

Vibroseis deconvolution: a synthetic comparison of cross correlation and frequency domain sweep deconvolution

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ABSTRACT

Vibroseis data is extremely useful in exploration seismology as it provides a method for controlling the frequency range of seismic data. The trace recorded from a vibroseis source will not contain the minimum phase wavelet associated with a dynamite source; rather the sweep will be embedded in the data. The removal of the embedded sweep is traditionally completed by cross correlation of the recorded trace with the generated sweep, converting the sweep to a Klauder wavelet. Tested with synthetic data is the method of frequency domain sweep deconvolution, where the trace is divided by the sweep in the frequency domain. The results of the synthetic tests are compared to determine the future potential of frequency domain sweep deconvolution.

INTRODUCTION

The vibroseis source is widely used in seismic acquisition, as it is a non-destructive method with a controllable frequency range. The higher the preserved frequencies from the vibroseis source, the better the resolution of the thin beds associated with heavy oil reservoirs and reservoir geophysics. In vibroseis data, the recorded trace has an embedded sweep. It is necessary to remove the sweep from the trace to resolve the reflectivities of the beds. This is traditionally completed with the use of cross correlation, where the sweep is cross-correlated with the trace creating an embedded Klauder wavelet. Sheriff (1990) defines the Klauder wavelet as the auto-correlation of a linear vibroseis sweep. This definition includes non-linear sweeps as they can be characterized by numerous linear sweeps.

This paper examines the potential of utilizing frequency domain division to remove the sweep from the recorded trace. Several models are examined in this study to determine the advantages and disadvantages of this method. The sweep shape, earth filtering and the effects of noise are examined to attempt to predict the success of this technique when applied to real data.

CROSS CORRELATION

Cross correlation is the industry standard for removal of an embedded sweep. Vibroseis deconvolution utilizes the concept that the autocorrelation of a sweep is equal to a Klauder wavelet. The autocorrelation is a measure of the similarity of a waveform with a time-shifted version of itself, with the maximum occurring at zero-lag. After cross correlation, the trace will only contain information that is common to both waveforms, therefore the method acts as a filter for unwanted frequencies. A required filter can be implemented by designing a specific sweep. The results of cross correlation are extremely sensitive to changes in the sweep. Problems that

occur in association with the sweep can partially be attributed to attenuation and improper vibration (Ristow and Jurczyk, 1975).

The basic seismic convolutional model for a vibroseis source is

$$x(t) = r(t) * s(t) \quad (1)$$

where $x(t)$ is the recorded trace, $r(t)$ is the geological reflectivity, $s(t)$ is the sweep and $*$ is the convolution operator. To remove the sweep, the trace is cross correlated (\otimes) with the sweep. The equation for the deconvolved sweep is

$$x_{CC}(t) = r(t) * s(t) \otimes \bar{s}(t) \quad (2)$$

where $\bar{s}(t)$ is the sweep input into the ground. This equation can be simplified to

$$x_{CC}(t) = r(t) * k(t) \quad (3)$$

since the cross correlation of two identical sweeps is defined as a Klauder wavelet, $k(t)$. Cross correlation collapses the sweep to a Klauder wavelet at impedance contrasts and filters the data with the sweep parameters. The filtering of the data may be a problem if the sweep was improperly designed or if there were errors during acquisition.

FREQUENCY DOMAIN SWEEP DECONVOLUTION

Frequency domain sweep deconvolution is based on the same convolutional model as cross correlation, however it uses the frequency domain to simplify the equation to

$$X(f) = R(f)S(f) \quad (4)$$

The conversion into the frequency domain allows the processor to remove the sweep through division. There are several advantages to this method. In the noise free case where the entire spectrum is covered by the sweep and a perfect answer for the reflectivity can be obtained. Another advantage of this method is that the spectrum is whitened with no residual effects of the sweep remaining. In cross correlation the sweep shape creates a filter whose spectrum is equal to the square of the sweep's spectrum. The complete removal of the sweep for the swept frequencies is important as additional resolution may be obtained in the taper zone of the sweep. This would create the opportunity during field acquisition for increased tapers times to achieve maximum amplitudes as well as including the use of non-linear sweeps with no permanent effects on the seismic.

