Two-component towed-streamer MP-FWI imaging

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Summary

Two-component deghosting of towed streamer seismic data has been a staple of processing for many years, making use of the opposite polarity of the receiver ghost in hydrophone (P) and vertical geophone (Z) data. Here, we show how those co-located hydrophone and vertical geophone records from towed streamer acquisition can be used in MP-FWI imaging. We compare a P-only inversion with one that simultaneously uses both P and Z records. Since the P and Z data have complementary amplitude spectra, the two-component inversion has a more uniform spectral signal distribution to update from. The inclusion of this additional information about the wavefield from the Z component provides additional constraints to the inversion, guiding it towards a more robust solution. This results in more rapid convergence of the inversion - reducing computational resource usage - and reduced noise in the resultant reflectivity image.

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Introduction

Multi-parameter full-waveform inversion (MP-FWI) imaging has, in recent years, achieved high-resolution images of subsurface reflectivity (e.g. McLeman et al., 2023) by using the complete recorded wavefield, including primary reflections, ghosts, and multiples. The use of more accurate physics means that multiples, instead of being treated as noise, are now a useful source of additional subsurface information. MP-FWI imaging, therefore, naturally makes use of both the upgoing and downgoing wavefields.

The most common form of multi-sensor towed-streamer acquisition consists of co-located hydrophones and vertical geophones, which provide pressure and particle velocity measurements, respectively. If the wavefield is treated as a combination of upgoing and downgoing wavefields, the pressure (P) will record the sum of upgoing and downgoing since it is omnidirectional. The vertical velocity (Z) is a directional measurement and therefore records the difference between upgoing and downgoing wavefields. The receiver ghost is therefore recorded with opposite polarity on the P and Z components. This gives complementary notches in their amplitude spectra (Figure 1). This complementarity of P and Z has been widely used in conventional processing for several years to attenuate the receiver ghost, yielding superior results compared with approaches that use the P record only.

MP-FWI imaging using towed-streamer data has traditionally used only the hydrophone component. However, the same benefits achieved with two-component deghosting can be realised through MP-FWI imaging of two-component towed-streamer data. We compare a P-only inversion with one that simultaneously uses both P and Z data. The inclusion of the additional information about the wavefield from the Z component provides additional constraints to the inversion, guiding it towards a more robust solution. This results in more rapid convergence of the inversion and reduced noise in the resultant reflectivity image.

Method and results

The dataset used in this example was acquired in the Norwegian Sea in 2014. It used 14 dual-sensor streamers, 7 km long, towed 75 m apart at a depth of 20 m and a source depth of 8 m. The calm sea state and a deep cable tow depth of 20 m were noted early on as potential challenges for the inversion, due to the sharp receiver ghost notch at around 37.5 Hz in the amplitude spectrum of the hydrophone data. Visco-acoustic diving-wave-only FWI up to 17 Hz maximum frequency and MP-FWI imaging (simultaneously updating for Vp and P-impedance) up to 30 Hz maximum frequency were performed using the hydrophone data only, since below 20 Hz, the streamer geophone had poor signal-to-noise content. MP-FWI imaging updates were performed up to maximum frequencies of 45 Hz, and then 64 Hz, using both hydrophone and geophone data. The modelled vertical velocity and pressure records were reaped from a single forward propagation, meaning the impact on the computational requirement per iteration was small compared to an equivalent single-component inversion.

Previous work (e.g. McLeman et al., 2023) has shown that MP-FWI imaging using one-component data can produce high-quality results. However, a deep cable tow and calm sea state will result in deep receiver ghost notches in the hydrophone amplitude spectrum, as observed for this particular dataset, and that may limit the signal that can be recovered in that notch. Two-component data provides a more even distribution of signal across the bandwidth as demonstrated in Figure 1.

