LARGE-SCALE 3D HIGH-RESOLUTION NEAR-SURFACE IMAGING OVER NORDKAPP

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Summary

The 3700km2 Nordkapp Basin area, Barents Sea, was recently acquired with a wide-spread source-over-spread design. With its 6 sources sitting on top of 18 multi-sensor streamers, one sail-line can record a dense carpet of 108 sublines separated by only 6.25m. By thinly sampling the near offset over the full azimuth, this new source-over-spread setup is particularly well suited to image the steeply dipping salt flanks that extend up to the water-bottom. After application of a dedicated processing sequence carefully designed to honour the full resolution of the recorded data, the obtained high-resolution image is able to distinguish even small-scale geological features. This large 3D volume was also compared with an NFH image. Using the full benefits of the hexa-source, a high-end processing sequence was applied to the NFH data to overcome the usual weak signal-to-noise ratio of such records. The comparison between the two final images confirms the high-resolution quality of the source-over-spread volume, which includes enhanced lateral resolution, especially along the crossline direction, and access to AVO and RMO information. On the other hand, the very thin vertical sampling of the NFH data extends the recorded bandwidth by two octaves, making it a possible complement to the source-over-spread image.

Large-scale 3D high-resolution near-surface imaging over Nordkapp

Introduction

Shallow hazard assessments and recent growing interest for both offshore mineral exploration and wind farm foundations are leading to more and more near-surface-oriented acquisition designs and technologies to accurately image the near surface. Deploying sources above the streamers (source-over-spread) is a recent example of marine acquisition design innovation and demonstrates improvements in subsurface imaging resolution from shallow to deep (Vinje and Elboth, 2019). Moreover, by recording the commonly lacking near incidence angles, source-over-spread can provide unique shallow high resolution (Poole et al., 2020). In situations where acquisition is designed for deep targets and the near-offset coverage is limited, recent developments using Near Field Hydrophone (NFH) data offer an alternative to better image the very near surface (Dutta and Hatchell, 2019). Moreover, the NFH data has, on top of its zero-offset information, the possibility to record seismic signal with an uncommon sampling resolution of 0.5 ms, bringing potential imaging resolution of up to 1000 Hz. Whilst the benefits of NFH imaging have been proven, it remains a challenging task due to its single-fold nature and strong contamination by direct arrival and bubble energy. We review the implementation of recent technological developments to refine the NFH imaging and benchmark it with the source-over-spread high-resolution volume.

Source-Over-Spread Imaging

To image the complex geology of the Nordkapp basin, a new seismic survey was recently acquired with a widespread hexa-source sitting on top of 18 streamers, plus an additional source present in front of the streamers. This acquisition set-up was designed to optimize the near-offset coverage in a dense grid with a bin size of 6.25 m x 6.25 m, and thus better image the interface between salt and sediment where hydrocarbon traps are expected (Dhelie et al., 2021). The widespread sources also enable the recording of wide-azimuth coverage for offsets up to 500 m, leading to a full 3D record in the very near surface. In addition to the fine lateral sampling, multi-sensors were used to optimize the receiver deghosting and ensure a high vertical resolution. To be fully accurate, a high-resolution image needs to be migrated with the correct subsurface velocity, and the source-over-spread acquisition is particularly well suited for this purpose. As mentioned in Salaun et al. (2020), the combination of residual moveout (RMO) information recorded for all incidence angles and the long-offset information recorded by the source situated in front of the streamers lead to a precise velocity inversion. A high-end processing sequence was then tailored to produce a detailed 3700 km^2 near-surface image. Notably, it involved navigation uncertainty corrections, based on direct arrival inversion (Salaun et al., 2019), which are critical for retrieving the location of the recording devices. These corrections ensure proper binning, leading to a good alignment of the data for all azimuth sectors post-imaging. This step was followed by a shot-by-shot designature and a multi-sensor deghosting via summation of the hydrophone and geophone components. For optimal summation, 3D obliquity corrections of the z component were applied, guaranteeing similar deghosting quality for all incidence angles and azimuths. To benefit from the wide-azimuth nature of the source-over-spread near offsets, a 5D regularization was then performed, followed by a pre-stack depth migration (PSDM). In addition to a structural image (Figure 1), the source-over-spread data also gives access to AVO attributes even in the very near surface. The obtained image offers full 3D resolution with a similar quality along the inline and crossline directions. This image also reveals the steep dips generated by the salt tectonics. With its high resolution, this volume paves the way for the characterization of small-scale geological features. This dataset also provides a new reference for near-surface imaging that we propose to assess against NFH imaging.

