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OPTIMAL DECONVOLUTION USING WIENER TRANSFORM FOR COMPENSATION OF TIME VARIANCE AND NON-MINIMUM PHASE

By

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ABSTRACT

Seismic deconvolution was introduced by Robinson in 1954 based on Wiener filter theory. If all filters in the signal path, including the seismic source, are minimum phase, there is nothing to annoy geophysicists about deconvolution performance. Since many types of non-explosive seismic sources which have nonminimum-phase character have been introduced to the seismic world, many types of deconvolution techniques for nonminimum-phase data have been developed using Wiener filter theory and other methods. However, these deconvolution techniques have not completely solved the deconvolution problem for nonminimum-phase data and have often made it more complicated. Furthermore, a unified deconvolution technique applicable to all types of seismic data has not been developed previously.

General description of deconvolution techniques and review for Wiener-Levinson deconvolution (henceforth W-L deconvolution) are made, and conventional deconvolution techniques, especially the addition of white noise in design of deconvolution operators, are criticized. Even 1 % additive white noise introduces considerably large phase distortion, and increasing the noise level progressively degrades the performance of deconvolution.

In order to simplify and unify the process of deconvolution for nonminimum-phase data including Vibroseis data, the Wiener transform is introduced.

By using the Wiener transform, generation of minimum-phase equivalents to nonminimum-phase wavelets, correction of time variance of the seismic data, and generation of allpass phase compensators are easily and optimally carried out under the criterion of minimum mean-square error.

As an optimal deconvolution technique for nonminimum-phase data, a time-variant inverse attenuation filter followed by phase-compensated spiking deconvolution is proposed (named Sengbush-Hato deconvolution, henceforth S-H deconvolution), and it is shown that this technique is optimal under a wide range of conditions and types of seismic data. It is also shown that attenuation is accompanied with minimum phase using McDonal et al's experimental data (1958), and time-variant minimum-phase inverse attenuation filter is used in S-H deconvolution of seismic data.

This optimal deconvolution technique is applied to a synthetic seismic trace which was formed using a dense reflectivity function and a watergun signature, and its performance is far superior to spiking and gapped deconvolution, where the performance is measured by calculating the correlation coefficient and the relative time shift between the desired output and each deconvolution output after bandlimiting with the desired seismic pulse.

High performance of S-H deconvolution is confirmed by computer simulations. For time-variant inverse-attenuated traces with and without 3 % additive natural noise, the correlation coefficients of S-H deconvolution are always over 0.83 compared to 0.72 or less for the other types of deconvolution. In addition, SH deconvolution by compensating for phase distortion has no relative time shift, whereas all of the others show time shift; 42 msec in the case of the watergun signature used in the simulation. Even for time-variant attenuated traces without time-variant inverse attenuation filter, S-H deconvolution keeps the largest correlation coefficient and has little or no phase shift. Also, wide tolerance is confirmed for misestimation of the attenuation constant used in generating the time-variant inverse attenuation filter in S-H deconvolution.

Applicability of S-H deconvolution to Vibroseis data is also shown by using a Klauder wavelet and a sparse reflectivity model for the high attenuation case. For time-variant attenuated trace without inverse attenuation filter, S-H and Ristow-Jurcyzk (1975) deconvolution have the largest correlation coefficient and no relative time shift.

For time-variant inverse-attenuated trace, all of the deconvolutions, including no deconvolution, except for spiking deconvolution, have nearly perfect correlation coefficient, more than 0.98, and no relative time shift because of the special character of Klauder wavelets.

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INTRODUCTION

Since the advent of effective non-explosive seismic sources such as, Vibroseis^{TM} (CONOCO), steam guns, waterguns, airguns, etc, has had a tremendous impact on seismic exploration. These systems have supplied more effective seismic data acquisition techniques on the one hand; on the other hand, these systems have forced geophysicists to change their data processing techniques due to their nonminimum-phase character.

From the mid of 1970's, outstanding studies of deconvolution technique for Vibroseis data have been made by Ristow and Jurczyk (1976), Bickel (1982), Gibson and Larner (1984), and others based on Wiener-Levinson inverse filtering theory introduced by Enders Robinson (1954). Wavelet deconvolution techniques were also developed by DeVoogd (1974) and Berkhout (1977), and many others. However, these techniques do not have general applicability to all types of nonminimum-phase seismic data; for example, Ristow-Jurczyk method deconvolution can handle only Vibroseis data.

Time variance and nonminimum phase of seismic data have been big problems in deconvolution. These problems can not be solved by simple techniques and performance of techniques used has not been measured quantitatively.

Additive white noise has always been considered absolutely essential to Wiener filter theory-based deconvolution. These facts have been a big barrier to establishing optimal deconvolution of nonminimum-phase data.

In this study, it is shown that additive white noise introduces phase distortion that previously has not been recognized or compensated for; additive white noise is not only unnecessary but also produces inferior performance of deconvolution. It is also shown using McDonal et al's experimental data in Pierre shale (1958) that the attenuation filter derived from its amplitude spectrum is minimum phase.

Considering the problems of deconvolution described above, a unified and simplified technique of optimal W-L deconvolution that uses the Wiener transform to compensate for time variance and nonminimum phase is proposed. This technique (S-H deconvolution) can be applied without modification to all types of nonminimum-phase data including zero-phase seismic source data.

Explicit algorithms are given and definite measures of performance demonstrate the superiority of S-H deconvolution.

As examples of application of Wiener transform, minimum-phase conversion, generation of inverse attenuation filters, and generation of optimal phase compensators and its application are carried out in order to show validity of Wiener transform.

S-H deconvolution is applied to a watergun signature seismic model consisting of a realistic dense reflectivity and a watergun signature. The results are compared quantitatively with several Wiener theory-based deconvolution procedures by using the correlation coefficient and relative time shift.

Using the same data, the superior performance of S-H deconvolution for cases of mismatched attenuation constant used for generating time-variant inverse attenuation filters is established.

Optimal deconvolution is also applied to a Klauder wavelet seismic model consisting of a sparse reflectivity and a Klauder wavelet in order to study the generality of optimal deconvolution being applicable to any type of nonminimum-phase data.

GENERAL DESCRIPTION OF DECONVOLUTION

Since Robinson (1954) introduced seismic deconvolution based on Wiener filter theory, it has been one of the most powerful tools for improving resolution of seismic data.

Furthermore, non-explosive seismic sources such as Vibroseis™ system (Crawford, 1960), steam guns such as Vaporchoc™ (CGG), and others, have improved seismic data acquisition because of their simple operation and controllability of the source waveform.

Continuing development of seismic data acquisition is accompanied by continuing development of the seismic data processing, especially deconvolution.

Deconvolution for nonminimum-phase data as well as other conventional deconvolution is classified into two major categories, Wiener models based on Wiener filter theory, and others. In this chapter, for these two models, important and outstanding works are reviewed briefly.

Wiener Models

Wiener filters have been used as the most popular statistical deconvolution for spectral broadening of nonminimum-phase data as well as regular seismic data due to its high performance and its ease to use, but this deconvolution technique is based on the following assumptions: 1) the reflectivity series is random and white, 2) the natural noise is random and stationary, and 3) the effective seismic pulse is minimum phase and time-invariant. On real seismic data, these assumptions are not satisfied, especially on data acquired by nonminimum-phase sources because of the special character of the source signatures. In spite of these difficulties in applying Wiener filters, this technique has been widely used for the deconvolution of nonminimum-phase data.

