# Improving the results of shallow marine surveys imaging with reconstructed low frequency seismic data

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## Summary

Full waveform inversion (FWI) is the main process to derive an accurate velocity model to improve sub-surface seismic imaging. The presence of low frequency contents in seismic data is very important for FWI. They help to mitigate cycle skipping and are key to estimate the correct velocity-model background. Despite the improvements in seismic acquisition and receiver technology, it is still challenging to have seismic data with good signal-to-noise ratio (SNR) below 4 Hz. This is mainly due the presence of strong ambient noise and/or due to physical limitations of the seismic source. Noise attenuation is routinely used to boost the SNR, however it fails to deliver reasonable results when the input SNR is very poor. An alternative solution is to reconstruct the low frequencies from the higher frequencies which have better SNR. In this abstract we show a field data example using a low frequency reconstruction (LFR) method to recover the low frequency contents of towed marine seismic data for the purpose of improving the performance of FWI and consequently improve the imaging results.

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## Introduction

Seismic imaging faces notable challenges in shallow marine surveys due to the variability in near-surface geology, limited low-frequency content, and the dominance of multiple reflections. To map seismic events to their true locations, an accurate estimate of the velocity model is crucial. Recently, Full waveform inversion (FWI) become the industry standard method to reconstruct a detailed velocity model. It iteratively minimizes the difference between observed field and numerically simulated seismic data through a least-squares approach. To mitigate the inherent nonlinearity of the objective function and alleviate the risk of cycle-skipping, it is essential to incorporate high-quality low frequencies and/or start the inversion process with an accurate initial velocity model (Virieux and Operto, 2009).

Acquiring data with good signal-to-noise ratio (SNR) below 4 Hz is still challenging due to the limitations of the seismic sources and ambient noise contamination. Denoise methods usually fail to extract useful low frequency signal for FWI. Bekara et al. (2022) proposed a different signal processing-based approach for low frequency reconstruction (LFR). The signal below a cut-off frequency is estimated using an autoregressive filter estimated from higher frequencies. The LFR method showed significant potential to mitigate cycle-skipping in the presence of salt and high velocity geo-bodies (Djebbi et al. 2022).

In this abstract, we present an application of the proposed LFR method to improve imaging for a shallow marine data set acquired offshore Norway. The estimated model improves the imaging quality and the reflectors continuity. We briefly describe the LFR approach, then we show the low-frequency reconstruction results, FWI estimated models as well as the imaging improvement.

## Methodology of LFR

The LFR method uses the fact that a sparse signal in time maps into a superposition of pure linear harmonics in the frequency domain which are perfectly predictable using an autoregressive model. This assumption is not valid for real data and to overcome this problem, the LFR is applied over a local sliding time-space windows to account for the non-stationarity of the seismic data. The reconstruction is done in the frequency-slowness domain to enforce the sparsity assumption, to include the spatial correlation of the seismic data into account and to honour the constraint of the “signal cone” of the wavefield. After the reconstruction, the data mapped back from the frequency-slowness domain to time-space domain. A full description of the method is given in Bekara et al. (2022).

## Field data example

We apply the proposed method to re-build the low frequency contents of towed-streamer marine seismic data below 4 Hz for the purpose of starting to run FWI. Figure 1-a shows couple of shot gathers in the 0-5 Hz frequency band. Given the data quality after denoise, low frequencies should be ignored for the first pass of FWI. Starting FWI at higher frequencies comes with an increased risk of cycle-skipping and requires a more accurate initial model. Here, we apply LFR in the shot domain to reconstruct the signal below 4 Hz and the result is shown in Figure1-b. The process did an excellent job in cleaning the data and clearly achieved a sensible reconstruction particularly for the highlighted events. The refractions events, useful to reconstruct a background FWI velocity model are recovered. Also, the low frequency noise level is reduced which makes FWI more stable.

The data (10,000 $km2$) consist of several merged surveys acquired offshore Norway. The water bottom is shallow and ranges between 75 m to 150 m. FWI was run with a maximum offset of 6 km and using cascaded frequency staging up to 10 Hz (starting 0-4 Hz with 1 Hz increment) (Ramos-Martinez at al. 2016). The first stage of the FWI sequence was run using predominately reconstructed data. Figure 2 shows the velocity model before and after FWI. The background velocity model is modified with large updates with values up to ±800 m/s. The shallow high velocity in the left part of the model is removed and resulted in better imaging of the shallow reflectors. Without the reconstructed low frequencies, FWI is not able to change the background model without converging into a local minimum.

