# Surface seismics with DAS: An emerging alternative to modern point-sensor acquisition

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## Abstract

Land seismic acquisition is moving toward "light and dense" geometries, with point receiver systems believed to be an ultimate configuration of choice. Cableless land nodal systems enable more flexible spatial sampling at the price of eliminating even small arrays. For large surveys in a desert environment, such spacing remains insufficient to address the complex near surface, while recordings with single sensors exhibit a significant reduction in data quality. At the same time, exploration problems increasingly demand smaller uncertainty in all seismic products. While 1 m geophone sampling could have addressed these problems, it remains out of economic reach as point sensor cost plateaus. We examine an emerging alternative technology of distributed acoustic sensing (DAS) that revolutionized borehole geophysics but is still mostly unknown in the seismic world. Fully broadband DAS sensors promise massive channel count and uncompromised inline sampling down to 0.25 m. Their distributed nature offers the unique capability to conduct a continuous recording with multiscale grids of "shallow," "deep," and "full-waveform inversion" receivers, all implemented with a single set of fixed cables and only one round of shooting. These distinct features allow us to simultaneously pursue near-surface characterization, imaging of deeper targets, and velocity model evaluation. Specifically, in a desert environment, distributed sensors may offer superior data quality compared to point sensors, whereas DAS capability of "seismic zoom" in the near surface becomes instrumental for near-surface characterization. Finally, simultaneous acquisition of surface seismic and vertical arrays that can be achieved easily with DAS can effectively address the exploration of subtler targets such as low-relief structures. We support these findings with a field case study from a desert environment and synthetic examples. With many distinct advantages, surface seismic with DAS emerges as a compelling alternative to modern point-sensor acquisitions.


## Introduction

Distributed acoustic sensing (DAS) has proven itself as an alternative recording for seismic data both downhole (Mestayer et al., 2011; Daley et al., 2013; Parker et al., 2014) and at the surface (Hornman et al., 2013; Freifeld et al., 2016; Yavuz et al., 2016; Ajo-Franklin et al., 2017). Most industrial applications are centered around borehole geophysics, where DAS occupies less real estate in the wells, provides significantly more competitive per-channel prices, and suits permanent instrumentation. Many limitations, such as along-the-well directivity, lack of 3C recording, and array-like averaging over significant gauge lengths (GLs) of 15–50 m, all were discounted in favor of accessing a large number of channels and the simplicity of wellbore installations. It appears that the industry has reached a consensus on endorsing borehole DAS. Even though actual progress and implementation by the service industry and operators remain somewhat uneven, it is undeniable that borehole DAS became a primary industrial application from onshore to offshore. This is not the case for usage of DAS for surface recording, which remains a field of active research. It appears that surface seismic may benefit much more from DAS as it already uses orders of magnitude more channels than borehole geophysics but continuously strives for more. Also, surface recording requires much easier logistics than borehole. We believe at least one reason for the slow progress is the lack of clear industry use cases for surface seismic with DAS. Just as oil is first found in the mind, new seismic acquisition requires a clear grasp in our minds as a starting point of the journey. In this article, we attempt to articulate a clear industry case for surface seismic with DAS in general and the desert environment in particular. We go beyond simple considerations of channel count to include scrutiny of optimal data quality, sensitivity, and ability to address long-standing issues such as the complex near surface.

## Surface seismic with DAS

The concept of surface seismic with DAS as visualized in Figure 1 may offer these key advantages:

- massive channel count with cheaper per-channel cost than point sensors
- uncompromised inline sampling
- flexible multiscale recording suitable for looking "shallow" and "deep" as well as for generating a "full-waveform inversion (FWI) velocity survey" with dedicated low-frequency arrays
- completely broadband nature of the DAS sensor

We start with a high-level review of DAS acquisition for surface seismic purposes. Then we examine each of these aspects in detail as well as the value of the combined package. Using a mix of real and synthetic examples, we aim to articulate and support an industrial case for surface seismic with DAS specifically for desert environments.

## Understanding DAS sensors

DAS sensors are distinct from any other sensors we use. DAS measures dynamic strain using the phase interferometry principle (Hartog, 2017). The most straightforward explanation can be

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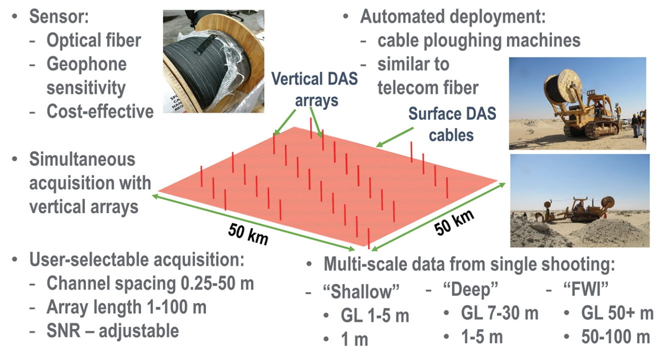


**Figure 1.** Surface seismic with DAS enables acquisition of "shallow," "deep," and "FWI" receiver grids combined with simultaneous recording of vertical arrays spliced into the seismic grid.

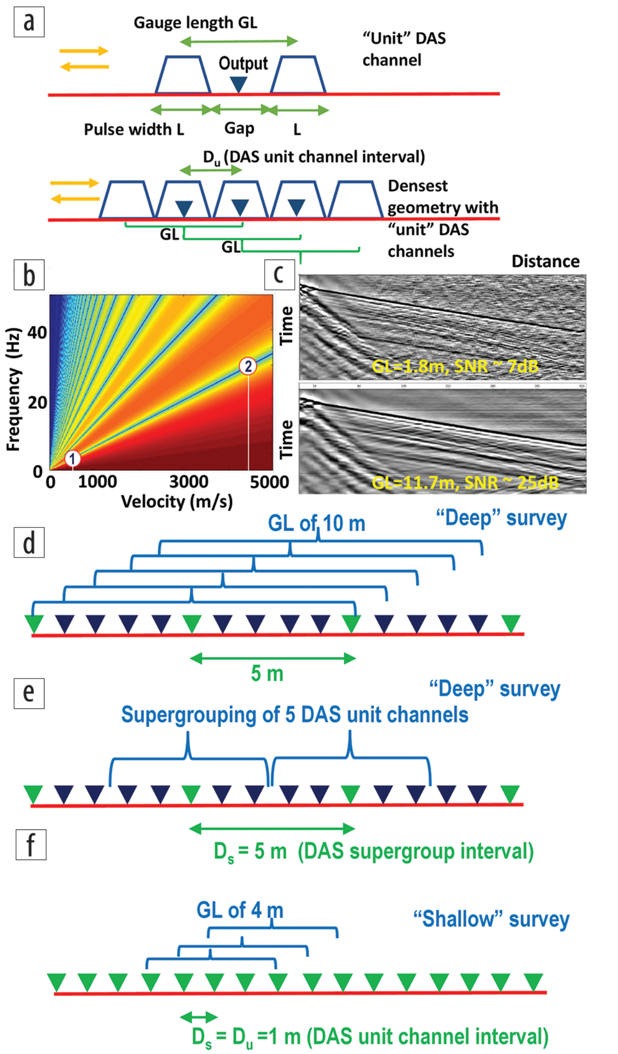


**Figure 2.** (a) Schematic of measuring dynamic strain using dual-pulse technique with two reference signals of light propagating along an optical DAS fiber. (b) The amplitude response of the DAS array computed using equation 1 and showing how the point strain rate is averaged to produce the final response by distributed DAS sensor with GL of 150 m and pulse width of 3 m. (c) Effect of GL on S/N. DAS multiscale capability allows simultaneous recording of two or more surveys using a single fiber cable and only one round of shooting. Deep surveys (d) without and (e) with additional supergrouping. (f) Shallow survey.

produced by invoking the simplest form of the dual-pulse interrogation technique. Let us describe a "unit" DAS channel. Two reference pulses of light are sent along an optical fiber (Figure 2a). Those pulses interact with natural imperfections of the fiber generating reflected signal through so-called Rayleigh scattering. Temporal variations of the phase lag between the backscattered signal at the front and end of the GL are transformed into a strain rate representing a final output measured by a unit DAS channel location at the midpoint. For this unit channel, phase lag should be analyzed around a particular two-way time required for the light to travel to this channel from the interrogator. Sending a series of two-pulse sequences and analyzing phase lags for all recorded times delivers a strain rate at every location along the cable (Hartog, 2017).