Ristow and Jurczyck (1975) introduced phase-compensated spiking deconvolution (henceforth called R-J deconvolution) to Vibroseis data. Subsequently, Bickel (1982) and Gibson and Larner (1984) studied the effects of additive natural noise and additive white noise on the performance of deconvolution for Vibroseis data and their effect in the design of phase compensators. They also studied the effect of applying an inverse attenuation filter. However, their deconvolution techniques based on R-J deconvolution is applied only to Vibroseis data, which has zero-phase source wavelet.

Other Models

Other deconvolution techniques which are not based on Wiener filter theory have been developed, including: 1)

Homomorphic deconvolution (Ulrych, 1971), 2) Maximum-likelihood deconvolution (Kormylo and Mendel, 1983), 3) Minimum-variance deconvolution (Mendel, 1981), 4) Q-adaptive deconvolution (Hale, 1985), and 5) Minimum-entropy deconvolution (Wiggins, 1978). Jurkevics and Wiggins (1984) summarized merits and demerits of these model-based deconvolution techniques well.

These techniques may not require some of the assumptions which are required in the Wiener method, but they require other assumptions. Some such as maximum-likelihood and minimum-entropy deconvolution assume that the reflectivity function is sparse, which is not realistic model of the real seismic process. Furthermore, some types of model-based deconvolution techniques do not work well under certain condition, such as homomorphic deconvolution, which in the case of small amplitude spectrum, introduces ambiguity in the phase values associated with the very small amplitudes in the signal spectrum.

WIENER-LEVINSON DECONVOLUTION

As has been described in previous chapter, many authors have studied deconvolution for nonminimum-phase data, including Vibroseis data, using Wiener filter theory, and there is no doubt that Wiener filter theory will continue to be used as one of the most useful deconvolution techniques in the future because of its performance, its ease in practical usage, and its freedom from parameter estimation. In this chapter, a review of Wiener-Levinson deconvolution (W-L deconvolution) will be made and then some problems of traditional W-L deconvolution will be considered.

Convolutional Model

The convolutional model of the seismic data generation process in the signal path is expressed as follows:

$$s = c * r + n, \tag{1}$$

where s is the seismic data, c is the effective seismic pulse, r is the earth's reflectivity, and n is the additive natural noise. The convolutional model of the effective seismic pulse c is shown as follows:

$$c = b * h * a * i, \tag{2}$$

where b is the seismic source signature, h is the ghost and reverberation filter, a is the earth's attenuation filter, and i is the response of the recording instruments such as the DFS-V™ (Texas Instruments) and geophone. Filters a and h are minimum phase. Some types of sources such as the Klauder wavelet (Klauder, 1960), which is the autocorrelation of the Vibroseis sweep, steam guns, waterguns, and some others are not minimum phase. The filter i, especially when active electric circuits are used, is not minimum phase.

In general, noise is classified into two components, which are random noise and coherent noise such as ground roll and refractions. However, in the study of W-L deconvolution here, only random noise is taken into account; the coherent noise being presumed to be adequately suppressed by patterns and f-k filter before deconvolution.

Assumptions

In order to perform optimal W-L deconvolution, the following assumptions must be satisfied;

1) Reflectivity r is white and random,
2) Noise n is random and stationary,
3) Effective seismic pulse c is minimum phase and time-invariant.

W-L Deconvolution Process

The goal of W-L deconvolution developed by Robinson is to find the inverse of c from the seismic data by solving the Wiener-Hopf normal equation (eq. 3) and then to apply the inverse to the seismic data in order to remove the filter c,

$$\phi_L * w = \delta , t \geq 0, \tag{3}$$

where ϕ_L is the truncated autocorrelation of the windowed-seismic data, δ is an impulse, and w is the deconvolution operator, which is the inverse of the minimum-phase equivalent to the effective seismic pulse c.

In the process, the window length must be chosen carefully to obtain the characteristics of random process, and also to keep the time variance of the effective seismic pulse from adversely affecting deconvolution performance. In addition, because truncation of the autocorrelation function is directly related to the spectral smoothing in the frequency domain which estimates the power spectrum of the effective seismic pulse, the truncation length and the ratio of the window-to-truncation length must be selected carefully also. The process of spectral smoothing is described in detail by Sengbush (1983, p134).

Traditionally, whenever the W-L deconvolution operator is generated, a small quantity is added to the diagonal component of the normal equation, so-called prewhitening, in order to make the solution stable. However, prewhitening always reduces the performance of W-L deconvolution (Shugart, 1973).

After being filtered by the inverse w, the seismic data becomes as follows:

$$s * w = c * r * w + n * w. \quad (4)$$

If the inverse w is almost perfect, that is if $c * w \cong \delta(t)$, the deconvolved seismic data is

$$s * w \cong r + n * w. \quad (5)$$

Since W-L deconvolution greatly enhances noise in the lower and higher frequency band of the seismic data where the signal-to-noise ratio is very low, the frequency-band of the deconvolved data must be restricted by applying a bandpass filter, called the d-filter, which has known and desirable characteristics,

$$s * w * d \cong r * d + n * w * d. \quad (6)$$

If the noise is very small, the final form of the convolutional model after W-L deconvolution is as follows:

$$s * w * d \cong r * d. \quad (7)$$

Problems of W-L Deconvolution

In application of W-L deconvolution to real data, the following problems occur; 1) the effective seismic pulse may not be minimum-phase and is not time-invariant, 2) the reflectivity is not random and not white, 3) the noise is not random and not stationary, and 4) the noise is not small enough to be ignored.

Concerning the noise, it must be suppressed sufficiently by proper field processing and proper data processing before applying deconvolution because W-L deconvolution does not enhance signal-to-noise ratio, but rather its performance is degraded by presence of the noise. The degradation of the W-L deconvolution performance is described under various noise conditions by Berkhout (1977).

Many efforts have been made to solve or to bypass the problems described above, such as signature deconvolution, which is preprocessing by the nonminimum-phase inverse of the source signature before deconvolution, phase estimation by bispectrum (Matsuoka and Ulrych, 1984), the Wapco process by Compagnie Generale de Geophysique (Fourmann, 1974), and some others. However, these studies did not always solve the problems completely.

Among the problems mentioned, since only the source signature may contribute significant nonminimum-phase characteristics and the time-variant earth's attenuation may significantly affect the nonstationarity of the seismic data, these are core problems which should be solved at first. The problems of compensation of time variance and compensation of minimum-phase can be solved by using the Wiener transform which will be introduced in a later chapter.

CRITICISM ON CONVENTIONAL DECONVOLUTION

In spite of many author's efforts, especially Ristow and Jurczyk, Bickel, and Gibson and Larner, to study deconvolution for nonminimum-phase data, their techniques are not always the best way to solve this problem, but rather make it more complicated. In this chapter, several confusing factors are picked up and are criticized and then some discussions are made in order to build the optimal deconvolution technique for nonminimum-phase data.

Ultimate Goal

The ultimate goal of seismic data processing for stratigraphic interpretation is to obtain both high resolution and high signal-to-noise ratio data. In the deconvolution process, these two requirements for achieving the ultimate goal are contradictory to each other because the deconvolution process itself does not enhance the signal-to-noise ratio at all. Therefore, the additive natural noise, which is an important factor that degrades the performance of the deconvolution, should be suppressed sufficiently before applying deconvolution so that the deconvolution operator will be based on signal only.

