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Wavelet Estimation for Broadband Seismic Data

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SUMMARY

The volumes of broadband seismic data acquired and processed by the industry have grown rapidly. There is also an increasing emphasis on the benefits of broadband seismic for quantitative interpretation. The bottleneck for achieving a satisfactory quantitative interpretation and subsequently reservoir parameter estimation is the well tie, a process through which the seismic wavelet is estimated. However, broadband seismic data pose a challenge for well ties as the duration of the well log is often inadequate to estimate the low frequency decay towards zero frequency. Three distinctive techniques, namely parametric constant phase, frequency domain least-squares with multi-tapering and Bayesian time domain with broadband priors, are introduced in this paper to provide a robust solution to the wavelet estimation problem for broadband seismic data. A case study from North West Shelf Australia is used to analyse the performance of the proposed techniques. Generally, when the seismic data is carefully processed then the constant phase approach would likely offer a good solution. Broadband priors for the time domain least-squares method are found to perform well in defining low-frequency side-lobes to the wavelet.
Introduction

The volumes of broadband seismic data acquired and processed by the industry have grown rapidly. The spectral content of this new quality seismic is demonstrably superior to conventional seismic, both at the low and high frequency end of the spectrum. Although the broadband technology race started as an acquisition or processing dominated phenomenon, there is also increasing emphasis on benefits for quantitative interpretation (Reiser et al., 2015; Zabihi Naeini, 2014). It is our understanding that the upstream view is to always use broadband seismic unless there is a good reason not to. The motive is clear: by extending the low frequency content, seismic amplitude inversion, which is the building block of quantitative interpretation, depends less on the background model, the construction of which is still a subject of ongoing research (Zabihi Naeini and Hale, 2015). Full waveform inversion is another important application which demands more low frequencies (Baeten et al., 2013).

One could argue that the bottleneck for achieving a satisfactory quantitative interpretation and subsequently reservoir parameter estimation is the well tie, a process through which the seismic wavelet is estimated. The principles of making a well tie are essentially the principles of system identification adapted to the characteristic properties of seismic data and well-log synthetic seismograms. Rather than repeating these principles again, we refer to a tutorial by White and Simm (2003) that covers them in more detail. However, broadband seismic data pose a challenge for well ties as the duration of the well log is often inadequate to estimate the low frequency decay towards zero frequency (White and Zabihi Naeini, 2014). The low frequency decay of the amplitude spectrum is not the only issue; direct estimation of the low frequency phase is almost impossible. White and Zabihi Naeini (2014) proposed a practical solution to this problem which effectively consisted of performing the following steps: 1- estimate the wavelet using the available log length; 2- use multi-taper spectral analysis of the seismic data over a long time window to estimate the low frequency decay and modify the low frequency decay of the estimated wavelet accordingly; 3- modify the low frequency phase from the desired corner frequency to a multiple of 90° at zero hertz according to either the measured decay, or based on the processing and acquisition information, or even trial and error (see White and Zabihi Naeini, 2014 and 2015 for details).

Although the proposed approach above was a good start it did not capture all of the possibilities, and was very much a frequency-domain solution. Like many other applications, well tie technique has to be adapted to the problem at hand and the challenge of broadband seismic data is to find suitable ways around the lack of very long well logs. This implies that there is not necessarily only one way to carry out a well tie and that a variety of approaches has to be tested. In what follows we introduce three different algorithms: parametric constant phase, least-squares in the frequency domain using multi-tapering and least-squares in the time domain using a Bayesian approach. As described later, these techniques have different mathematical foundations but share a common characteristic: a robust solution with a better handle on the low frequency content.

Wavelet Estimation Methods

1- Parametric constant phase

As mentioned above, direct and accurate estimation of the low frequency phase is not possible from the well tie. A pragmatic approach is to use a constant phase approximation over the entire seismic bandwidth. This uses fewer degrees of freedom than estimating a phase spectrum and has some empirical basis in that, after processing, the phase of seismic wavelets is often approximately constant across the seismic bandwidth. When only a short log length is available this approach is especially suitable as, in practice, allowing the phase to vary with frequency could be unreliable. If required, one can modify the phase at the low frequencies towards zero frequency using the approach proposed by White and Zabihi Naeini (2014). In practice the source signature and recording system responses are often zero-phased in processing, thereby removing the main cause of phase variation towards zero frequency.

Our proposed strategy for computing the amplitude spectrum of the wavelet is to use multi-tapering over a long window and averaging over many traces around the well. The combined effect of multi-
tapering, long time window and averaging yields a spectrum with a much finer resolution and good stability giving a better chance of estimating the low-frequency cut-off. The amplitude spectrum is also coloured by the reflectivity spectra which are generally considered to be fairly smooth and have minimal effect at the very low frequencies (see Zabihi Naeini et al., 2016, for details). The phase, lag and scalar are estimated through a least-squares approach using the principles of maximum likelihood theory which also allows one to measure the accuracy of those estimates (Zabihi Naeini et al., 2016).

2- Frequency domain least-squares

Our proposed method here is to use exactly the same machinery and approach as Walden and White (1998) but to modify the auto- and cross-spectra calculation. Whilst traditionally Papoulis tapers are used to taper the auto- and cross-correlation estimates and then Fourier transform, we propose the use of multi-tapering on data segments, Fourier transform and then compute the auto- and cross-spectra. The advantage of using multi-tapers is in reducing the smoothing and leakage bias and has been discussed in more details in White and Zabihi Naeini (2014) and Zabihi Naeini et al. (2016).