There are several steps required for the removal of the sweep. If the sweep and trace are of different lengths they should be padded with zero values. Following this a Fourier transform is completed for both the trace and sweep. The trace is then divided by the sweep in the frequency domain to return the trace with no embedded

sweep. Finally an inverse Fourier transform is completed on the new trace to calculate the time domain deconvolved trace.

EFFECT OF SWEEP DESIGN

When the vibroseis technique was first implemented a linear sweep was the signal of choice. A sweep is an oscillating signal with a time variant amplitude and a frequency that varies monotonically with time (Goupillaud, 1976). A linear sweep is one that has an instantaneous frequency that is a linear function of time, where the auto-correlation is the Klauder wavelet. The sweep has tapered ends designed to control the background levels of the sweep auto-correlation and the side lobe reverberations (Goupillaud, 1975).

Non-linear sweeps do not have a frequency that is a linear function of time. When change in the frequency is slowest there will be depressed amplitudes. When a non-linear sweep is used, a different wavelet will be generated by the auto-correlation of the sweep. Four different sweeps (Figure 1) were used to examine the effect of the sweep shape on the results of cross correlation and frequency domain deconvolution. For cross correlation the corresponding Klauder wavelet marks each impedance boundary (Figure 2). For frequency domain deconvolution, since these are synthetic examples, the trace contained data for the entire spectrum giving an exact answer for the reflectivity. The results of the frequency domain sweep deconvolution were filtered to remove any frequencies not part of the sweep. The results of this method are independent of the sweep shape (Figure 3).

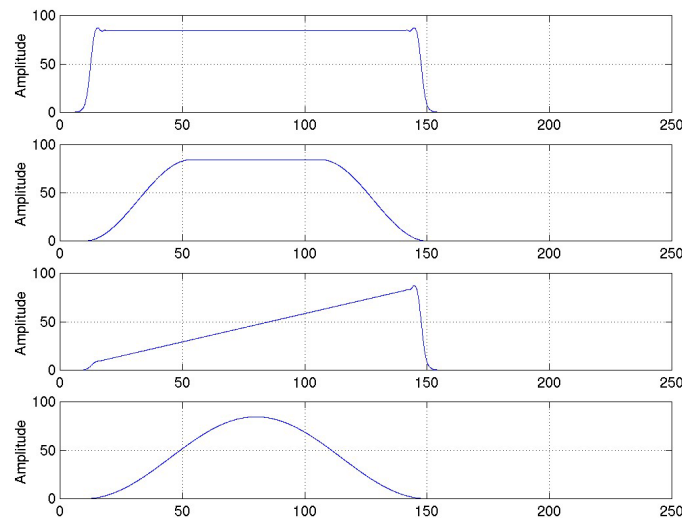


Figure 1. Sweeps designed for synthetic modelling. From top, linear sweep with 0.5s tapers, linear sweep with 5s tapers, non-linear sweep with 0.5s tapers and Gaussian sweep. Horizontal axis is frequency (Hz).