In this sense, we should remove all filters including the Klauder wavelet in case of Vibroseis deconvolution in order to obtain only the underlying reflectivity.

Addition of White Noise

Degradation of the performance of W-L deconvolution by the presence of additive natural noise appears as a phase distortion in the deconvolution output. In figure 1, a minimum-phase wavelet (b_m) and its noise-added version (b_n) which has 3 % natural white noise (pseudo-Gaussian distribution) are superimposed and show no visible difference. To these two wavelets, W-L spiking deconvolution is applied without additive white noise (fig. 2) in order to investigate the effect of additive natural noise. In figure 2, d_m and d_n are outputs of deconvolution to b_m and its 3 % natural noise-added version (b_n). d_m is nearly a spike at the time origin, but the waveform of d_n is totally destructive. In order to investigate effects by natural noise in detail in frequency domain, spectral analysis was carried out to both wavelets (d_m and d_n) and these results are shown in figure 3 and 4.

Amplitude spectrum (A_m) of d_m is ideally flattened but amplitude spectrum (A_n) of d_n is distorted (fig. 3). The same destructive tendency can be also seen on the phase spectrum (P_n) of d_n compared to the zero-phase spectrum of (P_m) of d_m (fig. 4). From these spectral analyses, degradation of performance of deconvolution can be realized

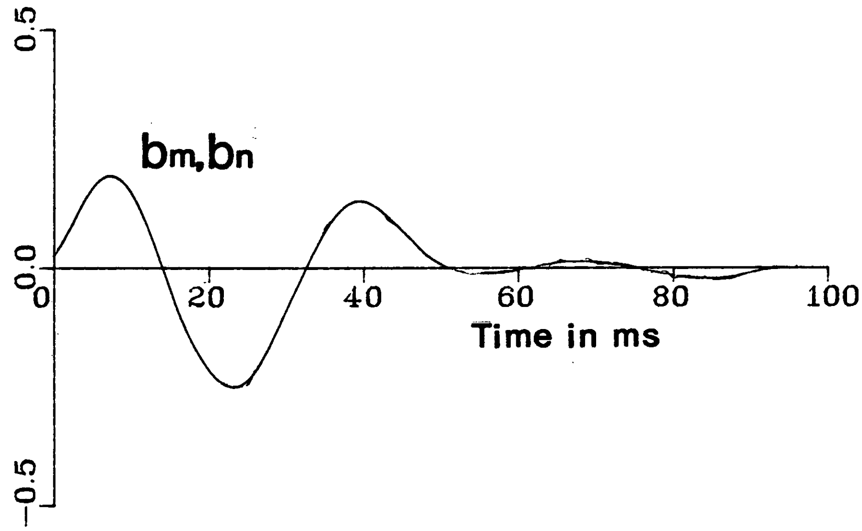

Figure 1. Minimum-phase wavelet b_m and 3 % natural noise-added wavelet b_n.

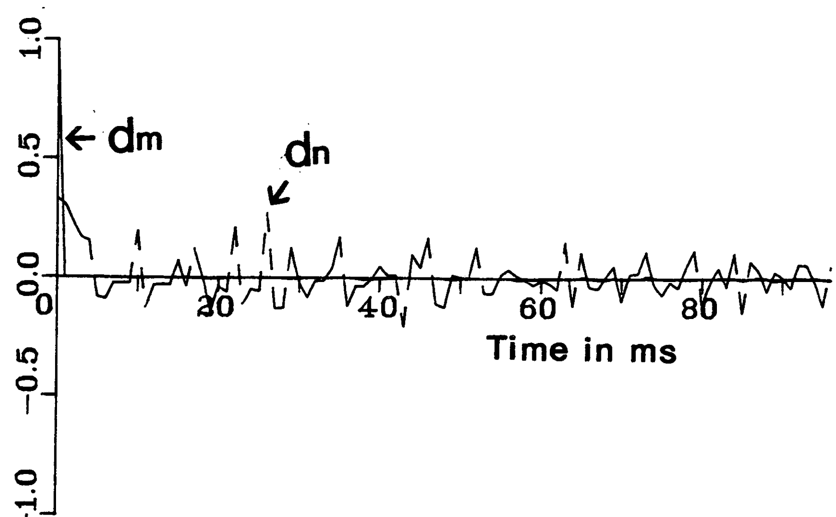

Figure 2. Deconvolution of b_m and b_n (d_m, d_n).

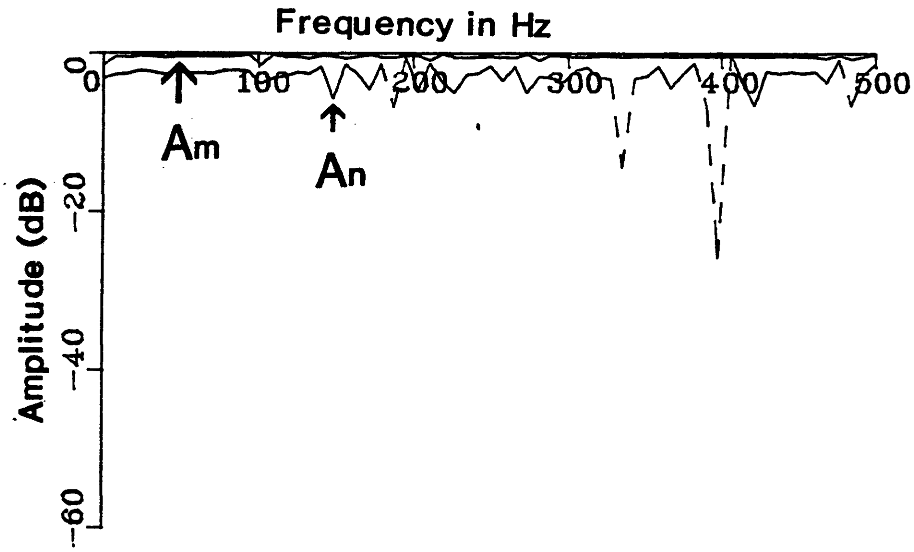

Figure 3. Amplitude spectrum of d_m and d_n (A_m, A_n).

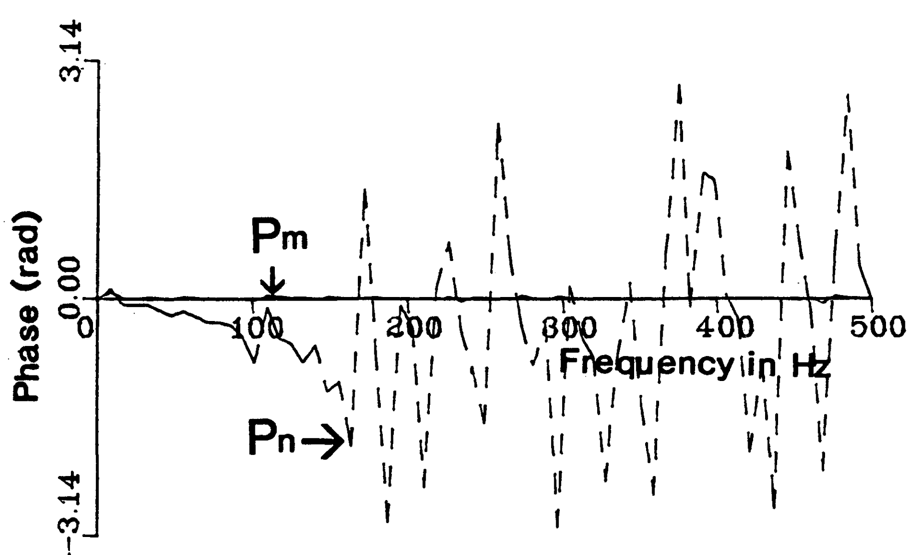

Figure 4. Phase spectrum of d_m and d_n (P_m, P_n).

when even a small additive natural noise exists on the seismic data.

