Single sensor and 1ms recording for improved imaging in the shallow subsurface

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Summary

Site investigations, for instance, in the emerging field of CCS (Carbon Capture and Storage), benefit from improved resolution in the overburden compared to traditional seismic surveys. This is typically achieved by recording data at a 1ms sample rate. However, the resolution of the imaged data does not only depend on the resolution in time but also on the spatial sampling. As such, streamers which form analogue groups may lose much of the anticipated uplift in the imaged data at higher frequencies. This paper describes the improved resolution from using single-sensor recorded data rather than analogue group-forming, as shown on a 1ms dataset acquired in the Norwegian North Sea.

Key Aspects

The paper demonstrates the effect of analogue group-forming on both resolution and noise content in the shallow overburden, when compared to a single-sensor equivalent.

Novelty

The paper investigates analogue group-forming compared to single-sensor acquisition within the emerging field of high-resolution seismic acquisition for carbon capture and storage.

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Introduction

Improved resolution, both spatially and temporally, are always sought for seismic data. This is especially true for the CCS market where the subsurface targets typically are relatively shallow (<1-2km), and special focus is on identifying potential CO_2 migration pathways in the shallow overburden. To meet these demands without significant capital investment on new streamers, seismic contractors often acquire this high-resolution data with their existing equipment (Widmaier et al, 2023).

The available commercial streamer pool can be classified into two categories: single-sensor streamers and group-formed streamers. Group-forming is the summation of data from individual neighbouring sensors in hardware to form a grouped response. Groups are used to improve the signal to noise ratio (SNR) of the acquired data; to reduce data bandwidth within the streamers; and to reduce the size of acquired datasets. In addition to reducing the spatial sampling, group-forming also imposes a group response in form of a wavenumber filter on the data, which disproportionately attenuates high-frequency, high-dip events (Martin et al, 2000). These are precisely the events that are expected to provide benefits from acquiring data at higher sampling rates. As such, forming groups can negatively impact the achieved resolution in the shallow overburden.

Method

To test the impact of group-forming on high-resolution acquisition and subsequent imaging, 3D, multi-component, 1ms data was acquired in the Norwegian sector of the North Sea using single-sensor streamers. The data was acquired with zero in-line offset from the source to the first channel to maximise the unaliased signal and provide the best possible data quality.

From a single CDP line of the raw, single-sensor data, two separate datasets were produced for comparison. Firstly, a single-sensor preconditioned dataset, in which the pressure (P), vertical and crossline velocity components (Z and Y, respectively) go through automated QC, preconditioning and noise attenuation that leaves the signal cone completely untouched; and secondly, a dataset that was formed into groups using a method equivalent to analogue group forming.

The simulated "group-formed" data was made by scaling the input data at each wavenumber by the group response from a legacy commercial streamer system which had a 12.5m group separation, with each group consisting of 10 elements distributed non-uniformly over 15m. The resulting group response is comparable to other commercial systems in use today. The effect of this group response compared to the single-sensor, noise-attenuated data is shown on FK spectra in Figure 1.

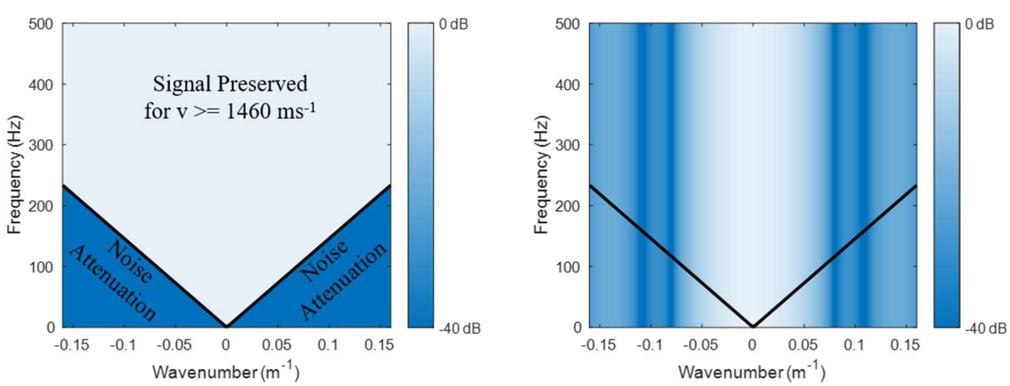

Figure 1 *The FK response of the single-sensor noise-attenuation (left) and group-forming (right). Note that the group-forming attenuates less at low frequencies and wavenumbers, leaving undesirable noise in the data.*