The results of Kirchhoff migration with the initial model and the derived model using LFR-FWI are shown in Figure 3. The top and bottom salt layers are nicely imaged, despite their complexity along with the carboniferous layer below the salt. Better continuity of the reflectors in the deep parts of the model is observed. We show in Figure 4 the angle gathers migrated with the initial and FWI models. The flatness of the angle gathers all over the section confirms the accuracy of the inverted models and the better imaging quality. The availability of reconstructed low frequencies contributed to achieve a good imaging of such a complex geological structure.

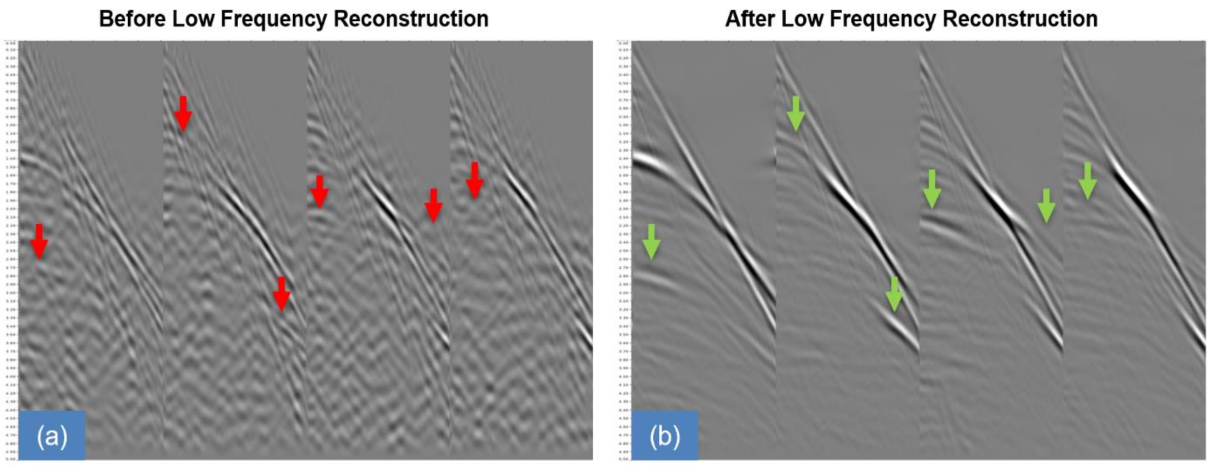


***Figure 1*** *Shot gathers in the 0-5 Hz band (a) before LFR, (b) after LFR below 4 Hz.*

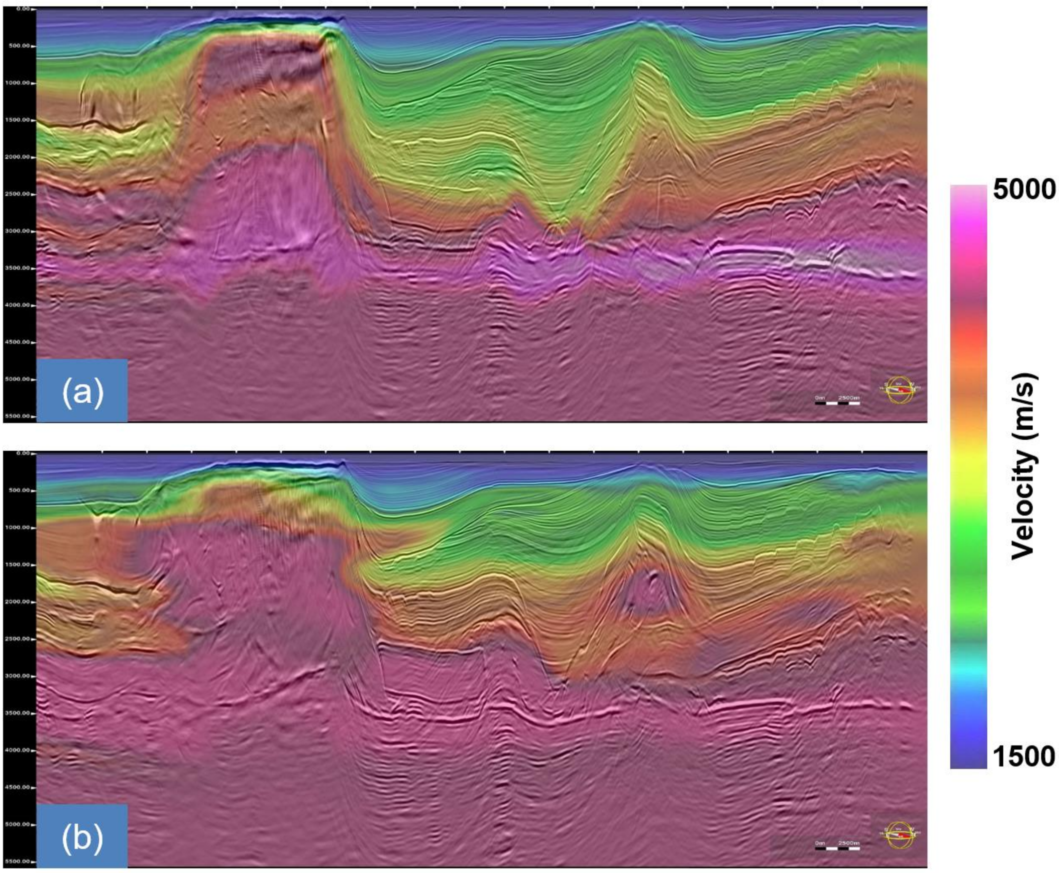


***Figure 2*** *Velocity models overlaid with Kirchoff images for (a) the initial model and (b) the FWI final model.*

**Conclusions**

We used low frequency reconstruction to improve imaging results for shallow marine. The solution reconstructs the low frequency contents of the seismic data from its high frequencies where the SNR is generally good. Application of the proposed solution to shallow marine data showed that the reconstructed low frequencies improved the accuracy of the background velocity model as well as imaging in presence of complex geology. The availability of reconstructed low frequencies allows us to be less dependent on a highly accurate starting velocity model and this will have a direct impact on reducing the turnaround time of imaging projects.