***DAS sensor as a linear array.*** GL and pulse width are two fundamental parameters of DAS acquisition. We define GL as the distance between the regions on the fiber where the scattering has occurred. Fundamentally, using GL creates a seismic array with an aperture equal to GL and infinitely small spacing between elements (Bakku, 2015). Pulse width also acts like an array. In the frequency-wavenumber domain, the average strain recorded by the unit DAS channel (Figure 2a) can be related to the point strain using the amplitude response filter (Bakulin et al., 2018a):

$$A(k_x,\omega)=\frac{\sin\left(\frac{k_x GL}{2}\right)}{\frac{k_x GL}{2}}\,\frac{\sin\left(\frac{k_x L}{2}\right)}{\left(\frac{k_x L}{2}\right)}, \qquad (1)$$

where $L$ is pulse width, $\omega$ is the angular frequency, and $k_x$ is along-the-cable wavenumber projection. Leaving directivity aside for a moment, this equation can be used as a simple proxy relating point-sensor acquisition with geophones and distributed fiber-optic cables. We immediately recognize $A(k_x,\omega)$ as the filter response of two arrays with apertures of GL and pulse width both having infinitely small spacing between elements. The amplitude response of a DAS "sensor" is plotted in Figure 2b. As GL is often greater than pulse width, and for simplicity, we focus on the effect of GL as a dominant factor. Recording DAS data with small GL is similar to a single-sensor or small geophone group and indeed is usually characterized by a low signal-to-noise ratio (S/N) typical of land single-sensor data. Likewise, recording with large GL is akin to a large geophone group and results in higher S/N due to the summation of the signal and suppression of the low-velocity noise. In practice, GL can vary from 1 to 100 m or more.

***Practical considerations of optical recording.*** Because the speed of light in typical fiber with a refraction index of 1.45 (Hartog, 2017) is very fast (approximately 206,753 km/s) but our measurement capabilities to sample the light are limited, it is worthwhile to switch to some realistic order-of-magnitude quantities representative of the real world. Let us assume the shortest realistic pulse width is 1 m. The light can travel such distance within only 5 ns (one-way time) or 10 ns (two-way time). To mimic geophone single-sensor acquisition, it may be tempting to select the shortest possible GL and smallest achievable channel spacing allowed by the equipment. For simplicity, let us take a gap of 1 m so that two pulses are separated by a single pulse width making GL = 2 m (Figure 2a). Unlike geophone measurement, the distributed nature of the optical system allows us to output the unit DAS channels at almost arbitrary sampling that in practice is anywhere above approximately 0.25 m. We emphasize that the DAS unit channel interval ($D_u$) is entirely independent of GL and is a property of the DAS optical recording system. This represents a fundamental difference between distributed and point recording systems. In point systems, a decrease in the sensor spacing requires a proportionate increase in the number of planted physical devices, which escalates the cost linearly. In contrast, in DAS recording, fiber cable has no markings whatsoever, whereas inline DAS unit channel spacing of approximately 0.25–1 m is a property of the recording system and is externally granted "for free." Again, for simplicity, let us select unit DAS channel spacing $D_u$ = 1 m (Figure 2a). Note that in this example, two neighboring DAS recordings would be 50% "overlapping" in terms of the optical path along the fiber contributing to the output measurements. In geophone recording, it would be analogous to recording two arrays of, say, three geophones (with, for example, 1 m intra-array sampling) that only differ by a single geophone, while two geophones are shared. With DAS, such a sharing is seamless along the light path and does not require separate fibers or separate recordings. While the described configuration with unit channel spacing (1 m) and shortest GL (2 m) are realizable with the recording equipment, in practice, larger GL, pulse width, and output spacings are used for the reasons explained in the following.

***Optimal GL.*** The selection of optimal GL requires balancing the following trade-off between optimal S/N and array filtering. The sensitivity of the DAS channel with the smallest GL is quite far from the geophone. It is intuitively clear that measuring elongation over a longer piece of fiber would result in a more significant cumulative deformation, implying larger sensitivity. In contrast, shorter GL would result in smaller sensitivity. Figure 2c compares data obtained with different GL with a fixed source and fiber. The smallest GL = 1.8 m delivers poor S/N measured as energy ratio of first arrivals to precursor energy ahead of them. Collecting the vast plurality of such low-sensitivity channels is not practical as sensitivity cannot be increased via summation in processing. Just as geophone strings are often connected in series to improve overall sensitivity, optical averaging along longer GL also increases sensitivity. However, selecting a GL that is too large may lead to attenuating certain frequency bands of lowest-velocity arrivals by DAS linear arrays. Therefore, the smallest possible GL that allows us to achieve the required sensitivity is what really counts in practice. We expect that with the development of modern DAS interrogators and engineered fibers, geophone sensitivity can become reached for desirable GL on the order of 10 m or even less. In that case, balancing the trade-off between S/N and array filtering would be easier to achieve.

***DAS supergroup interval.*** For the sake of argument, let us assume that a deep imaging application requires GL = 10 m. A DAS recording system typically still captures channels at a minimum possible sampling (1 m in our example). As a result, a geophysicist may elect the densest DAS sensor interval at 1 m, such that it includes positions marked by all blue and green triangles in Figure 2d. Note that neighboring DAS sensors overlap 90% in contributing fiber, whereas the volume of data would be significant. The more practical choice may be to deliver sparser output spacing of, say, 5 m, which is still acceptable for an imaging application. This could be achieved in two ways. One choice is simply to subsample and select every fifth unit DAS channel for output as marked by green triangles in Figure 2d. In this case, 80% of the DAS unit channels (blue triangles) will be discarded. Another choice would be to create a nonoverlapping DAS supergroup that would sum unit channels, say, within the aperture of the output spacing ($D_S$ = 5 m) or any predefined length of the secondary array (Figure 2e). Then, all DAS unit channels would contribute to the output data set. We intentionally call it "supergrouping" (with aperture $D_S$) to highlight the fact that the DAS unit sensor is already a first-order array, whereas this summation is done on top of that analogous to a supergrouping of already grouped field data in seismic processing (Bakulin et al., 2018b). Both DAS and geophone supergroups aim to increase S/N by suppressing optical as well as scattered geophysical noise.

