REVISITING THE VIBROSEIS WAVELET

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INTRODUCTION

The well-established Vibroseis source has been heavily used since its development in the 1950s (Crawford, et. al., 1960). Typically, a swept-frequency signal (or sweep) of length 2 - 10s is injected into the earth. The raw reflection record is complicated and uninterpretable. However, crosscorrelation with the theoretical reference sweep, or with a measured base-plate reference, simplifies the recording. The output is assumed to be the earth response convolved with the autocorrelation of the sweep (referred to as the Klauder wavelet).

Since Vibroseis was first developed a number of variations to the standard linear sweep have been investigated, with the general aim of optimising the character of the correlated Vibroseis wavelet. These include Vari and encoded sweeps (e.g. Edelmann and Werner, 1982), non-linear sweeps (e.g. Goupillaud, 1976), and pseudo-random Vibroseis (Cunningham, 1979). Often, decisions regarding sweep parameters are made in the field, based on unprocessed field records. There has been some research into the effects of phase (Cambios, 2000), and the influence of such processes as deconvolution (Gibson and Larner, 1984). However, this research does not seem to be widely considered in pragmatic Vibroseis sweep evaluation.

Hydrocarbon exploration is now targeting increasingly subtle traps, relying on incremental improvements in seismic technology. At the same time, for reasons of economics, Vibroseis technology is being deployed in new target areas (e.g. Coal Seam Gas (CSG) and coal exploration). For these reasons, it is timely to revisit the fundamental importance of the Vibroseis wavelet in seismic interpretation, and the many factors which control its character.

A primary purpose of this paper is to give an example of how Vibroseis wavelet evaluation can extend beyond a simplistic comparison of sweep autocorrelations to include the influence of earth attenuation, phase distortion and processing. We also comment briefly on the choice of reference signal for correlation.

LINEAR VERSUS EXOTIC SWEEPS

The shape, phase and frequency content of the correlated Vibroseis wavelet are influential in image resolution and interpretation. In turn, wavelet character is affected by more fundamental factors including source parameters, earth attenuation effects and geophone response. These factors may sometimes be difficult to quantify. One of the primary advantages of the Vibroseis source is that we have relatively good control over the source signal, since we can control the Vibroseis sweep. Many different sweep designs have been trialled throughout the history of Vibroseis, as listed above.

To illustrate some of the subtleties associated with Vibroseis sweep selection, we will outline an analysis arising from an intermediate-depth CSG survey in eastern Australia. We will consider the wavelet response for four different sweep designs, which all produce a nominal bandwidth of 10-130 Hz, but whose spectral details are different. Our reference is a standard linear sweep

(10-130 Hz), with sweep length and listen time of 6s and 3s respectively, and cosine tapers of length 0.2s.

The Vari-sweep system (e.g. Edelmann and Werner, 1982) is also receiving some attention in current CSG exploration. Here successive sweeps with slightly differing bandwidths are stacked, the theory being that some sidelobe energy will cancel during the summation process. Here, our Vari sweep has components 10-90, 50-130, and 30-110Hz. The length and taper of each component is the same as for the linear sweep. Figure 1a summarises the frequency versus time plots for these sweeps (green and red curves), and the corresponding frequency spectra are given in Figure 1b.

We have also examined two other, less common, Vibroseis input signals. The sweep design shown in blue on Figure 1a will be referred to as continuous piecewise linear (CPL). This sweep is constructed with a number of linear monotonically increasing sweeps designed such that the frequency spectrum is similar to that of the Vari sweep (Figure 1b), but with a reduced total duration. The CPL sweep examined has a total length of 12s, made up of 5 segments (0-1s, 10-30Hz; 1-3s, 30-50Hz; 3-9s, 50-90Hz; 9-11s, 90-110Hz; 11-12s, 110-130Hz).

