SPE-194950-MS

Surface Seismic with DAS Changes Land Acquisition

Andrey Bakulin and Ilya Silvestrov, Geophysics Technology, EXPEC Advanced Research Center, Saudi Aramco;
Roman Pevzner, Curtin University

This paper was prepared for presentation at the SPE Middle East Oil and Gas Show and Conference held in Manama, Bahrain, 18-21 March 2019.

Abstract

Distributed Acoustic Sensing (DAS), as a seismic sensor, 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. Achieving similar capabilities with point sensors could be done but would lead to ballooning acquisition costs, whereas surface seismic with DAS can deliver them at a cost less than conventional geophone acquisition available today.

Introduction

Modern complex hydrocarbon targets such as low-relief structures and stratigraphic traps require reliable, high-quality and high-resolution seismic images for their successful exploration, appraisal and development. Despite a lot of advances made in seismic acquisition and processing, seismic exploration on land remains challenging due to near-surface complexities that deteriorate data and images leading to relatively large uncertainty in interpretation compromising identification of smaller exploration traps. Among the issues, that complex near-surface conditions bring to seismic data, is a strong level of ground-roll noise and its associated backscattering that can completely deteriorate target reflection signals. In the past, large number of sources and receivers were combined into field arrays in order to attenuate this kind of noise directly during field recording. In recent years, seismic acquisition is moving from ‘heavy and spars’ to ‘light and dense’ surveys, i.e. away from large groups of sensors/sources towards finer spatial sampling with much lighter source and receiver field arrays and ultimately to point-source, point-receiver configurations (May, 2016). Theoretically, these changes are expected to enable better sampling of near-surface related noise together with more accurate recording of reflected signals, and should lead to cleaner images. In reality, this leads to acquiring huge volumes of noisy data that is challenging to process. The ideal acquisition in which sources and receivers are placed at a very dense grid in all directions remains uneconomic 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' isfar from being a supervolume that would allow replication in processing of large arrays previously available in the field.

As a consequence, 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' patterns in an economic way? This may sound too good to be true, but we prove that such capabilities can be achieved with distributed Acoustic Sensing.

DAS as a seismic sensor

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). Most of the successful applications of DAS in seismic industry were achieved in boreholes using different VSP geometries (Mateeva et al., 2014). Recently, so-called smart DAS upholes were introduced to build accurate near-surface models and to image deeper target horizons (Bakulin et al., 2017). A 2D seismic image obtained from only 300 DAS channels from the vertical portions of the fiber in six shallow holes (0-140 m) is shown in Figure 1. The resulting image matches legacy 2D surface seismic acquired with surface seismic that used large geophone/vibrator arrays. Since regular fiber-optic cables are mostly sensitive to deformation along the fiber axis, in this DAS image the horizontal sections of the cable were not used due to low sensitivity to reflected energy. However, with novel omnidirectional cables already in existence (Yavuz et al., 2016; Lim, 2016) and new versions being developed, we are able to record reflection data with DAS similar to surface seismic using horizontal fiber optic cables. Here we focus on the geophysical value proposition of surface seismic with DAS: what advantages it may offer over conventional acquisition with point sensors and whether it can enable new geophysical solutions that are currently out of reach particularly for onshore areas with complex near surface.

