In search of the Vibroseis first arrival

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Summary

The first step in correcting for time delays due to low-velocity weathered layers is to pick the first-arrival times of the refracting energy. But doing so for Vibroseis data can be difficult, as the seismic wavelet is often ringy and uncompact, resulting in cycle-skipped picks. Even when we manage to pick a waveform feature consistently, it's not clear where the first-arrival time is in relation to it. Here I present a novel method that shapes the seismic wavelet to a zero-phase Ricker wavelet, so that picking is easier and more reliable, and the time of the arrival is unambiguous. While it's not possible to do this perfectly, in part due to uncertainty in the amount of Q attenuation, the method still delivers a marked improvement.

Introduction

Correcting for time delays caused by low-velocity near-surface weathered layers is one of the oldest steps in land seismic processing (e.g., Gardner, 1939). The standard approach is this:

- Pick the times of the first arrivals.
- Interpret the depth and velocity of the weathered layers from these picks.
- Apply statics to correct for the weathered layers, in effect turning the near surface into a constant-velocity layer.

Here we are concerned with the first step – picking the first arrival time of each trace. One definition of the first-arrival time is the shortest time it takes for acoustic energy to travel from source to receiver. For impulsive sources, this can be interpreted as the time of the initial onset of source energy on the trace. For correlated Vibroseis data, however, this interpretation is unworkable.

The Vibroseis seismic wavelet is composed of, at a minimum, a convolution of the following:

- Klauder wavelet
- Far-field temporal derivative
- Q attenuation response
- Geophone response

The Klauder wavelet is the autocorrelation of the Vibroseis sweep, and thus is zero phase. We assume we have a reasonable approximation to it, although that is not always the case (Sallas, 1984).

The temporal derivative is a consequence of recording the far-field particle velocity generated from the applied ground force (Aki and Richards, 2002, §4.2.1). It can be closely approximated by a minimum-phase wavelet.

Q attenuation is caused by anelastic propagation and other effects, and tends to be severe in the near surface (Aki and Richards, 2002, §5.5). Its response is minimum phase but the amount of attenuation is typically unknown.

The geophone response depends on the sensor type. The traditional moving-coil velocimeter has the impulse response of a damped spring, with a resonant frequency typically around 10 Hz (Hons et al., 2008). The more recent MEMS accelerometer has, within the sweep frequencies, the response to particle velocity of a temporal derivative. Both responses are minimum phase.

Other effects like recording instrument responses are typically so mild in modern acquisition that they can be ignored. We also assume that the SEG polarity standard for Vibroseis data (Landrum et al., 1994) has been followed.

These components, and the resulting seismic wavelet (the convolution of the components), are displayed in Figure 1.

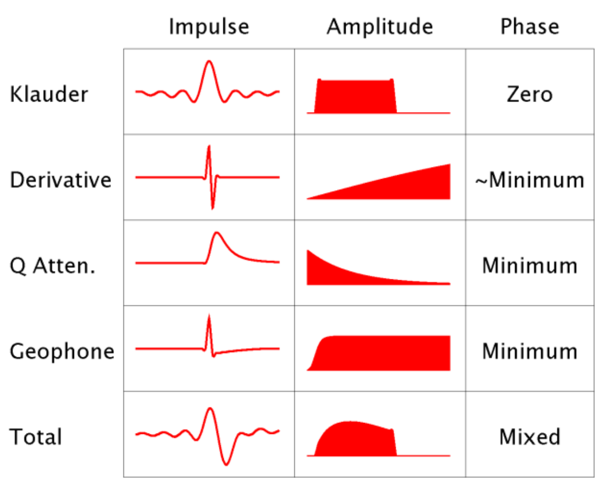

Figure 1: The impulse response, amplitude spectrum, and phase spectrum of various components making up a Vibroseis seismic wavelet. The total response is at the bottom. Note the ringy precursors well before time zero (the center).

