Smart DAS uphole acquisition system for near surface characterization and imaging

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Summary

We introduce the smart DAS uphole acquisition system using optical fiber as an alternative high-resolution and high-quality near-surface measurement. Distributed acoustic sensing (DAS) recording enables simultaneous listening from top to bottom with sub-meter channel spacing. Connecting individual wells using continuous fiber enables creation of a long and densely sampled imaging array with both downhole and trenched surface sensors. We refer to this array as the smart DAS uphole acquisition system. Downhole components provide direct measurement of near-surface velocity, whereas shallow horizontal segments can be used for surface-wave inversion or refraction tomography. Entire arrays can also be simultaneously used for deep reflection imaging. We present field test results validating the capabilities of this system to characterize the near surface, whereas deep imaging is discussed in other studies.

Introduction

Conventional seismic surveys are conducted from the surface. Therefore, we need to see through all the complexities along the way to correctly interpret structures of interest. Near-surface geology in arid environments typical of Saudi Arabia, present a number challenges associated with sand cover, topography and karsts (dissolution features). Every velocity anomaly along the way can distort our view of the reservoir if not accurately captured and accounted for during processing. Shallow near-surface anomalies are particularly hard to quantify because survey design is focused on deeper targets. Over time, exploration efforts have shifted towards more subtle traps such as low-relief structures with closures of 20-60 m, which require even greater accuracy from our near-surface models. As such, we are approaching the accuracy limit of indirect geophysical methods such as refraction tomography. Here we propose a new type of seismic acquisition scheme that can provide simultaneous characterization of the near-surface velocity as well as deep reflection imaging and demonstrate it on a field test.

On demand smart DAS upholes

The building block of our system is the smart distributed acoustic sensing (DAS) uphole shown in Figure 1a. A regular fiber-optic cable is used as the seismic sensor utilizing DAS (Miller et al., 2012). The fiber can be permanently installed or retrievable. Smart DAS upholes have significant advantages compared to the conventional uphole approach using geophones: the entire uphole survey can be recorded with a single shot (providing consistent waveforms) and very dense sampling can be used (from 0.25 m). In the case of permanently installed fibers, drilling and installation can be performed together whereas recording can be done later and repeated as needed with a single excitation of a higher-quality source(e.g., Vibroseis). Operationally, it enables on-demand acquisition for de-risking low-relief structures as shown in Figure 2.

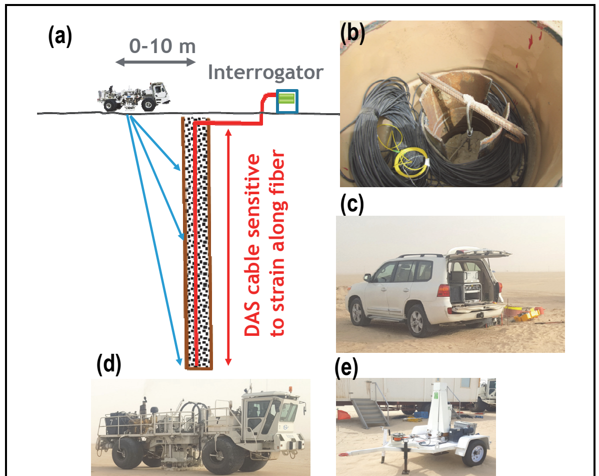

Figure 1. Smart DAS uphole system, showing (a) typical configuration, (b) smart DAS uphole after installation, (c) mobile DAS recording, (d) Vibroseis and (e) weight-drop sources.