Concerning additive white noise, conventional deconvolution processes including deconvolution of nonminimum-phase data such as those described by Bickel, and Gibson and Larner, apply small amounts of additive white noise on the Wiener-Hopf normal equation for the purpose of making the solution stable. However, to apply additive white noise which has the same effect as the presence of the additive natural noise is not appropriate. Even minimum-phase signatures produce phase distortion in the W-L deconvolution output if the white noise is added.

In order to study effect of additive white noise in deconvolution, W-L spiking deconvolution was applied to the minimum-phase wavelet b_m (fig. 1) used in previous simulation by changing amount of additive white noise. In figure 5, output (d_0) of W-L deconvolution to the wavelet b_m without additive noise is almost a spike, but the output (d_1) with 1 % additive white noise has bandlimited waveform. The results of spectrum analysis for both deconvolution outputs (d_0 and d_1) are shown in figure 6 and 7. In figure 6, the amplitude spectrum (A_m) of deconvolved wavelet (d_0) is sufficiently whitened, but the amplitude spectrum (A_n) of the deconvolved wavelet (d_1) loses its higher frequency components above 100 Hz rapidly. In figure 7, the phase

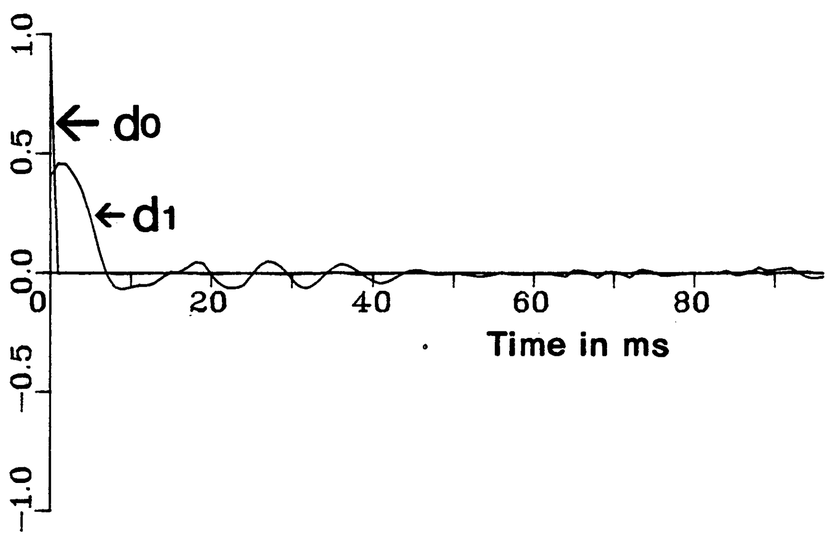

Figure 5. Deconvolution of b_m with and without 1 % additive white noise (d_1, d_o).

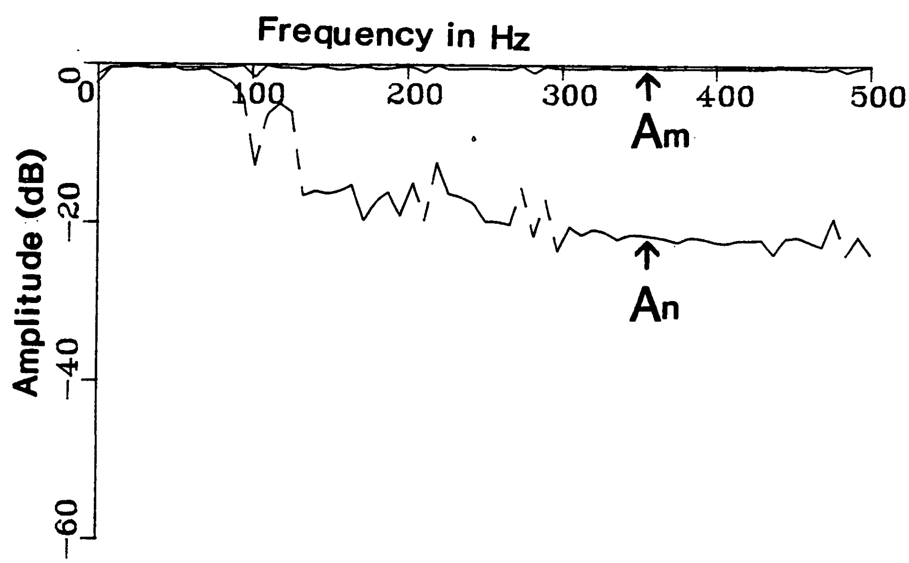

Figure 6. Amplitude spectrum of d_0 and d_1 (A_m, A_n).

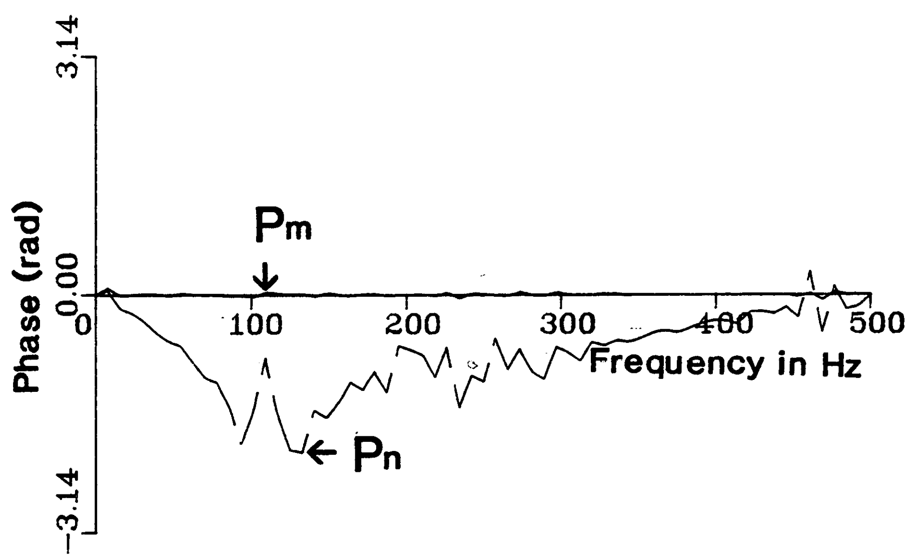

Figure 7. Phase spectrum of d_0 and d_1 (P_m, P_n).

