How reliable is statistical wavelet estimation?
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Summary

Well logs are often used for the estimation of seismic wavelets. The phase is obtained by forcing a well-derived synthetic to match the seismic, thus assuming the well log provides ground truth. However, well logs are not always available and can predict different phase corrections at nearby locations. Thus, a wavelet estimation method that can reliably predict phase from the seismic alone is required. We test three statistical wavelet estimation techniques against the deterministic method of seismic-to-well ties. We explore how the choice of method influences the estimated wavelet phase, with the aim of finding a statistical method which consistently predicts a phase in agreement with well logs (figure 1). We question whether well logs are always the optimum source of wavelet phase information and advocate the use of statistical methods as a complementary tool or reliable alternative.

Introduction

Wavelet phase mismatches frequently occur between final processed seismic data and synthetics created from well logs. During processing, deterministic zero-phase wavelet shaping corrections are often favoured over statistical approaches. The remaining phase mismatches are eliminated through additional phase corrections using well logs as ground truth. Thus a phase match between the data and synthetics is forced.

Irrespective of the validity of this phase correction method, well logs are not always available and can predict different phase corrections at nearby locations. Thus, there is a need for a wavelet estimation method that can reliably predict phase from the seismic data, without reliance on well log control. Such a method can be used for phase extrapolation away from wells, serve as a quality control tool, or even act as a standalone wavelet estimation technique.

We test three current statistical wavelet estimation methods against the deterministic method of seismic-to-well ties. Specifically, we explore the extent to which the choice of method influences the estimated wavelet phase, with the aim of finding a statistical method which consistently predicts a phase in agreement with that obtained from well logs (figure 1). We question whether well logs are always the optimum source of wavelet phase information and advocate the use of statistical methods as a complementary tool or reliable alternative.

Figure 1: How reliable is statistical wavelet estimation? We evaluate the level of phase agreement between three current statistical wavelet estimation methods and the deterministic method of seismic-to-well ties.

Methods

All of the statistical methods tested estimate phase using a consequence of the Central Limit Theorem; that convolution of any filter with a white time series (with respect to all statistical orders) renders the amplitude distribution of the output more Gaussian. Thus, the optimum deconvolution filter will ensure that the amplitude distribution of the deconvolved output is maximally non-Gaussian (Donoho, 1981). Hence, the wavelet phase can be found by phase rotating the seismic data until the amplitude distribution becomes maximally non-Gaussian.

The Wiggins (1978) blind deconvolution algorithm made use of this property via measurement of the kurtosis of the amplitude distribution. Kurtosis quantifies the deviation of a distribution from Gaussianity, and can be calculated for a discrete time series, \(x(t)\), using:

\[
\text{kurt}(x) = n \frac{\sum x^4(t)}{\left(\sum x^2(t)\right)^2} - 3 \quad (1)
\]

where \(n\) is the number of time samples and \(t\) is the discrete time. Thus, maximizing the kurtosis reveals the wavelet phase and enables the formation of the previously defined
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The first of these methods we have called Kurtosis Phase Estimation (KPE). This method employs a simplification to the Wiggins algorithm imposed by Levy and Oldenburg (1987), Longbottom et al. (1988) and White (1988) for time-stationary data, who assert that the wavelet phase spectrum in the latter stages of processing is accurately represented by a constant, frequency-independent phase. Thus, KPE searches for a constant phase rotation \( \phi \) which maximizes the kurtosis of the seismic amplitude distribution. The phase rotations are applied to each seismic trace, \( x \), to compute the rotated trace, \( x_{rot} \), via:

\[
x_{rot}(t) = x(t) \cos \phi + H[x(t)] \sin \phi \quad (2)
\]

where \( H[.] \) is the Hilbert transform.

Our implementation includes an initial amplitude-only deconvolution stage using a zero-phase wavelet, whose amplitude spectrum is derived via averaging the amplitude spectra of all traces involved and applying a time domain Hanning taper (Van der Baan, 2008). This raises the likelihood that the wavelet passband is greater than the central frequency, thus meeting the prime condition for using the Wiggins algorithm (White, 1988). Such an implementation results in a more stable phase prediction when using kurtosis as the measure of Gaussianity. Having thus obtained the wavelet amplitude spectrum and constant phase rotation, the optimum Wiener deconvolution filter can be formed and applied to the original seismic data. The result is the desired, maximally non-Gaussian, reflectivity series approximation.

The large reduction in the degrees of freedom resulting from the constant, frequency-independent phase approximation allows the kurtosis maximization method to be extended to handle time-dependent phase variations. Van der Baan (2008) has developed such a method, in which the seismic data is subdivided into overlapping time windows, within each a phase estimate is found using kurtosis maximization. Each phase is assigned to the centre of the time window from which it was estimated and linear interpolation is used to obtain the phase between evaluation points. This is the second statistical method tested and is titled Time-Varying Kurtosis Phase Estimation (TVKPE). Full details of this method can be found in Van der Baan (2008).

The third statistical method tested is Robust Blind Deconvolution (RBD). This method uses a modification to the mutual information rate, proposed by Van der Baan and Pham (2008), whereby the wavelet phase is estimated through maximizing negentropy (a generalized form of kurtosis) while alterations to the output whiteness are constrained to the wavelet passband. Rather than relying on kurtosis to reveal deviation from Gaussianity, the RBD technique makes use of all statistical orders via the negentropy. This technique has two immediate advantages: it does not break down for bandlimited data and it does not require the assumption of a constant wavelet phase. A simplified, but self-contained, derivation of the modified mutual information rate and examples of its use can be found in Van der Baan and Pham (2008).