***Flexible multiscale data with DAS.*** We have explained the selection of optimal DAS acquisition parameters assuming there is a single survey goal. This is a mentality imprinted on us by conventional geophone acquisition. If deep targets are our primary goal, then the design of the main acquisition parameters is driven almost exclusively by them. In contrast, all secondary objectives, such as near-surface characterization, are compromised or ignored. Pursuing any secondary purpose with geophones implies automatic and significant cost escalation. DAS allows us to do fundamentally better by acquiring multiscale data targeting two or more seemingly contradictory objectives at the same time. For example, S/N requirements for deep targets may require 10–20 m GL; however, such GL attenuates the ground roll needed for near-surface characterization. The solution is to output two or more "versions" of the DAS data with different GL at the same time. This is achievable with some DAS systems using a single round of shooting. Therefore, we obtain a measurement system unthinkable from the perspective of point geophone sensors: one data version recorded with small GL (point sensors) at submeter channel spacing ("light and dense") and another with large GL (effectively large geophone groups) still at submeter or larger spacing, or any combination of the two. While any other intermediate combination or DAS acquisition geometry can be generated, let us single out three specific geometries of most immediate use:

1) "Shallow" acquisition (example on Figure 2f) with small GL and densest channel spacing ("light and dense") enables near-surface characterization with finely sampled tomography, reflection-based methods, surface-wave inversion, elastic FWI, and machine learning-based methods — all harvesting benefits of unaliased data:
   a) Smaller GL and reduced sensitivity are acceptable because near-surface arrivals (surface waves, guided waves, and refractions) are of large amplitudes.

   b) Short DAS supergroup interval is desirable in order to not attenuate and sample these low-velocity arrivals treated as a signal for near-surface characterization.
2) "Deep" acquisition (example on Figure 2e) with large GL and moderate spacing that would be a "proxy" for conventional data targeting deep reflections ("heavy" but fully flexible in spacing):
   a) Large GL is required to detect very weak reflections (higher sensitivity and S/N from large arrays).
   b) Suppression of low-velocity near-surface arrivals is acceptable and even desirable.
3) "FWI velocity survey" acquisition with even larger GL (for example, 50 m or more) for low (1.5–8 Hz) and ultralow (0.1–1.5 Hz) frequencies:
   a) Very large GL boosts sensitivity further and creates a massive array for robust detection of weak low frequencies.
   b) DAS is a truly broadband sensor recording low and ultralow frequencies all the way to the nearly static strain.
   c) Array filtering of higher frequencies is acceptable along with even more aggressive suppression of low-velocity noise.

For geophone acquisition, we always face a polarizing choice of either "heavy and sparse" or "light and dense" (May, 2016). 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 S/N (Figure 7a). 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 S/N data that need more processing effort (Figure 7c). DAS relieves us from this dilemma (along the cable direction) and enables output of "heavy and dense" and "light and dense" simultaneously, thus allowing us to address multiple objectives without conflict.

Let us now move to a simple 2D case study aimed at illustrating the promise of seismic with DAS. A desert environment makes the choice between "heavy and sparse" or "light and dense" particularly tormenting. The rapid move to "light and dense" faces the most considerable headwinds associated with a complex near surface, diminishing data quality, and subtler exploration targets. At the same time, the channel count of point-sensor systems remains insufficient to address these challenges effectively (Bakulin et al., 2019b). We intend to show that, in a desert environment, seismic with DAS could be of particular value because it enables:

- superior data quality of distributed sensors as compared to point sensors, especially in the presence of a complex scattering near surface
- the capability of "seismic zoom" on the near surface capturing wavefield at unprecedented submeter sampling for near-surface characterization as well as noise suppression
- simultaneous acquisition of surface seismic and vertical arrays effectively addressing the exploration of subtler targets such as low-relief structures and stratigraphic traps

## A case study from a desert environment

Desert environments are known for their complex near surface and poor data quality. Long-wavelength velocity variations lead to incorrect imaging of low-relief structures (Bakulin et al., 2017), whereas small-scale heterogeneities lead to severe scattering and poor data quality (Bakulin et al., 2018, 2020). The most significant reduction in structural uncertainty is achieved by introducing uphole measurements; however, acquiring them at a different time from seismic results in elevation changes due to moving sand and makes integration with seismic challenging. One solution is to perform simultaneous DAS acquisition of surface seismic and vertical arrays. Figure 3a shows an actual field setup with continuous DAS cable trenched along the surface going into the uphole, turning around and coming back to the surface, and continuing to the next hole. Upholes instrumented with DAS were dubbed "smart DAS upholes," whereas a combined surface and vertical array geometry is often referred to as "smart DAS acquisition" (Bakulin et al., 2017; Alshuhail et al., 2019). Several 2D shot lines were acquired using a four-vibrator source array with a 10 m inline spacing and summed together. The GL of 7 m was used with a DAS supergroup channel spacing of 4 m. This resulted in 2850 source locations and about 1200 DAS channels, a quarter of which are downhole.

Let us first focus on "deep" survey imaging reflectors at depth. We used straight DAS cable in this trial, and while horizontally trenched segments are of no use for reflection imaging, vertical sections have desired directivity to near-vertical motion. While holes are sparse in the horizontal direction, the vertical antennae make up for this spatial sparseness by creating angle illumination and coverage that may be equivalent to surface seismic (Bakulin et al., 2017).

***Prestack data comparison.*** First, let us check the obtained prestack data quality. We intentionally focus on receivers close to the surface that would be more representative of surface seismic. Figure 3 compares common-receiver gathers obtained using a single DAS channel in a shallow hole at 15 m depth and legacy data using surface geophone arrays. We observe excellent kinematic agreement between reflected signals on both data sets. DAS data show more details because of the finer source sampling of 10 m compared to 60 m for legacy data. The lower levels of ground roll and other linear noise on legacy data are explained by the use of 72-geophone and five-vibrator arrays in the field. After we apply linear noise removal to DAS data and decimate to the same spacing, we see closer agreement between DAS and legacy geophone data.

***Broadband nature of DAS.*** A DAS sensor is truly broadband from zero frequency on the low side and restricted by array filter slope on the high side. For the same vibrator sweep (8–80 Hz), spectra of DAS and geophone data appear similar (Figures 3e and 3f), confirming the broadband nature of the DAS receivers.

***Imaged data comparison.*** Figure 3g compares seismic stacks obtained with DAS and legacy geophone data. Both shallow and deep reflectors are robustly imaged on the DAS data similar to surface seismic. An excellent tie of both images is seen at the intersection point all the way to 3 s (approximately 5 km depth).