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We now see why the Vibroseis first-arrival time cannot be defined as the initial onset of source energy. The seismic wavelet contains the zero-phase Klauder wavelet, whose onset is many seconds before time zero. Instead we might define the first-arrival time as:

> *The time of the initial onset of the source energy if the Klauder wavelet were replaced with a minimum-phase wavelet.*

It's often difficult to pick a consistent feature on Vibroseis data due to ringy precursors which can cause cycle skipping. And even when one can pick a waveform feature consistently, it's not clear where the true first-arrival time is in relation to it.

Motivated by the above definition, the seismic wavelet is often first shaped using an all-pass filter that converts the Klauder wavelet to minimum phase (Ristow and Jurczyk, 1975; Gibson and Larner, 1984). This can help to pick a consistent feature. But the difficulty of creating a causal wavelet out of one whose amplitude spectrum is both sharp edged and band limited means that precursors are not fully removed, so that finding the true onset of energy is still difficult. Below I propose a novel method which avoids these problems by shaping not just the phase but the amplitude spectrum.

Method

Instead of trying to make the seismic wavelet minimum phase, I propose replacing it with a wavelet which is:

- Zero phase
- Compact and simply shaped. Notably it's not ringy.
- Has almost all of its energy contained within the sweep frequency band.
- Has a single strong positive peak at time zero, but no other peaks.

Here I will use a zero-phase Ricker wavelet (Ricker, 1940; Hosken, 1988), whose impulse response is

$$(1 - 2\,r)\; e^{-r} \quad where \quad r = (\pi\, f_p\, t)^2$$

with amplitude spectrum

$$\frac{2\, f^2}{\sqrt{\pi}\, f_p^3}\; e^{-\frac{f^2}{f_p^2}}.$$

A Ricker wavelet and its amplitude spectrum are shown in Figure 2. Note that it has one peak and two troughs. This is critical. If a first-arrival picker is keying on positive peaks, there will be no signal precursors to confuse it, although of course noise might still do so.

The sole parameter for this wavelet is its peak-amplitude frequency f_p. I recommend an f_p value of no more than 40% of the highest sweep frequency to ensure that most of its energy is contained within the sweep frequency band.

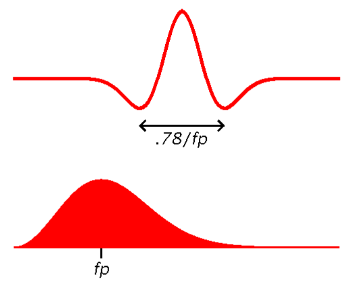

Figure 2: The impulse response (top) and amplitude spectrum (bottom) of a zero-phase Ricker wavelet with peak frequency f_p.

Given the modelled input wavelet (the total response described in the introduction) and desired output wavelet (a zero-phase Ricker), applying the shaping is straightforward: divide the discrete Fourier transform (DFT) of a seismic trace by the DFT of the modelled input, and multiply by the DFT of the desired output. Prewhitening is needed for the DFT of the modeled input to avoid division by zero, but the results are not sensitive to its precise level, as almost all of the energy of the desired output wavelet is within the sweep band.

Once a peak is chosen as the first arrival, there is no need to adjust the pick to the actual onset of energy by moving it to a previous trough, inflection point, or zero crossing – an exercise which is prone to error due to noise. Because the peak is at time zero of the seismic wavelet, it *is* at the first arrival time, and because it's a strong peak, its exact location is not much affected by noise.

But there's a fly in the ointment. All of this assumes we know the amount of Q attenuation that the seismic wavelet has suffered, and normally we don't. There are at least two approaches to overcome this. The first is to assume a fixed, reasonable amount of attenuation for all first arrivals. Although this will rarely be correct for any trace, it works surprisingly well. Because of the simple shape of the attenuation response, the main effect of incorrect Q is to cause a time shift in the position of the wavelet peak (Figure 3). Importantly, peak precursors are not generated. Although this shift is undesirable, it also arises when the seismic wavelet is not shaped, or when the Klauder wavelet is converted to minimum phase (Kobayashi, 2001).