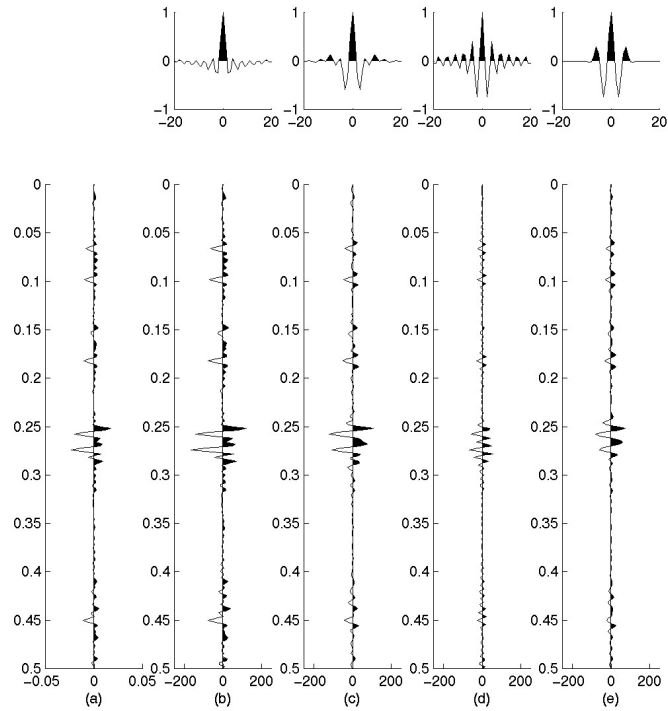


Figure 2. Cross correlation removal of the sweep. From left to right, (a) initial reflectivity, (b) cross correlation of linear sweep with 0.5s tapers, (c) linear sweep with 5s tapers, (d) non-linear sweep with 0.5s tapers and (e) Gaussian sweep. Small boxes on top are the associated Klauder wavelets. Vertical axis is time(s) and horizontal axis is amplitude.

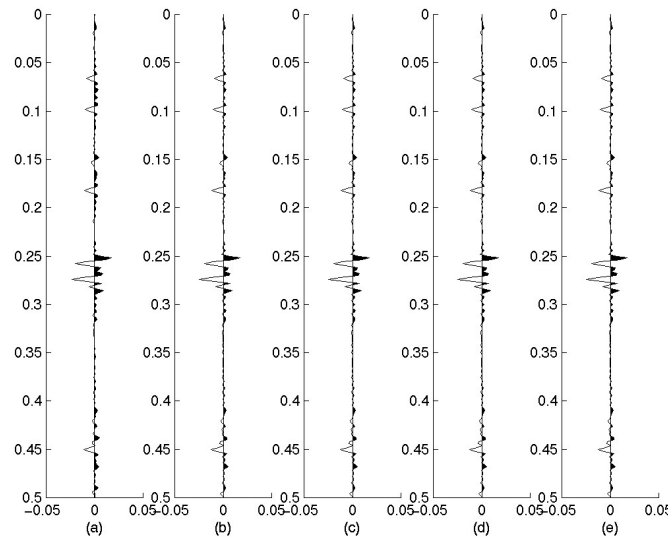


Figure 3: Frequency domain sweep deconvolution. From left to right, (a) initial reflectivity, (b) frequency domain deconvolution of linear sweep with 0.5s tapers, (c) linear sweep with 5s tapers, (d) non-linear sweep with 0.5s tapers and (e) Gaussian sweep. All of the sweeps provide identical results. Vertical axis is time(s) and horizontal axis is amplitude.

EFFECT OF NOISE

The signal-to-noise ratio is critical for the acquisition of good quality data. Much of the noise can be controlled with proper receiver patterns, good base plate to ground coupling and amplitude control in the field. For this study random noise is modeled into the convolutional equation to test the effect of the noise on the deconvolution methods. The noise is additive to the convolutional equation and is written as

$$x(t) = r(t) * s(t) + n(t) \quad (5)$$

where $n(t)$ is random noise. The signal-to-noise ratio for the additive noise is based on the mean power spectrum of the trace.

For cross correlation both terms in the summation are convolved with the reversed time sweep. This replaces the sweep on the left side of the addition with a Klauer wavelet but leaves the noise convolved with the reversed time sweep resulting in

$$x(t) = r(t) * k(t) + n(t) * s(-t) \quad (6)$$

The noise after cross correlation is filtered in the upper frequencies due to the sweep shape. This helps to remove the effect of high frequency noise. The results of the synthetic modelling with the addition of noise are shown in Figure 4. The synthetic models show that the noise has only a small effect on the results of cross correlation even with increasing signal-to-noise ratios. There are small effects visible in association with the small reflectivities.