Finally we have also examined a 65Hz pseudo-random signal (Cunningham, 1979; Strong, 2003; Strong and Hearn, 2004) of length 7.9s. In our example, this consists of 511 cycles of a 65Hz carrier signal having polarity reversals according to a pseudo-random code. The reversals effectively broaden the bandwidth on either side of the carrier frequency (Figure 1b, magenta).

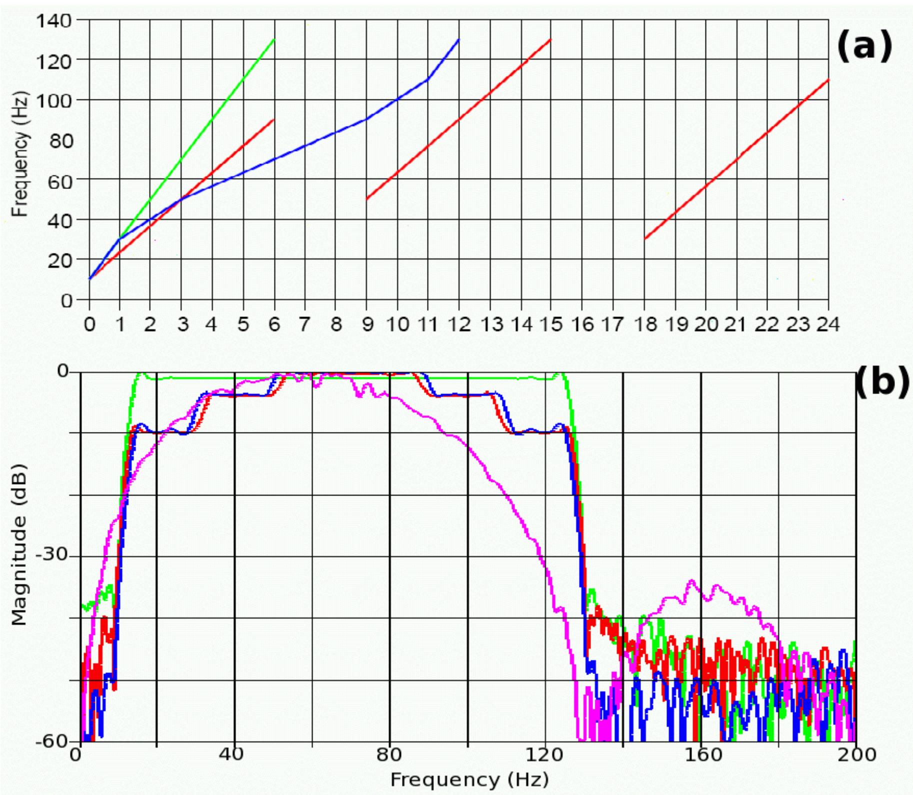

Figure 1: (a) Frequency versus time, and (b) Magnitude versus frequency, for the tested Vibroseis sweeps: Linear sweep (green), Vari sweep (red), CPL sweep (blue), Pseudo-random (magenta).

ZERO-PHASE AUTOCORRELATION WAVELETS

A simplistic, but common, approach to comparing Vibroseis sweeps is to consider the shapes of the theoretical sweep autocorrelations. From an interpretation point of view, a desirable autocorrelation wavelet would intuitively be as close to a spike as possible. In practical terms, we seek an autocorrelation wavelet that has a sharp central peak with minimal "ringy" sidelobes.

Figure 2a shows a comparison between the autocorrelation responses of our four test sweeps. The autocorrelation of the linear sweep is ringier than the others, with the sidelobe oscillations related to the high-frequency limit of the sweep. The autocorrelation for the Vari sweep has achieved the desired cancellation of some sidelobe energy. The CPL sweep gives an almost equivalent result to the Vari sweep, consistent with its design criterion. As indicated in Figure 1a (assuming the sweep is followed by 3s of listen time), this has been achieved with 15s acquisition time, compared with 27s for the Vari sweep. The pseudo-random system yields the simplest wavelet, with minimal energy beyond the first side lobe. However it exhibits a slightly wider central peak. Based on this simplistic analysis, the CPL sweep would arguably give the preferred zero-phase seismic image for the least field effort.

