Simultaneous estimation and correction of nonstationary time-shifts and phase rotations

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Summary

Constant phase rotations and constant time shifts are the constant and slope of a polynomial approximation to the seismic wavelet phase. Errors in the estimation of either one cause a bias in the subsequent estimation of the other. It follows that estimations of time-shifts followed by subsequent phase estimates, as is commonly done in well tying, is subject to this bias meaning that alignment errors cause compensating phase errors and a very questionable solution. A strategy is presented to overcome this bias whereby the alignment is estimated though correlation of trace envelopes and it is demonstrate that this is much more accurate. This strategy is then extended to the nonstationary case where, in a series of numerical experiments, it is demonstrated that nonstationary phase rotations and time delays can be reliably measured with good quality data.

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Fundamental motivation

Working from the convolutional model for a seismic trace, a synthetic seismogram intended to be compared with processed seismic data has two basic uncertainties: its starting time and the wavelet phase. The first arises because the log information is not available for the shallow section and the second arises because of shortcomings in the deconvolution process. Assuming that the wavelet phase can be approximated by a constant, then is follows that the crosscorrelation of the synthetic, $u(t)$, with the real trace, $s(t)$, is given (in the frequency domain) by

$$\widehat{c_{us}} = \widehat{c_{w_0w_0}}(f)\widehat{c_{r_0r_0}}(f)e^{i(\theta+2\pi f\Delta t)}$$

where $\widehat{c_{w_0w_0}}(f)$ is the Fourier transform of the wavelet autocorrelation, $\widehat{c_{r_0r_0}}(f)$ is a similar construct for the reflectivity, θ is the wavelet phase, and Δt is the time shift (or delay) of the reflectivity. Since autocorrelations are zero phase this is a statement that the phase of the crosscorrelation is a linear function of frequency whose intercept gives the wavelet phase and whose slope give the reflectivity delay.

Thus both the slope and intercept of the phase of the crosscorrelation function must be measured.

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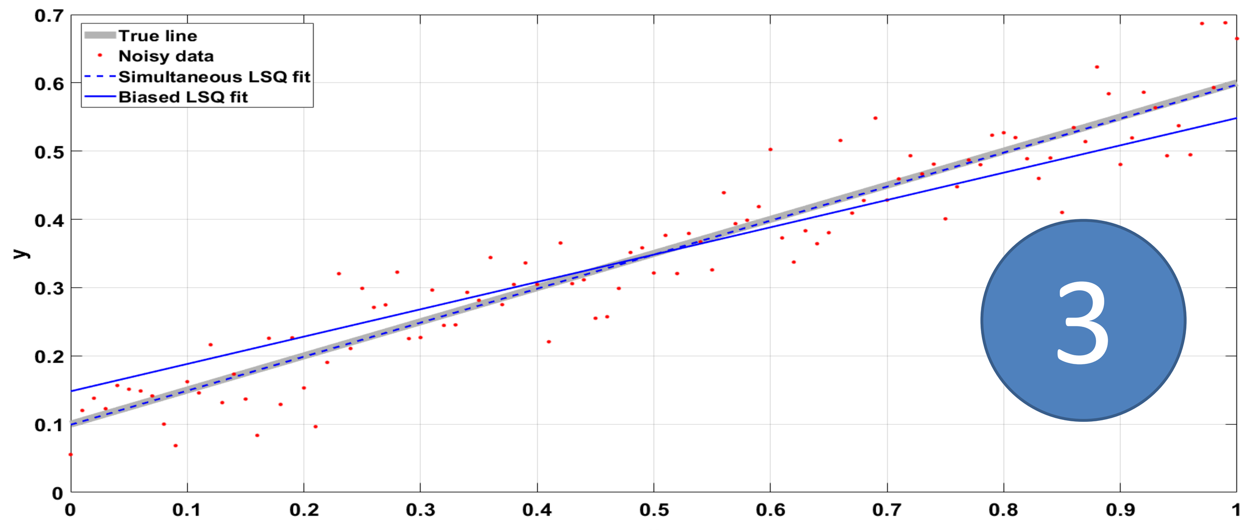
Why phase and delay are correlated: Straight-line fitting, biased or simultaneous



An example of straight-line fitting to noisy data with both a simultaneous and biased solution. The slope and intercept of the true line are 0.5 and 0.1 while the simultaneous least-squares solution estimates 0.498 and 0.099. In the biased case, the slope is constrained to be 0.4 and the resulting least-squares estimate for the intercept is then 0.148.