The second approach is to estimate the amount of Q attenuation as it varies in both location and offset, such as in Hatherly (1982). This is a difficult but necessary step for finding the true first-arrival time of Vibroseis data. I did not attempt this in the examples below, but instead kept the estimated attenuation fixed.

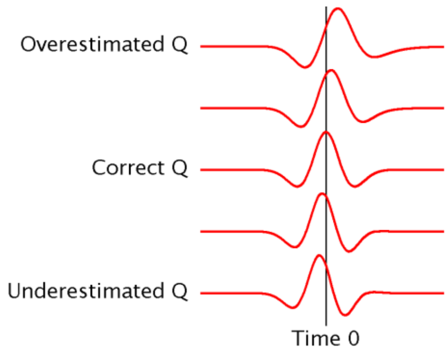

Figure 3: Using the wrong amount of Q attenuation shifts the peak of the output wavelet away from the true arrival time (that is, time 0). The wavelet becomes lopsided, but maintains its simple shape without peak precursors.

Some changes to the automatic picking algorithm are recommended for shaped first arrivals. Specifically:

- Positive peaks should be picked.
- Tests such as Coppens' (1985) energy-ratio test should be centered about $.75/f_p$ seconds *before* each candidate peak.
- Once a peak has been selected as indicating the first arrival, no adjustment should be made to the time.

Examples

Figure 4 shows three data sets: (1) with unfiltered arrivals, (2) with the Klauder wavelet converted to minimum phase, and (3) with the proposed shaping filter. The proposed filter removed almost all ringyness, leaving the first arrivals easier to pick. A close examination shows that these first arrivals look remarkably like our target Ricker wavelet.

To assess the quality of first-arrival picks, we can fit a weathering model to them and from this predict where the first arrival times should be according to the model. We can then examine the differences between the actual and predicted pick times. If the picks are of high quality then the fit should be a good one and these differences should be small.

Figure 5 shows histograms of the differences for the three data sets. Their standard deviations are 1.7, 1.8, and 1.3 ms, respectively. The proposed method has a better fit to its weathering model than the others, suggesting that its picks are more consistent. Further examination reveals that the first two data sets have more cycle skipping, particularly at the far offsets. Surprisingly, converting the Klauder wavelet to minimum-phase had the worst fit of the three.

Final Comments

Shaping the first arrival to a zero-phase Ricker wavelet can improve picking, primarily by removing ringy precursors. But a Ricker wavelet is not the only possible choice, nor are we restricted to zero phase. A constant- or minimum-phase Ricker might offer advantages, so long as its first peak is shifted to time zero.

One of the benefits of this method is that it produces a robust and unambiguous estimate of where the onset of energy would be if the seismic wavelet were minimum phase, even in the presence of noise. But this is only truly accurate if we know the degree of Q attenuation for the first arrival of every trace. Addressing this may be the topic of future work.

We should not expect this method to work in every case. There are too many effects that are not accounted for, such as estimated Klauder wavelets that poorly reflect the true applied ground force (Sallas, 1984), array effects (Vermeer, 1990), geophone ground coupling (Krohn, 1984), and shingling (Cassinis and Borgonovi, 1966). In most cases, however, it is surprising how closely the data matches the modeled seismic wavelet, suggesting that the seismic wavelet is more knowable than is generally thought.