THE EFFECT OF EARTH ATTENUATION

In reality, the higher frequencies of the seismic signal are attenuated as they pass through the earth, and this effect should also be considered when comparing Vibroseis sweeps. Figures 2b and 2c show the autocorrelation wavelets when earth attenuation is incorporated in the modelling (e.g. Strong and Hearn, 2007), for depths appropriate to coal and petroleum targets respectively. At the coal scale (Figure 2b) we see that the linear sweep is again ringier than the other three signals. In the higher-attenuation petroleum situation (Figure 2b), the high frequency sidelobe energy is essentially filtered out by the earth. Overall, the Vari and CPL sweeps are arguably more stable and slightly more compressed than the linear and pseudo-random options. Again the CPL sweep would be preferred for field economics.

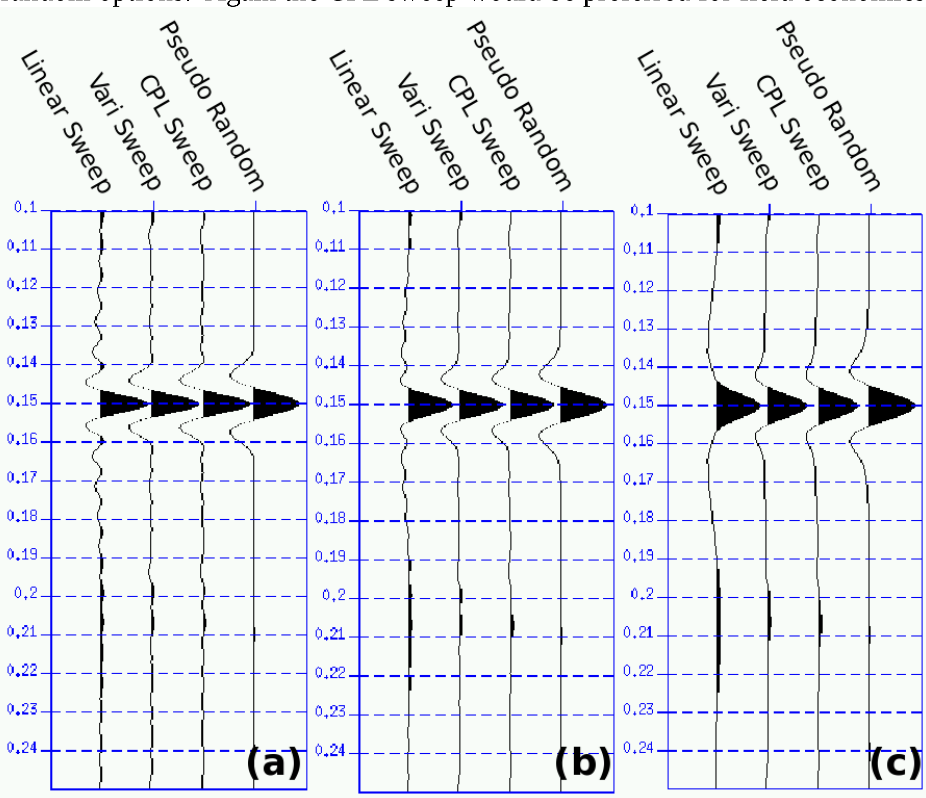

Figure 2: Autocorrelation of test Vibroseis signals (Linear sweep, Vari sweep, CPL sweep, Pseudo-random signal) for the case of (a) no attenuation; (b) attenuation for a coal target at 400m (Vav=3000 m/s, Qav=90); and (c) attenuation for a petroleum target at 1200m

(Vav=3000 m/s, Qav=100). Here, and in the following figures, the nominal event time is 0.15s.