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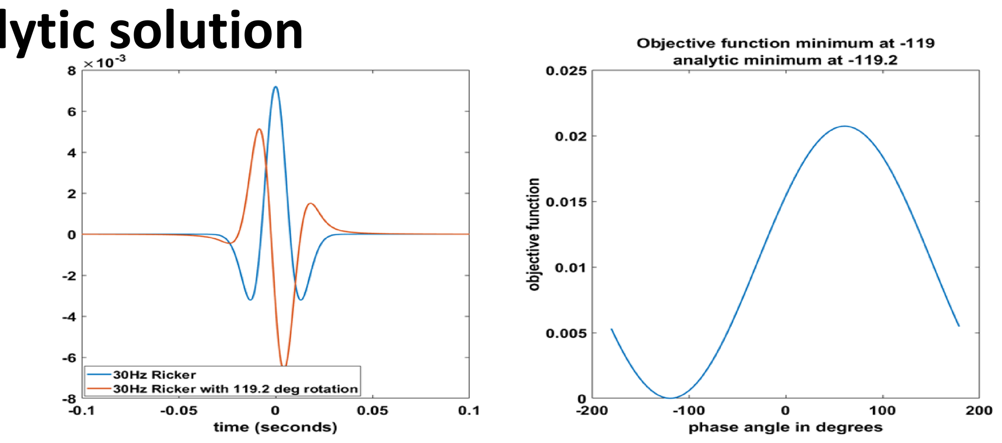
Measurement of Phase: direct search or analytic solution



(Left) A 30 Hz Ricker wavelet and the same wavelet after a phase rotation of 119.2^o. (Right) The curve shows the objective function$\|s(t) - R_\theta u(t)\|^2$as mapped out by direct calculation at all integer phase angles between -180 and 179. The curve has a minimum at 119^o while the analytic solution gets exactly 119.2^o.

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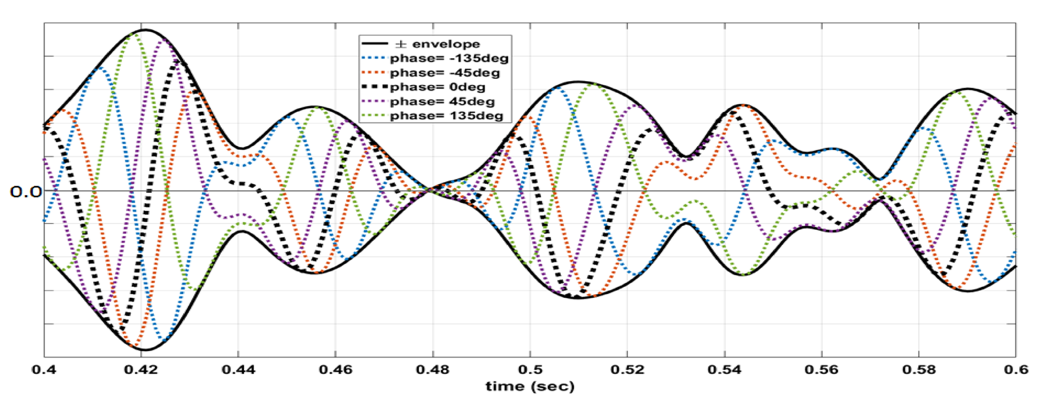
Phase independence of trace envelope



A portion of a seismic trace is shown together with its envelope (positive and negative) and a number of phase rotations. The envelope contains all of the phase rotations.

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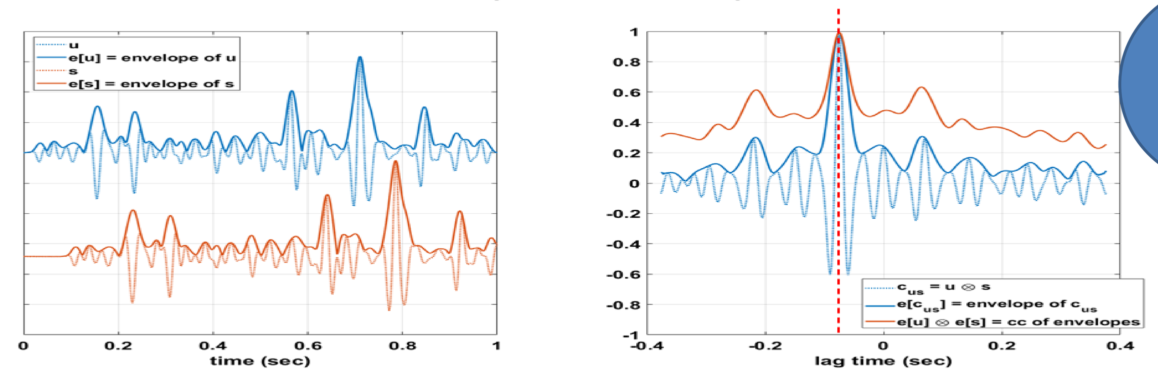
Measurement of delay without phase rotations



At left are the reference trace $u(t)$, the seismic trace $s(t)$, and their envelopes. By construction $s(t)$ is identical to $u(t)$ except for a 0.075 sec time shift. At right are the three possible correlations and all three succeed at detecting the shift because there is no phase rotation. A red dashed line indicates the correct lag.

