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Assessing the Value of Low Frequencies in Seismic Inversion

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SUMMARY

We discuss methods to quantify the impact, reliability and value of low frequencies as provided in modern towed streamer broadband acquisitions. Acquisition, processing and inversion all have a role to play in creating reliable low frequency data. In this paper, focusing on marine data, we discuss various aspects of low frequency technology, associated uncertainties and QC methods. We address two key questions: Can broadband deliver the low frequencies? What value do they have? We show that scanning for the crossover frequency at well locations, where the background model is optimally known, is a useful way to visualize the impact, and quantify the value, of the low frequencies. Uncertainties due to unknowns such as wavelet errors at low frequencies and optimal regularization parameters such as sparseness constraints are discussed. Using this method, with a North Sea 3D multi-client data example consisting of a broadband and a conventional towed streamer acquisition, we show that broadband data provides valuable information, compared to conventional data that has been broadband processed.

Introduction

The value of broadband seismic data has long been recognized in the geophysical community and is currently the focus of renewed attention due to the advent of improved acquisition techniques (ten Kroode *et al*., 2013). Acquisition, processing and inversion all have a role to play in creating reliable low frequency data. In this paper, focusing on marine data, we discuss various aspects of low frequency technology, associated uncertainties and QC methods. We address two key questions: Can broadband deliver the low frequencies? What value do they have and how can this be quantified?

Acquisition

The ability to acquire more reliable low frequencies is driven mainly by using on average deeper tow streamers, resulting in improved signal-to-noise in the very low frequency range between perhaps as low as 2 to 3 Hertz. A sometimes forgotten fact is that any shape of streamer, including non-broadband flat streamer tow, results in ghosts that vary as a function of offset and time. This makes offset dependent tuning even more complex than in the case of primaries only. In order to obtain stationary and angle independent wavelets and a reliable AVO estimate, ghost offset (or angle) dependency must be removed. In a conventional processing sequence this is often overlooked and eventually hidden in a time and angle dependent wavelet, whose reliability is questionable. Alternatively, the offset-dependent ghost may become part of a directivity correction: these are designed to align notches across offsets, in effect moving notches around. A more sensible solution is to perform a true deghosting step (Poole, 2013). A key issue in this step is the signal-to-noise at the low frequencies.

Processing & QC

Preserved amplitude processing for the low frequencies is still in its infancy. Visual inspection of the data is standard, on full bandwidth and in frequency bands; but does this allow for fully informed decisions as to the validity and accuracy of the processing? Migrating the data in order to perform comparisons at wells is increasingly used; however, more reliable and sufficiently long well-log measurements are needed for this (Schakel and Mesdag, 2014), and this is often not given.
After migration, the spectra of seismic data can be significantly changed, in particular in areas of steep dip. Post-imaging processes such as spectral analysis and wavelet determination should be performed in the direction normal to the reflector. Khalil *et al*. (2015) show an example where the interpretation of low frequency data is significantly improved using this technique, showing that even visual QC of the low frequency content of seismic data has much room for improvement.

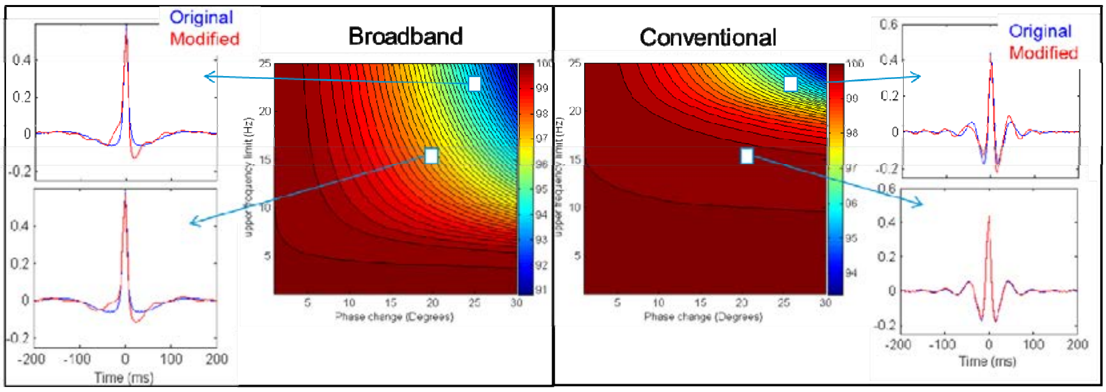

Figure 1 *Sensitivity analysis of a wavelet with respect to phase errors in the low frequencies. The colour maps show the maximum of the correlation x 100.*