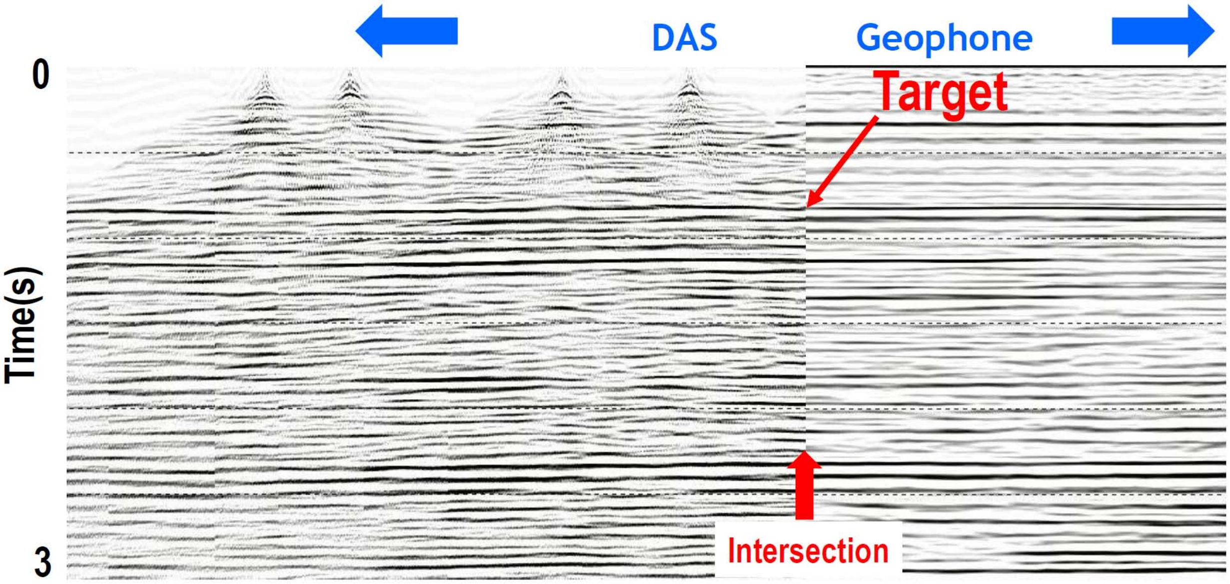

Figure 1—Comparison of seismic images obtained with DAS land sensors in shallow boreholes (0-100 m) (left) vs conventional 2D seismic with large geophone arrays (right).

To grasp the geophysical implications, we have to fully understand this new DAS sensor as it is very distinct from any other seismic sensor currently in industrial use. DAS measures dynamic strain using two reference pulses of light propagating along an optical fiber (Figure 2). 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:

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

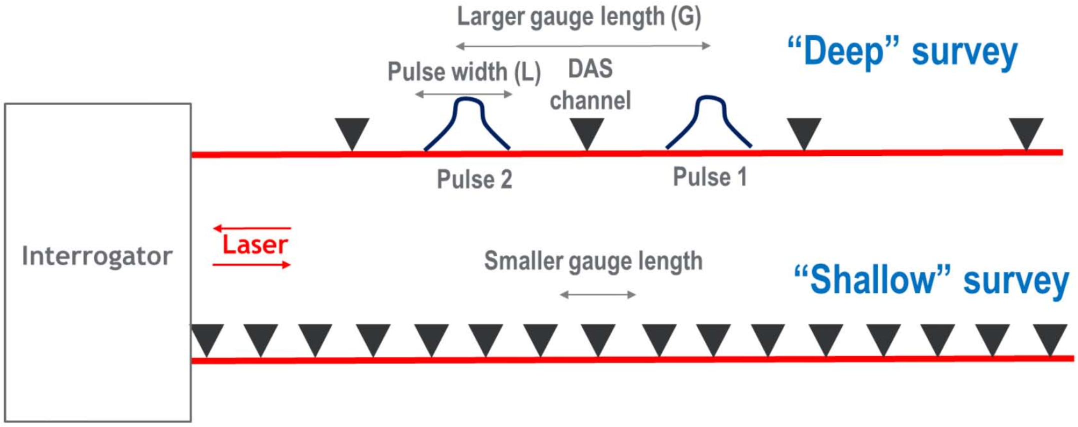

Figure 2—Schematic of measuring dynamic strain using two reference pulses of light propagating along an optical DAS fiber. Top and bottom figures show two different acquisition schemes that can be simultaneously recorded with DAS on a single fiber cable.

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 recordings obtained with point-sensor acquisition using 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.

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 in desert environment. Likewise, recording with longer 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 such as ground roll. In practice, G can vary from 0.25 to 50-100 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 multiple point sensors with small spacing (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 10-25 m or more, which is usually too large for conventional array forming, thus generating lower SNR data that needs far more processing effort and might even be below noise threshold for efficient processing. 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 2). 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 in a cost-effective way. While any other intermediate combination or "DAS acquisition geometry" can be generated, let us single out two specific geometries of most immediate use for usual configuration with "deep" exploration target and "shallow" complex near surface such as the case for onshore land acquisition:

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').

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 3 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.

