Three Images from One North Sea Dark Fibre - PP, PS, and Multiple Imaging

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Summary

Distributed Acoustic Sensing on seafloor fibre optic cables (Surface DAS) provides a cost-effective alternative to Ocean Bottom Seismic. Measuring the change of a fibre's optical response over time yields a record of strain along the cable, which can be converted into a seismic signal. While DAS is routinely used for PP primary imaging, the remainder of the wavefield is usually discarded. Here we apply three distinct imaging techniques to a Central North Sea Surface DAS dataset, presenting PP, PS, and multiple migrations. The results showcase the imaging potential of Surface DAS data beyond PP reflections, including in the cross-cable direction.

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Introduction

Fibre optic cables have been employed in seismic acquisition for more than a decade. Their cost efficiency and reliability over an extended period of time have established fibre optic as a valuable tool for downhole applications such as Vertical Seismic Profiles (VSP) and reservoir monitoring (Moore et al., 2022). More recently, Distributed Acoustic Sensing on fibres deployed horizontally on the seafloor (Surface DAS) has emerged as an alternative to the more conventional acquisition geometries of Towed Streamer or Ocean Bottom Seismic (Raknes et al., 2023).

The short pulses of light used to interrogate the fibres can be detected at distances of dozens of kilometres at an exceedingly high spatial sampling rate. In many areas, unused fibres in existing telecommunications cables ('dark' fibres) can be tapped, potentially eliminating the need for additional infrastructure and significantly reducing acquisition cost on the receiver side to that of an interrogator box.

In this abstract, we examine the data quality, discuss processing challenges, and present three imaging results for a Surface DAS dataset acquired from a single dark fibre, assessing the respective quality of PP and PS images and exploring a multiple imaging scheme.

Acquisition, DAS Data Characteristics, and Pre-Processing

In March 2023, the Norwegian government issued a new exploration license for a prospective carbon storage block in the southern Norwegian North Sea. A seafloor telecommunications cable, installed in 2010, traverses the target storage area at a water depth of ~80m. One fibre within the cable was interrogated from onshore (~120km away) during the acquisition of a wide-tow, quad-source streamer dataset in September of the same year. This yielded a full 3D shot carpet, with two additional 2D tie lines shot along the cable (Dhelie et al., 2024). Acquired at a virtual receiver spacing of 1m and a sampling interval of 1.6ms, the data were resampled to 3m and 4ms, respectively, for further processing.

As predominantly the displacement component parallel to the fibre is recorded, the resulting measurement can be likened to the horizontal component from a seabed geophone. While at small angles of incidence, compressional signal is polarized parallel to the cable direction and therefore recorded optimally, it is strongly attenuated at large angles. The reverse holds for shear waves; large angles are dominated by slow PS energy and shallow surface (Scholte) waves. Even at smaller angles, the PP signal remains heavily masked by the PS arrival of both primaries and source-side water bottom multiples (Figure 1a). Due to oversaturation (exceeding of the dynamic range), the direct arrival is corrupted in places, with the damage ranging from mild clipping to complete amplitude reversal.

The pre-processing flow applied prior to final imaging consisted of deblending and desaturation, followed by a noise attenuation sequence including coherency preserving low rank denoise before

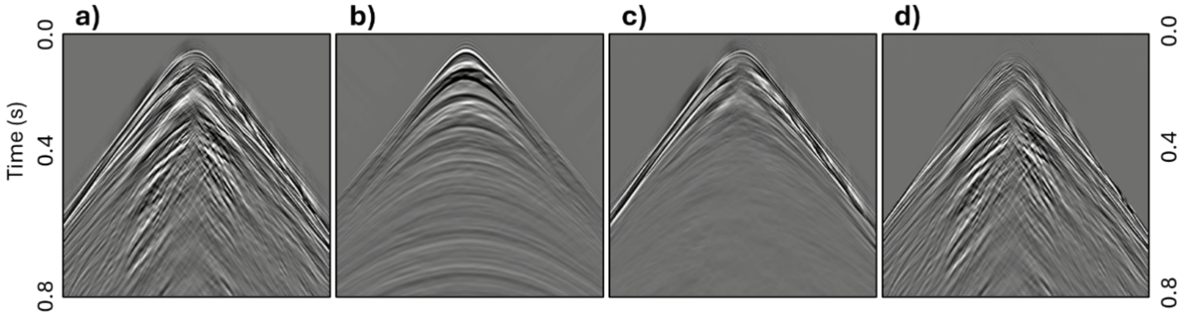

***Figure 1**. a) Denoised shot gather with dominant shear reflections and surface waves at large angles relative to cable direction. b) PP model from Born modelling. c) Extracted PP signal. d) Residual.*