Wavelet

Given broadband data, one of the first questions we may ask concerns the quality of well-ties we can expect, given long enough well data (Schakel and Mesdag, 2014), and comparing conventional and broadband seismic. Correlation is generally used to measure the quality of the well-tie. In order to quantify the sensitivity of wavelets with respect to small phase errors, we change the phase of the broadband and conventional wavelets only in the low frequency range. Figure 1 shows the colour map of correlation between a base wavelet, either conventional or broadband, and its phase rotated

equivalent, where the phase error (x-axis) is between 0 Hz and an upper frequency (y-axis). We see that broadband wavelets are more sensitive to small errors in the lower frequencies, and we can exploit this sensitivity to obtain better ties between the wells and seismic.
In an AVO context, elastic inversion requires precise knowledge of the ghost angle dependency of the wavelet. This is often ignored, and angle dependent wavelets are created statistically. Again, the message is: Treat ghosts with true 3D deghosting technology during the processing, so that ghost deconvolution is not part of the inversion.

Inversion

Building accurate subsurface models and quantitative prediction of reservoir properties requires spatially continuous data with bandwidth down to dc (0 Hz). In what follows we assume that the seismic, conventional or broadband, has a crossover frequency ***f****c* below which the seismic cannot provide information and where the background model must fill the gap. In our examples, inversion refers to a two-step procedure: the reflectivity is first estimated by linearized Bayesian inversion with iterative weighted least squares to find the reflectivity; this is followed by a band limited integration of reflectivity and addition of the low-frequency background model. The integration is done in a frequency range between ***f****c* and a high frequency limit. The method to investigate the impact of low frequencies does not rely on the precise nature of the inversion method; however, it does require well log data. Away from the wells we may use other information such as tomographic velocities. We use Gardner's relation to link between the background velocity and impedance. Identifying the crossover frequency ***f****c* is equivalent to finding the informative frequency range of the seismic data. For a given geology, the cross-over frequency depends on: the reliability of the estimated wavelet(s), discussed above; a priori knowledge used in the inversion (e.g. sparseness constraints or other regularizing terms), discussed below; as well as the frequency content of the background model and its associated uncertainties.

A note on sparseness constraints

Regularising terms in an inversion scheme impose prior knowledge onto the solution model parameters; so it is important to understand their impact. Consider the velocity and reflectivity models shown in Figure 2a, chosen to highlight the value of broadband seismic. We perform a single-trace post-stack Bayesian inversion using a conventional and a broadband wavelet and vary the amount of sparseness imposed on the solution. Figures 2b&c show that the broadband data is much less sensitive to the sparseness constraint. In the case of conventional data (Fig. 2c) increasing sparseness improves the resolvability of the reflectivity associated with the sharp velocity contrast, at the cost of deteriorating the reflectivity for the velocity gradient. For the conventional data, the slow velocity change has to come from the background model, whereas the broadband seismic has enough low frequency information to properly estimate this trend.

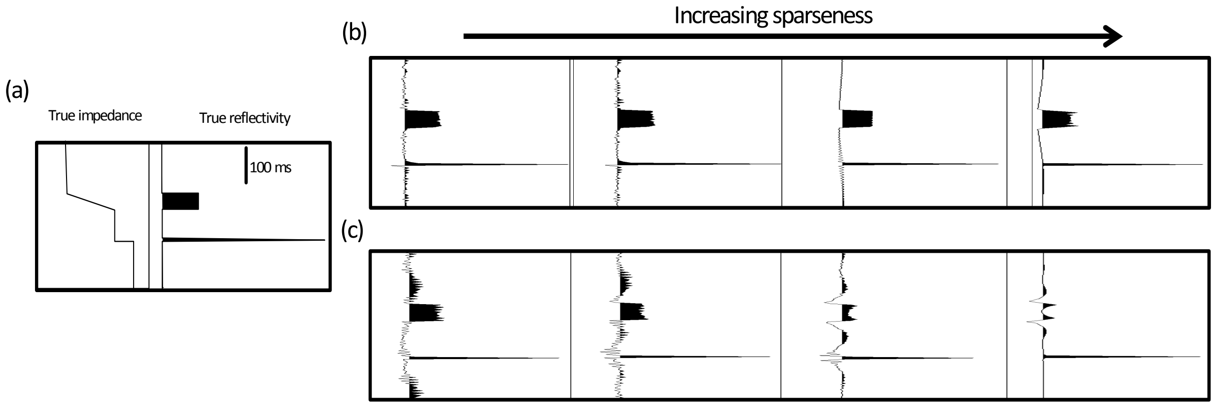

Figure 2 *(a) Velocity and reflectivity models used to create synthetic data. (b) and (c) Estimated reflectivity profiles for broadband and conventional synthetic data, respectively, using different levels of sparseness in the inversion.*