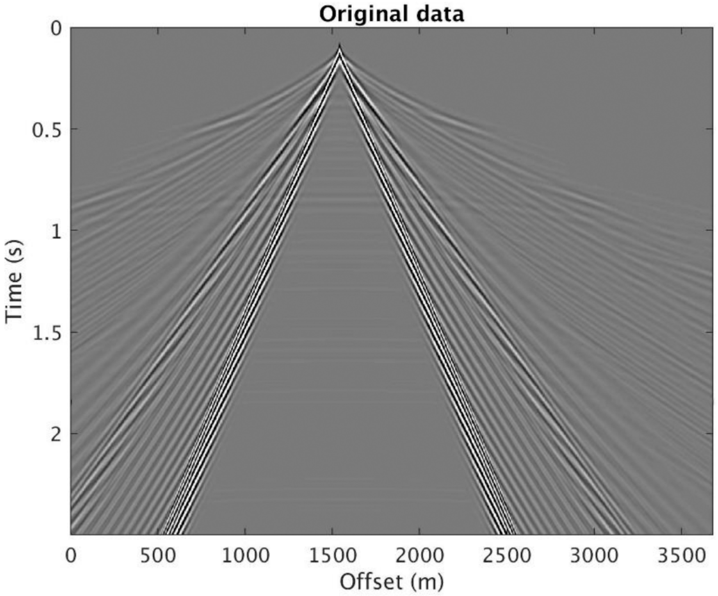

Figure 3—Synthetic seismic shot gather produced by elastic model inspired by an onshore field in Saudi Arabia. Vertical force simulates vibrator, whereas vertical geophones are shown at 0.5 sampling that is currently not economically achievable with standard exploration surveys on land (usually 10-25 m).

"Shallow" survey with DAS

The objective of the "shallow" survey is to obtain a detailed velocity model for the near surface (usually with lowest velocity) typically using surface waves or early arrivals as a signal. Using a small G is a natural selection for large signals characterized by low propagation velocities. Most near-surface methods strongly benefit from dense spatial sampling because of shallow focus of interest and low propagation velocities. For example, one common method to obtain a detailed near-surface model is surface-wave inversion. It relies on picking dispersion curves of ground roll and other near-surface modes on velocity-frequency panels, inverting them for a local 1D model, and merging such models at different locations into a 3D near-surface model. 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 4a) that are almost identical to single-sensor horizontal geophones at 0.5 m (not shown). If we compare them with conventional single-sensor geophone seismic data spaced at 25 m (Figure 4b), we observe that DAS panels have clear advantage 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 compromises. Geophone 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 ground roll signal and smearing of dispersion curves.

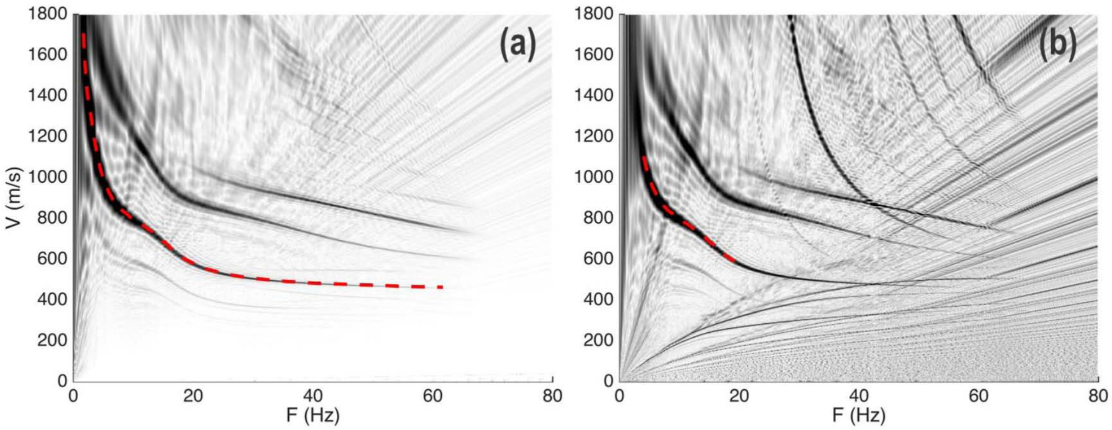

Figure 4—Velocity-frequency panels obtained in a model with 500 m/s slowest velocity with (a) densely sampled DAS data sampled at 0.5 m (G=7 m, L=3 m) and (b) conventional single-sensor geophones at 25 m.

A synthetic data example showing usage of surfaces waves to retrieve the near-surface velocity model is presented in Figure 5. The near-surface velocities have a realistic distribution with the lowest S-wave velocity going down to 210 m/s. DAS system with a small gauge length and fine receiver sampling enables recording strong and aliased surface waves as can be seen both in time and frequency domains. This provides reliable and accurate picking of dispersion curves and leads to good match between true and inverted velocity models after running inversion algorithms.