Acknowledgments

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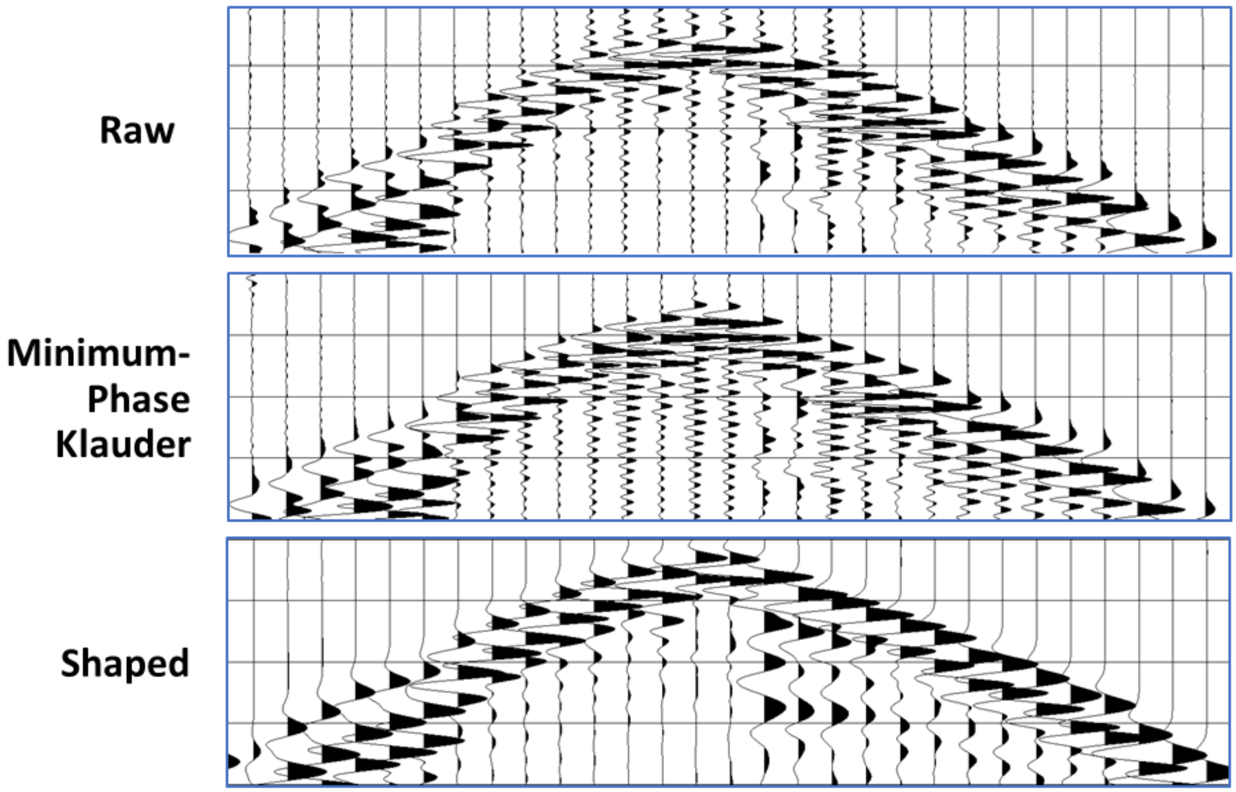

Figure 4: Vibroseis first arrivals having a linear sweep of 8 to 80 Hz, showing the raw data (top), the data with the Klauder wavelet converted to minimum phase (middle), and the data after the proposed shaping (bottom). Despite having a narrower frequency band than the others, the proposed method's simple unringy first arrivals are easier to pick. Data complements of Explor.

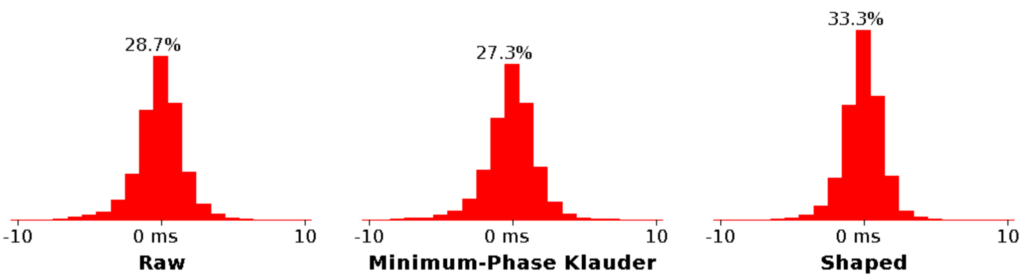

Figure 5: Histograms of the difference between the actual first-arrival pick times and their predicted pick times after fitting a weathering model. The proposed method (right) has a better fit than picking the raw data (left) or the data with the Klauder wavelet converted to minimum phase (center).

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