Role of the cross-over frequency

To remove uncertainties in wavelet estimation and processing, we demonstrate the workflow with synthetic noise-free CMP gathers created by convolution of reflectivities from a North Sea well-log and two angle-independent wavelets with different bandwidth (Figure 3a). A smooth version of the well-log serves as the background low-frequency model. Figure 3b shows the relative misfit between the true velocity model and the velocity model obtained from combining the AVO inversion with the background low-frequency model. The broadband synthetic data in blue have lower errors and can recover a much larger portion of the low-frequency content of the subsurface velocity model. The plateau in the misfit value of around 3% is caused by smoothing of the well-log.

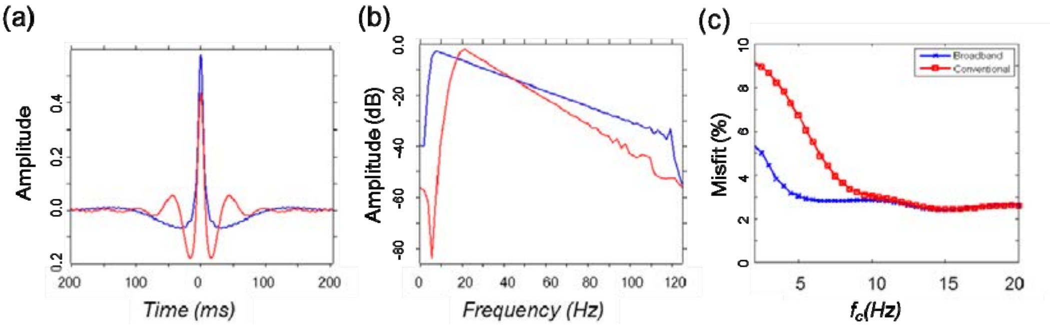

Figure 3 *(a) Broadband (blue) and conventional (red) wavelets used to create synthetic data. (b) Estimated relative misfit between the well-log (P-wave velocity) and inversion results for broadband and conventional data with respect to the crossover frequency.*

Figure 4 illustrates the procedure in more detail, using a single trace at the well location. The trace is inverted for different crossover frequencies, down to 2 Hz, and combined with the background model. Below ***fc*** the seismic does not contribute to the inversion, either for conventional or broadband data. As we rely more and more on the seismic data, by lowering ***fc***, we should see no deterioration in the quality of the inversion so long as the seismic is reliable and provides value in the added frequency range. We see in this example that the broadband data are reliable down to roughly 3 Hz, whereas the conventional data start to struggle at around 8 Hz.

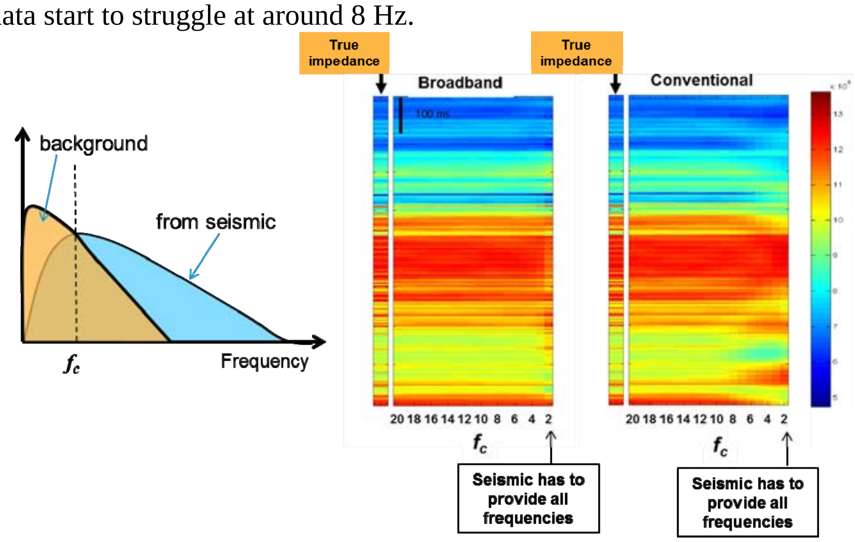

Figure 4 *Broadband and conventional inversion results for P-wave velocity as a function of the crossover frequency* ***fc****. The true P-wave impedance is also shown, on the left of each image. The seismic has to provide the information down to the crossover frequency fc.*