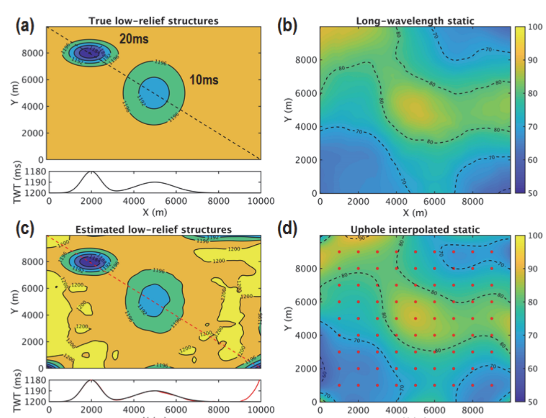

Figure 2. Mapping of low relief structures using uphole-based near-surface models: (a) synthetic low-relief structures and (b) long-wavelength static time-shifts derived from near-surface part of SEAM II Arid model (Oristaglio, 2015); (c) reconstructed structural map and (d) long-wavelength static values derived from interpolating uphole grid drilled at 1x1 km. Note the good estimation of near-surface statics and consequently reliable reconstruction of target low-relief structures in (c).

When a prospect suffering from near-surface uncertainty is identified, we design a regular or adaptive grid of upholes that are quickly drilled and instrumented with the fiber and measured with single shot per point. With uphole spacing of 1 km on a regular grid, a 10 x 10 km prospect would require 81 upholes. Figures 2c and 2d confirm that long-wavelength statics, derived directly from uphole interpolation alone, provides a very accurate solution allowing low relief-structures (closure as small as 10-20 ms) to be mapped reliably. This example is simple, yet realistic enough to demonstrate that smart, on demand DAS upholes could become a valuable part of our geophysical toolbox when exploring for subtle structures. Of course, smarter placement of upholes based on the value of information combined with other methods also becomes possible, but uphole measurement calibration is preferred over any indirect approach.

Smart DAS uphole acquisition system and field test

Utilizing optical fiber gives us an opportunity to go one step further by connecting optical fiber between upholes as shown in Figure 3a. This creates a continuous imaging array with both surface and downhole channels that could be recorded with a single recording box referred as interrogator. Such an array could be used for a variety of "shallow" and "deep" applications and would be an excellent fit-for-purpose solution in areas with near-surface challenges because of the following reasons:

- A grid of smart DAS upholes can completely resolve long-wavelength statics and deliver a near-surface model with the accuracy needed for low-relief structures.
- Buried data is of higher signal-to-noise ratio compared to surface reflection data (due to reduction in recorded surface waves) and can provide angular coverage and images comparable to surface seismic.
- A combined smart DAS uphole and surface seismic survey (i.e., using the same sources) offers a unique apparatus for characterizing the near surface.
- The combined survey makes it a self-contained package that can de-risk prospects of interest.

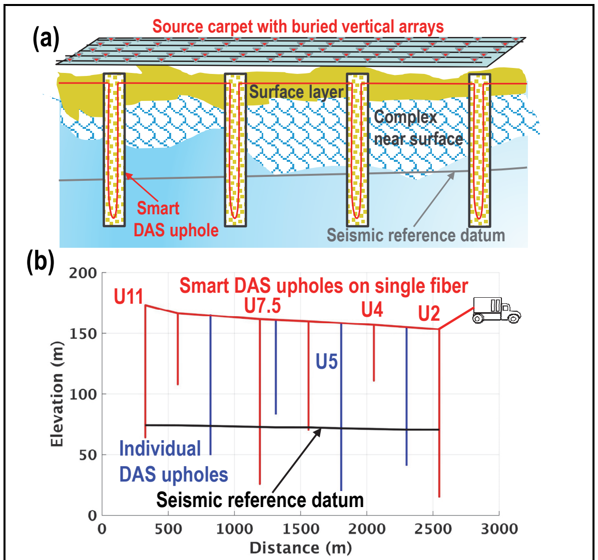

Figure 3. Schematic (a) and actual field geometry (b) of simultaneous recordings with smart DAS acquisition system in multiple wells acquired with a carpet of sources. Field acquisition contains six vertical arrays on a single fiber with average uphole spacing of 400 m and average depth of 100 m.