application of shot-by-shot de-bubble and source-side de-ghosting (Liao et al., 2024). The dense receiver spacing allowed for very effective denoising in the shot domain, crucial given the very sensitive nature of DAS and the consequently high levels of noise. Therefore, the accurate separation of PP and PS wavefields became the far greater challenge for the project. PP/PS separation based on moveout discrimination at this stage proved damaging to shallow PP events. Instead, two different approaches for signal extraction were implemented for PP and PS, to minimize amplitude leakage.

PP Imaging

In order to recover PP signal masked by strong PS arrivals, a PP model (primaries and water column multiples) was derived from the de-migration (Born modelling) of a Towed Streamer reflectivity volume. This model served as a guide to purge PS signal and residual noise from the DAS data via amplitude discrimination in the f-k_x-k_y domain (Figure 1). Following PP extraction, to compensate for the attenuation of PP signal intrinsic to the DAS acquisition method, an angle-dependent amplitude correction was applied in the sparse τ-p domain.

As the amplitude of the first order water bottom multiple exceeds that of the primary arrival due to constructive interference with the receiver ghost, Kirchhoff Mirror Pre-Stack Depth Migration was applied, with the additional advantage of slightly extending the illumination in the crossline direction. The resulting image shows excellent detail all the way down to and within the reservoir (Figures 2a, 4a), including structural dip orthogonal to the cable (Figure 3a).