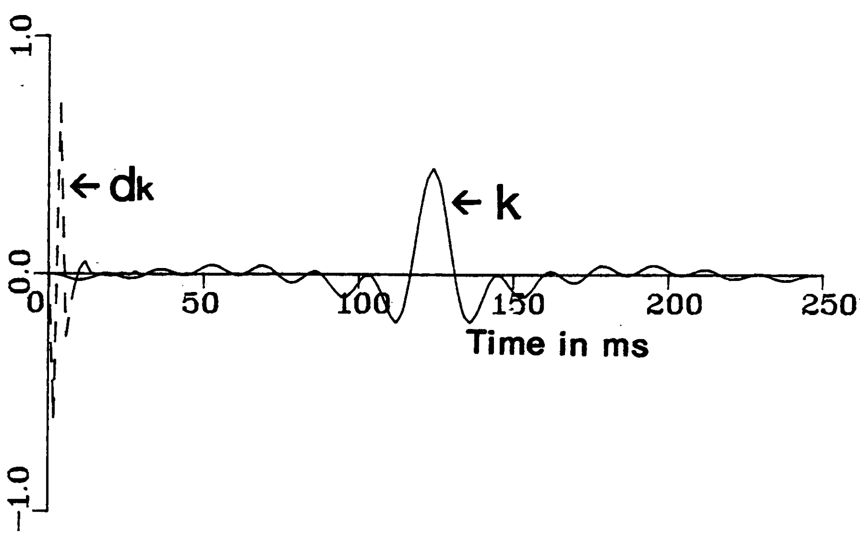

Figure 8. Klauder wavelet k and its deconvolution operator d_k without additive white noise.

spectrum (P_n) of the deconvolved wavelet (d_1) is distorted compared to the zero-phase spectrum (P_m) of the deconvolved wavelet (d_0).

In fact, since any finite-length time function always has non-zero spectral value at every point except possibly on a set of measure zero even if it is designed as bandlimited signal, the probability of unstable solution of the Wiener-Hopf normal equation is vanishingly small. As a matter of the fact, a stable deconvolution operator (d_k) of the Klauder wavelet (k) can be obtained by solving Wiener-Hopf normal equation without additive white noise (fig. 8).

In this sense, we do not need to apply any additive white noise in design of the W-L deconvolution operator.

Unified Treatment

Conventional deconvolution techniques for nonminimum-phase data can not be applied to the other types of nonminimum-phase seismic data. For instance, R-J deconvolution can not be applied to mixed-phase data because the output of R-J deconvolution consists of convolution of reflectivity with Klauder wavelet by applying the minimum-phase version of Klauder wavelet to the spiking-deconvolved seismic data.

The optimal deconvolution technique should have applicability to any type of nonminimum-phase data including Vibroseis data. All filters which are convolved with reflectivity should be removed to obtain the underlying reflectivity only, and the d-filter whose character is well-known and desirable must be applied to the deconvolved data in order to bandlimit the noise.

TOOLS FOR SIMPLIFICATION AND UNIFICATION

In this chapter, according to criticisms mentioned in the former chapter, in order to simplify and unify the complicated deconvolution process for nonminimum-phase data, the Wiener transform is introduced and typical applications of the Wiener transform are shown. In addition, influences of the additive white noise on the Wiener transform are discussed.

Wiener Transform

The Wiener transform is defined as the solution to the deterministic Wiener-Hopf normal equation without additive white noise. In another words, the Wiener transform is W-L spiking deconvolution without additive white noise applied to a deterministic stable finite-length function. So, the Wiener transform of y, expressed as W(y), is obtained by solving equation (8),

$$\phi_y * w = \delta , \quad t \geq 0, \tag{8}$$

where ϕ_y is the exact complete autocorrelation of y. Thus, the solution of equation (8) is the optimal finite-length inverse of the minimum phase equivalent of y, that is,

$$W(y) = y_m^{-1}. \tag{9}$$

Equality means equality in the sense of minimum mean-square given by

error between the two functions. So, if ϕ_y is violated by truncating the autocorrelation, shaping the autocorrelation, or adding white noise, W(y) is no longer the Wiener transform of y.

Minimum Phase Conversions

One of typical examples of application of the Wiener transform is to generate the minimum-phase equivalent to a function y, which is calculated optimally by applying the Wiener transform to y twice without additive white noise, that is,

$$W(W(y)) = y_m. \tag{10}$$

Three kinds of nonminimum-phase seismic source, the Klauder wavelet (k), the Vaporchoc signature (v), and the watergun signature (w), and their minimum-phase equivalents (k_m, v_m, and w_m) calculated by applying the Wiener transform twice without additive white noise are shown in figure 9, 10, and 11, respectively. Although there are other well-known methods to generate the minimum-phase equivalent y_m from y, such as the Hilbert transform (see Appendix A) (fig. 12) and the Z-transform (see Appendix B), the Wiener transform is apparently the simplest and easiest method to use, and insures optimality in the sense of mean-square error.

In order to examine the influence of additive white

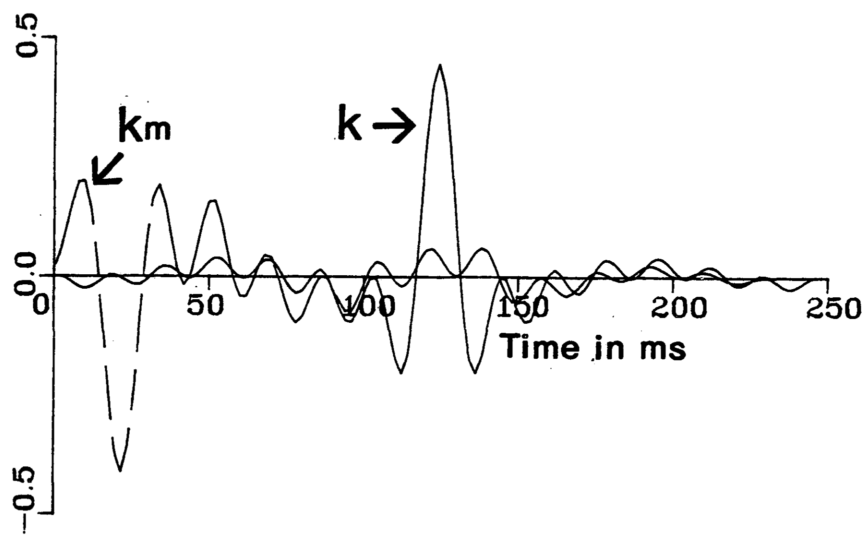

Figure 9. Klauder wavelet k and its minimum-phase equivalent k_m.

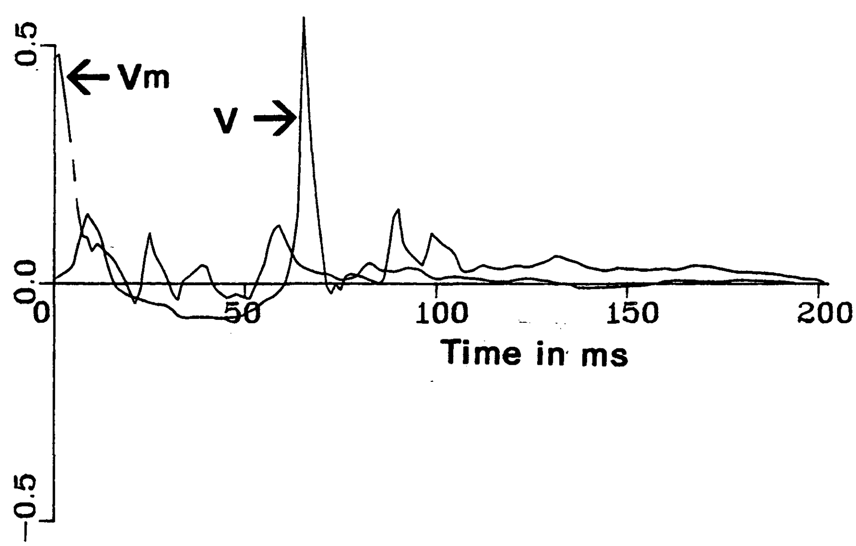

Figure 10. Vaporchoc signature v and its minimum-phase equivalent v_m.