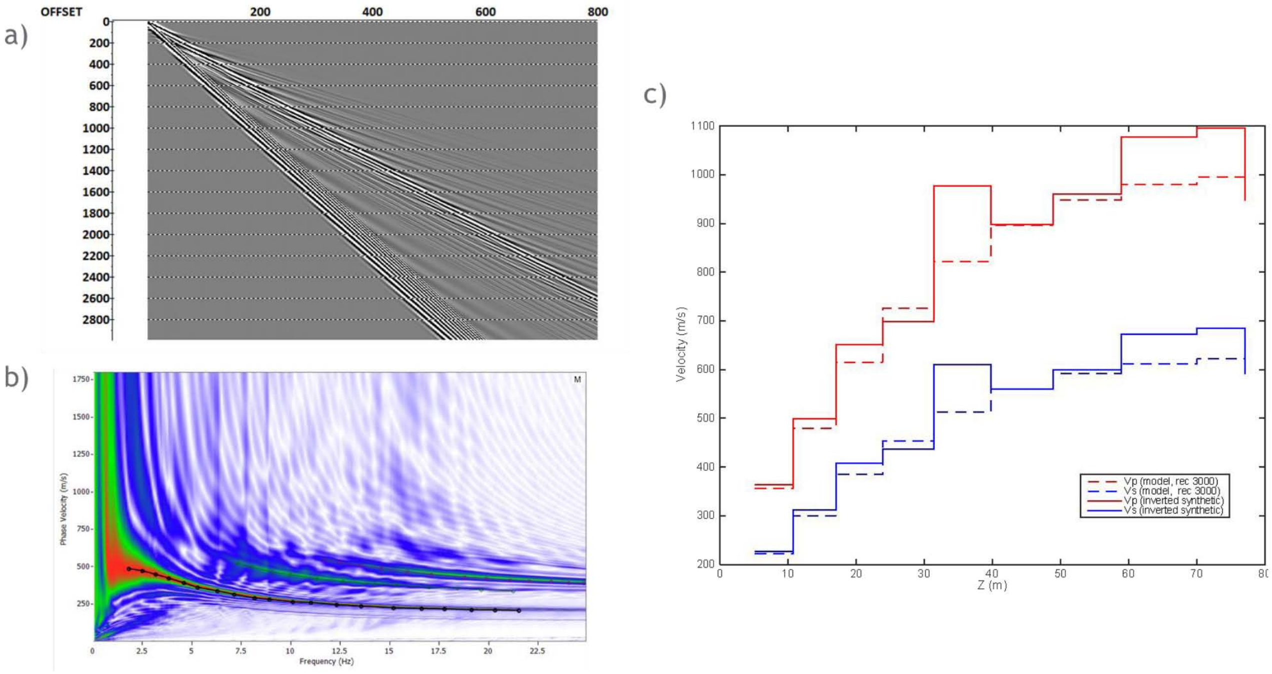

Figure 5—Synthetic data example of surface wave inversion from "shallow" DAS data: (a) a synthetic common-shot gather; (b) velocity-frequency panel and picked fundamental dispersion curve; (c) initial (dashed lines) and inverted (solid lines) velocity models.

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). "Shallow" DAS survey delivers such data without any additional shooting effort. Figure 6 shows a zoomed part of the shot gather similar to Figure 3 but with 50 m sampling. Since conventional single-sensor acquisition with geophones is unable to properly sample in space strong ground roll noise, we are unable to filter it out and uncover reflections due to aliasing (Figure 6a,b). With DAS acquisition performed with 0.5 m sampling, the noise is efficiently filtered out and shallow reflections become very clear and coherent. This simple demonstration confirms that insufficient sampling of shallow reflections with conventional geophone data is the real cause of "reflection blind spots" commonly present in 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).