A limitation of this method is that the wavenumber filter had to be applied at the native 3.125m hydrophone spacing, and this introduces some errors in the response for the signal at very high frequencies (>240 Hz) and wavenumbers (>0.16 m^{-1}). The total error is a 15.7dB increase in the modelled group compared to the real group, within the wavenumber range of the aliased signal. There is also an expected increase in the level of noise of up to 4dB due to the reduced number of hydrophones in the single-sensor streamer, compared to the real groups that are being modelled.

Results on Raw Data

The impact of the group response on the resolution of hydrophone data is visible even in the shot gathers prior to processing (Figure 2). The group-formed shot gathers clearly demonstrate a loss of high-frequency information compared to the preconditioned single-sensor data in the shallow events close to the water bottom, and in particular, the direct arrival shows significant attenuation. Due to the shallow depth of the reflectors, much of the data recorded from the shallow subsurface contains high dips despite the zero-offset acquisition and therefore is notably attenuated by the group response.

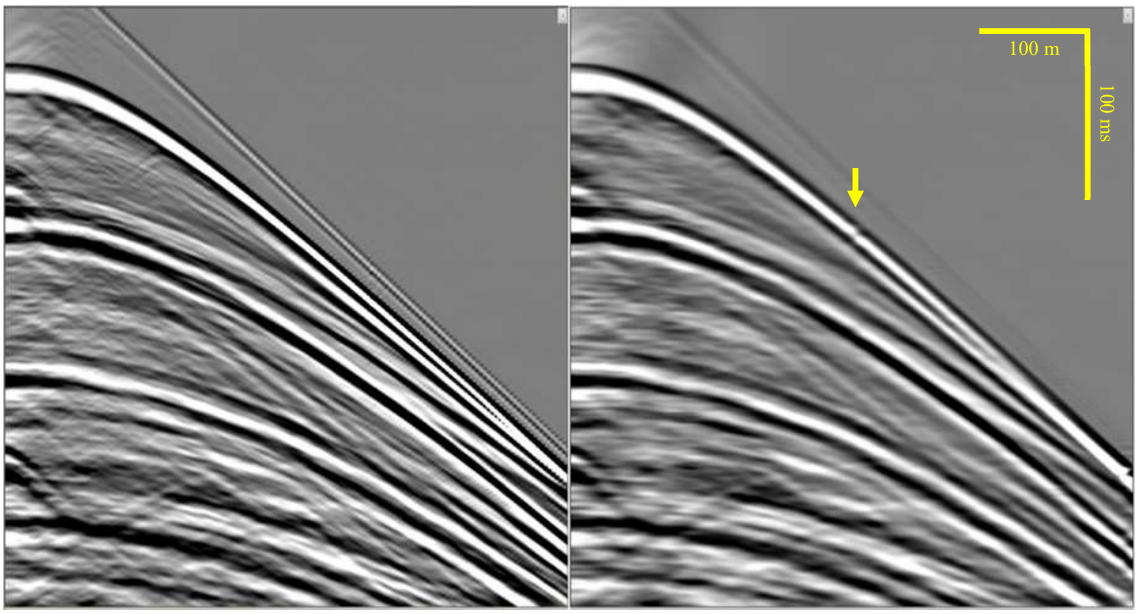

Figure 2 *1ms hydrophone shot gather after single-sensor preconditioning (left) and after imprinting the group response (right). The yellow arrow shows the effect of a bad channel within the analogue group forming – in the single-senor case the channel is identified and automatically interpolated as part of the preconditioning process.*

There are also some amplitude and phase anomalies in the group-formed data caused by individual noisy or weak channels in the raw data. These bad channels are identified in the automated QC in the single-sensor preconditioned data and subsequently interpolated from the surrounding data, but in an analogue group forming these errors are carried forwards by summing them into a group prior to any QC. The affected traces (an example is indicated by the yellow arrow in Figure 2) are very apparent with the original channel spacing preserved in this data, but it may be much more challenging to identify where the data has been summed into 12.5 m groups.