NFH Imaging

NFHs, located immediately above the source array, were first introduced to record near-field wavelets from air guns, with derivation of notional signatures being the main objective (Ziolkowski et al., 1982). The streamer data processing flow benefits from this additional information for designature-related steps, from 1D shot-by-shot to directional designature. But these sensors can also be seen as additional receivers sitting directly on the source array, offering a unique way to record near offset data independent of the main streamer array. NFHs, with their sample rate of 0.5 ms or less, have the potential to provide very high vertical resolution. However, the hexa-source shooting implemented in this survey involved a sail-line separation of 600 m for a crossline source separation of 87.5 m, leading to obvious gaps between the sequences and hence limiting the NFH imaging to a 2D product in our comparison scenario.

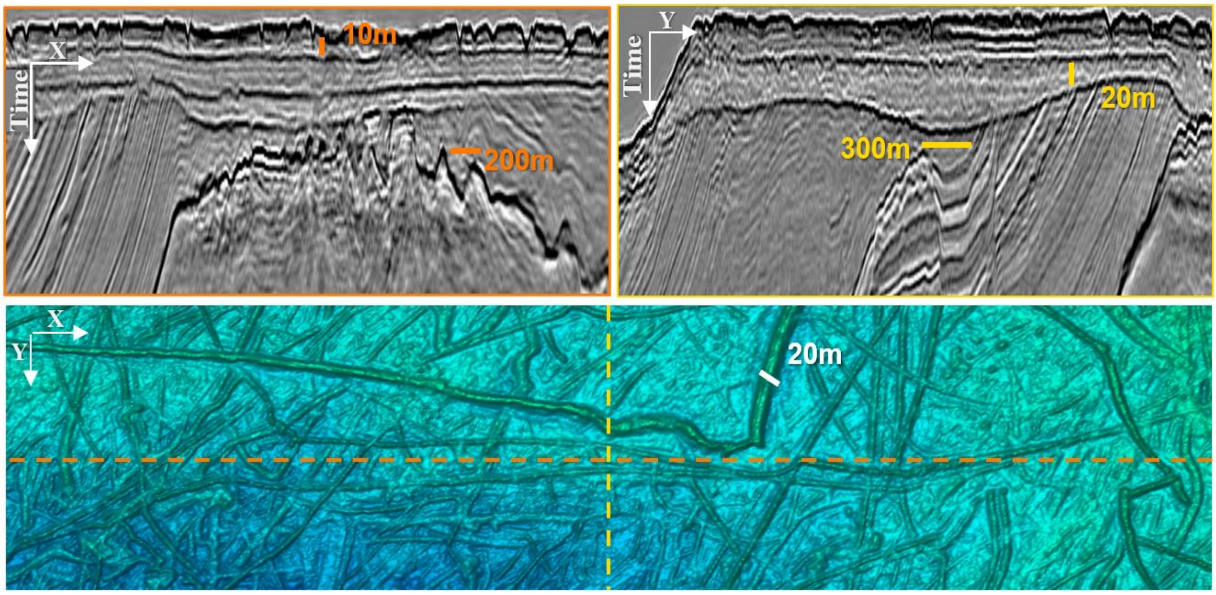

Figure 1: *Source-over-spread acquisition volume exhibits high resolution in both x and y directions (top). Strongly dipping events are imaged without any spatial or temporal aliasing, leading to a true 3D high-resolution volume. Ice tracks of 20 m width and smaller are nicely revealed on the interpreted water bottom horizon (bottom).*

To image the full potential of the recorded NFHs, despite their poor signal-to-noise ratio, a full processing sequence was performed. The strong direct arrival (DA) that constitutes the main data of interest when deriving notional signatures is a clear obstacle when using them for imaging, generally leading to a strong low-cut filtering early in the NFH imaging processing sequence. To avoid this and preserve as much of the low-frequency content as possible, an adaptive subtraction of the DA model was applied. Notional signatures were inverted from the NFHs using an iterative method and were used to form a beam generating the DA model. Due to uncertainties in both the gun array geometry and the frequency-dependent sea-surface reflectivity, the obtained DA model required further adaption in order to achieve optimal attenuation. With NFHs being only four meters below the surface on average, their records are very sensitive to ambient noise and needed a dedicated denoising step for each channel (Figures 2a, b). For the ghost attenuation, contrary to the multicomponent streamer dataset, the NFH data relied on a hydrophone-only approach. To properly fill-in the ghost notches, ghost wavefield extrapolation was used in a 3D implementation, with each gun array acting as an individual cable of a receiver array (Figures 2c, d). Due to the high sampling rate, sea-surface undulations were well recorded by the data. This information can be exploited to derive the swell height per shotpoint to refine water column statics. In this context, the flat water-surface assumption is not sufficient and we must consider the sea state. Wave height (Figure 2e) was estimated on a trace-by-trace basis and was subsequently incorporated into the deghosting to properly account for its influence on the ghost shape. Obtained values were in accordance with the 4 m maximum swell heights measured during the acquisition. Due to the small number of traces per shot and the fine sampling interval, the NFH image is more sensitive to wave height variation than the streamer data. In order to cope with the very irregular fold of the NFH data and preserve the recorded resolution, a variety of imaging strategies were investigated. Of these, the preferred approach used pre-migration trace densification involving both shotpoint and cable interpolation combined with a least-squares migration scheme, leading to clear uplift of the 2D migrated image (Figures 2f, g) compared to the raw Kirchhoff PSDM. To honour the vertical resolution, the PSDM sampling interval was set to 0.5 m, four times denser than the main source-over-spread image. The lateral resolution, however, was similar, with a 6.25 m x 6.25 m bin size.