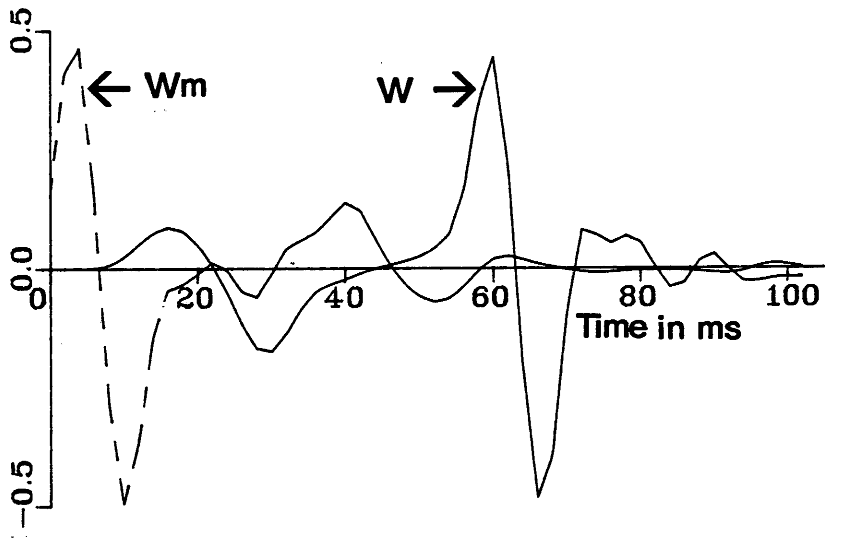

Figure 11. Watergun signature w and its minimum-phase equivalent w_m.

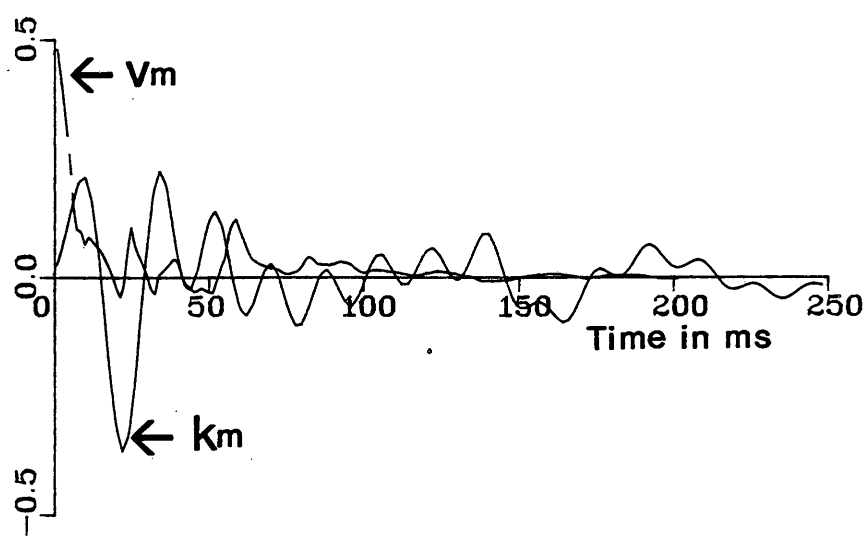

Figure 12. Minimum-phase equivalent of Klauder wavelet k_m and Vaporchoc signature v_m by Hilbert transform.

noise on minimum-phase conversion, the minimum-phase equivalent to the Klauder wavelet is obtained by applying the Wiener transform twice without and with 0.1 % additive white noise ($k_{0.0}$ and $k_{0.1}$) (fig. 13) and the amplitude spectrum of both minimum-phase equivalents were computed ($K_{0.0}$ and $K_{0.1}$) (fig. 14).

In figure 13, it is realized that even very small additive white noise ,0.1 % in this case, makes a big difference between noise-added minimum-phase version ($k_{0.1}$) and noise-free minimum-phase version ($k_{0.0}$). In figure 14, the amplitude spectrum $K_{0.1}$ is more whitened than amplitude spectrum $K_{0.0}$ even though added white noise is very small. It should be realized that additive white noise on Wiener transform in minimum-phase conversion works as a bias on the amplitude spectrum of minimum-phase version.

In addition, spiking deconvolution without white noise was applied to both noise-added minimum-phase version ($k_{0.1}$) and noise-free minimum-phase version ($k_{0.0}$), and the correlation coefficient value (henceforth CC value) (see Appendix C) between each deconvolution output and a spike at the time origin was calculated. The CC values for the deconvolution outputs are 0.9987 and 0.9999, respectively.

Since the minimum-phase equivalent must be one and only one wavelet among wavelets which have the same amplitude spectrum, the noise-added version can not be the

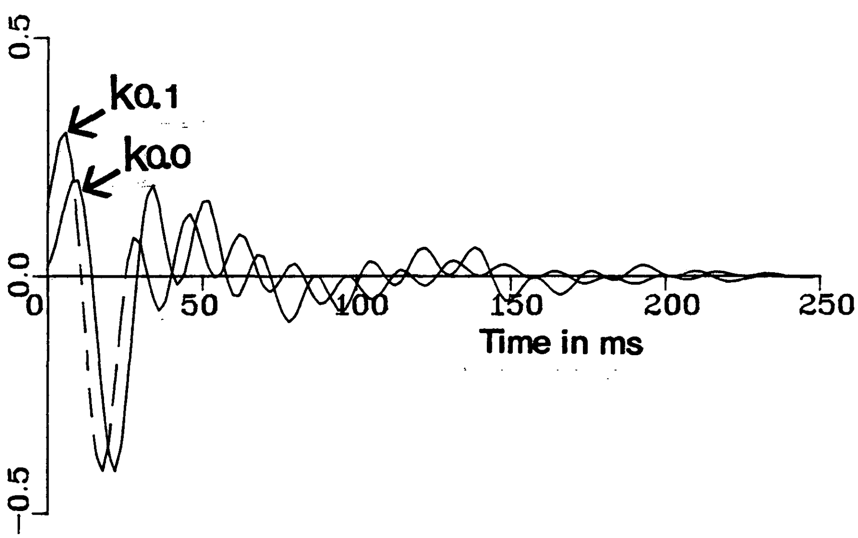

Figure 13. Minimum-phase equivalent of Klauder wavelet with and without 0.1 % additive white noise ($k_{0.1}$ and $k_{0.0}$).