MINIMUM PHASE AND DECONVOLVED WAVELETS

There are a number of complex issues associated with the deconvolution of Vibroseis data (e.g. Gibson and Larner, 1984; Ulrych and Matsuoka, 1991). We will comment further on phase issues below. It is often standard practice in processing centres to convert Vibroseis data to minimum phase and then apply an appropriate deconvolution algorithm. This can produce large changes in the character of the seismic wavelet, and in resultant interpretations. When Vibroseis sweeps are evaluated in the field, the effect of this processing is rarely considered. To demonstrate the degree to which standard processing can change the Vibroseis wavelet, we have converted the wavelets in Figure 2 to minimum phase using the Hilbert Transform approach (Figure 3). We have then applied gapped predictive deconvolution (autocorrelation second-zero crossing) to those results (Figure 4).

In Figure 3 we again see that the minimum-phase Vari, CPL and pseudo-random wavelets are very similar, with the linear sweep again being ringier. Note however, that the linear sweep tends to have more energy towards the start of the pulse (in the first trough and peak), especially for the unattenuated and low attenuation (coal) examples.

Since the linear sweep wavelet is more front-loaded after minimum phase conversion, the predictive deconvolution operator would be expected to perform better. In spectral terms, this is due to the linear sweep having a more balanced frequency spectrum (Figure 1b). Figure 4 indicates that for the unattenuated cases, the Linear sweep yields a slightly simpler deconvolved wavelet than the other tested sweeps. This advantage is less obvious when earth attenuation is included.

This example illustrates that the deconvolution process needs to be considered in the evaluation of Vibroseis sweeps. In this example, the deconvolution analysis might prompt the use of the standard linear sweep, in preference to the more exotic options.

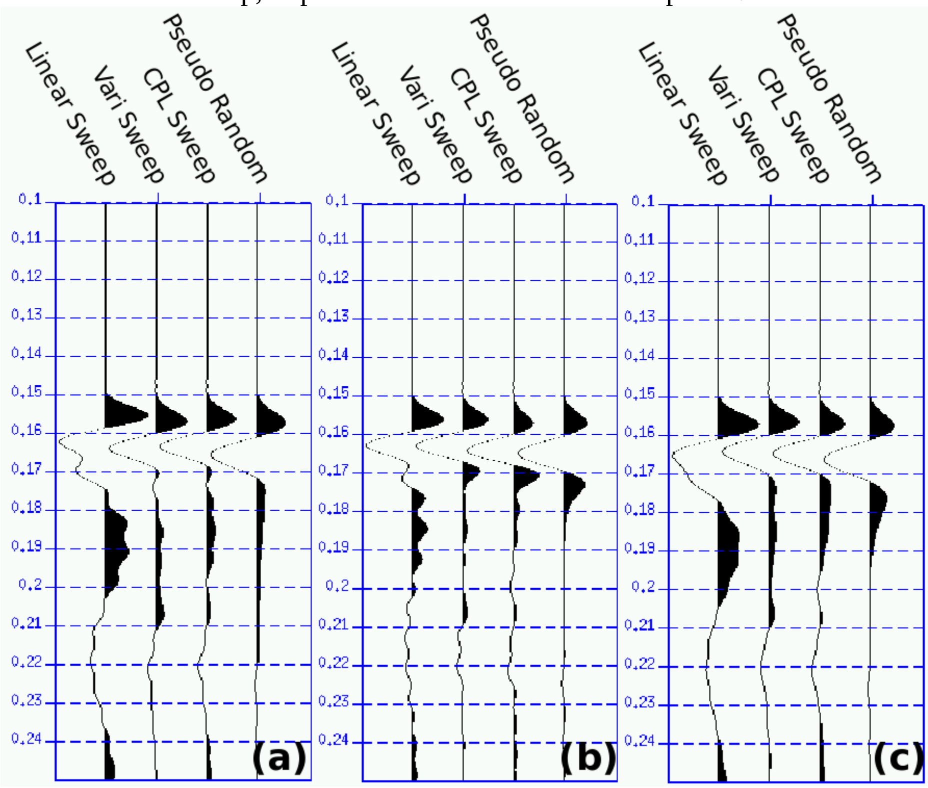

Figure 3: Minimum phase conversion of test Vibroseis wavelets in Figure 2. (a) no attenuation; (b) attenuation for a coal seam at 400m (Vav=3000 m/s, Qav=90); and (c) attenuation for a

petroleum target at 1200m (Vav=3000 m/s, Qav=100).