To evaluate the concept and demonstrate these advantages, an onshore field test was conducted in Saudi Arabia. Figure 3b shows actual field geometry with ten smart DAS upholes along a 2D line. The fiber was permanently installed in all upholes, with six of them connected using continuous fiber to record the seismic survey. This resulted in 1,122 DAS channels at 4 m spacing with 299 channels located in vertical holes.

Smart DAS uphole results

Figure 4 displays waveforms recorded in DAS upholes and compares them with conventional upholes using geophones. One can see that geophone waveforms show significantly more variability in arrival time due to changing source excitation and coupling. Velocities

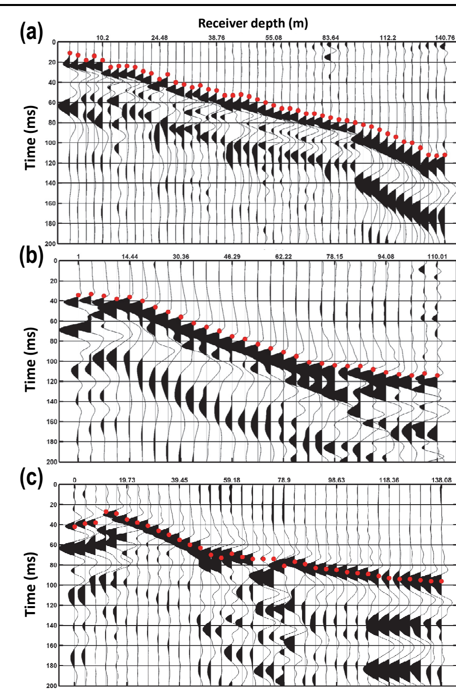

Figure 4. Example of picked uphole gathers acquired as part of the field tests showing (a) conventional uphole U4 using geophone and accelerated weight drop (AWD) source, (b) DAS uphole U11 with AWD source and (c) DAS uphole U5 with Vibroseis source.

estimated from DAS and geophone upholes are in good agreement (Figure 5a).

At the seismic datum level, we observe significant variability of the uphole times along the line (Figure 5b) that likely manifest as mid-wavelength statics variations that could distort mapping of low-relief structure of interest.

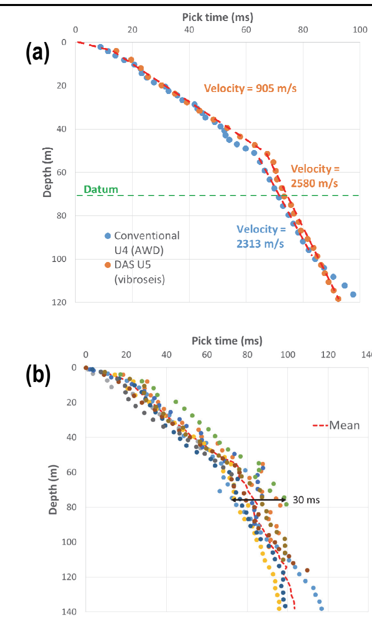

Figure 5. Comparison of first-break picks from various upholes: (a) adjacent wells (~300 m) using conventional (blue) and DAS fiber (orange) receivers; (b) all ten DAS upholes acquired using a Vibroseis (stack of ten sweeps).

Reflection data with DAS

With carpet shooting at the surface we can also evaluate downhole DAS data for reflection imaging. Figure 6 shows that such data is comparable to legacy surface seismic data. Since legacy seismic is acquired with a 72-geophone array, we perform simple noise removal on DAS data and then observe one-to-one correspondence between reflections on both gathers. In addition, we see almost identical frequency content, confirming that DAS is perfectly suitable for deep reflection imaging (discussed in a separate study).