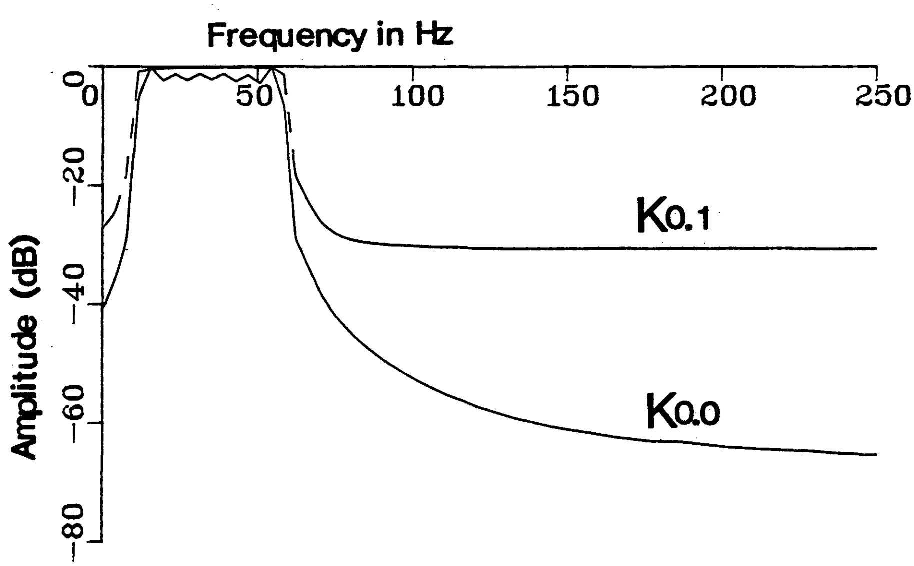

Figure 14. Amplitude spectrum of $k_{0.0}$ and $k_{0.1}$ ($K_{0.0}$, $K_{0.1}$).

minimum-phase equivalent to the Klauder wavelet (k) because the noise-free version is guaranteed to be the minimum-phase equivalent.

Allpass Phase Compensator

As already mentioned in the former chapter, if W-L spiking deconvolution without additive white noise is applied to seismic data which contains a nonminimum-phase filter element y in the signal path, the W-L deconvolution operator does not invert y, but does generate y_m^{-1}. Consequently, this difference introduces phase distortion $\theta_y-\theta_m$, where θ_y and θ_m are the phase spectrum of y and y_m, respectively. Therefore, we must apply $y^{-1}*y_m$, whose phase spectrum is $\theta_m-\theta_y$, to the seismic data before or after the W-L spiking deconvolution in order to compensate for the phase distortion introduced by W-L spiking deconvolution. This allpass phase compensator is, however, unstable because of unstability of y^{-1}, which is inverse of the nonminimum-phase filter y. To bypass this problem, Fourmann (1974) introduced the allpass phase compensator g, called the Wapco operator. This allpass phase compensator is easily obtained by convolving y with the Wiener transform of y, that is,

$$g = y * W(y). \qquad (11)$$

The allpass phase compensator is stable and its phase spectrum is $\theta_y - \theta_m$, which is the same as the phase distortion introduced by W-L spiking deconvolution. Folded g, that is g(-t), has the desired phase spectrum $\theta_m - \theta_y$ and must be convolved with seismic data either before or after W-L deconvolution. Because convolution of g(-t) with the seismic data is the same as crosscorrelation of g with the seismic data, the process of allpass phase compensation is summarized as follows:

1) Compute allpass phase compensator g = y * W(y),
2) Correlate g with the seismic data before or after spiking deconvolution.

The combination process of the allpass phase compensator and W-L spiking deconvolution is called phase-compensated spiking deconvolution hereafter.

The following computer simulations using the Klauder wavelet, the Vaporchoc signature, and a watergun signature show the deterministic phase-compensated spiking deconvolution process.

The Klauder wavelet (k) and its Wiener transform (W(k)), which is the deterministic deconvolution operator, without additive white noise are shown in figure 15. Because the Klauder wavelet is zero phase, it has shifted by its half length L/2 to produce causality. Figure 16 shows W-L spiking deconvolution (g_k') of k, which is the same as the allpass phase compensator, and phase-compensated spiking

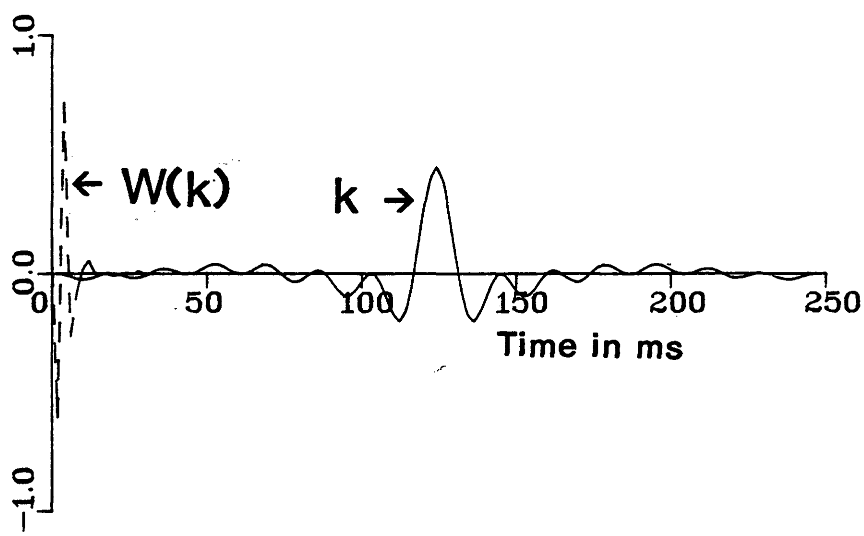

Figure 15. Klauder wavelet k and Wiener transform W(k).

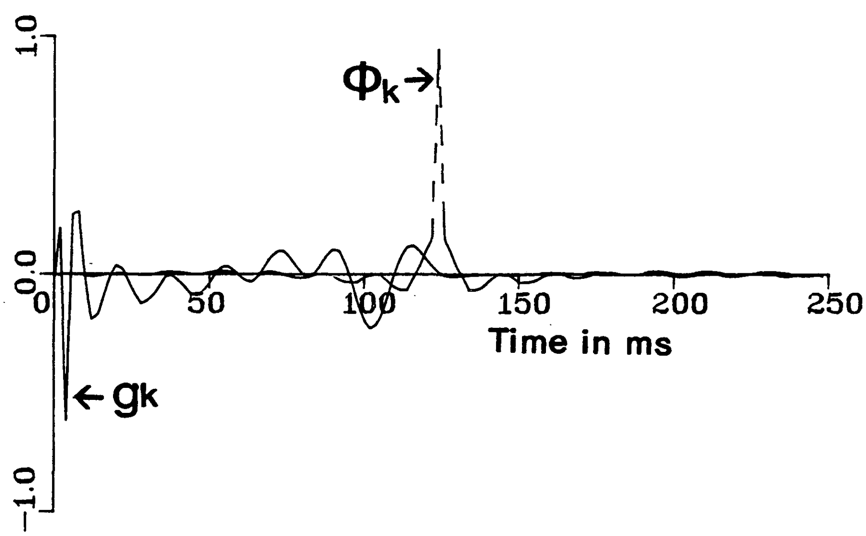

Figure 16. Phase compensator g_k of Klauder wavelet and phase-compensated spiking deconvolution ϕ_k.

deconvolution (ϕ_k) obtained by taking autocorrelation of g. ϕ_k is sharp spike and is shifted by L/2 to position it at the original time zero of the Klauder wavelet.

