Surface DAS processing in a CCS field

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Summary

Distributed Acoustic Sensing (DAS) is gaining increased attention in the Carbon Capture and Storage (CCS) industry as a feasible cost-effective method for subsurface imaging and monitoring. This study examines the processing and imaging challenges of surface-acquired DAS data in the North Sea with a primary objective of assessing the quality of final images as well as enhancing industry knowledge on processing this type of data. Of note in this study is the successful separation of weak PP and strong PS wavefields with the assistance of an external reflectivity. Additionally, mirror migration was performed to image the first-order water bottom multiples, instead of primary migration, leading to superior imaging results. This processing led to high-quality PP images at both the overburden and reservoir levels. Despite using a single DAS cable, the imaging extends up to 1.5 km from the cable location at a depth of 2 km, demonstrating the advantages of a 3D shot carpet.

Introduction

As a novel and fast-emerging technology, Distributed Acoustic Sensing (DAS) has attracted notable attention, particularly in the Carbon Capture and Storage (CCS) industry, as a potential means of cost-effective subsurface imaging and monitoring. In this study, we present the processing and imaging challenges and results of surface-acquired DAS data with a full aperture 3D shot carpet, collected in the North Sea. With a specific goal of understanding the achievable imaging quality and extent for potential CO_2 plume monitoring, we look to showcase the capabilities of this DAS technology in a prospective CCS field. This could further the industry knowledge with regards to the processing and imaging of this data type.

DAS acquisition, QC and processing

In September 2023, a 3D Towed Streamer survey was acquired over a CCS licence in the North Sea, with the goal of achieving subsurface control of the potential CO_2 storage area and to act as a baseline for future 4D monitor surveys. However, prior to acquisition it was noted that a telecommunication fibre, installed in 2010, ran through the licence. As Dhelie et al. (2024) notes in more detail, this provided the opportunity to acquire DAS data in this fibre cable during the acquisition by utilizing the same 3D source carpet.

Figure 1 a) shows a shot gather of the raw DAS data where the shot location is directly above the fibre. Despite the distance between the survey area and the interrogator unit exceeding 100 km, all the typical events are clearly present in the gather, including direct arrivals, diving waves, reflected primaries and multiples. Strong PS mode-converted waves are also recorded and mask most of the PP signals in the deeper part of the gather. Figure 1 b) highlights the challenge of DAS amplitude over-saturation (exceeding the slew rate limit [SEAFOM 2024]) caused by the strong direct arrival as well as the water bottom multiples. This effect is challenging to fully address in processing and, due to the sample-by-sample discontinuity, causes the filtering processes to work sub-optimally (e.g. spatial integration, de-signature). This effect could be mitigated during acquisition but here a targeted de-saturation routine (Figure 1c) is effective in correcting the discontinuities and provides continuous events for subsequent processing.

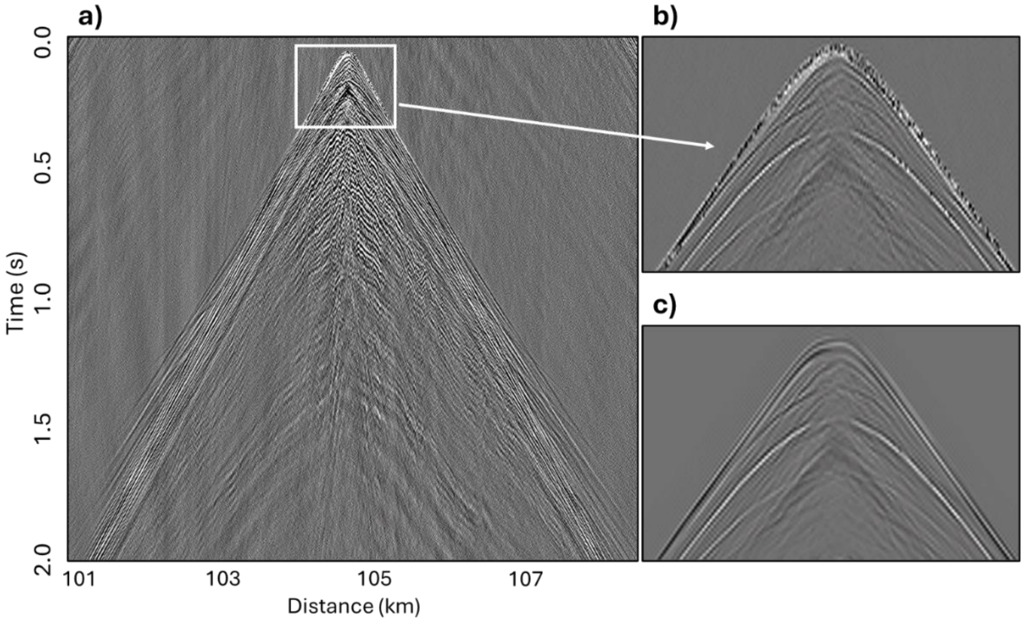

Figure 1 *A shot gather of a) raw DAS data shows the typical seismic events being recorded with the distance from the interrogator noted on the X axis, b) shallow zoom-in of the area highlighted by the white square showing DAS amplitude over-saturation, and c) after de-saturation.*