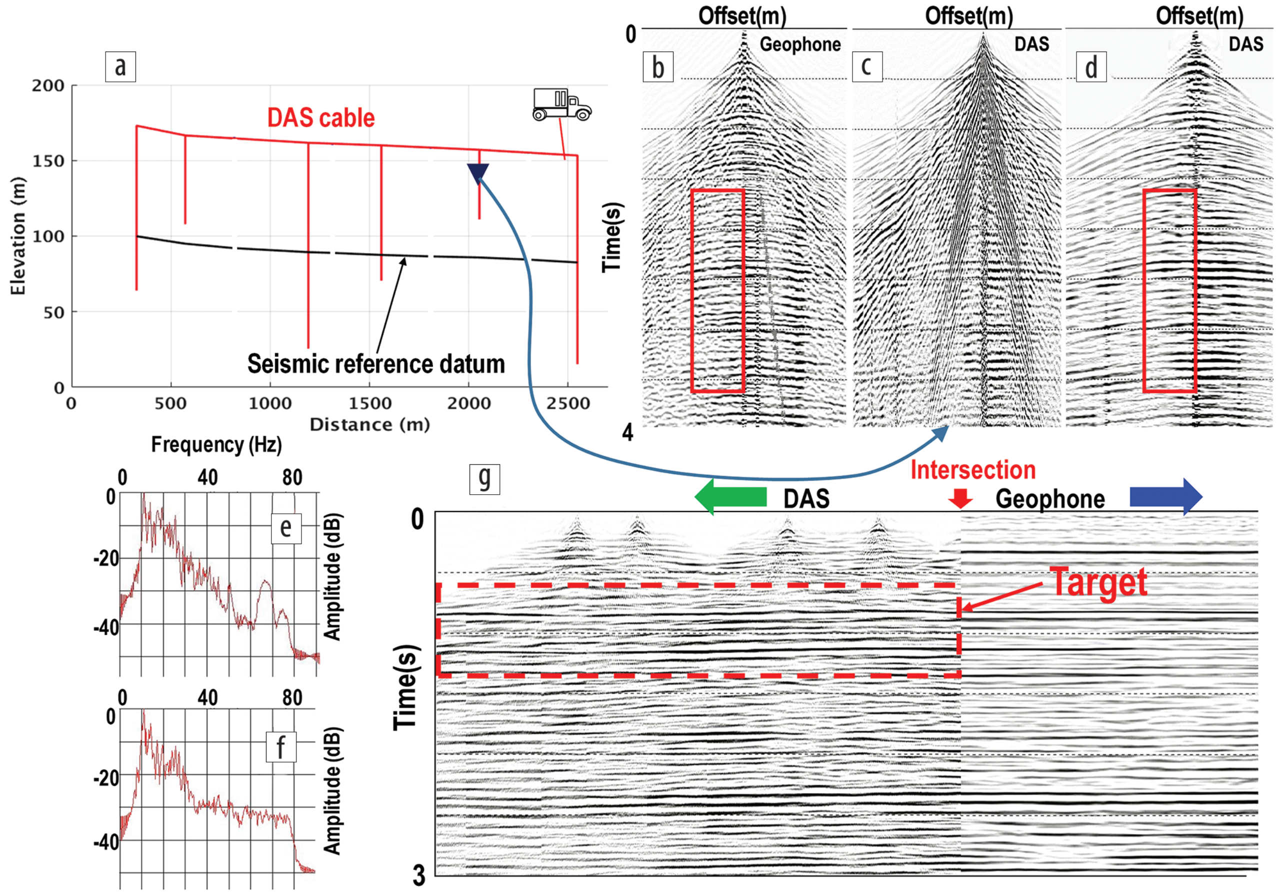


**Figure 3.** Sketch of 2D field geometry for onshore experiment with simultaneous DAS acquisition of surface seismic and vertical arrays. (a) Comparison of DAS and legacy geophone data extracted from a 3D seismic survey. Prestack common-receiver gathers obtained with surface geophone group and single DAS receiver at 15 m depth: (b) raw legacy seismic gather with 60 m source spacing, (c) raw DAS gather with source spacing of 10 m, and (d) same DAS gather after linear noise removal and decimation to 60 m source spacing. Spectra of (e) legacy geophone and (f) DAS data after noise removal show similar behavior. (g) Comparison of 2D images obtained with DAS (left) and surface legacy seismic (right). The vertical arrow marks where both lines intersect each other at 45°. Observe the excellent tie between main reflectors. The dashed box identifies the subsurface area around the target reflector equivalent to the depth image from Figures 4b and 4c.

Such an agreement confirms the excellent sensitivity of DAS recordings, and the ability to obtain equivalent images to surface seismic, despite large spacing between shallow holes.

***Value of near surface for a more accurate and focused image.*** A significant motivation to perform simultaneous DAS acquisition of surface seismic and vertical arrays is in reducing structural uncertainty for mapping so-called low-relief structures with a relief of 10–30 ms (20–60 m) in the presence of complex near surface (Bakulin et al., 2017). Alshuhail et al. (2019) demonstrate a significant reduction in structural uncertainty when comparing results of standard refraction tomography applied to surface data alone and simultaneously acquired surface and vertical array data. Specifically for the SEAM Arid model, mapping errors (averaged along the target horizon) were reduced by a factor of three — from 18 m (9 ms) to 5 m (3 ms). Such accuracy would enable reliable mapping of structures as small as 15 ms (30 m) that could be missed with surfaced data alone. For this limited case study, let us demonstrate two main points: (1) the ability to perform depth imaging from topography on land and (2) the strong sensitivity of the image to the near-surface velocity model.

Accurate knowledge of the near surface with slow velocity and significant variations is critical for depth imaging. Near-surface models derived from refraction tomography and other methods based on surface data often lead to poor depth imaging from topography. Uphole data are usually required to resolve the issue. Figure 4 shows the comparison of reverse time migrated (RTM) images obtained with two velocity models that only differ in the first 200 m: one based on legacy uphole from the area and another based on smart DAS upholes from the case study. With lower near-surface velocities constrained from DAS upholes, we see an immediate improvement in target reflector continuity (Figure 4c). In the presence of uphole data, the depth image (Figure 4c) becomes robust and similar to a time image (Figure 3g) that is often hard to achieve without accurate near-surface velocities.

***Zoom into the near surface: Surface waves.*** Data from trenched surface cables with 4 m channel spacing are dense and unaliased enough to zoom into the near surface. Compared to modeled gathers, such data (Figure 5a) clearly resemble a horizontal geophone response (Figure 5b) more than that of a vertical geophone (Figure 5c). More specifically, both DAS and horizontal geophone data contain no reflections in the cone of near offsets. These densely sampled DAS data with small GL are suitable for surface-wave inversion. Picked dispersion curves (Figure 6a) are inverted for

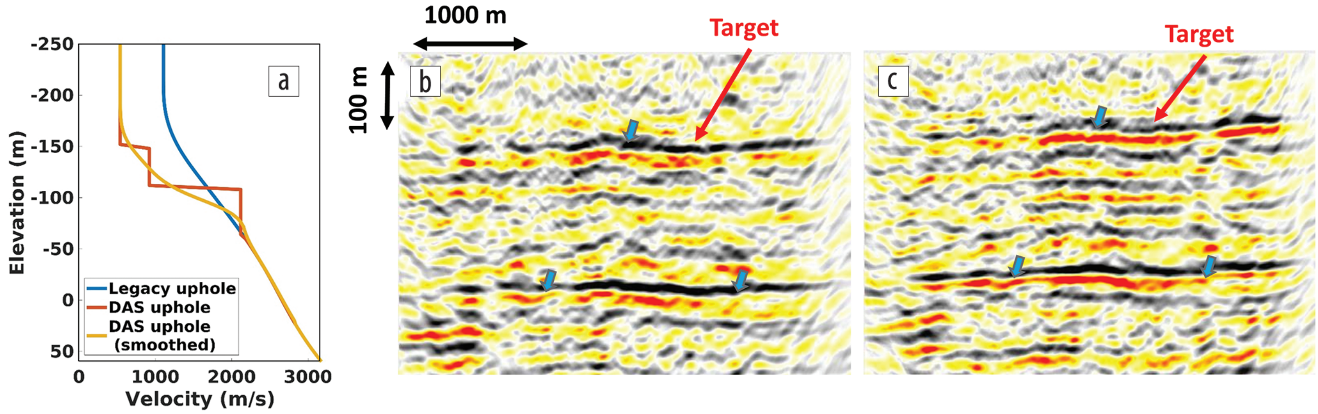


**Figure 4.** Effect of near-surface velocity on depth imaging from topography. (a) Velocity profiles through the near surface using legacy uphole data in the areas versus smart DAS uphole. RTM images from the surface (zoomed area near the target equivalent to dashed box in Figure 3g) obtained by migrating the same DAS vertical array reflection data using: (b) velocity depth model based on legacy uphole and (c) velocity model updated only in near surface part with smart DAS upholes. With a more accurate near-surface model with lower velocities constrained from DAS upholes, we see an immediate improvement in the target reflector continuity.