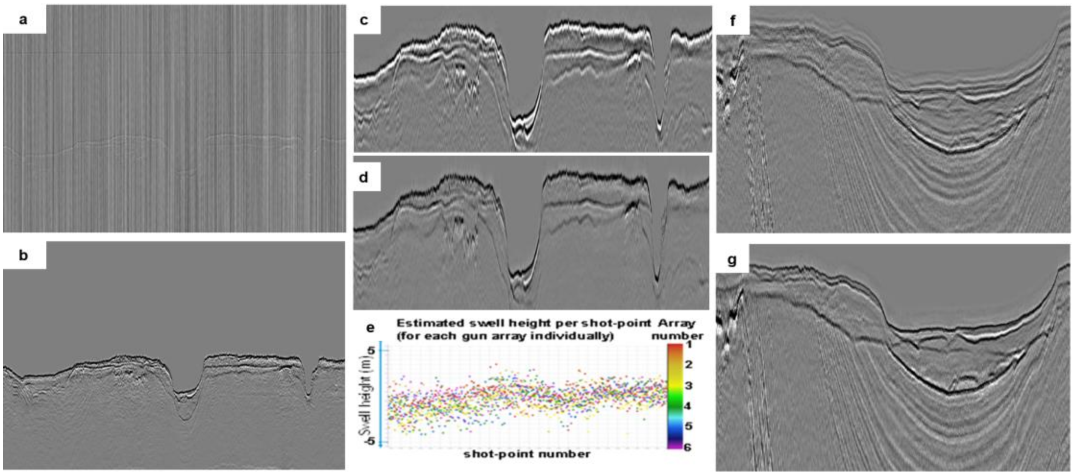

***Figure 2**: High-end NFH imaging flow - a) Raw NFH common channel; b) Processed NFH; c) 2D stack after direct arrival removal and designature; df) 2D stack after source and receiver deghosting; e) Swell height statics corrections; f) Raw PSDM; g) Final NFH image.*

Near-Surface image comparison and discussion

Despite the irregular fold and low signal-to-noise ratio of the NFH data, the applied high-end processing sequence allowed for good preservation of the full frequency bandwidth (Figure 3), including the low-frequency band, which was heavily contaminated by ambient noise. On this line, situated vertically below the source, the NFH and source-over-spread images are comparable down to 150 m below the sea surface. The NFH image broadens the high-frequency part of the spectrum, providing additional relevant content above 250 Hz. When compared with the source-over-spread image, the final NFH image (Figure 4) shows an uplift in vertical resolution but cannot compete in terms of lateral resolution, notably along the crossline direction. In particular, the steeply dipping sediment events, visible close to the salt, are more sharply imaged with the source-over-spread data than with the NFH data, exhibiting the difficulty of zero-offset-only imaging for such geologies. The two datasets are complementary, providing a 3D shallow hazard survey quality for the source-over-spread data and very high vertical resolution, along 2D lines, for the NFH data. In the context of pure NFH imaging, the shooting interval could be increased, whilst reducing the record length, thus increasing the lateral resolution. Denser source lines would also allow full 3D imaging with an unprecedented resolution that may not require streamers.