Use of horizontal DAS cables for near surface

Horizontal sections of DAS cable (trenched at one meter) record data similar to horizontal geophones because of the predominant directivity along the fiber. With dense sampling of 4 m, surface DAS data is perfectly suitable for surface-wave inversion. Figure 7 shows measured dispersion curve and inverted S-wave profile at one of the locations. Despite the dominantly horizontal directivity, the

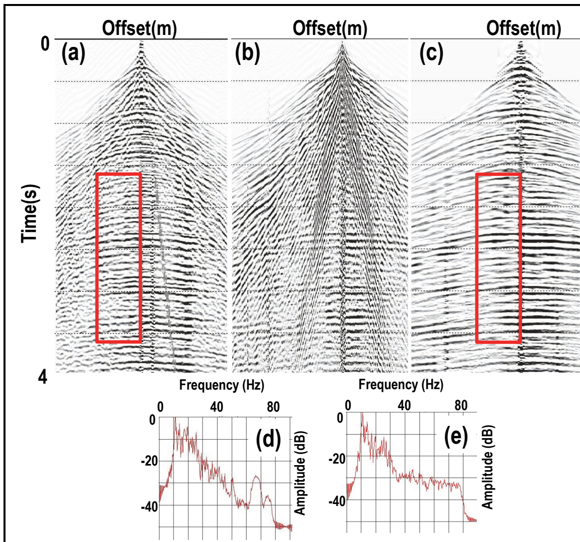

Figure 6. Comparison of prestack common-receiver gathers obtained with surface geophone (legacy 3D seismic) and a DAS receiver at 15 m depth: (a) raw legacy seismic gather with 60 m source spacing, (b) raw DAS gather with source spacing of 10 m, and (c) same DAS gather after linear noise removal and decimation to 60 m source spacing. Spectra of legacy geophone (d) and DAS data (e) after noise removal show similar behavior.

trenched DAS cable also records early arrivals corresponding to P-wave refractions (Figure 8). Enhancement with supergrouping (Bakulin et al., 2016), allows robust first-break picking and enables refraction

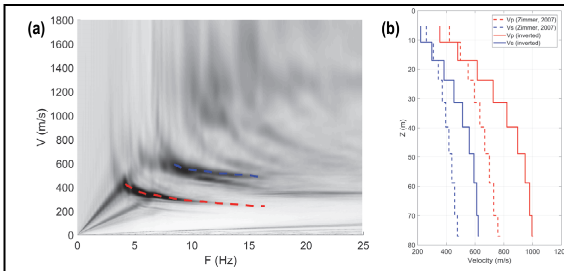

Figure 7. Surface-wave inversion with horizontal cable: (a) velocity-frequency panel with dispersion curve, (b) inverted velocity profiles.

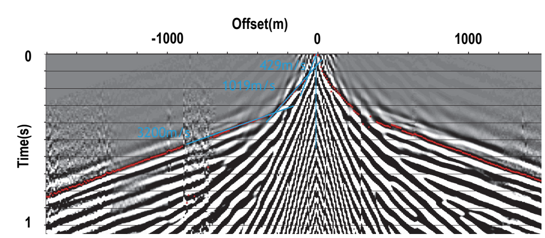

Figure 8. First break picking of horizontal cable data for refraction tomography (shown after supergrouping).

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tomography. Availability of both uphole and tomography on the same dataset enables joint utilization of both data and the derivation of spatially detailed models that are calibrated at upholes.