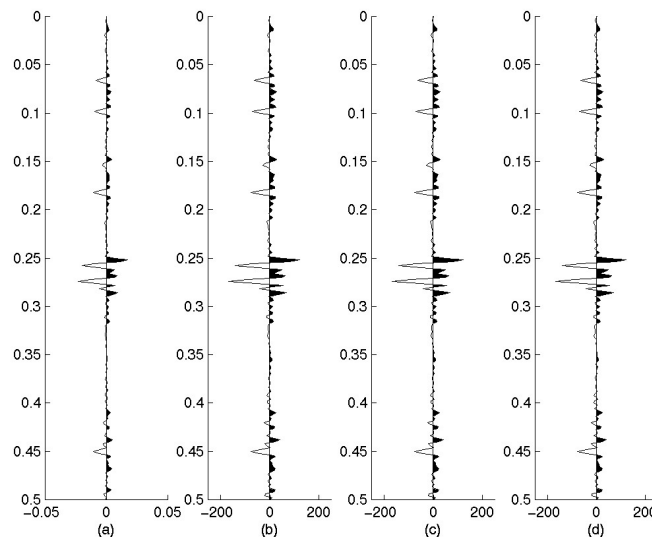


Figure 4. Cross correlation with increasing signal-to-noise ratios. (a) is the reflectivity, (b) result of cross correlation when there is no noise, (c) Signal to noise ratio of 4 and (d) is a signal to noise ratio of 1.5. Vertical axis is time(s) and horizontal axis is amplitude.

For frequency domain deconvolution the noise is also additive to the convolutional equation. When the sweep is removed in the frequency domain, the noise is divided by the sweep. This results in

$$X_{FDD}(\omega) = \frac{R(\omega)S(\omega)}{\overline{S}(\omega)} + \frac{N(\omega)}{\overline{S}(\omega)}, \quad (7)$$

where the sweep is removed from the first part of the summation but the noise is amplified. This can be accounted for by two methods. The first is by filtering out the frequencies that are not included in the sweep. This will remove all the amplified noise. The second method is to add a small (1%) noise factor to the sweep, eliminating any division by zero and reducing the amplification of the noise. The results (Figure 5) of the frequency domain sweep deconvolution for increasing signal-to-noise ratios is comparable to cross correlation. This method is extremely dependent of the amount of bandpass filtering completed to remove the noise.

Any remaining noise in the trace will be further reduced when the data is stacked.

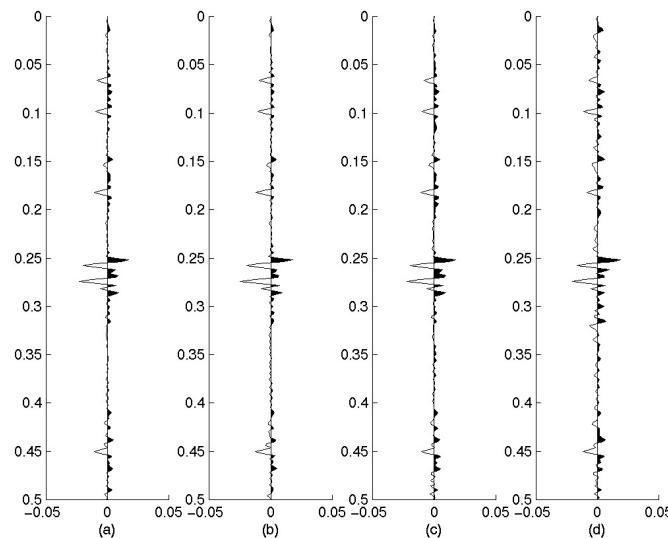


Figure 5. Frequency domain sweep deconvolution with increasing signal-to-noise ratios. (a) is the reflectivity, (b) result of frequency domain deconvolution when there is no noise, (c) Signal to noise ratio of 4 and (d) is a signal to noise ratio of 1.5. Vertical axis is time(s) and horizontal axis is amplitude.

EFFECT OF MINIMUM PHASE GROUND FILTERING

As a source penetrates the ground and is measured by a series of geophones the signal is altered by a filtering effect. The filter is more significant for a vibroseis source than for dynamite. Both Gibson and Larner (1984) and Cambois (2000) have discussed the effect of earth filtering. All the authors identify problems associated with the earth effect and suggest that it has an embedded minimum phase wavelet. This is supported by the lack of problems for an impulsive dynamite source. Since a

vibro seis source creates an embedded zero-phase wavelet and the earth filter is minimum-phase, the result is a mixed phase wavelet. Cambois converts the mixed phase wavelet to zero-phase by constructing a minimum phase equivalent and filtering the vibro seis record to match the phase. Once this is completed it is possible to use minimum phase spiking deconvolution to remove the minimum phase, creating a zero phase record. Cambois (2000) suggests that the sequence of processes to convert the phase is impractical as the conversion to minimum phase is time consuming and the low frequency shape of the spectrum is too complicated for linear sweeps.