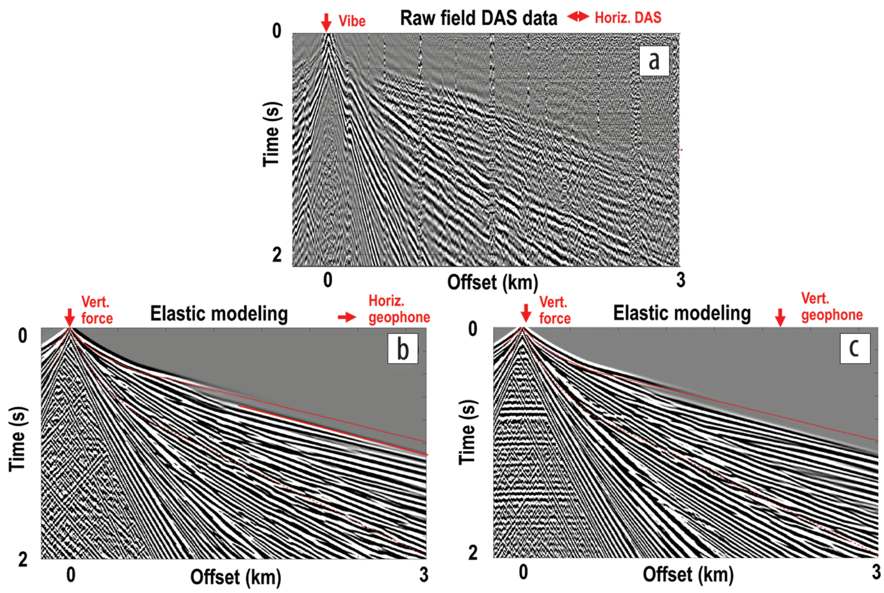


**Figure 5.** Common-shot gathers from (a) the trenched surface portion of DAS cable versus (b) synthetic elastic data modeling horizontal and (c) vertical component. Horizontal DAS cable is trenched at 1 m depth. Observe the excellent quality of the field gather and general agreement with modeled response of horizontal as opposed to vertical geophones.

near-surface shear-wave velocity (Figure 6b). The 2D S-wave velocity model from DAS data has a good similarity with the multilayered velocity model constructed from DAS upholes (Smith et al., 2019). The P-wave velocity profile obtained during the surface-wave inversion based on some a priori relations shows good correspondence to one of the upholes (Smith et al., 2019). Such cross-validation illustrates that reliable near-surface velocity models can be obtained successfully from the surface-wave inversion of unaliased DAS data.

Multiscale recordings from the same source can be combined to adaptively subtract ground roll recorded with a “shallow” survey from data of the “deep” survey. While other methods attempt to model ground roll using a complex workflow with inversion (Strobbia et al., 2011), a shallow DAS survey delivers perfect measurements of actual unaliased ground roll simultaneously with the deep acquisition, enabling more efficient and accurate subtraction.

The experimental dispersion curve (Figure 6a) becomes weak above 17 Hz for two possible reasons. First, substantial lateral velocity variations seen in Figure 5a may violate the assumption of smooth lateral variations required for a robust dispersion curve to develop. Second, DAS array filtering and supergrouping may attenuate higher frequencies. Indeed, synthetic modeling confirms that while a continuous dispersion curve is obtained with 1 m geophone data (Figure 6c), it becomes broken up on DAS data with a field geometry (Figure 6d). Such low velocities in the near surface demand an easily achievable adjustment in DAS acquisition parameters: shortening GL and using denser channel spacing of 0.25–1 m. Such acquisition parameters would eliminate array filtering at these frequencies and allow reduction of the spatial window, resulting in the finest vertical and lateral resolution in shallow velocities.

***Data quality of distributed sensors versus point sensors in the presence of complex scattering near surface.*** The case study mentioned earlier compared DAS data to an older seismic acquisition with 72-geophone arrays (Figure 7a). Since then, acquisition progressed to arrays with 36, 24, 12, and now nine geophones (Figure 7b). Point-receiver data are becoming available (Figure 7c). Outside of the Middle East, the move to point recording was relatively uneventful due to the smaller impact of the arrays and simple near surface. In contrast, the desert environment data quality is dramatically affected by the size of the geophone array (Figure 7) with exceptional complexity observed with point sensors (Figure 7c). Bakulin et al. (2020) suggest that severe phase distortions caused by near-surface scattering are the main culprit. Averaging of the phase was proven to improve data coherency dramatically. A DAS array with 7 m GL (Figure 7d) is less than a geophone interval of 8.33 m and only about one-third of the 25 m linear dimension of the nine-geophone group (Figure 7c). However, even small (two-level) DAS averaging leads to much better data quality: first doing 7 m averaging over GL and then additional supergrouping of four-unit DAS channels spaced at 1 m. A DAS land sensor may provide better data quality than point geophone for two main reasons:

1) Even the shortest unit DAS channel is equivalent to a miniature array with infinitely small spacing. This leads to small but practically significant phase averaging that is proven to stabilize the wavefield significantly in the presence of severe near-surface scattering (Bakulin et al., 2020).
2) Coupling is better and more robust overall. The distributed nature of DAS leads to diversifying the

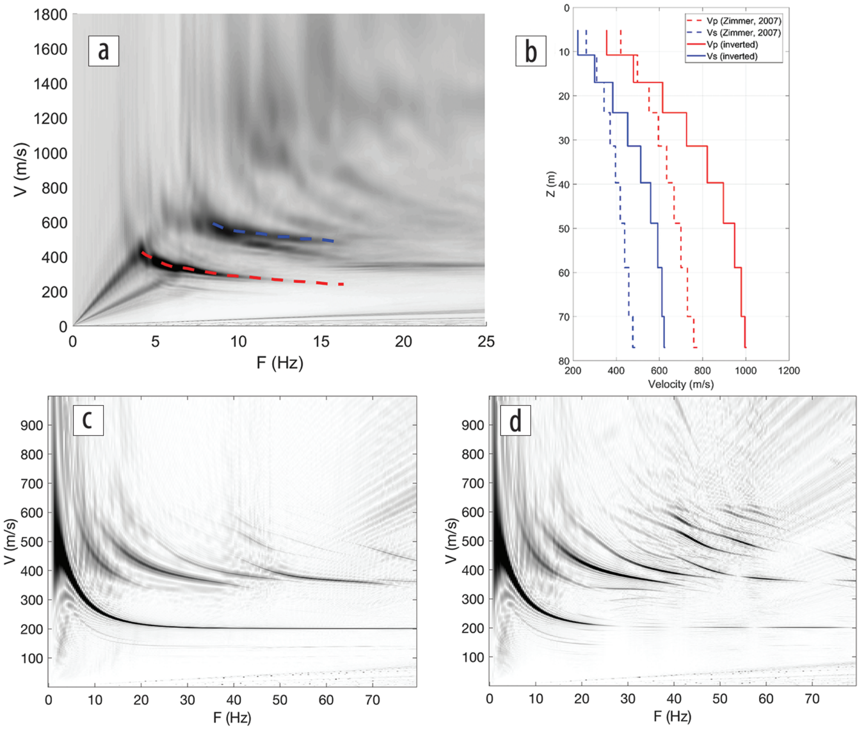


**Figure 6.** An example of surface-wave inversion using field data recorded with trenched DAS cable: (a) dispersion curves picked on DAS data; (b) near-surface velocity profiles after inversion using different relations between P- and S-wave velocities. Reduced energy above 17 Hz on (a) can be explained by DAS array filtering as replicated with synthetic velocity-frequency panels: (c) dense single geophone data at 1 m sampling and (d) simulated DAS data with a field geometry (GL = 7 m, $D_u$ = 1 m, $D_S$ = 4 m). Near surface is characterized by the lowest shear-wave velocity of 200 m/s.