The spectra and FK transform of the shot gather plotted in Figure 3 demonstrate how the group response attenuates signal in the higher frequencies and higher dips. Between 100 and 200 Hz, there is a 10 to 15dB difference in power. This suggests single-sensor data can be used to record sufficient high-frequency data with a much smaller seismic source, with reduced environmental impact, and in some cases, potentially allowing for an uplift in operational efficiency from an increased number of sources compared to a group-formed equivalent.

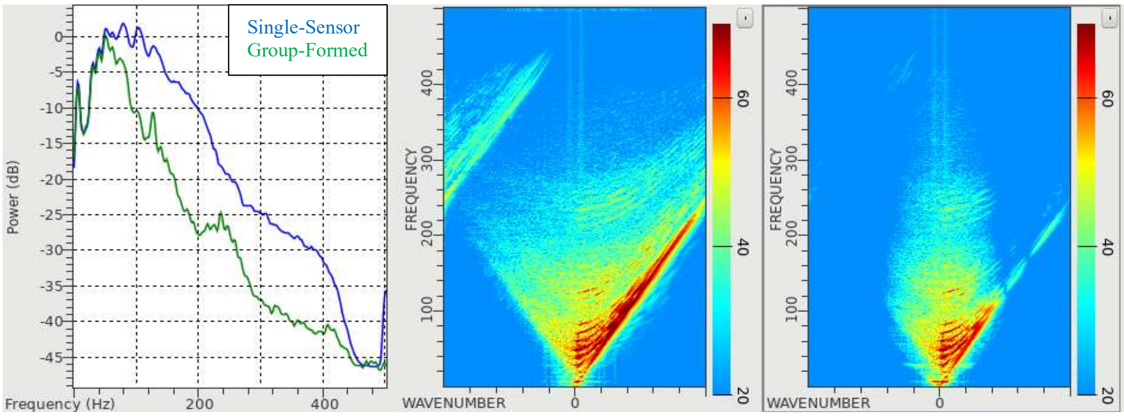

Figure 3 *Amplitude spectra for a hydrophone shot gather (left); FK spectra for a hydrophone shot gather with single-sensor preconditioning and noise attenuation (centre) and group-forming (right). The wavenumber axes are in the range 0 to 0.16m*$^{-1}$.

Results on PreSTM Data

To better represent the effect of the group-forming on the final image, both datasets were processed (using both P and vertical acceleration (A_Z) components) using the same processing sequence. Where additional de-noise was required for the group-formed data to account for the lack of single-sensor noise attenuation, these processes were also applied to the single-sensor data, to prevent the possibility of differences accumulating from divergent processing.

Low Frequencies

Although the main objective was to test the effect of group-forming on the high frequencies, there are also significant differences in the low frequencies. The final stacks with a 60 Hz high-cut filter applied (Figure 4) show a significant increase in noise content in the group-formed data compared to the single-sensor preconditioned data. The noise originates from low-frequency transversal vibration waves in the streamer with a low phase velocity on the A_Z component. On single sensor data with dense sensor spacing, these waves are recorded without aliasing (Teigen et al, 2012) and are easily attenuated, e.g. in the FK domain. In the group-formed data this noise is strongly aliased and much more difficult to attenuate. This makes it very challenging to get an acceptable SNR level for the A_Z data below ~20Hz, and a significant denoising effort is needed all the way up to 40Hz - physical design elements in an analogue, group-formed streamer may reduce the effect of this noise, but cannot entirely remove it.