Adapting DAS acquisition to near surface

When a DAS signal is recorded, it utilizes a certain segment of the fiber to produce this measurement. The length of this segment is known as the gauge length. As such, distributed sensing with DAS fiber is akin to recording with a geophone group having aperture equal to the gauge length (Bakku, 2015). While typical seismic/VSP DAS acquisition utilizes a gauge length of 7-15 m or more, near-surface studies require special attention because of the extremely low velocities. Indeed, comparing Figures 4a and 4b closely, we observe lower frequency content for DAS. Figures 9a and 9b confirm that useable frequency band is 10-63Hz for geophone and 3-48 Hz for DAS uphole waveforms. Figure 9c shows modeled responses for DAS and geophone in an uphole with 300 m/s that demonstrates that frequencies above 40 Hz are strongly filtered by the DAS "array" with gauge length of 7.5 m. To get the highest possible resolution in the shallow near surface, we have to use a smaller gauge length to allow higher frequencies to be recorded. Of course, smaller gauge lengths would lead to lower signal-to-noise ratio (SNR) and may require stronger sources or acquiring deep upholes with two different gauge lengths: small (say 2 m) to characterize the shallowest part with lower velocities, and large (say 7.5 m or more) gauge lengths to get penetration to the target horizon. It should be noted that 7.5 m (or higher) gauge length is non-damaging to the signal and preferable (because of higher SNR) for reflection imaging (Figure 6) where lower-frequency, weaker signals with much higher apparent velocities are of primary focus. Luckily, gauge length is a parameter set inside the interrogator. Therefore we can record data with DAS "arrays" adjustable in the field whereas newer systems could directly output several datasets corresponding to multiple gauge lengths simultaneously.

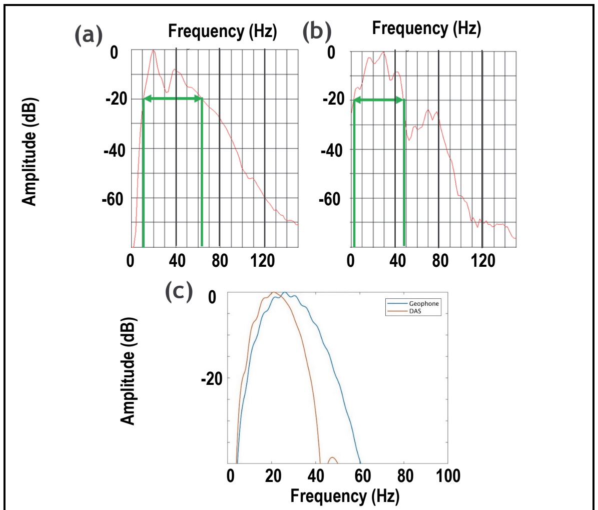

Figure 9. Amplitude spectra of first breaks (0-200 ms window) for (a) conventional uphole data acquired with accelerated weight drop, (b) smart DAS uphole data using 7.5 m gauge length and (c) modelled DAS and geophone response for a synthetic uphole in a homogeneous medium with 300 m/s. Observe that particular DAS array with 7.5 m gauge length attenuated frequencies above 48 Hz, whereas geophone attenuated lower frequencies below 10 Hz. Using smaller gauge length of DAS array should enable recording of higher frequencies without compromise on the low frequencies.

Conclusions

We have introduced a smart DAS uphole acquisition system in order to enable more accurate and more flexible near-surface characterization that is a must when exploring for low-relief structures. With instrumented fiber from top to bottom, uphole surveys can be conducted with a single source and have reliable and consistent waveforms not only for first-break picking, but also for full-waveform inversion of both velocities and attenuation. Low fiber cost facilitates permanent installation that allows us to separate drilling/installation and recording stages during operations allowing for more efficiency. This enables the concept of on-demand smart DAS upholes that could be invoked to address near-surface challenges at a prospect level in quick and reliable fashion. Grids of upholes can deliver very accurate long-wavelength statics for reliable mapping of low-relief structures.

Smart DAS upholes can be further connected by a continuous fiber and enable seismic acquisition using sizeable arrays 10-50 km long. Vertical arrays are straightforward for reflection imaging because of their directivity and improved data quality due to burial. Horizontal sections are useful for surface-wave inversion and first-break tomography or FWI.

We have presented field test results with ten smart DAS upholes and illustrated the potential capabilities. Special attention needs to be paid to selecting the proper gauge length (or multiple gauge lengths) for DAS acquisition to ensure that the near-surface objective is not compromised, especially in the presence of extremely low velocities such as those detected in the shallowest portion of the upholes or in the surface-wave inversion studies. DAS allows us to achieve all of these objectives at once by delivering very densely sampled data starting from 0.25 m with adjustable DAS arrays.

Acknowledgments

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