Whilst DAS data is known to be susceptible to high levels of random and coherent noise, the majority of examples have been in a wellbore setting (e.g. Moore et al., 2022). Other than the saturation effects noted above, our observed surface DAS data is largely free of random and coherent noise, likely due to the trenching of the fibre cable. What little noise exists is easily addressed by FX and FK de-noise techniques applied in the shot domain, thanks to the high spatial sampling (3 m) of the DAS data.

The surface setting of the DAS in this example provides a major challenge in the form of strong PS wave arrivals. To retrieve the PP signal that is heavily masked by these PS arrivals, a guided de-noise approach was applied, utilizing a de-migration (Born modelling) of the Towed Streamer PP reflectivity image. This de-migration provides a guide estimate for subsequent thresholding to remove PS energy and achieve PS and PP separation, as shown in Figure 2. Whilst PP and PS separation is achievable via moveout discrimination, the use of a legacy reflectivity with de-migration is a valuable tool to improve the separation quality.

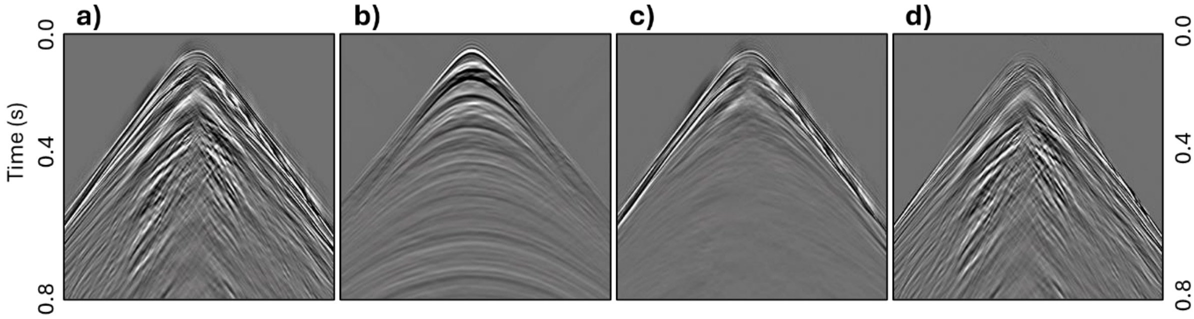

Figure 2 *De-migration guided PP and PS wavefield separation: a) Input shot gather, b) de-migration guide, c) output PP data, and d) PS data.*

Unlike point sensors such as hydrophones, DAS data directivity is primarily controlled by the 3D incidence angle of the wave into the fibre, which varies depending on the mode of the wave. As Figure 3 shows, this variation is notable in a surface setting. A directivity compensation is thus applied to mitigate the amplitude modulation with tapering towards zero angle to avoid over-boosting of noise.