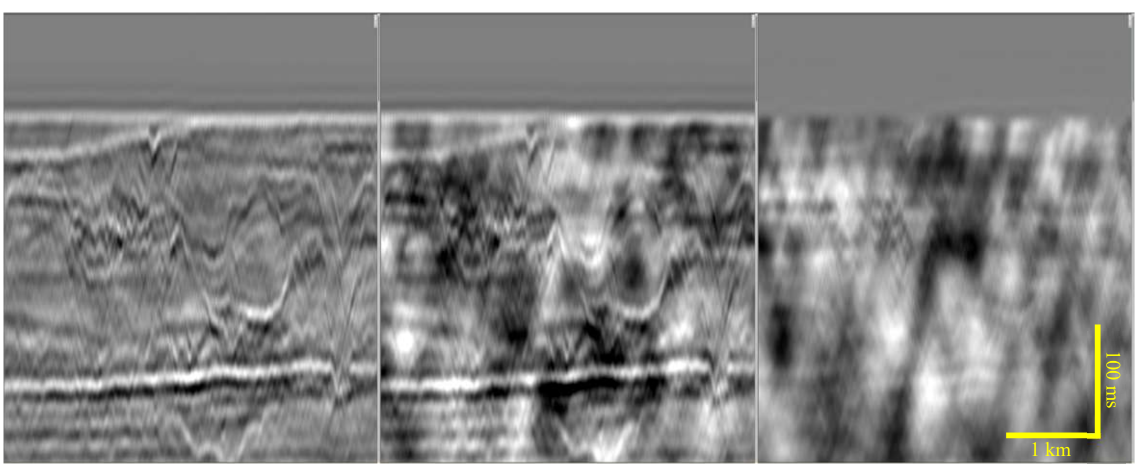

Figure 4 *PreSTM stacks of the single-sensor preconditioned data (left), group-formed data (centre) and difference (right), 0 – 60 Hz.*

High Frequencies

Figure 5 shows the data with a 60 Hz low-cut filter applied. The stacks show a clear loss of resolution in the near-subsurface in the group-formed data. Most events within 100ms of the sea floor are severely attenuated and notably less sharp than in the preconditioned single-sensor data, and some events may be absent entirely. Also evident in the group-formed data is significantly increased amplitude in the residual water-bottom peg-leg multiple, which has been poorly predicted due to the different attenuation of spatial frequencies in the sea floor event compared to the multiple (yellow arrows in Figure 5). This is a good example of how group forming negatively influences subsequent processing steps thereby reducing the overall quality of the seismic data.

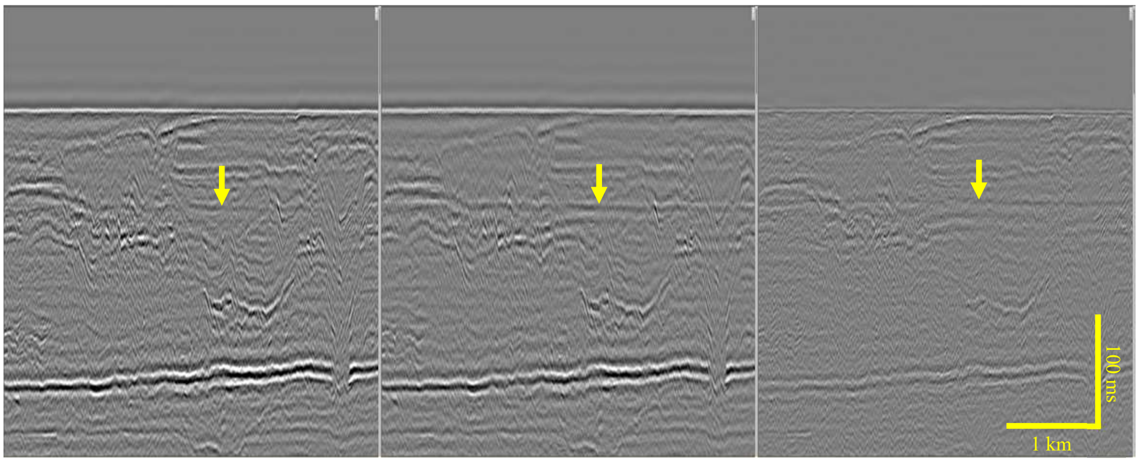

Figure 5 *PreSTM stacks of the single-sensor preconditioned data (left), group-formed data (centre) and difference (right), 60–500 Hz. Yellow arrows indicate the difference in the residual water-bottom peg-leg multiple between single-sensor and group-formed data.*

Conclusions

These results demonstrate the impact on data quality of using conventional streamer systems with large group lengths to acquire high-resolution seismic data. There is a clear effect on the signal in the shallow subsurface that notably diminishes the gains from recording data at higher sampling rates. These results demonstrate how acquiring single-sensor data and applying suitable preconditioning at the original channel spacing allows us to preserve this information correctly. Imaging both data sets with identical processing flows shows a clear uplift in the shallow subsurface for the single-sensor data compared to the group-formed equivalent. The uplift in data quality comes from both the preservation of useful signal and the greater noise attenuation power of applying extensive noise attenuation to the single-sensor data. The application of inverse receiver-group filters was not investigated as part of this study, nor the application of extensive, additional noise attenuation to the group formed data. These processes may decrease the differences between the two types of data.

References

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