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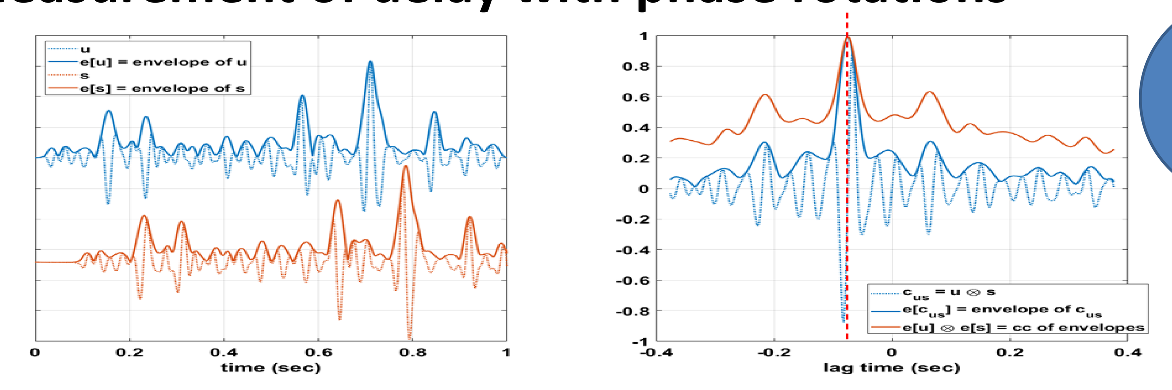
Measurement of delay with phase rotations



Similar to #6 except that the seismic trace $s(t)$ differs from $u(t)$ by both a 0.075 sec time shift and a 90^o phase rotation. On the right, the maximum of the standard correlation $u \otimes s$ fails to pick the correct time shift but the other two correlations do correctly find the shift.

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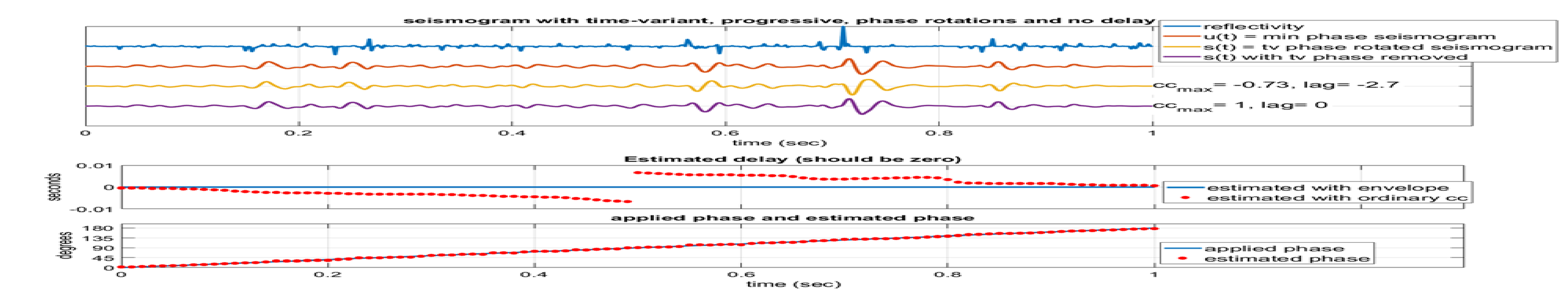
Nonstationary case: phase only



An initial minimum-phase seismogram, $u(t)$, (top panel) is subjected to a time-variant phase rotation where the phase is linearly increasing, and no time-variant delay, to produce trace $s(t)$. Both time–variant delay analysis and time-variant constant phase analysis were conducted. The middle panel shows that only the envelope crosscorrelation gets the correct zero delay. In the bottom panel, the time-variant phase estimates are seen to be very accurate. Crosscorrelation values (top panel) are with respect to $u(t)$.