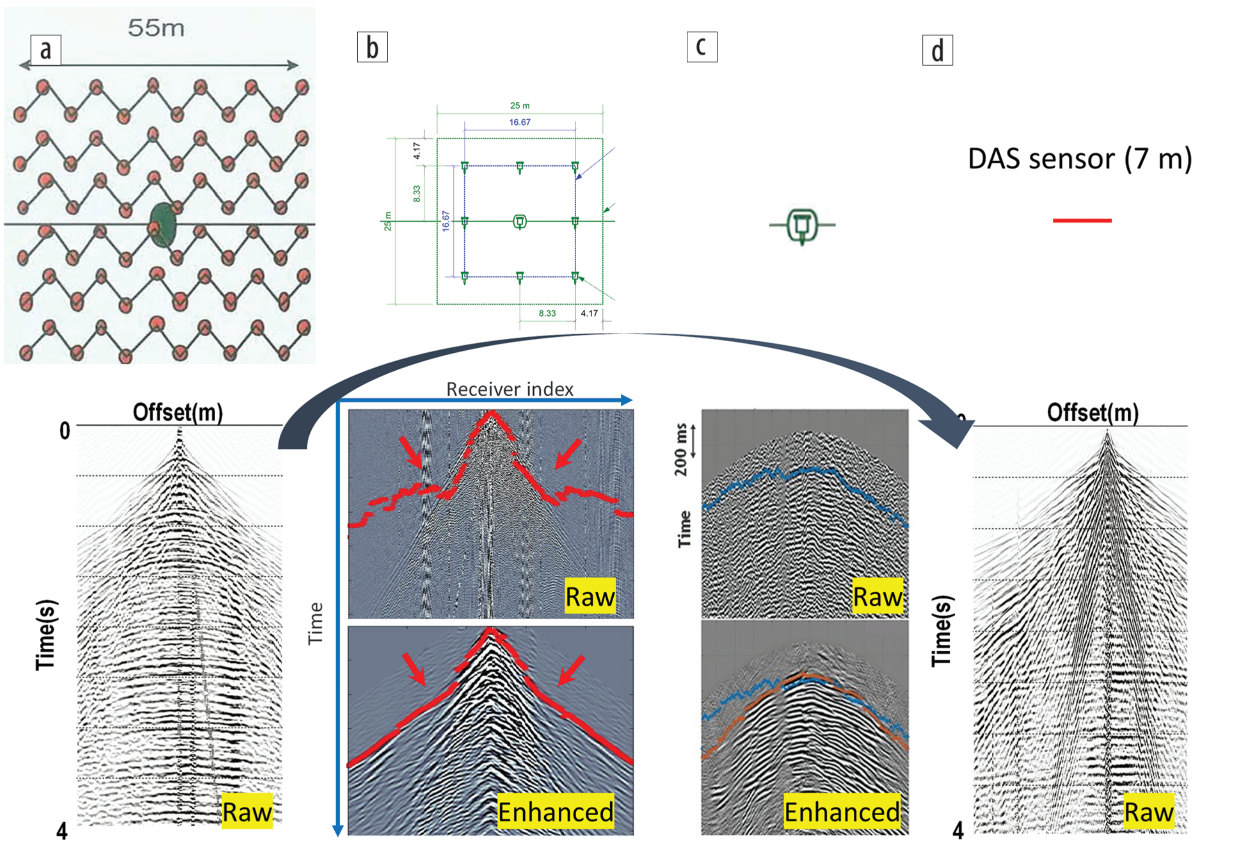


**Figure 7.** Progression of seismic acquisition and associated data quality from (a) 72-geophone array, (b) nine-geophone array, (c) single sensor, and (d) DAS data with a 7 m GL.

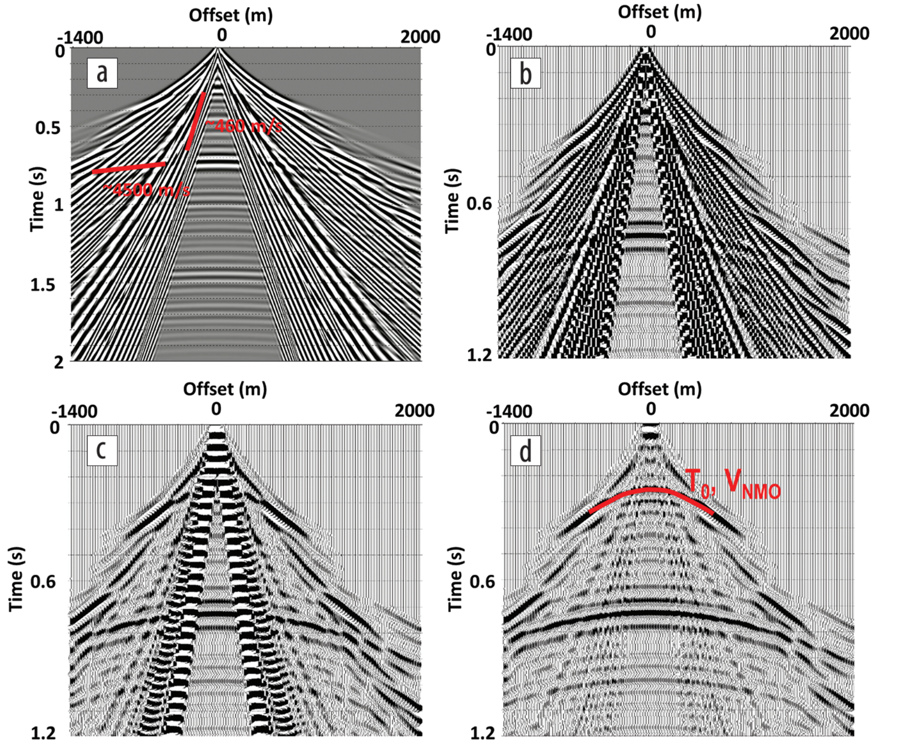


**Figure 8.** (a) Synthetic seismic shot gather produced by an elastic model inspired by an onshore field. Vertical force simulates surface vibrator with Ricker wavelet (center frequency of 17 Hz), whereas vertical geophones are shown at 0.5 sampling, currently not economically achievable with standard exploration surveys on land (usually 10–25 m). Zoomed upper portion of the same gather showing how shallow reflections can be uncovered using densely sampled seismic data: (b) unprocessed production-style single-sensor common-shot gather at 25 m sampling; (c) processed gather from (b) after filtering using 25 m sampling interval; (d) filtering result using 0.5 m sampling interval (and resampling to 25 m for display) as could be achieved with DAS acquisition.

coupling risks. If poor coupling starts to affect say 10%, 20%, or 50% of the distributed sensor length, the loss of coupling will be gradual and proportional to the coupled portion of the DAS channel. In contrast, the coupling of point geophone is hit or miss.

## Other benefits of shallow survey with DAS

Apart from surface-wave techniques, a shallow DAS survey also enables a plethora of reflection and refraction techniques benefiting from the dense receiver sampling that is expensive to replicate with geophones. Let us examine them on synthetic data recorded with omnidirectional DAS cable. Figure 8a shows a shot gather from a simplified 1D elastic synthetic model inspired by one of our fields. Faint reflections are covered by a thick train of linear noise.