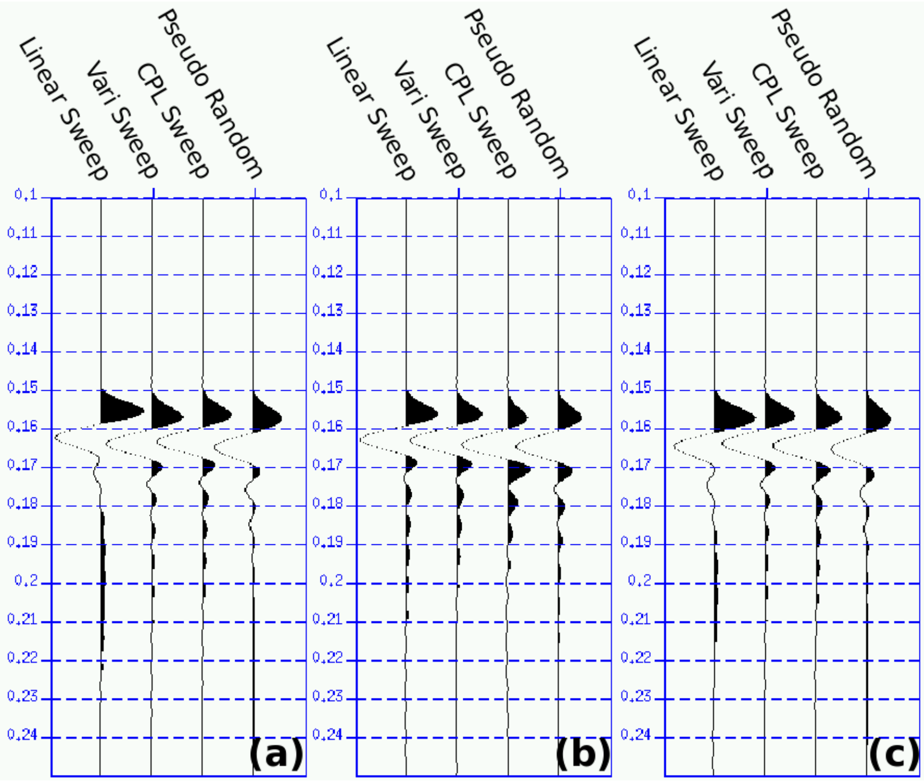

Figure 4: Predictive deconvolution of test Vibroseis wavelets in Figure 3. (a) no attenuation; (b) attenuation for a coal seam at 400m (Vav=3000 m/s, Qav=90); and (c) attenuation for a petroleum target at 1200m (Vav=3000 m/s, Qav=100).

THE COMPLEXITIES OF PHASE

As illustrated above there are a number of issues that affect the shape of the correlated Vibroseis wavelet. One of the more complex issues relates to the phase of the recorded signal. In a perfect world the reference sweep and the recorded signal would have the same phase. This is often assumed to be true in seismic processing (and in the examples given above). However, there are factors that can change the phase of the recorded signal. These include near-surface phase-rotation effects, correlation of acceleration reference signals with velocity recordings, and phase verse offset effects (especially important for converted wave surveys). It has been shown that for real data the phase of the correlated wavelet may not be zero and can be mixed (Gibson and Larner, 1984) or, for long offset data, can be approximately minimum phase (Dong et al., 2004).