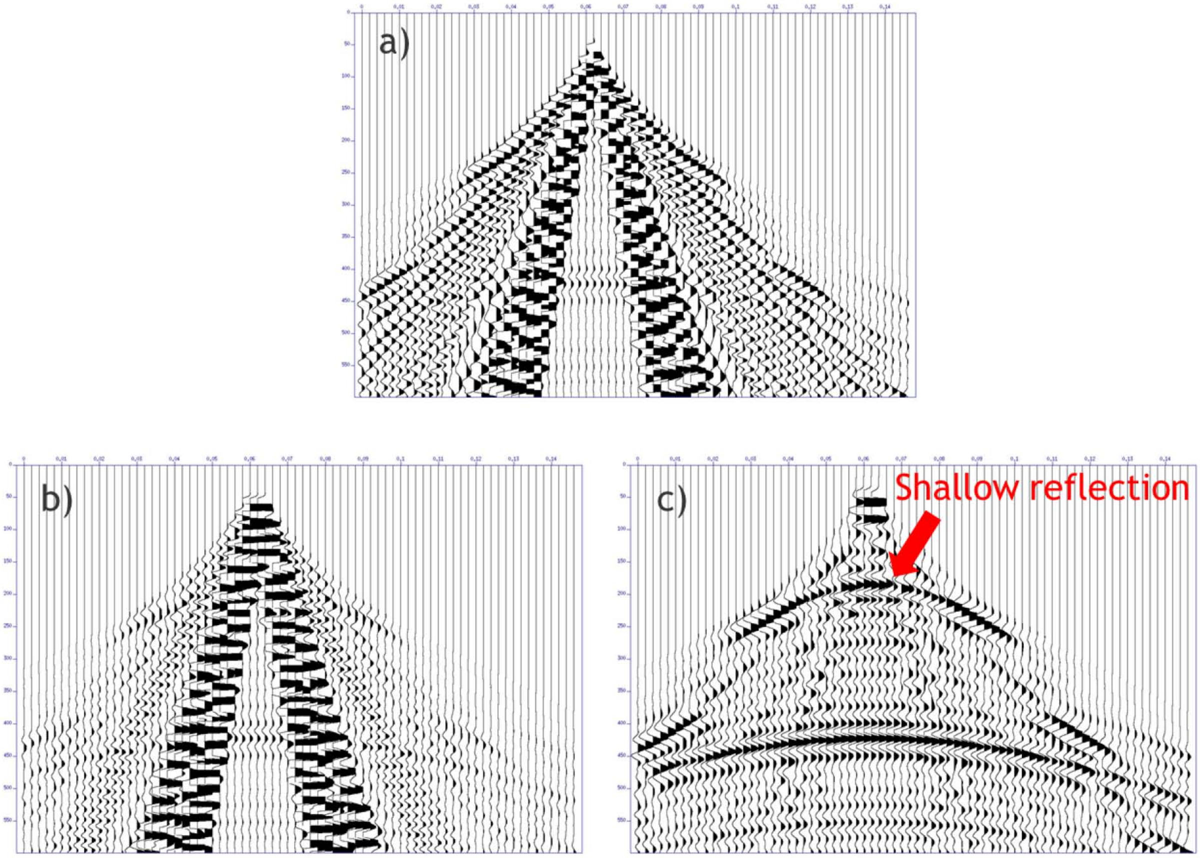

Figure 6—Synthetic data example showing how shallow reflections can be uncovered using densely sampled seismic data: (a) production-style single-sensor common-shot gather at 50 m sampling; (b) filtering results using 25 m sampling interval; (c) filtering results using 0.5 m sampling interval as could be achieved with DAS acquisition.

"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, ground roll and other slow near-surface arrivals can still obscure those signals. In this case, we can opt for a DAS survey with large gauge length 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 7). This is equivalent to a large geophone group that would suppress ground roll noise, while preserving reflections. 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).

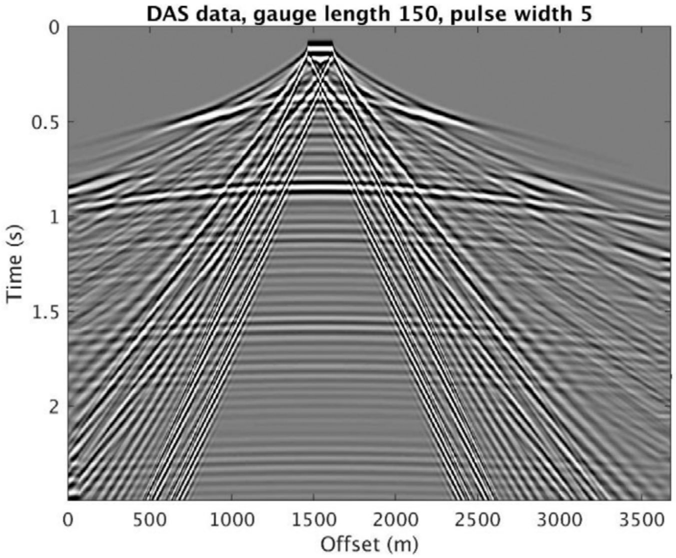

Figure 7—Shot gather recorded using DAS with a gauge length of 150 m and pulse width 3 m (G=150 m and L = 3 m). Observe strong suppression of linear near-surface arrivals and compare to the raw gather from Figure 5 recorded with single geophones.

Field data example of a "shallow" survey with DAS

While we have shown an example of DAS reflection data in Figure 1, let us illustrate a "shallow" DAS survey. The DAS cable was trenched at one meter depth along the surface as shown in Figure 8. In this test, we used gauge length G=7 m and spacing of 4 m between output DAS channels. Compared to modeled responses, such data (Figure 9a) clearly resembles a horizontal geophone response (Figure 9b) more than a vertical geophone (Figure 9c). This densely sampled DAS data with small G is ideal for surface-wave inversion since we know that it preserves low-velocity ground roll and enables picking and inversion of the resulting dispersion curves (Figure 10a) for near-surface shear-wave velocity (Figure 10b). The 2D S-velocity model obtained after the inversion of all dispersion-curves picked at windows of the DAS data is shown in Figure 11a. This model has good similarity with the multi-layered velocity model constructed from uphole information obtained at the same site (Figure 11b). The P-wave velocity profile that was also obtained during the surface-wave inversion based on some a priori relations shows very good correspondence to one of the upholes (Figure 11c). This illustrates that reliable near-surface velocity models can be successfully obtained from the surface-wave inversion of DAS data.