***Weathering reflection seismic.*** One such near-surface technique is so-called weathering reflection seismic (Martin et al., 2009) that requires the specialized acquisition of microspreads with very dense 2 m source spacing to pick zero-offset times and moveout velocities for the shallowest near-surface reflectors. A shallow DAS survey delivers such data without any additional shooting effort. Figure 8b shows a zoomed part of the shot gather similar to Figure 8a but with 25 m sampling. Since conventional single-sensor acquisition with geophones cannot sample strong ground roll noise properly, we are unable to filter it out and uncover reflections due to aliasing (Figures 8b and 8c). After the processing of shallow DAS data with 0.5 m sampling, the noise is efficiently filtered out, and coherent shallow reflections are unveiled (Figure 8d). An insufficient sampling of shallow reflections causes "reflection blind spots" in conventional seismic volumes. A densely sampled DAS shallow survey eliminates this problem and enables the use of shallow reflections and diffractions for building near-surface velocity. Likewise, DAS can enable other reflection-based techniques such as i-stats (Yilmaz, 2013) that are currently not supported by modern geophone acquisition because of insufficient sampling for the near surface.

## Benefits of FWI velocity survey with DAS

FWI velocity surveys and deep surveys are characterized by long propagation and attenuation as well as weak reflected or refracted signals demanding larger source and receiver arrays to detect faint signals and suppress noise. Small-array and point-sensor data (Figures 7b and 7c) show the challenge by exhibiting fragile first breaks and no reflections. Deep refracted or reflected signals by themselves do not require dense sampling. However, with point sensors, we chase dense sampling to suppress slow near-surface arrivals obscuring those signals. For deep and FWI velocity DAS surveys, we can select a larger GL that could improve our detection of weak signals and suppress near-surface arrivals according to equation 1. For the sake of demonstration, let us select a large GL of 150 m and a pulse width of 3 m (Figure 9). Such a DAS array suppresses 450 m/s ground roll from 3 Hz while preserving reflections and refractions (4500 m/s and more) up to 30 Hz (see points 1 and 2 in Figure 2b). Significantly enhanced P-wave arrivals would be suitable even for a high-frequency acoustic reflection FWI.

***Multiscale blended low-frequency recording.*** Geophone acquisition struggles to deliver low frequencies of 1.5–8 Hz even with massive supergrouping with 200–500 m aperture (Bakulin et al., 2019a). With a DAS FWI velocity survey, we can solve this by making an even larger GL of 50–300 m and increasing sensitivity and S/N. DAS could also enable recording of ultralow frequencies 0.1–1.5 Hz (with active or passive sources) and extend the bandwidth of FWI and penetration of surface-wave inversion. We envisage blended shooting of low- and mid-high-frequency sources and simultaneous recording with dedicated multiscale DAS receiver grids (shallow, deep, and FWI). Dedicated high-S/N, low-frequency DAS sensors may significantly improve land FWI in the desert environment currently handicapped by challenging point-sensor data.

## Challenges

***Reaching and exceeding geophone sensitivity.*** We estimate that DAS sensors with a typical GL of approximately 10 m did not attain geophone sensitivity across the entire seismic frequency band. However, achieved DAS sensitivity is already above and beyond specifications for nonseismic applications (railroad and pipeline monitoring, perimeter security, etc.) that represent the largest market share of DAS industrial use. Therefore, only the development of a more massive application such as surface seismic can motivate the optical industry to reach this critical milestone. From a technical perspective, achieving and exceeding geophone sensitivity remains feasible with additional targeted development in interrogation capabilities and engineered sensing fiber.

***Directivity challenge.*** Conventional straight DAS cable is mostly sensitive to horizontal motion. While useful for recording shear waves and ground roll, P-wave seismic requires an excellent sensitivity to near-vertical motion. The solution is to utilize omnidirectional cables. Let us demonstrate the capability of one specific type called "helically wound cable" (HWC) (Hornman et al. 2013; Kuvshinov, 2016). HWC represents essentially a long fiber wrapped around a plastic tube leading to a mostly omnidirectional sensor in the vertical plane containing the cable, which behaves like a distributed fiber-optic hydrophone would (Kuvshinov, 2016). An excellent example of how the DAS directivity challenge for surface seismic can be addressed is a study performed as part of the CO2CRC Otway Project in Victoria, Australia (Freifeld et al., 2016; Dou et al., 2017). For comparison, straight and helical cables were trenched at the same depth of 80 cm. Figure 10b shows that straight DAS cable reliably records shear waves and ground roll having horizontal polarization and also captures some portion of refracted arrivals but not weak reflections. In contrast, HWC cable exhibits excellent sensitivity to vertical motion and unambiguously records P-wave reflections (Figure 10a).

While HWCs offer an initial simple solution, they are bulky (with a diameter of at least 15 mm, Figure 10c) and consume significant excess fiber per linear length of the cable. For example, HWC used here with so-called 30° lay resulted in a 1.17:1 ratio of fiber to actual cable length, implying that 1.17 km maximum fiber can serve only 1 km of the actual recording. There is an active investigation of alternative designs, including those avoiding wrapping and offering a full usable length.

***Coupling and deployment.*** Recording robust data requires effective coupling with the ground, which is currently achieved by a minimum burial of approximately 20–100 cm. For laying telecommunication fiber, there are a plethora of automatic cable plowing machines that cut a narrow slit and place cable without opening a trench. Figure 11 shows fiber cable plowing for smart wells in a desert environment. Burial of 100–120 cm is desirable for permanent placement to prevent cable from being exposed to the surface for an extended time, whereas laying for exploration surface seismic could be minimal at 10–20 cm. To minimize surface disturbance, it is desirable to record data without burial. While this is possible, such surface cables become susceptible to wind noise and exhibit reduced coupling. An active area of research is to evaluate new methods and cables that can provide sufficient coupling while minimizing surface disturbance.

***Azimuthally dependent nature of DAS array.*** A DAS array in any plane containing the cable is described by equation 1. However, for 3D seismic shooting, linear arrays create azimuthal directivity.

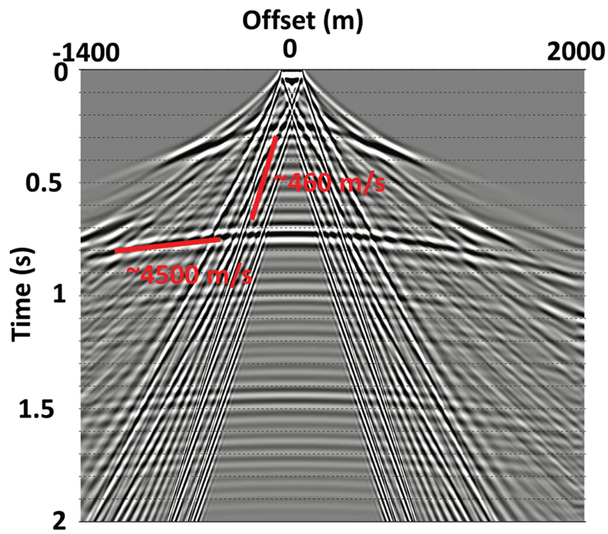


**Figure 9.** Shot gather recorded using the DAS sensor with a GL of 150 m and pulse width of 5 m. Observe strong suppression of linear near-surface arrivals and compare to the raw gather from Figure 8a recorded with single geophones. Corresponding array response for the DAS sensor is shown in Figure 2b.

