m “shallow” DAS survey data subjected to simple processing (shown at 25 m after completion of filtering).

“Deep” survey with DAS

The second type of survey is more similar to conventional surveys targeting deep reflection events. With long propagation and attenuation, reflected signals are weak and require larger source and receiver arrays to boost signal and suppress noise. Reflected signal by itself does not require dense sampling for deep targets. However, groundroll and other slow near-surface arrivals can still obscure those signals. In this case, we can opt for a DAS survey with large G that could improve our detection of weak signals and also suppress near-surface arrivals (considered as noise here) according to Equation (1). For illustrative purposes, let us select a gauge length of 150 m and a pulse width of 3 m (Figure 8). This is equivalent to a large geophone group that would suppress 450 m/s groundroll from 3 Hz, while preserving reflections (4500 m/s) up to 30 Hz (see points 1 and 2 on Figure 4a). Since DAS array forming already accomplishes significant noise attenuation, we may elect (still fully flexible) for a “sparse” sensor sampling optimal for deep reflection imaging such as 25 m. We also should keep in mind that spacing smaller than G/2 would imply overlapping "DAS arrays" similar to what is employed in supergrouping (Bakulin et al., 2016).

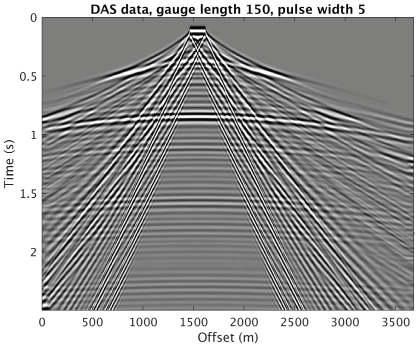

Figure 8. Shot gather recorded using DAS with a gauge length of 150 m and pulse width 3 m (G=150 m and L = 3 m). Observe strong suppression of linear near-surface arrivals and compare to the raw gather from Figure 5 recorded with single geophones.

Field data example of "shallow" survey with DAS

While we have showed an example of DAS reflection data on Figure 1, let us illustrate a "shallow" DAS survey. Trenched horizontal DAS data acquired with G=7 m and spacing of 4 m is shown in Figure 9a. Compared to modeled responses, such data clearly resembles a horizontal geophone response (Figure 9b) more than a vertical geophone (Figure 9c). Such densely sampled DAS data with small G is ideal for surface-wave inversion since we know that it preserves low-velocity groundroll and enables picking and inversion of the resulting dispersion curves (Figure 9d) for near-surface shear-wave velocity (Figure 9e). Why does the experimental dispersion curve become weak and vanish above 17 Hz whereas the vibrator sweeps up to 80 Hz? Surface-wave inversion relies on smooth lateral variations in order for a robust dispersion curve to develop. However, in field data exhibiting strong lateral velocity variations (Figure 9a) such an assumption may break down for very slow velocities (250 m/s) with 14 m wavelength at 17 Hz. Acquiring DAS data at an even denser spacing of 0.25 to 1 m instead of 4 m used here and reducing the spatial window may offer a better chance to sample the higher-frequency part of dispersion curves and lead to better capturing of fast lateral variations in shallow velocities.

Conclusions

Distributed Acoustic Sensing promises a paradigm change in land seismic acquisition provided the directivity of the cables and shallow deployment/coupling can be solved at a production scale. Unlike conventional point sensors, DAS acquisition delivers multi-scale data using fixed measuring fiber/cable with acquisition geometry set inside the recording interrogator box. This leads to new and significant geophysical implications. First, uncommitted and flexible channel sampling along the fiber is attainable. Second, DAS systems can output several datasets from a fixed cable each with its own "array" aperture (gauge length) and channel spacing. All this multi-scale data is output from a single cable (possibly with multiple fibers) and only single round of shooting. We have presented a simple yet realistic example of a simulated DAS surface seismic survey that employs this functionality to look shallow and deep at the same time. The "shallow" survey is focused on the near surface and is achieved by using small G and very fine channel spacing ('light and dense'). In contrast the "deep" survey is targeted at deep reflections and uses large G and moderate spacing adequate for reflection imaging ('heavy and sparse'). DAS field data confirm this capability for imaging shallow and deep targets simultaneously.

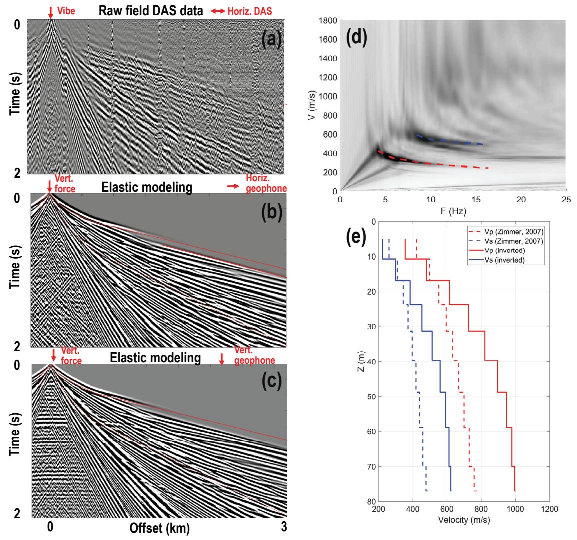

Figure 9. Field common-shot gather from "shallow" DAS survey (a) versus elastic synthetic modeling of a) vertical component and b) horizontal component. Horizontal DAS cable is trenched at 1 m depth. Observe the excellent quality of the field gather and general agreement with modeled response of horizontal as opposed to vertical geophones. (d) Dispersion curves picked on dense DAS data. (a) Near-surface model reconstructed using dispersion curve from (d).

Seismic acquisition using DAS enables an important and seamless "seismic zoom" functionality similar to visual zoom in Google Earth. With small G and dense spacing we can zoom into the near surface, whereas with large G and bigger spacing we can unzoom and get clearer picture of deeper targets. Such functionality is not achievable with conventional point sensors. New algorithms can be developed for seismic land processing to fully leverage this new capability and obtain uncompromised solutions for "shallow" (near surface) and "deep" (reflection) challenges facing onshore seismic acquisition.

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