Figure 8—Horizontal trenching of a DAS cable at the surface.

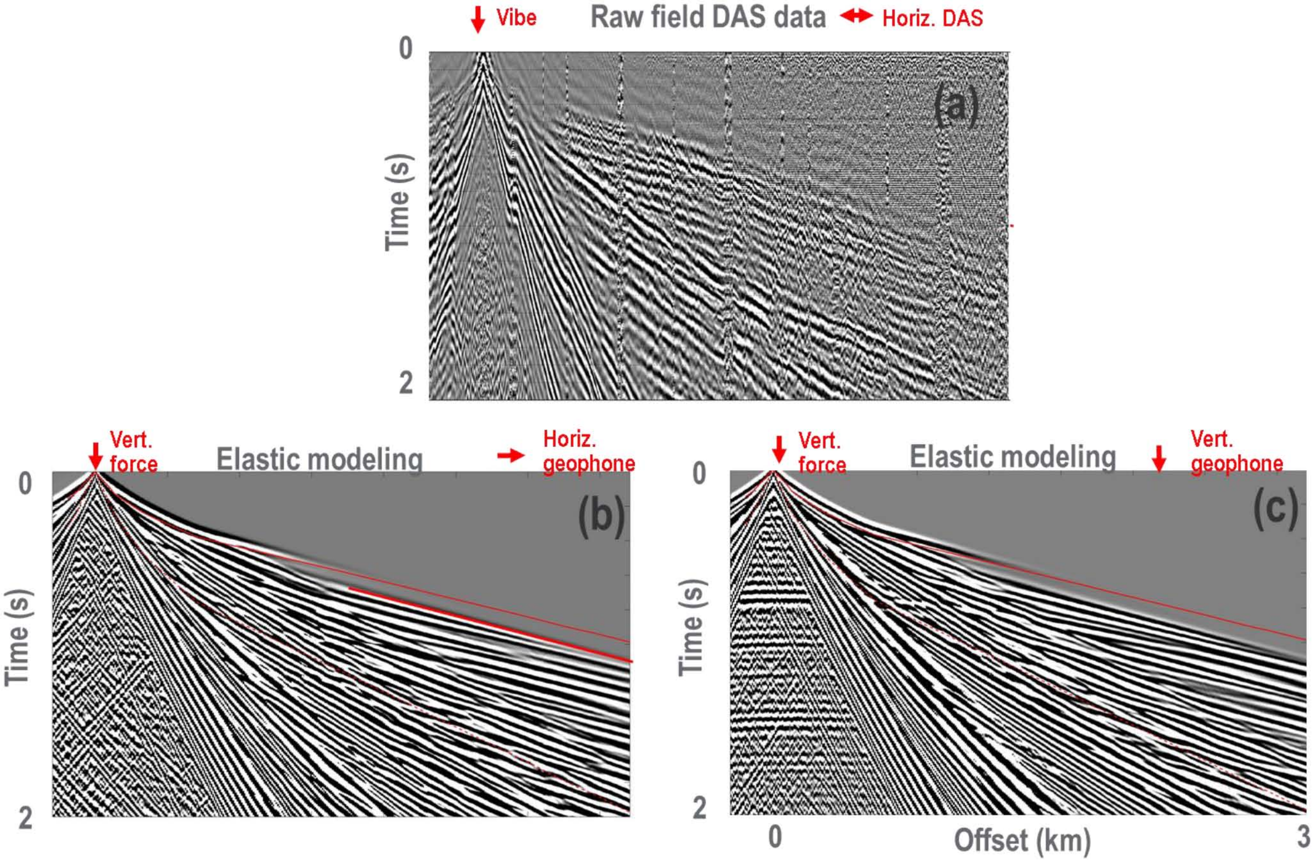

Figure 9—Field common-shot gather from "shallow" DAS survey (a) versus elastic synthetic modeling of a) vertical component and b) horizontal component. Horizontal DAS cable is trenched at 1 m depth. Observe the excellent quality of the field gather and general agreement with modeled response of horizontal as opposed to vertical geophones.