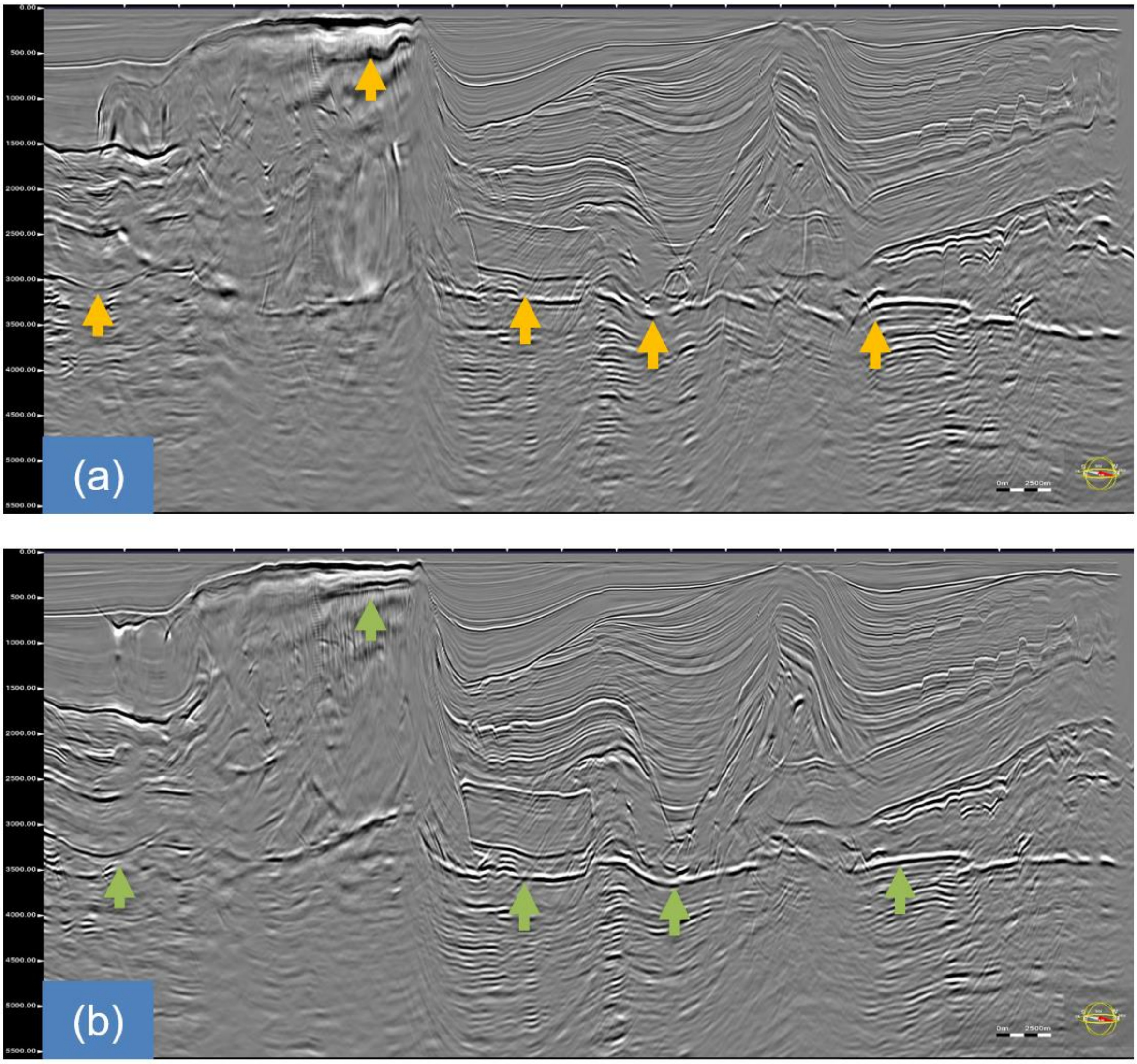


***Figure 3*** *Inline section of Kirchhoff migration with (a) initial velocity model and (b) the FWI model.*

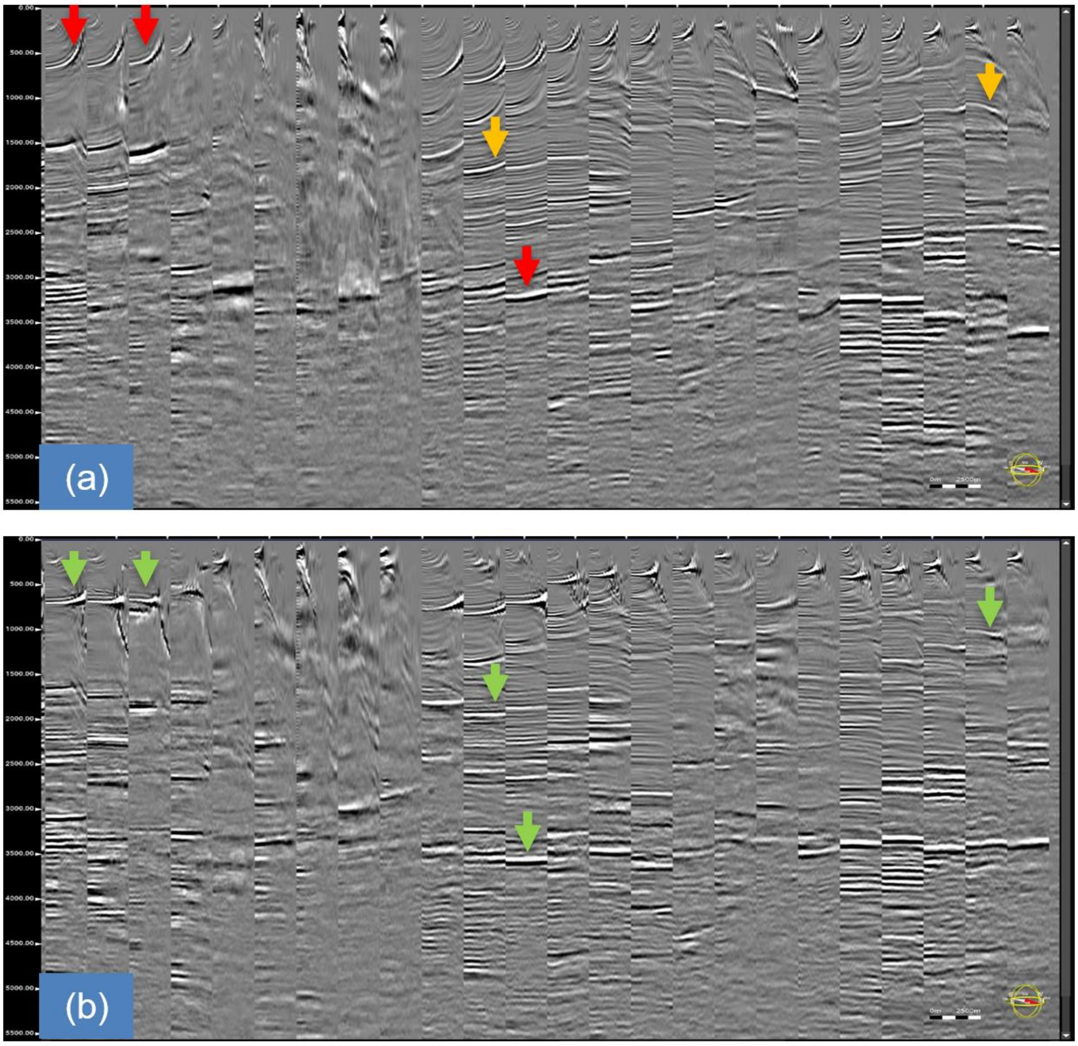


***Figure 4*** *Inline angle gathers for the Kirchhoff migration with (a) the initial velocity model and (b) the FWI model.*

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