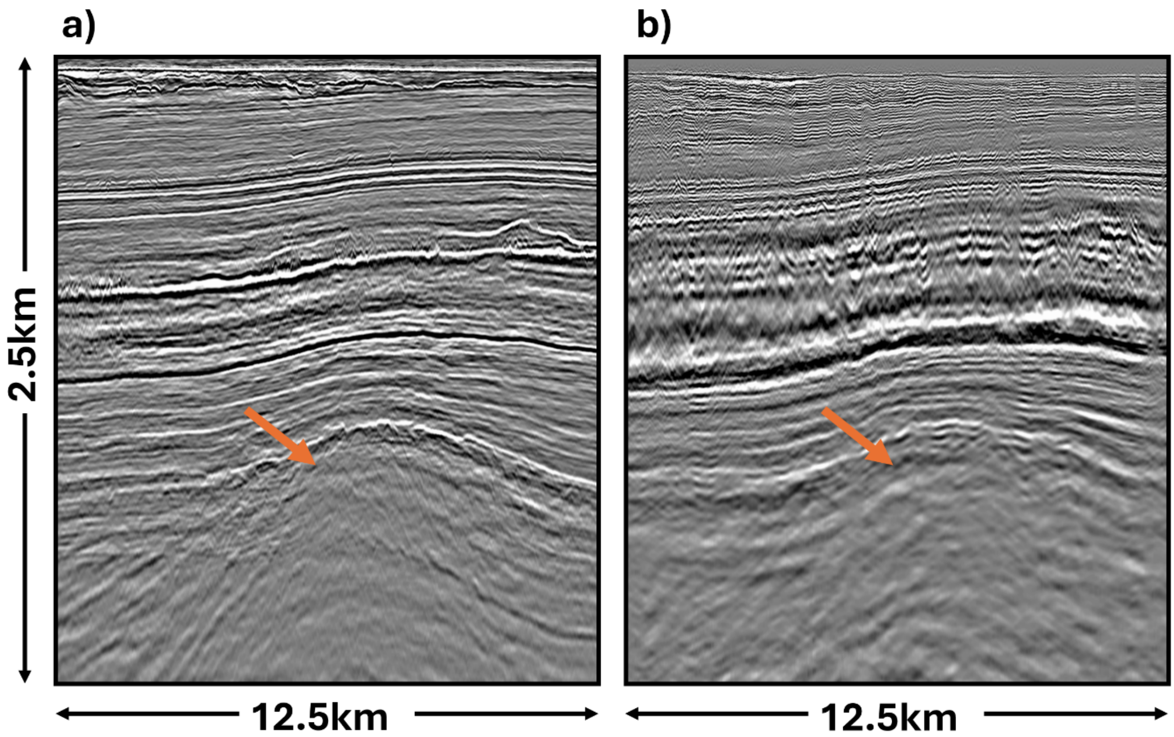

Figure 2. *Migrated stacks from 2D lines, inline view, reservoir indicated by orange arrows. a) PP mirror migration. b) PS primary image.*

PS Imaging

Concurrently, the PS data from the 2D tie lines were imaged. Ideally, all PS energy would have been contained in the residual of the PP extraction; however, in practice, significant PS leakage was observed. While acceptable for PP imaging, where PP signal preservation is prioritized and residual PS arrivals are easily eliminated in post-processing, this is undesirable for PS imaging. As a primary-guided PS extraction is not feasible in the absence of an accurate 3D shear velocity model and PS events dominate PP arrivals almost everywhere, we instead used velocity filtering and linear Radon in the shot domain to attenuate PP arrivals in the denoised data and applied source-side Model-based Water-layer Demultiple (MWD) in preparation for PS primary migration.

An initial shear velocity model was obtained by applying the V_p-V_s relationship from a neighbouring field of comparable geologic character. Adequate shear velocities were obtained through an iterative sequence of PS imaging, horizon picking, and event registration with the PP stack, although they could be further improved via model updating techniques such as tomography or FWI. A comparison of the final PS result to a PP image obtained from the 2D lines shows broad structural agreement down to the prospective reservoir, with the PS image exhibiting significant stretch below the base chalk and loss of high frequencies at depth (Figure 2).

Multiple Imaging

The intrinsically 2D nature of the receiver geometry available in a single cable DAS recording severely restricts the image coverage in the crossline direction. Mirror migration, or first-order water bottom multiple migration, utilizing virtual sources at twice the actual elevation above the receivers, allows minor improvements over primary imaging in terms of the coverage orthogonal to the cable.

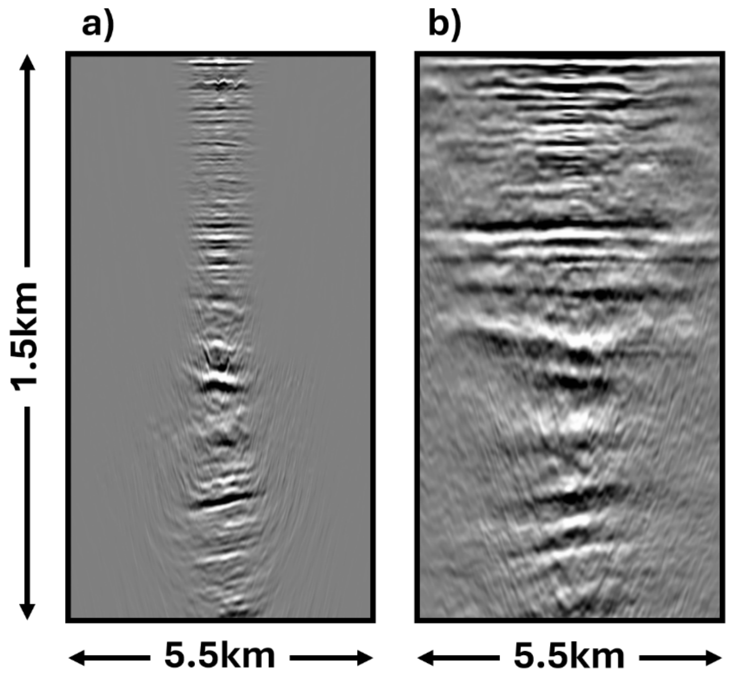

Figure 3. *Migrated stacks from 3D shot carpet, crossline view. a) PP mirror migration. b) Multiple imaging.*