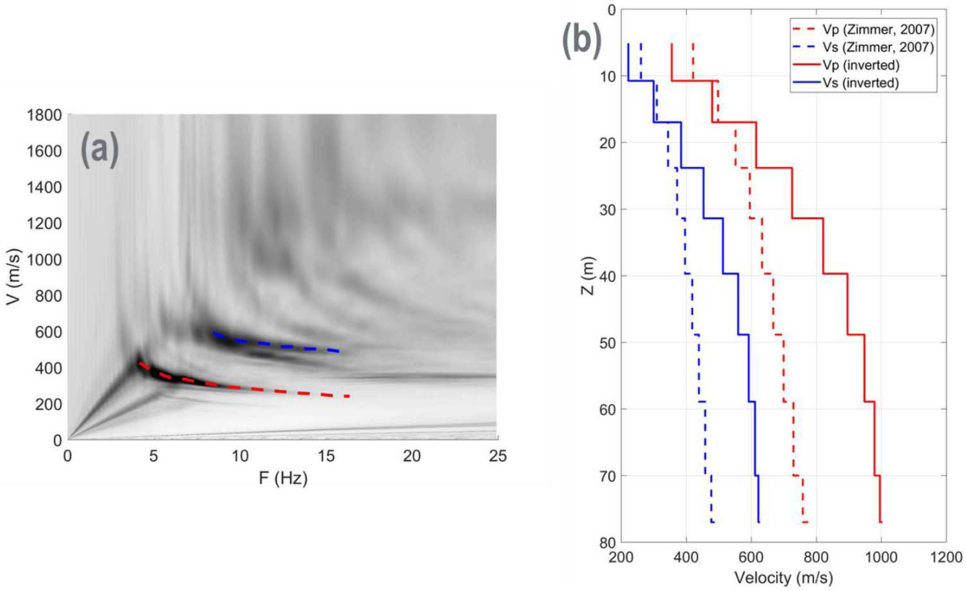

Figure 10—An example of dispersion curves inversion from dense DAS data: (a) dispersion curves picked on DAS data; b) near-surface velocity profiles after inversion using different relations between P and S velocities

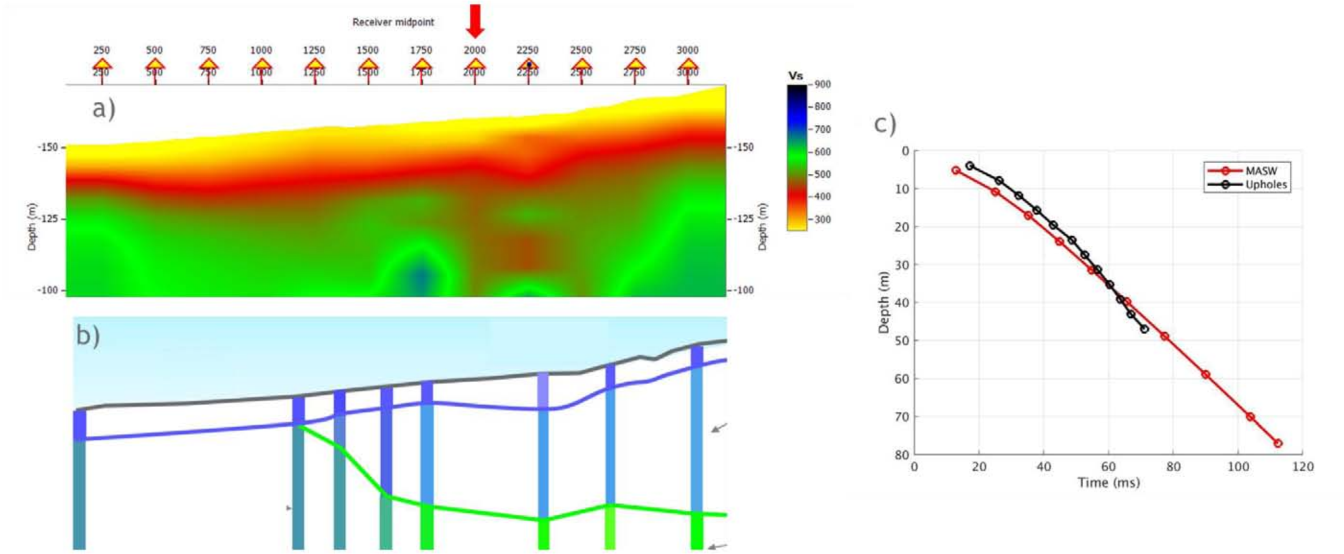

Figure 11—Surface-waves inversion result: (a) S-velocity model obtaining by inverting dispersion curves; (b) multilayered near-surface velocity model constructed from uphole data; (c) comparison of travel-times picked at one of the upholes and surface-waves inversion result for P-wave velocity model.