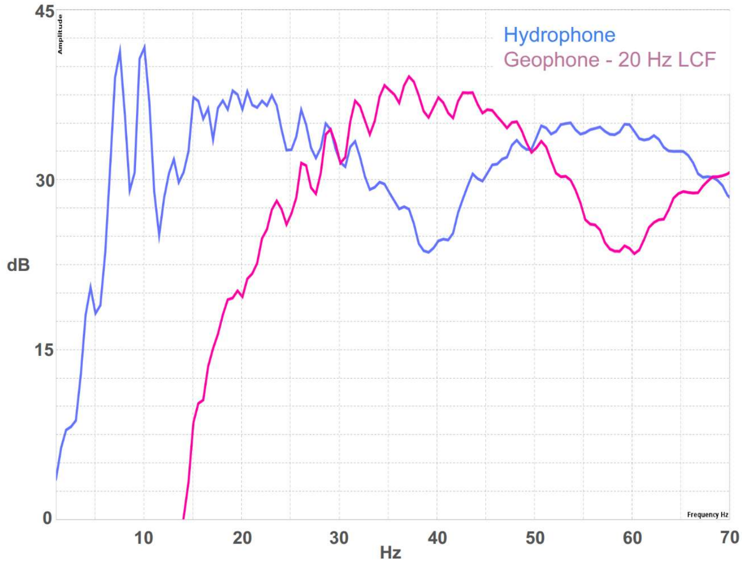

Figure 1 *Near-channel amplitude spectra of hydrophone (blue) and geophone (pink) data from a representative 2D line. A 20 Hz low-cut filter was applied to the geophone data due to the poor signal-to-noise ratio below that frequency. Note how the opposite polarity of the downgoing wavefield in the two sensor types results in complementary peaks and troughs in the spectra.*

Figure 2 shows amplitude spectra from 150 to 1000 ms TWT below the seabed from MP-FWI imaging reflectivities at 64 Hz maximum frequency after 11 iterations using both P and Z (black curve) and from a P-only inversion with otherwise identical parameterisation after 2, 5, 8 (yellow and orange curves) and 11 iterations (red curve). Below approximately 33 Hz the spectra appear very similar, because the starting model already predicted the recorded data well within the bandwidth of the previous inversion.

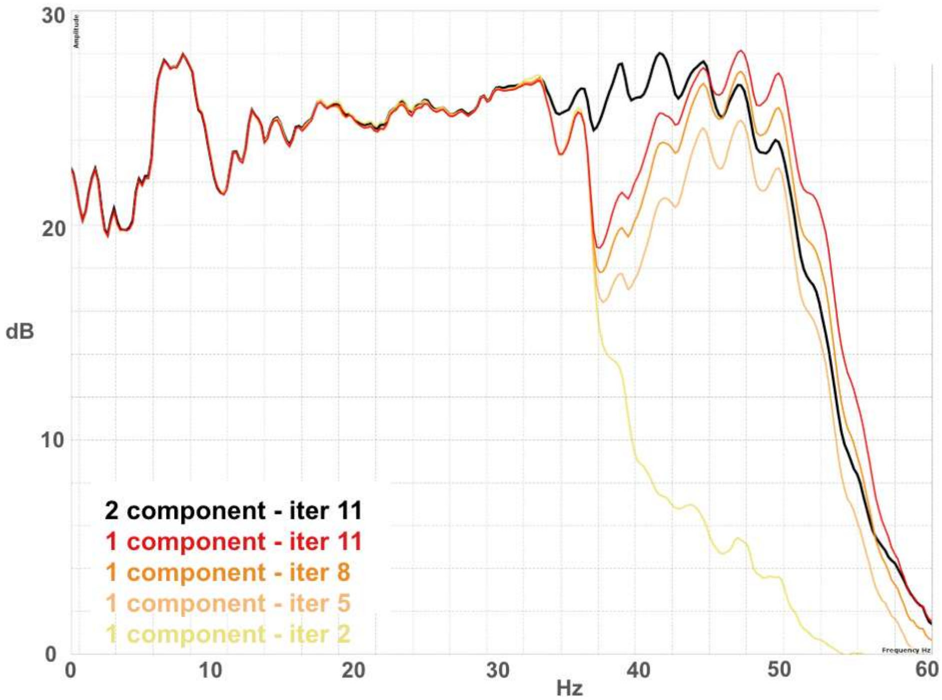

Figure 2 *Amplitude spectra of reflectivity volumes from one-component and two-component 64 Hz MP-FWI imaging. The one-component results are shown after 2 (yellow), 5, 8 (orange) and 11 iterations (red). The two-component result is shown in black after 11 iterations.*

There is a notch in the amplitude spectrum from the single-component inversion - the receiver ghost notch for a hydrophone. This notch is being filled in, but it is happening gradually because the low signal level in the hydrophone recording at these frequencies provides limited information to drive the inversion. These frequencies are well-represented in the geophone data due to constructive interference from the receiver ghost and are thus well resolved after 11 iterations in the two-component inversion. The complementary information provided by the vertical geophone in the two-component inversion resulted in faster convergence, with fewer iterations required.