Real data example

We now compare the post-stack inversion of data from two acquisitions, one broadband and one conventional, using multi-client data from the UK North Sea. Both datasets have gone through similar broadband processing and both have been de-ghosted. In both cases, we evaluate how well the deghosting of the conventional data has performed and determine the value of the low frequencies. Figures 5a and 5b show the estimated acoustic impedance along a selected inline, and figures 5c and

5d show map views. Two sonic well-logs converted to impedances are overlaid on the impedance sections. Note that well B is not exactly on the same inline as the section; nevertheless it provides valuable qualitative guidance as to the match with the estimated impedance. The tomography model is used as the low frequency background model and well-logs are not used in the model building. Impedance time slices are shown in figures 5c and 5d. Broadband inversions (Figure a, c) give a better match to the wells and higher resolution than the conventional inversion (Figure b, d). Some effects are subtle to see, due to the fact that both data are broadband processed. In order to verify and quantify the value of the low frequencies, we plot the mismatch between the estimated impedances to well-log A (Fig. 5e) with respect to different cross-over frequencies ***fc*** as described above. Figure 5f shows the spectra of the input and model seismic from the two inversions, as well as the residuals. Figures 5e and 5f show that the added low frequencies from the broadband seismic are modelled in the inversion, and provide information to the determination of the acoustic impedance.

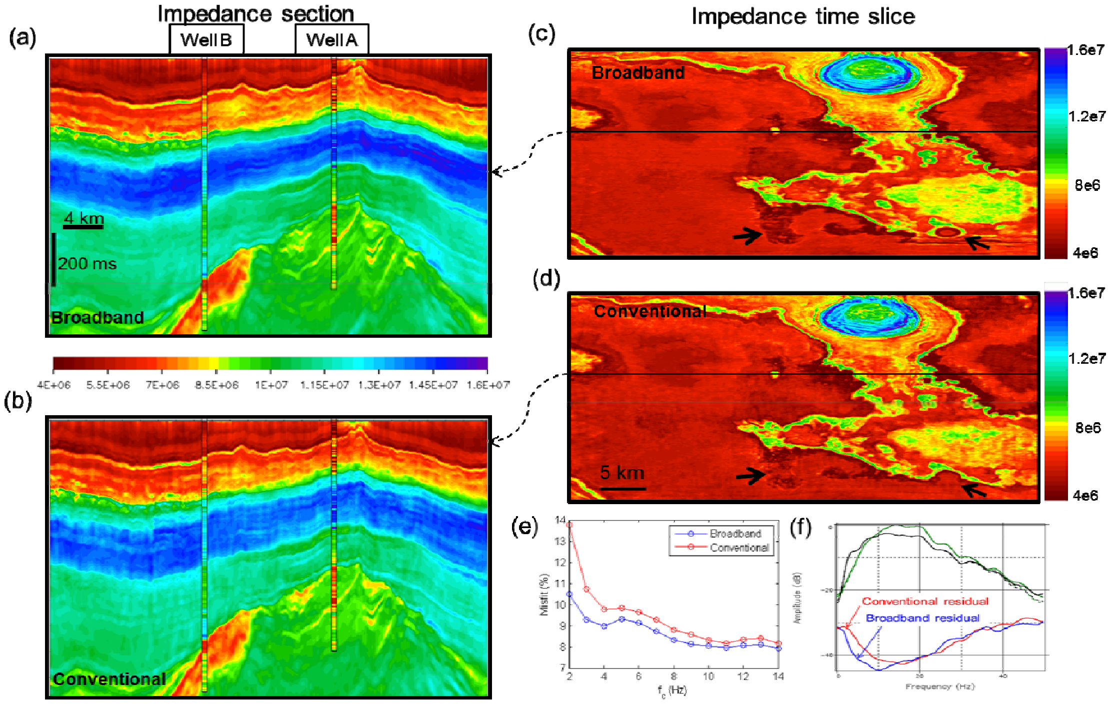

Figure 5 *Estimated acoustic impedance from post-stack inversion of datasets with (a) broadband and (b) conventional acquisitions and along one inline (arrow) as well as one a time-slice (c and d). (e) Misfit between estimated impedances and well-log A for different values of* ***f****c. (f) Spectra of the input and modelled data, as well as the spectra of the residuals. Seismic data courtesy of CGG Multi-Client and New Ventures: BroadSeis Cornerstone 3D.*

Conclusion

Scanning for the crossover frequency at well locations, where the background model is optimally known, is a useful way to visualize the impact of, and quantify the value of the low frequencies. Uncertainties due to unknowns such as wavelet errors at low frequencies and optimal regularization parameters such as sparseness constraints are better addressed with broadband data. Using a North Sea 3D multi-client data example, we showed that data acquired for broadband imaging provides added low frequency information, compared to conventional data that has been broadband processed.

References

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