To investigate the affect that phase shift can have on the choice of the Vibroseis sweep we have considered the extreme case where the recorded signal is 90 degrees out of phase from the reference sweep. This would be the situation for a pure geophone recording (particle-motion velocity) being correlated against a theoretical reference (generally indicating particle-motion acceleration at the source). Figure 5 displays the crosscorrelation results for this scenario. Notice that the correlation wavelets are now anti-symmetric, centred on the nominal event time. As before we see that the Vari and CPL sweeps give the sharpest response while the pseudo-random wavelet is the simplest.

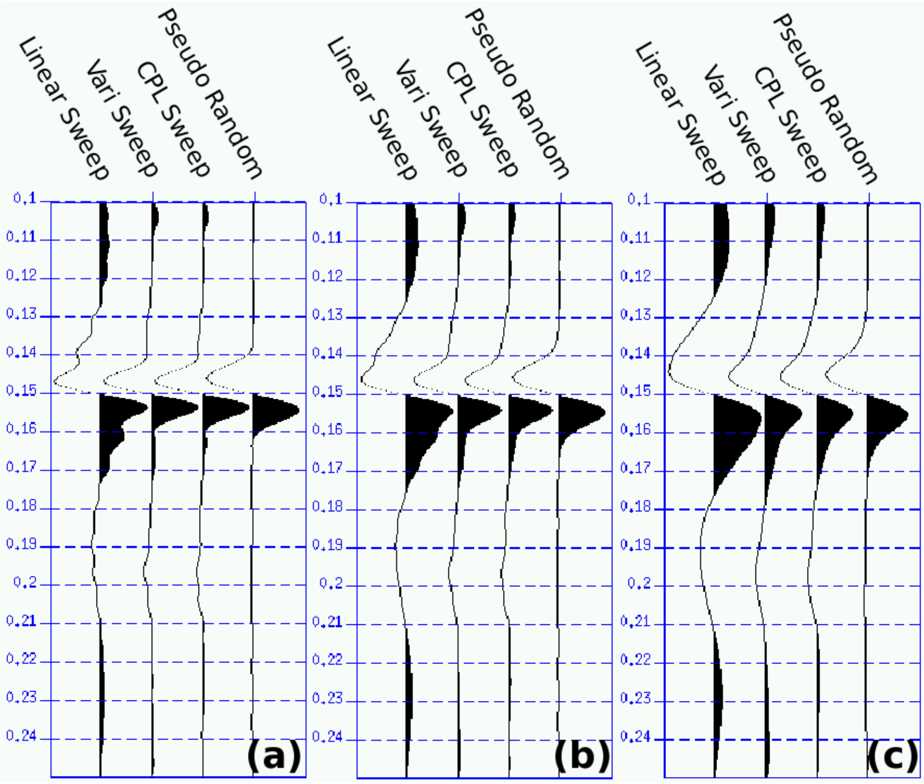

Figure 5: Crosscorrelation of test Vibroseis signals (Linear sweep, Vari sweep, CPL sweep, Pseudo-random signal), with 90 degree phase shift between recoding and reference, for the case of (a) no attenuation; (b) attenuation for a coal seam at 400m (Vav=3000 m/s, Qav=90); and (c) attenuation for a petroleum target at 1200m (Vav=3000 m/s, Qav=100).

In Figure 6 the wavelets from Figure 5 have been converted to minimum phase and deconvolution has been applied as before. Once again we see that there has been a significant improvement in the shape of the linear sweep wavelet. There is also very little difference between the wavelets for the different sweeps. It is also interesting to note that although the wavelets in Figures 2 and 5 are very different, after deconvolution the differences are much less striking (Figures 4 and 6). This suggests that minimum phase conversion and deconvolution may accommodate some of the complexities associated with correlating signals which have different phase.