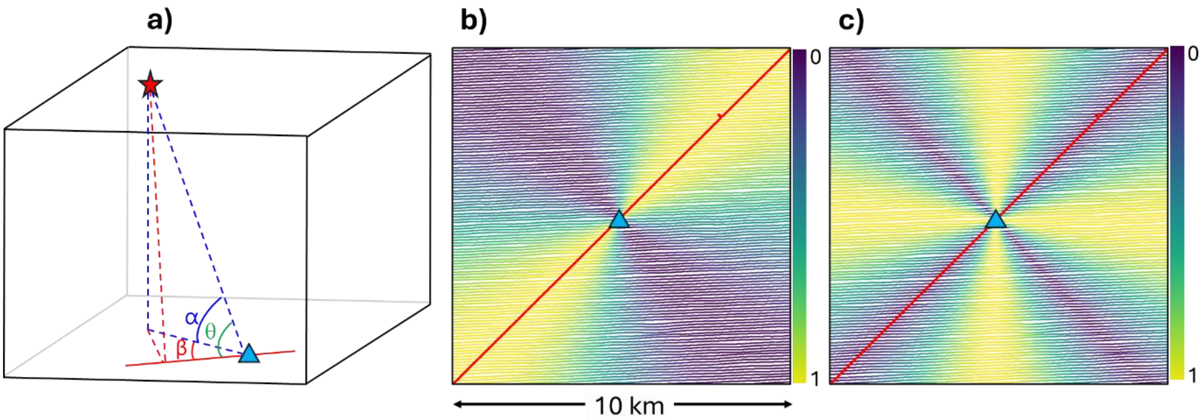

Figure 3 *a) Diagram shows the source-to-receiver incident angle α, source-to-fibre azimuthal angle β, and 3D incidence angle θ. DAS angle directivity can be approximated by $cos^2(\theta)$ for P arrivals and $sin(2\theta)$ for S arrivals. In this survey orientation, b) shows the predicted normalized amplitude approximated by the directivity of a PP wave, and c) of a PS wave. Red solid line indicates the fibre orientation, blue triangle shows the DAS channel location and red star indicates the shot location. The horizontal lines on b) & c) plot the source lines acquired in this survey.*

Migration

Following the PP-PS wavefield separation and directivity compensation, pre-stack Kirchhoff depth mirror migration was performed to image the first-order water bottom multiples. This mirror migration provides improved imaging results compared with primary migration, as (due to the flat water bottom) it utilizes the constructive interference of source-side multiple, receiver-side ghost and its peg-leg multiples, which in combination have a stronger amplitude than the primary alone. This is analogous to hydrophone-only imaging of a seabed receiver, as outlined in Figure 4. However, it should be noted that, whilst weak, the primary energy and high order multiples still contaminate the image and need to be attenuated via moveout or model-based methods.

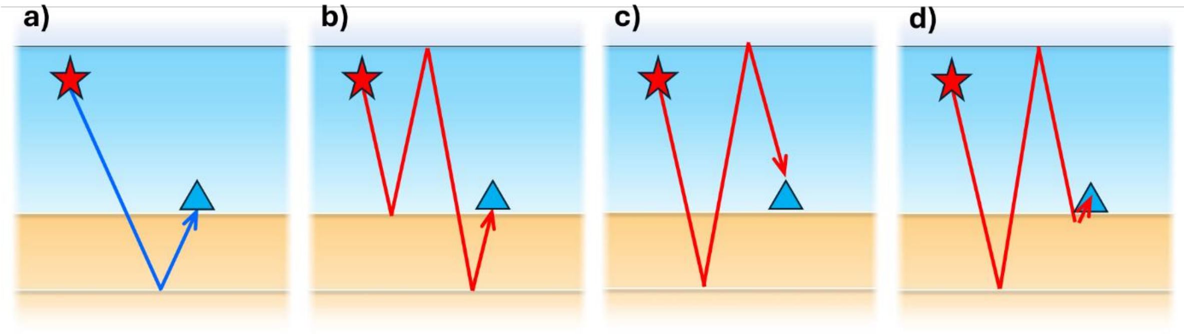

Figure 4 *Schematic diagram of migration using (a) a primary event, and (b) mirror migration using a combination of the source side multiple, (c) receiver side ghost and (d) peg-leg multiple.*

Kirchhoff imaging of the data was used to understand the spatial extent of illumination achievable with a single DAS fibre. Figure 5 shows depth slices at key levels where we can see the DAS capabilities of imaging shallow polygonal faults with high spatial and temporal resolutions, and deep structures with a total extent in the crossline direction up to 3 km at the depth of 2.5 km. Meanwhile, Figure 6 highlights the achievable quality of DAS data with both the overburden and the target "dome" closure structure, key for CO_2 storage, well illuminated. A comparison can also be made against a 2D image utilizing only a single shot line acquired over the DAS fibre, highlighting the importance of a 3D shot carpet to accurately image the 3D structure of the entire storage unit.