For this study, a minimum phase earth filter was designed with a Gaussian spectrum. This filter was convolved with the trace before the addition of any random noise. This gives a convolutional equation of

$$x(t) = r(t) * e(t) * s(t) + n(t) \quad (8)$$

where $e(t)$ is the minimum phase earth filter. With frequency domain sweep deconvolution, the spectrum is whitened for the sweep and any remaining spectral shape is due to earth filtering. It should be possible to determine the spectrum of the earth filter after the sweep has been removed for the swept frequencies. Problems arise for the prediction of the earth filter for the frequencies not covered by the sweep.

Through modelling an initial examination of the two methods was made. The first test is for a linear sweep with the minimum phase earth filter. The results of the methods are comparable. Both show phase rotation for the seismic after the sweep is removed (Figure 6). The minimum phase can be removed with any minimum phase deconvolution, in this case Wiener spiking deconvolution (Figure 7). For the second test a Gaussian sweep was convolved with the trace. Both of the methods show significant phase rotation due to the minimum phase earth filter. However, after minimum phase deconvolution the frequency domain sweep deconvolution provides a significantly better result (Figure 8). For the removal of the minimum phase earth filter the wavelet is estimated from the original trace. For cross correlation the embedded wavelet is incorrectly estimated due to the filtering effects of the sweep and is not properly removed. For frequency domain deconvolution there are no residual effects of the sweep and the wavelet can be more accurately estimated. The wavelet's spectrum can only be estimated for the frequencies that are covered by the sweep and the spectrum must be estimated for any other frequencies.

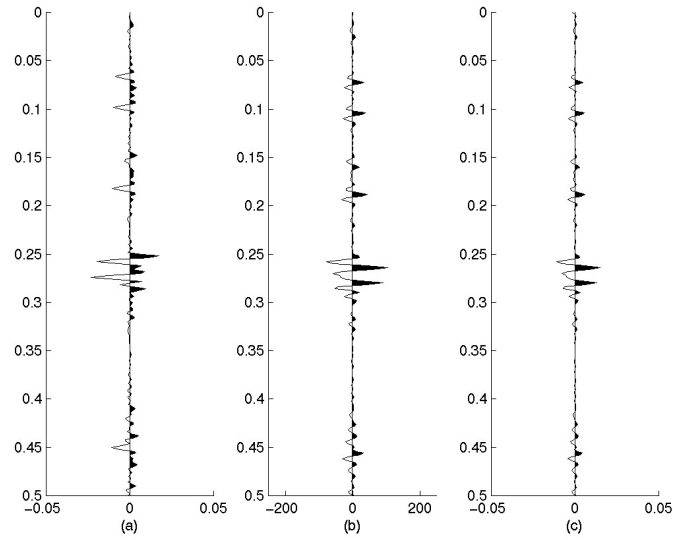


Figure 6. (b) Cross correlation and (c) Frequency domain sweep deconvolution compared to the (a) reflectivity for a linear sweep results with the addition of minimum phase earth filtering. Both show phase rotations. Vertical axis is time(s) and horizontal axis is amplitude.