The seismic-to-well ties were achieved using the commercially available CGG Veritas Hampson-Russell software suite, and guided by the methods of White and Simm (2003). Sonic logs were calibrated using well check-shot data to ensure that the time-depth relationship matched that of the seismic. These were used with the density logs to calculate impedance and reflectivity series for each well site. An initial zero-phase statistical wavelet, with amplitude spectrum calculated from the square root of the amplitude spectrum of the autocorrelation of each trace, was extracted from the seismic. This wavelet was used to construct synthetic seismograms at each well location, as per the convolutional model of the seismic trace. Applying alterations to the wavelet amplitude and phase spectra, such that a maximum correlation is found between the synthetic and seismic traces, allowed a deterministic wavelet to be estimated at each well location. This process, automated by the software, allows either frequency dependent or independent (constant) phase wavelets to be estimated. It implicitly assumes that the well logs provide ground truth and that the wavelet is invariant in both time and space.

Figure 2: Seismic-to-well tie (synthetics blue, tie-locations red). Left: uses frequency-independent (constant) phase wavelet (correlation = 81%). Right: uses frequency-dependent phase wavelet (correlation = 89%).
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Results

We use three datasets from different parts of the North Sea to extract and compare the results of statistical and deterministic wavelet estimation. We enforce that all seismic-to-well ties use a constant phase wavelet since resulting frequency-dependent wavelets were deemed to be unrealistic. All well-ties have correlation coefficients around 70% over a time window at least twice the length of the estimated wavelets.

The resulting wavelets estimated from each dataset can be seen in figures 3, 4 and 5. Each wavelet phase is given in the figure captions. A constant-phase approximation of the RBD wavelet was created to provide a phase for comparison. Correlation coefficients between frequency-dependent RBD wavelets and their constant-phase approximations were always greater than 0.95. This indicates that the wavelet phase in each dataset is well described by the frequency-independent approximation.

The KPE and RBD methods both estimated wavelet phases to within 22° of the deterministic seismic-to-well tie prediction (figures 3, 4 and 5). A 20° phase discrepancy is often difficult to detect visually. For all three datasets the KPE method estimated wavelet phases in close agreement with those of the deterministic method, with the smallest discrepancy just 5°. Cross-correlation tests confirmed the good match between statistical and deterministic wavelets in all cases with a minimum correlation coefficient of 0.77, and an average of 0.91.

Close inspection of figures 3, 4 and 5 reveals that the most noticeable difference between the deterministic and statistical wavelets occurs in the number of sidelobes. The statistical methods lead to much simpler wavelets without the detailed side lobes of the seismic-to-well tie wavelets. We constrained the deterministic wavelets to have constant, frequency-independent phases. Relaxing this constraint produced higher correlation coefficients between the synthetic and seismic trace (figure 2); yet the resulting wavelets had an excessive number of sidelobes and looked unrealistic. This problem, noted by Ziolkowski (1991), may be a consequence of using synthetic to seismic correlation to estimate a wavelet; if the initial correlation is too low, the method may contaminate the resulting wavelet and merely output the filter required to remove the source time function and all remaining undesired components of the earth response. It is thus possible that the sidelobes in the constant phase seismic-to-well tie wavelet are also simply artifacts to beautify the seismic-to-well tie.

Numerous reasons exist why well logs may not represent ground truth – the fundamental assumption in any seismic-to-well ties. However, the close correspondence of all wavelet estimates gives us confidence that both the statistical and deterministic methods have reproduced the true seismic wavelet at the reservoir location.

We examined all three datasets for time-varying wavelet changes. The results of the TVKPE method show wavelets estimated using three time windows (with 67% overlaps). Wavelet 1 (blue) is the shallowest, while wavelet 3 (red) is the deepest. Dataset 2 (figure 4) displayed the largest variations, with a decrease in phase with depth. Only minor variations with two-way traveltime were detected for dataset 1 and 3 (figures 3 and 5 respectively).

Conclusions

Deterministic corrections are commonly applied to rectify phase mismatches between final processed seismic data and synthetics created from well logs. These corrections force the synthetics and seismic to match by assuming the well logs provide ground truth. However, different nearby wells often suggest different phase corrections and well logs are not always available.

Statistical methods can be used to estimate wavelets from the seismic data alone, without the need for well control. Thanks to improvements in data quantity, bandwidth and noise suppression, allied with refining of the statistical techniques, these methods can now robustly estimate a non-physical transfer function. Frequency-dependent statistical wavelet estimation is also viable, leading to realistic looking wavelet estimates, contrary to results often generated by frequency-dependent seismic-to-well ties, which tend to produce a non-physical transfer function.

The statistical methods can therefore be employed as a reliable quality control tool for the deterministic methods, a way of interpolating the wavelet phase between non-matching wells or act as standalone tools in the absence of wells.

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Figure 3: Wavelets estimated from Dataset 1 (clockwise from top left): deterministic seismic-to-well tie ($\phi = 98^\circ$), KPE ($\phi = 84^\circ$), RBD ($\phi \approx 83^\circ$) and TVKPE ($\phi_{avg} = 73^\circ$).

Figure 4: Wavelets estimated from Dataset 2 (clockwise from top left): deterministic seismic-to-well tie ($\phi = 58^\circ$), KPE ($\phi = 36^\circ$), RBD ($\phi \approx 31^\circ$) and TVKPE ($\phi_{avg} = 47^\circ$).

Figure 5: Wavelets estimated from Dataset 3 (clockwise from top left): deterministic seismic-to-well tie ($\phi = -2^\circ$), KPE ($\phi = 3^\circ$), RBD ($\phi \approx 6^\circ$) and TVKPE ($\phi_{avg} = 5$).
EDITED REFERENCES
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REFERENCES