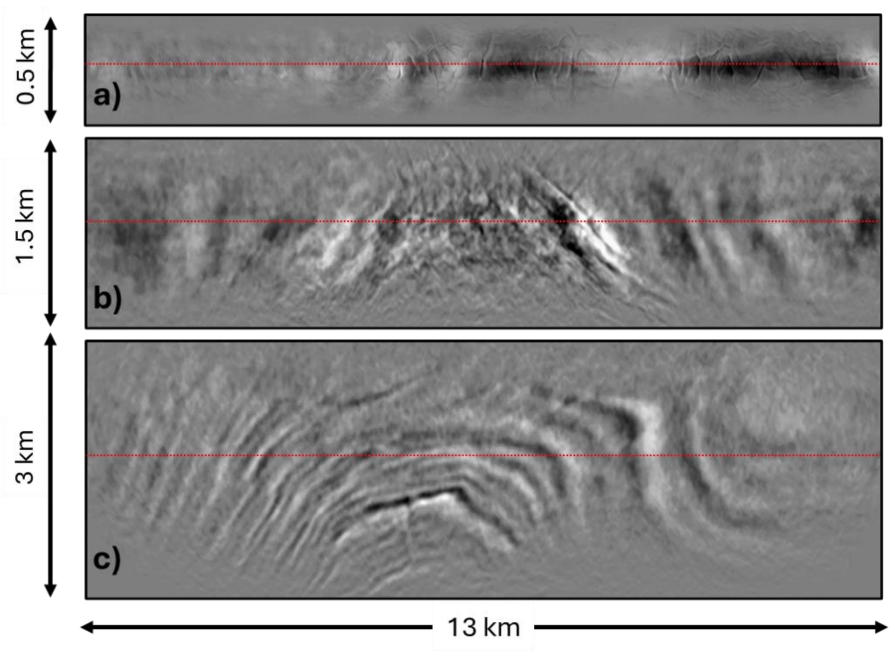

Figure 5 *Depth slices of PP imaging results of DAS at a) 450 m, b) 1400m and c) 2700 m. Red line indicates fibre location at surface with up to 1.5km either side of the fibre at the storage unit being imaged.*

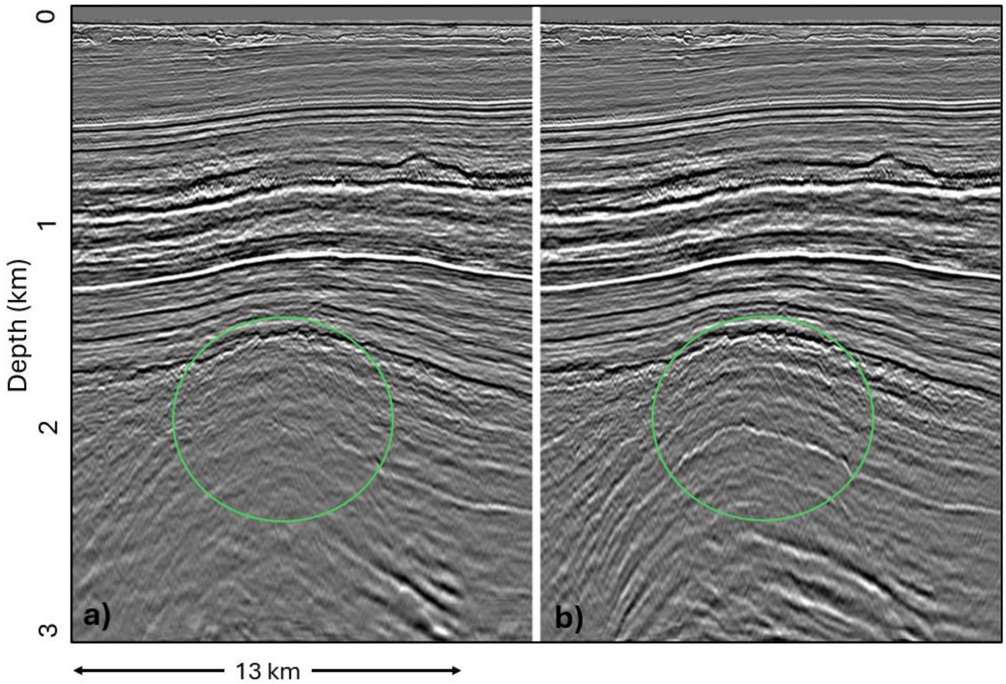

Figure 6 *Inline views of PP imaging results from a single fibre: a) DAS 2D imaging from a 2D shot line and b) "2.5D" imaging utilizing the 3D shot carpet. Intended CO_2 storage reservoir is indicated by the green circle, with imaging in this area heavily compromised by use of a 2D shot line only.*

Conclusions

The DAS imaging result presented in this study verifies the ability of surface fibre-optic cable to image the subsurface, with a high-quality image achieved at both overburden and reservoir level. The advantages of a 3D shot carpet have been illustrated and, despite using a single DAS fibre, an interpretable image extending up to 1.5km away from the fibre at 2 km depth has been achieved. These findings offer encouragement for CCS operations, in that the CO_2 storage units can be imaged with surface DAS fibre, allowing for the potential of utilizing surface DAS technology in a monitoring system. These findings could be further extended by interrogating multiple fibre-optic cables, including surface and subsurface implementations. Use of multiple cables may become necessary to extend the image further enabling monitoring as the CO_2 plume expands.

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