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 10a) such an assumption may break down. Acquiring DAS data at an even denser spacing of 0.25 to 1 m instead of the 4 m spacing 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. The sampling and the correct choice of DAS parameters becomes especially critical for very slow velocities such as 200 m/s when the wavelength becomes as small as 11 m at a frequency of 17 Hz. This is illustrated in Figure 12 where synthetic frequency-velocity panels are shown for such kind of velocity model. As can be seen, 1 m single-sensor data provides sharp surface-wave signal along the entire band of frequencies allowing to pick dispersion curves up to 80Hz. In contrast, 7 m gauge length used in the field experiment starts to filter out higher frequencies starting from 28 Hz leading to suboptimal quality of dispersion curves. This shows that accurate selection of DAS parameters is required in different geological conditions. Fortunately, DAS acquisition only requires continuous fiber-optic cable whereas selection of gauge length and channel spacing can be done at the recording unit thus giving us a very flexible tool to address every type of geologic conditions on the fly.

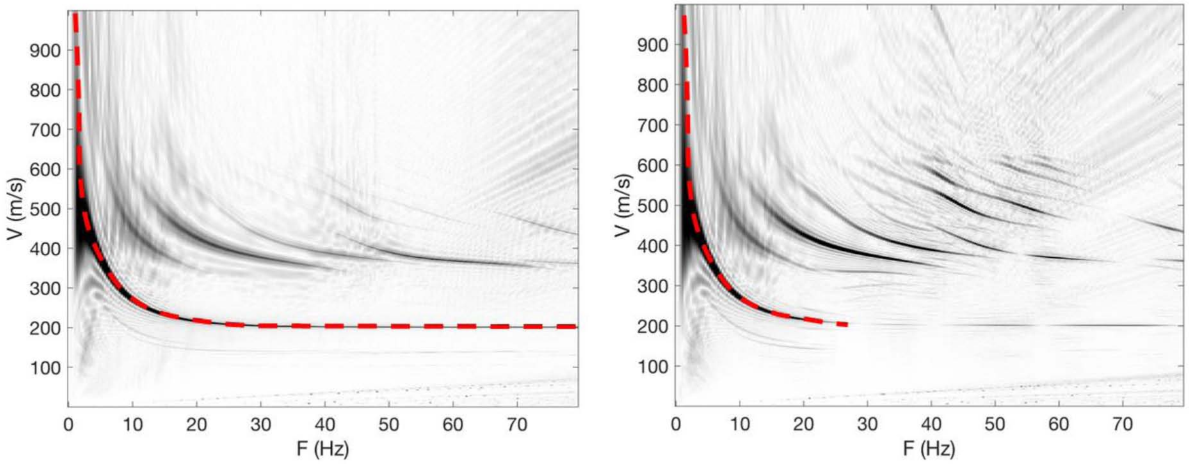

Figure 12—Synthetic velocity-frequency panels obtained in a low-velocity model with 200 m/s slowest S-velocity velocity obtained from (a) dense single geophone data at 1 m sampling and (b) DAS data sampled at 1 m with gauge length G=7 m.

Surface seismic with DAS

Considering novel omnidirectional fiber cable designs that are able to record reflection data, we can use DAS as a surface seismic sensor instead of conventional geophones or accelerometers. Cable ploughing machines can trench fiber optic lines in an automated way, similar to how it is currently done with telecommunications cables (Figure 13). Therefore, all components exist to enable surface seismic acquisition using DAS. This can be a flexible and a fit-for-purpose solution for resolving near surface complexities and enabling depth imaging from topography at the same time. We can accommodate DAS-instrumented upholes into the same recording system and obtain both uphole and surface data at the same time. The highly sampled surface data can be used for near-surface studies using surface, refracted and reflected waves together with upholes information. The same DAS data but with larger gauge length G can be used for depth imaging incorporating both surface recordings and upholes as vertical seismic arrays. Since all recordings are done together – same elevation, same near surface – this would give a much better chance to image subtle hydrocarbon targets in the presence of complex near surface.

Figure 13—Cable ploughing machines deploying continuous cables in shallow trenches as a method of automated placement of DAS seismic cables for surface seismic.

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 a 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 gauge lengths and very fine channel spacing (‘light and dense'). In contrast the "deep" survey is targeted at deep reflections and uses large gauge lengths and moderate spacing adequate for reflection imaging (‘heavy and sparse'). DAS field data confirm this capability for imaging shallow and deep targets simultaneously.

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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