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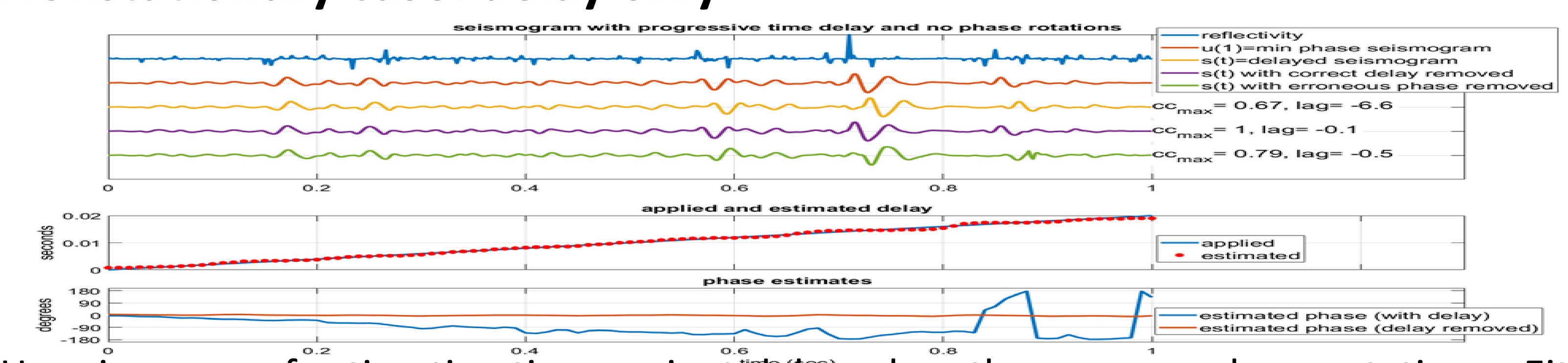
Nonstationary case: delay only



Here is a case of estimating time-variant delay when there are no phase rotations. Either normal or envelope crosscorrelations estimate the delay correctly. Phase estimates are shown as made after delay removal and without delay removal and only the former are correct. Versions of $s(t)$ are shown corrected for the estimated delay (purple) and corrected for the erroneous phase estimated without delay removal. Only the former correlates well with $u(t)$.

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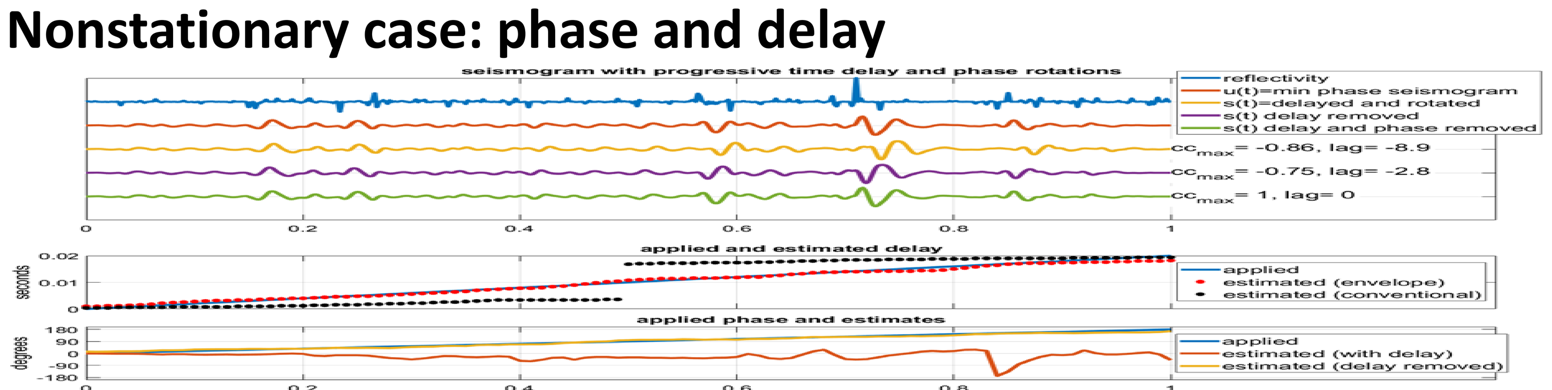
Nonstationary case: phase and delay



In this case, both a time-variant delay and a time-variant phase have been applied to the reference trace. The envelope correlation method has successfully estimate the delay while conventional correlation has not. When this delay is removed, the phase is estimated with good accuracy. When the phase is estimated without first removing the delay, the result is nearly zero.

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Conclusions

Both nonstationary delay and nonstationary phase can be estimated with considerable detail provided that the delay is estimated and removed first with an envelope crosscorrelation. The phase estimate then follows by standard methods.

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