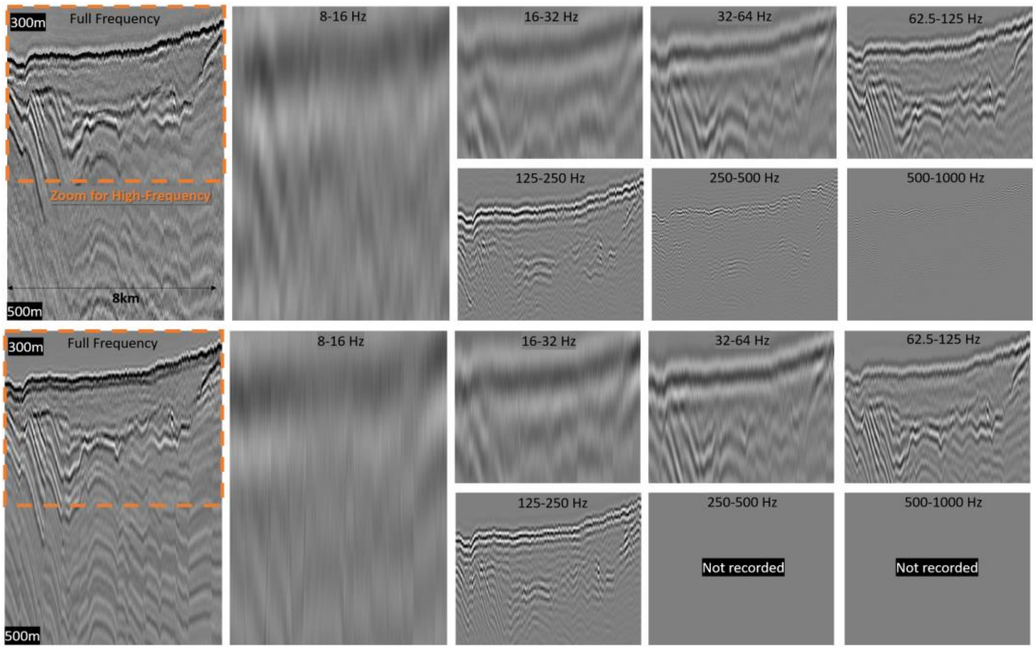

***Figure 3**: Octave panels of NFH (top) and source-over-spread images (bottom).*

Conclusion

On this Barents Sea survey, where the strong and irregular water bottom sits around 300 m deep, recovering the geological information with a single-fold zero offset NFH data is challenging. A high-end, tailored processing flow was designed to process the NFH recordings, and the resulting image provided very high vertical resolution. This image was compared with a newly acquired source-over-spread survey designed to specifically overcome the Nordkapp geological challenges and offer a high-definition image from top to bottom. The comparison between these two volumes confirms that source-over-spread data is superior in lateral resolution, allowing for delineation of highly dipping subsurface events. While the source-over-spread image maintains its high resolution in deeper sections of the formation, the resolution of the NFH image reduces after a few hundred meters. However, on the first hundred meters below the water bottom, NFH imaging provides an improved vertical resolution thanks to its high recorded sampling rate and can precisely image the thin geological features. In this case study where these two datasets were available, we have highlighted the benefits and limitations of NFH imaging over a source-over-spread dataset, the most notable limitation being the lack of spatial resolution. The NFH image could, however, be used as additional information to refine the source-over-spread image for near-surface characterization.

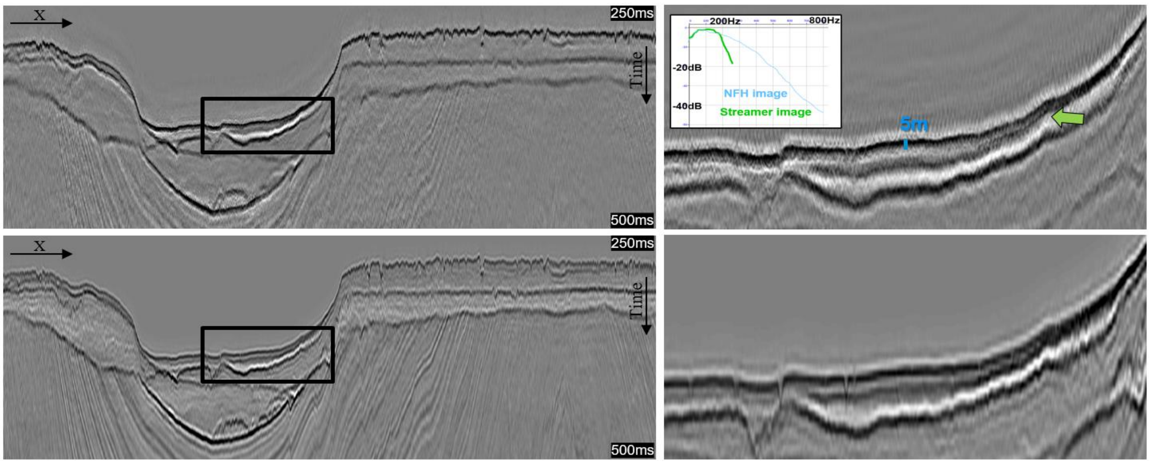

Figure 4: *NFH imaging (top) vs source-over-spread imaging (bottom), with zoomed sections on the right. Just below the water bottom, thin sediment layers (green arrow) are revealed by the extended bandwidth in the NFH image.*

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