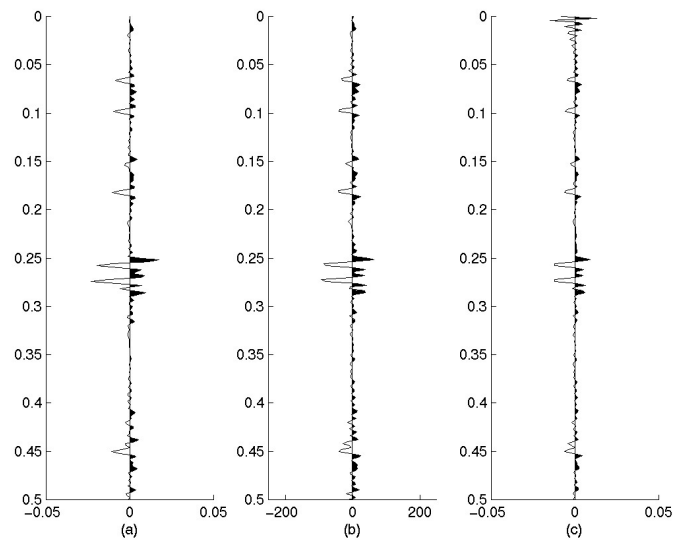


Figure 7. (b) Cross correlation and (c) Frequency domain sweep deconvolution compared to the (a) reflectivity for a linear sweep results with the addition of minimum phase earth filtering after minimum phase deconvolution. Most of the phase rotation has been removed. Vertical axis is time(s) and horizontal axis is amplitude.

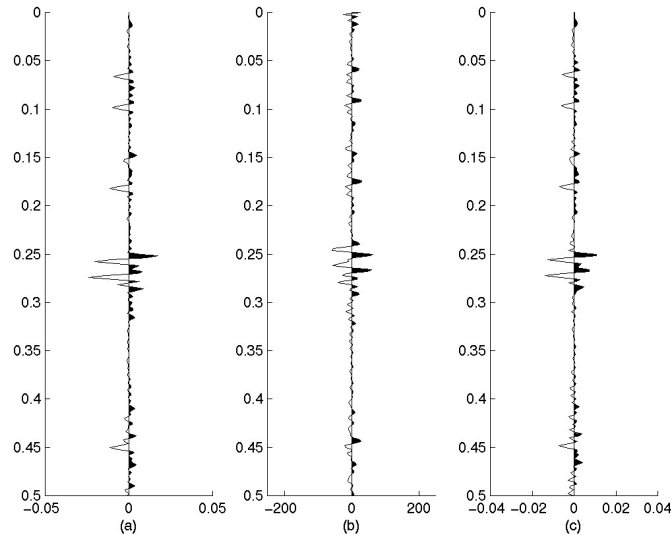


Figure 8. (b) Cross correlation and (c) Frequency domain sweep deconvolution compared to the (a) reflectivity for a Gaussian sweep results with the addition of minimum phase earth filtering after minimum phase deconvolution. The phase rotation has been removed for Frequency domain method but not cross correlation. Vertical axis is time(s) and horizontal axis is amplitude.

CONCLUSIONS

For a linear sweep with small tapers both frequency domain sweep deconvolution and cross correlation methods give similar results. Cross correlation has an advantage since the data is filtered during the sweep deconvolution, however this limits the post-acquisition control of the filtering. Frequency domain sweep deconvolution requires the application of filtering or the addition of a noise factor to reduce the noise that is amplified in the frequencies not covered by the sweep. For non-linear sweeps, the results of frequency domain sweep deconvolution were slightly better than cross correlation. The Klauder wavelet associated with cross correlation is dependent on the shape of the sweep, with the Gaussian sweep producing large negative side lobes. All of the sweeps produce the same result for frequency domain sweep deconvolution as the sweep is completely removed. Following the sweep removal, a filter can be designed to shape the reflectivity spike. Frequency domain sweep deconvolution exceeds the quality of cross correlation when the filtering effects of the ground are added to the trace. Frequency domain sweep deconvolution removes the effects of the sweep, leaving only earth filtering spectral changes. The earth filtering can be subsequently removed with minimum phase deconvolution.

Future work includes modelling with Q filtering to further test the effects of earth filtering and comparing the minimum phase removal by Cambois (2000) to frequency domain sweep deconvolution. After the modelling is completed this method will be tested on real data.

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REFERENCES

- Cambois, G., 2000. Zero-phasing the zero-phase source, *The Leading Edge*, Vol. 19, No. 1.
- Gibson, B. and Larner, K., 1984. Predictive deconvolution and the zero-phase source, *Geophysics*, Vol. 49.
- Goupillaud, P.L., 1976. Signal design in the “Vibroseis” Technique, *Geophysics*, Vol. 41.
- Ristow, D. and Jurczyk, D., 1975. Vibroseis deconvolution, *Geophysical Prospecting*, Vol. 23.
- Sheriff, R.E., 1990. Encyclopedic dictionary of exploration geophysics, Society of Exploration Geophysics.