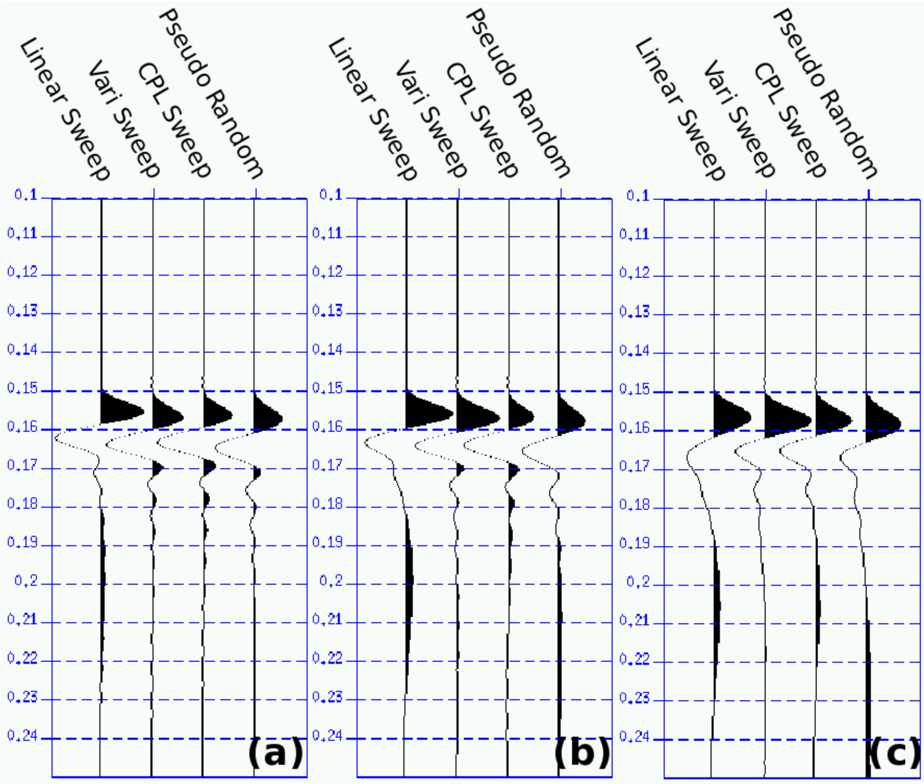

Figure 6: Vibroseis wavelets from Figure 5 following minimum-phase conversion and predictive deconvolution for the case of (a) no attenuation; (b) attenuation for a coal seam at 400m (Vav = 3000 m/s, Qav=90); and (c) attenuation for a petroleum target at 1200m (Vav = 3000 m/s, Qav=100).

CHOICE OF CORRELATION REFERENCE

Vibroseis recordings are typically correlated against the theoretical sweep, even though this is not what is actually injected into the ground, and certainly not what arrives at the geophone. Intuitively, an alternative reference sweep might incorporate mechanical imperfections at the source, and the filtering effects in the earth and at the geophone. Numerical tests show, however, that the standard approach is reasonable.

To illustrate this point, Figure 7 shows a linear reference sweep and a modified sweep that includes some simple attenuation, proportional to frequency. The latter is meant to more meaningfully represent the sweep actually being recorded. In Figure 8 we compare the autocorrelation of the attenuated sweep with a crosscorrelation of the attenuated and reference sweep, for the zero phase and deconvolved cases. In both instances we see that the crosscorrelation has a sharper response with higher amplitude. This suggests that the crosscorrelation of the recorded signal with a theoretical sweep would have better resolution confirming that the optimum output wavelet is indeed obtained when the theoretical sweep is used as the reference for correlation.