3- Time domain Bayesian least-squares

Gunning and Glinsky (2006) introduced a well tie algorithm formulated in the time domain as a Bayesian inverse problem. The algorithm simultaneously estimates all the wavelet coefficients and the Bayesian formulation allows one to incorporate uncertainties associated with the time-depth mapping, positioning errors and other useful parameters. The Bayesian approach provides tools for computation of full posterior uncertainties of the model parameters. Their approach treats the issue of the wavelet length as a model selection problem which may be estimated via Bayesian model selection theory. The length is selected using the Bayesian model evidence, closely connected to the BIC (Bayesian information criterion), and this is very effective at combatting overfitting of noise in the wavelet tails. However, for broadband data, the desired wavelet would potentially require a long wavelet to accommodate the low frequency content efficiently. To overcome the overfitting and wavelet length issue, Zabihi Naeini et al. (2016) proposed priors which are specifically targeted to handle the low frequency character of the wavelet in this algorithm.

Examples

A broadband dataset from the North West Shelf of Australia has been used in this paper. The majority of the area is gently dipping and we used two sub-cubes of data around two wells. The seismic dataset is sampled at 4 ms, has a high signal to noise ratio and also exhibits a very good bandwidth from 3 Hz to approximately 80 Hz as will be seen in the estimated wavelets. In the following we compare the performance of the wavelet estimation techniques introduced in this paper: constant phase, frequency domain least-squares with Papoulis and multi-tapering, and Bayesian time domain least-squares with and without broadband priors.

Figure 1 shows a well tie plot at well 1 including the Vp, Vs, density (Rho) logs, the synthetic seismogram using the estimated constant phase wavelet shown on the right, the recorded seismic at the well and the residual. The well tie is performed using the available log length of 900 ms as shown in Figure 1. The estimated phase, lag and the corresponding errors are also displayed. The amplitude spectrum of the wavelet demonstrates the broad bandwidth of the input seismic dataset. The low-frequency decay, manifested in the long and smooth tails of the wavelet, indicates that our proposed strategy of using a long time window of the seismic combined with multi-tapering works very well.

The correlation coefficient (CC), proportion of the energy predicted by synthetic seismogram (PEP, White and Simm, 2003) and the RMS error of the data-synthetic misfit (RMSE) are also reported in the Figure. As can be observed this wavelet results in a very good quality tie. When there is more than one well, the RMSE can be used in a subsequent impedance cross validation QC, which offers a more stringent test of wavelet accuracy than the well tie diagnostics. In the following, to save space, we show the well tie plots only when required. Where there is no significant difference visually, we only show the estimated wavelets.

Figure 2 shows two wavelets from the frequency domain least-squares method. The wavelet in Figure 2a is from Papoulis tapering; the wavelet in Figure 2b is from multi-tapering. It is evident that the low frequency decay is not captured when Papoulis tapering is used. Multi-tapering indicates a low-cut
decay without estimating it well and at the cost of a slightly noisier spectrum. Also the kink in the phase spectrum around 80 Hz (possibly due to low S/N) does not look realistic. One would ideally like to have a smooth spectrum similar to that of Papoulis but with a better decay. This can be achieved by imposing the low amplitude decay from the multi-taper wavelet on the Papoulis wavelet. Furthermore the kink in the phase spectrum at 80 Hz can be smoothed. The final result is shown in Figure 2c; in which the wavelet now appears to be more realistic. It can be observed that the well tie QC attributes (RMSE, PEP and CC) do not change significantly with such modifications at the low end of the spectrum. This demonstrates the insensitivity of the well tie process to the very low frequency content. Nevertheless, these attributes show a high quality well tie and moreover the outcome is consistent with the constant phase wavelet in Figure 1.

**Figure 1** a) Well tie plot and b) the estimated wavelet at well 1 using a constant phase wavelet. The well tie QC attributes are also shown. Overall this shows a very high quality well tie.

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In the Bayesian time domain method, Gunning and Glinsky (2006) treat the problem of wavelet length as a model-selection problem, and compute the most likely wavelet model amongst N models with different length. Such an approach is generally not suitable for broadband seismic data as it produces a short wavelet which does not carry the expected low frequency content, resulting in a mis-tie. The broadband constraint proposed in Zabih Nacimi et al. (2016) tackles this by imposing strong correlations on the side-lobe wavelet coefficients in a longer wavelet. Figure 3 shows the well tie plot from this method but with a user defined wavelet length and with the broadband constraint applied. The estimated wavelet is much improved compared with the one without the constraint and exhibits a sharp decay at low frequencies. RMSE, PEP and CC are also improved when compared to Figure 3c.
Conclusions

Three wavelet estimation methods for broadband seismic data have been proposed and tested on a case study from the North West Shelf of Australia. All three methods performed well. They also performed well in cross-validation tests (not shown here). A recommended work flow for general use would be to run the constant phase method prior the other two in order to understand the well tie and its potential challenges. Any improvement from the other two methods can then be judged against this.

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References


Figure 3  a) well tie plot, b) estimated wavelet with broadband priors, and c) without priors.