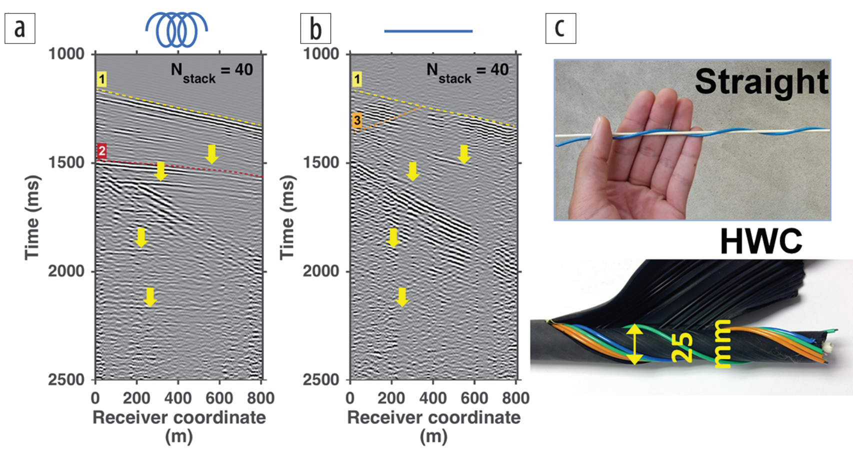


**Figure 10.** Shot gathers are displayed after recording with (a) omnidirectional HWC and (b) straight linear DAS, whereas (c) shows actual pictures of straight (top) and HWC (bottom) cables. The orbital vibrator was used as a surface seismic source. Observe clear reflections on HWC marked by arrows and no reflections on straight DAS. (All displays are courtesy of B. Freifeld and J. Correa, Lawrence Berkeley National Laboratory).

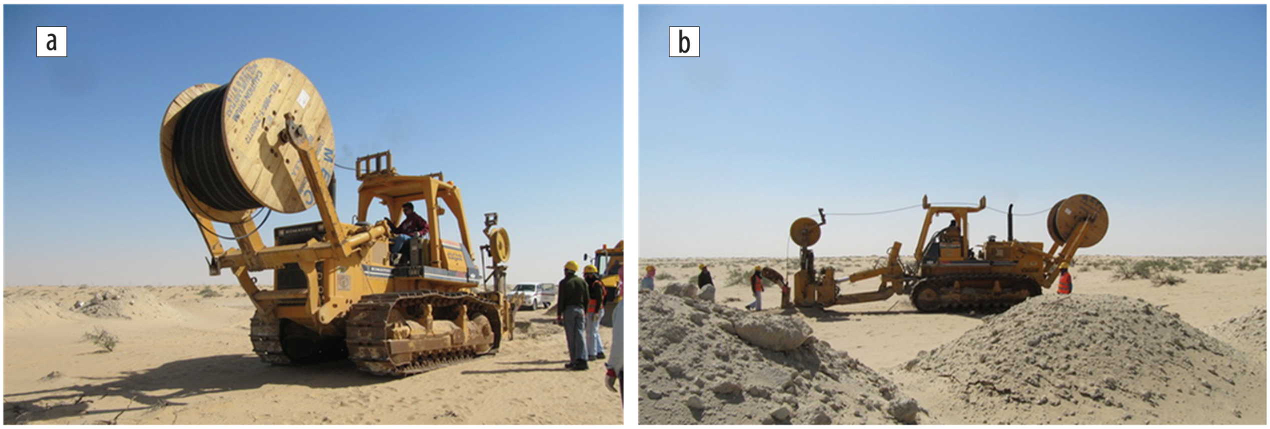


**Figure 11.** Cable plowing machines deploying continuous cables in shallow trenches as a method of automated placement of DAS seismic cables for surface seismic. (a) A cable spool is carried in front, and (b) a blade at the back splits the ground while the cable is placed at depth by feeding it down a chute located on the back of the blade.

Geophone arrays are usually designed to be isometric in shape (say 3 × 3 or 6 × 6, etc.), which is hard to achieve with fiber if we want to maintain maximum coverage (Figure 1). There are possibilities to reduce azimuthal preference in the field or in processing. For example, "fat" lines of fibers can be trenched (say, several parallel cables tightly spaced at 5–10 m), so more isometric DAS arrays can be designed in processing. Alternatively, orthogonal lines of cables can be laid with cost-effective cables and simplified coupling. Addressing this challenge could open access to a cost-effective 3D seismic acquisition with significantly larger channel count and uncompromised sampling in cable direction.

## Conclusions

DAS promises a paradigm change in land seismic acquisition. Unlike conventional point sensors, DAS acquisition allows recording multiscale receiver grids using fixed measuring cables. Main acquisition parameters such as DAS array length and channel spacing are 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 data sets from a fixed cable, each with its own "array" aperture (GL) and channel spacing. All of these multiscale data are output from a single cable (possibly with multiple fibers) and 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 GL and dense channel spacing. In contrast, a deep survey focuses on deeper subsurface and uses large GL adequate for reflection imaging. The FWI survey allows dedicated recording of low and ultralow frequencies with sensor arrays of unparalleled sensitivity all the way to zero frequency and outstanding noise-removing properties.

Multiscale DAS receiver grids enable an important and seamless seismic zooming functionality analogous to visual zoom in Google Earth. A grid from a shallow survey lets us zoom into the near surface, while a deep survey grid permits us to zoom out and get a clearer picture of deeper targets. The FWI survey grid allows zooming out even further using large offsets and dedicated low-frequency DAS super-arrays. Such flexibility is not achievable with conventional point sensors. New adaptive multiscale processing algorithms can fully leverage this new capability and obtain uncompromised solutions for shallow (near surface), deep (deep reflections), and FWI surveys (velocity), all of which currently face quality and cost challenges with point-sensor acquisitions.

DAS seismic can be supplemented with vertical arrays at any point by simple predrilling smart DAS upholes and splicing them into surface seismic arrays. Simultaneous DAS acquisition of surface seismic and vertical arrays in the desert environment offers a cost-effective path to improve data quality and reduce structural uncertainty. It also paves the way to a robust depth imaging from topography. In addition to shallow, deep, and FWI surveys, vertical arrays or smart DAS upholes allow accurate constraining and calibration of the near-surface model. Since all data are acquired at the same time (e.g., same elevation, same near surface), we remove all obstacles to efficient data integration and enable cross-validation. Depth imaging from topography becomes robust and accurate with vertical arrays, just like deep depth imaging is significantly reinforced with well-data calibration. Truly diverse multiscale DAS hybrid data offer a practical path to joint inversion and quantification of exploration uncertainty.

As for channel count, independence of channel spacing and GL in optical recording gives us the ability to output DAS channels at 0.25–1 m spacing. With a typical cable length of 10 km and 1 m channel spacing, this produces 10,000 channels. Cables of 50 km length are appearing, delivering 50,000 channels. Current interrogators (smaller than the size of carry-on luggage) currently record only one or two fibers (100,000 channels). Super-interrogators with 16–48 fibers are feasible or existing boxes can be simply stacked. Therefore, 1 million- to 10 million-channel DAS systems are within technical reach at an affordable cost. The arms race of channel count with point sensors faces headwinds of escalating costs and diminishing data quality, particularly in desert environments demanding massive supercrews. With DAS promising more competitive channel cost, better data quality, and flexibility, would we dare reinvent surface seismic acquisition just like we are effectively doing with borehole geophysics moving to DAS? Time will tell. TLE

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## Data and materials availability

Data associated with this research are confidential and cannot be released.

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