By contrast, imaging the multiples in the data allows us to extend crossline coverage much further, particularly in the shallow. In principle, the free-surface multiple content of the data (including both peg-legs and longer period) provides illumination at distances from the cable limited only by the extent of the shot carpet. Since surface multiple legs are necessarily PP, but the greater part of the recorded data consists of shear arrivals, we are effectively imaging only source-side multiples.
Proceeding receiver by receiver, pairwise deconvolution of traces allowed us to gradually build up an image of the subsurface (Poole et al., 2024). The resulting multiple imaging shows greatly improved lateral coverage (Figure 3b), but while the broad structural dip at depth is captured, the image loses detail below 1.5km, likely due to the strong velocity contrasts in the chalk (Figure 4b). While this preliminary result is noisier than the mirror migrated image, future work will focus on optimising both pre-processing flow and imaging parameters to mitigate the residual noise and realise the maximum achievable imaged depth.

Conclusions

We have explored three distinct imaging techniques on a Central North Sea Surface DAS dataset. Although the solitary cable is well over a decade old and was not designed for DAS applications, the recorded data is of sufficient quality to produce a PP image adequate for the purposes of overburden and reservoir understanding. We also demonstrate proof of concept PS and multiple migration results, showcasing the potential of utilizing the full wavefield, depending on the imaging objectives.

Specifically, the possibility of extending coverage in the crossline direction using multiple imaging has intriguing implications for the efficient design of future Surface DAS acquisition geometries.

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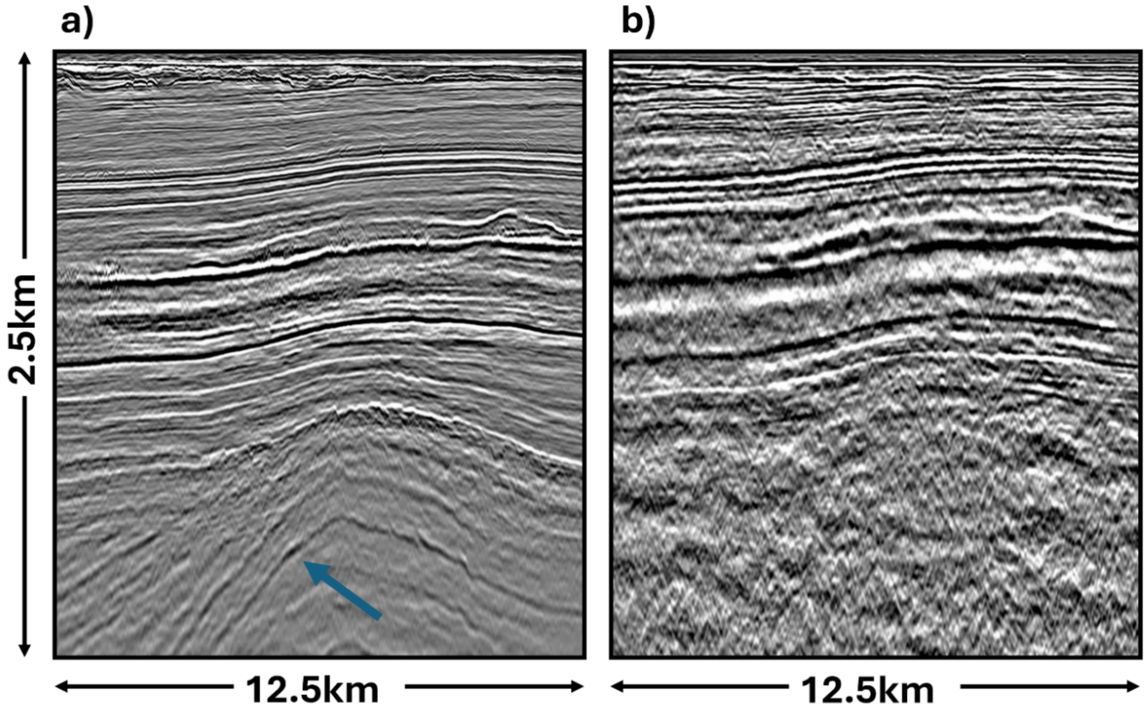

Figure 4. *Migrated stacks from full 3D shot carpet, inline view. a) PP mirror migration. Note: The additional events at reservoir level compared with Figure 2a (indicated by blue arrow) dip in the cross-cable direction and are therefore not captured using only 2D lines. b) Multiple imaging.*

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