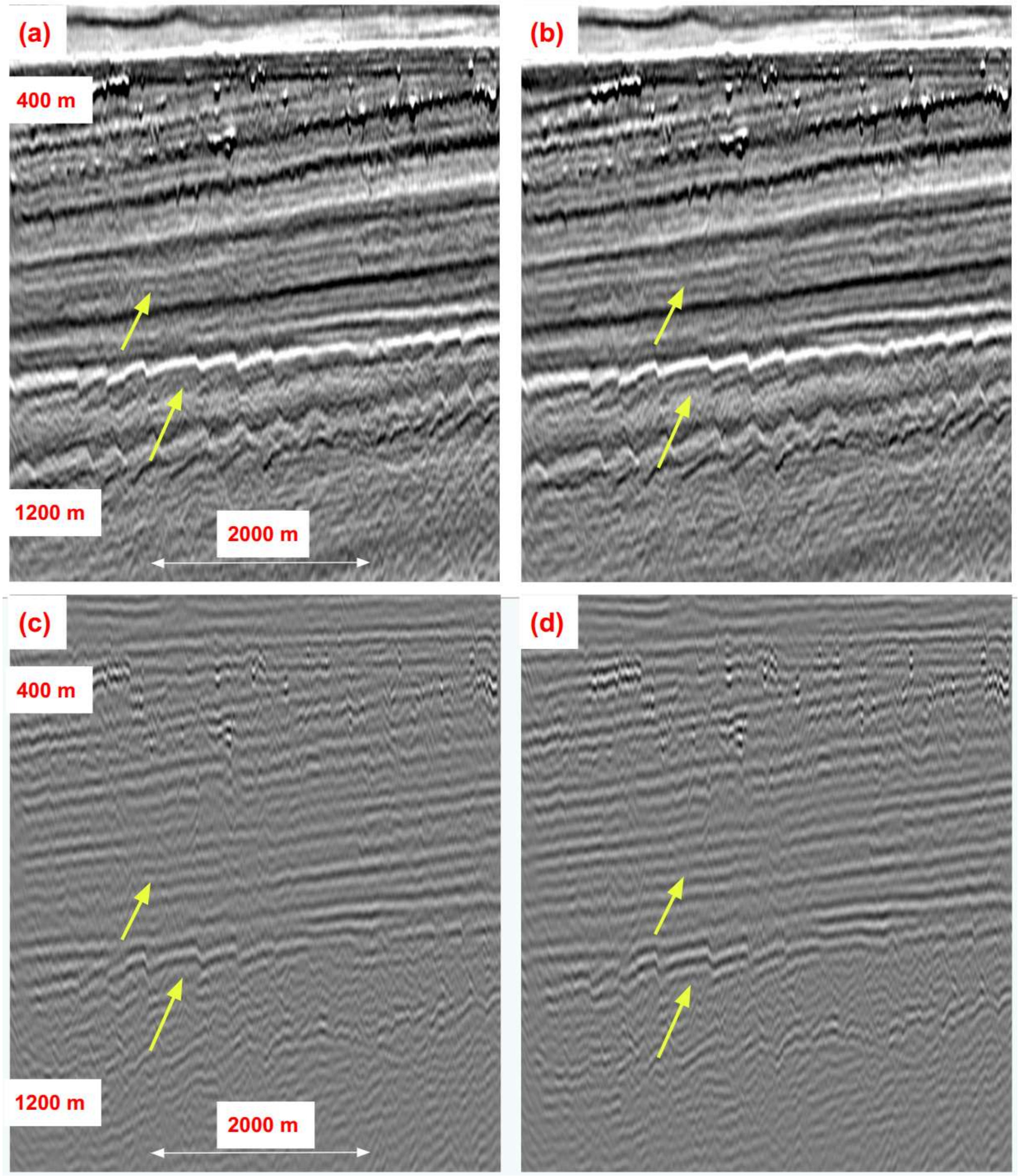

Figure 3 *Sections through the reflectivity image from one-component (a) and two-component (b) MP-FWI imaging at 64 Hz after 11 iterations. Panels (c) and (d) show the same comparison with a 30-45 Hz bandpass filter applied to show the benefit of the two-component inversion within the receiver ghost notch.*

Figure 3 shows a comparison of the reflectivity images from the one- and two-component inversions after 11 iterations. In addition to the spectral differences from Figure 2, the noise level is reduced in the two-component inversion, with reflectors appearing sharper and more continuous. The bandpass-filtered images show that the noise level in the two-component image is noticeably reduced within the receiver ghost notch, as expected given the amplitude spectra shown in Figure 2. The additional information from the geophone data has resulted in an improved subsurface image after the same number of iterations, with better event continuity.

Conclusion

We have shown that a simultaneous inversion of pressure and vertical particle velocity from towed-streamer acquisition can be used to the benefit of MP-FWI imaging. The complementary receiver ghost notches in the amplitude spectra of the two receiver types provides additional information about the wavefield to the inversion. The resulting reflectivity image has a lower noise content than an equivalent one-component inversion. The two-component inversion also converges in fewer iterations. Since the pressure and vertical velocity can be reaped from a single propagation, the reduction in iterations required leads to a superior image with reduced computational resource usage.

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References

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