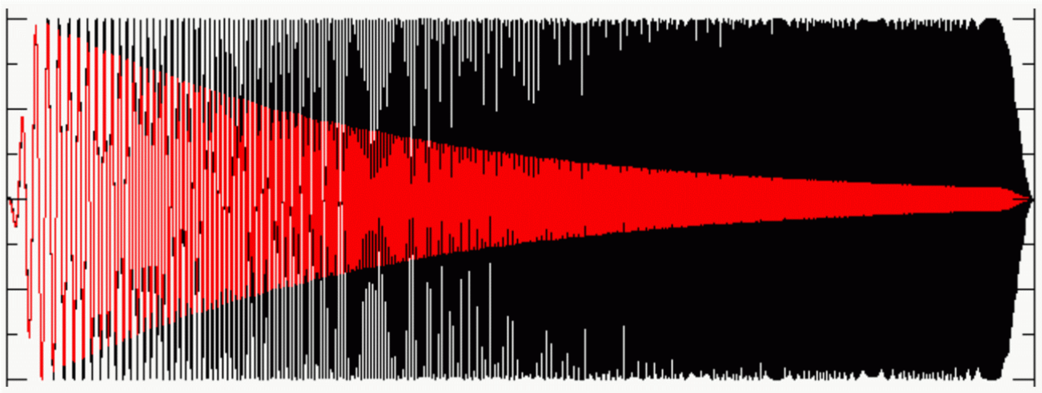

Figure 7: Linear Vibroseis sweeps: no attenuation (black); attenuated (red)

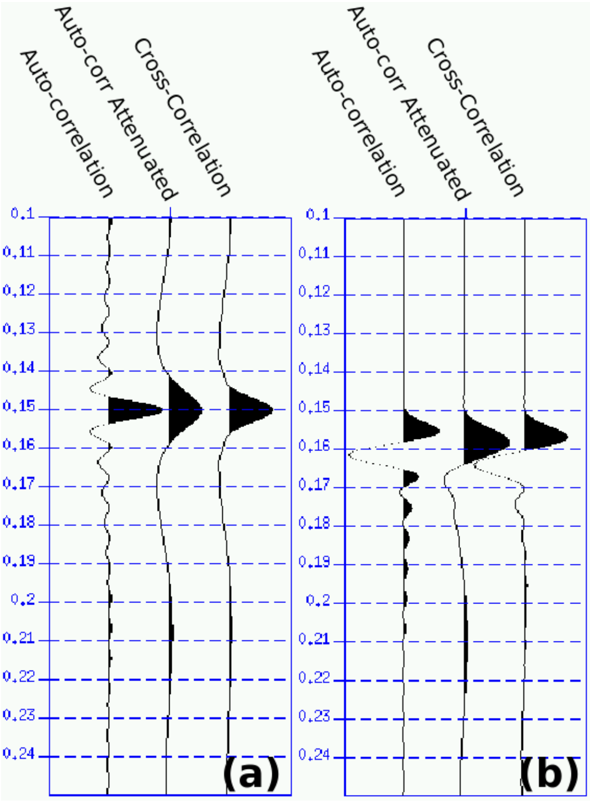

Figure 8: Comparison of correlation response for different reference sweeps. (a) Zero phase wavelets and (b) wavelets after minimum-phase conversion and gapped deconvolution. In each case the three traces are: autocorrelation of theoretical reference, autocorrelation of attenuated sweep, crosscorrelation of attenuated sweep and theoretical reference.

CONCLUSION

Comparisons between different Vibroseis sweeps are often carried out in the field, based on unprocessed shot records. This may not necessarily lead to valid decisions regarding the choice of sweep. In our example, a simplistic zero-phase autocorrelation analysis suggests that the more exotic Vari and CPL sweeps can produce sharper wavelets with a reduced number of sidelobes. However, once standard processing techniques such as minimum phase conversion and deconvolution are included, differences are much less obvious. Dorling et al. (2009) includes a field example of this conclusion.

The potential influence of phase shifts has been illustrated with the extreme case of a geophone recording correlated against an accelerometer reference. Correlation of out-of-phase signals can lead to major changes in the shape of the expected zero-phase wavelet. However, once minimum phase conversion and deconvolution are applied then the phase distortions may be significantly removed. Finally, we have demonstrated that the common approach of correlating against a theoretical reference is valid.

Overall these examples suggest that deconvolved Vibroseis images are remarkably robust with respect to the fine detail of sweep design, phase effects and choice of correlation reference. The analysis helps to explain why the Vibroseis technique achieves consistent practical success in the face of a range of daunting theoretical assumptions.

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