To the Vaporchoc signature (v) and the watergun signature (w), the same process described above was applied. Stable deconvolution operators (W(v) and W(w)) are obtained (fig. 17 and 19) and sharp spikes (ϕ_v and ϕ_w) are generated at the time origin (fig. 18 and 20).

In case of applying phase-compensated spiking deconvolution to zero-phase seismic data, the result must be delayed by L/2 in order to shift the data to the original time origin. Performance of phase-compensated spiking deconvolution is estimated by computing the CC value between a spike and both the output of spiking deconvolution (g_k, g_v, and g_w) and the output after phase compensation (ϕ_k, ϕ_v, and ϕ_w). These values are listed in Table 1.

In general discussion about allpass phase compensator g, whenever some additive white noise is added in design of deconvolution operator by chance or unnecessarily or some additive natural noise exists on the seismic data, the same amount of additive white noise must be added to allpass phase compensator g. Figure 21 shows the Klauder wavelet (k) and its W-L deconvolution (d_k) with 0.5 % additive white noise. After applying phase compensation with and without 0.5 % additive white noise to the spiking-deconvolved

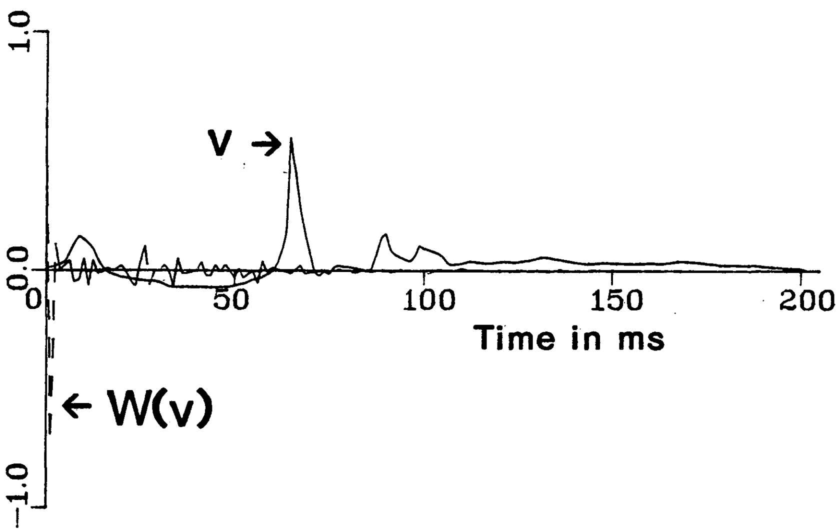

Figure 17. Vaporchoc signature v and Wiener transform W(v).

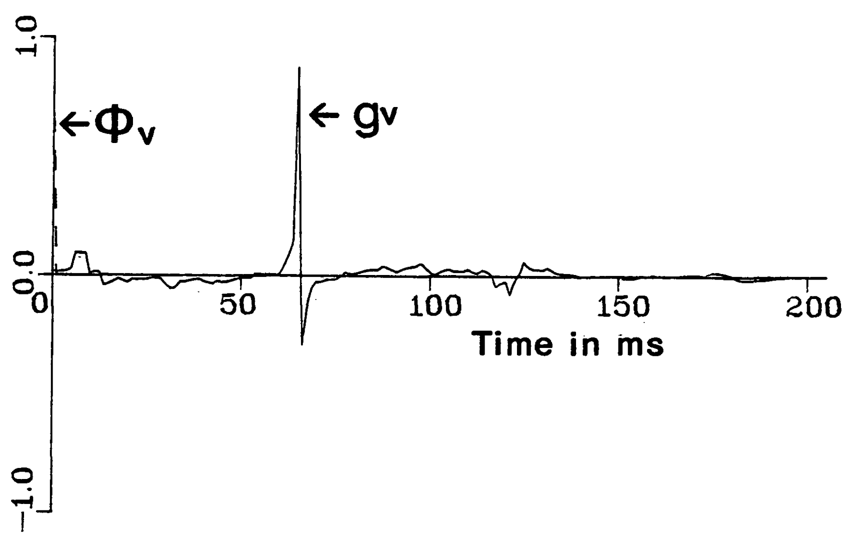

Figure 18. Phase compensator g_v of Vaporchoc signature and phase-compensated spiking deconvolution ϕ_v.

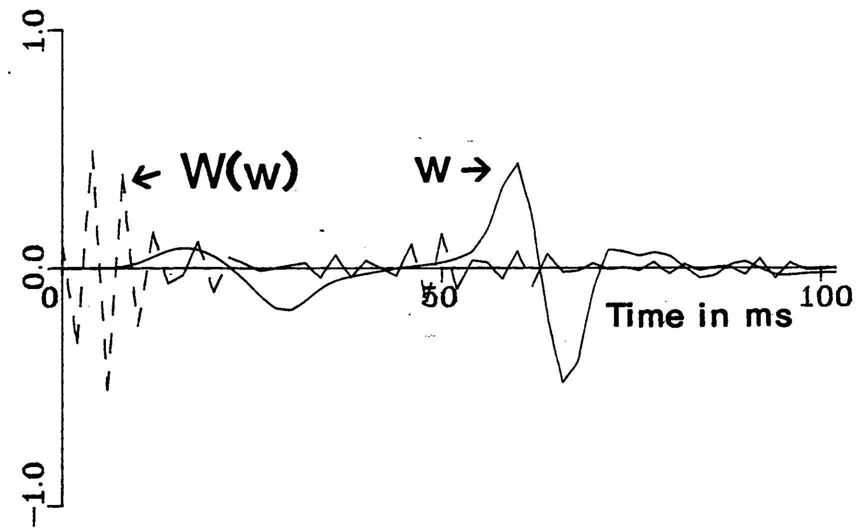

Figure 19. Watergun signature w and its Wiener transform W(w).

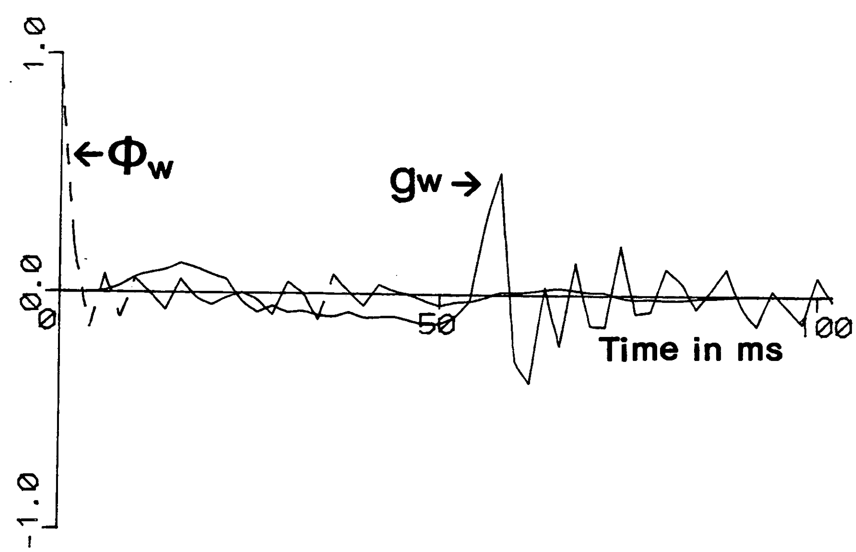

Figure 20. Phase compensator g_w of watergun signature and phase-compensated spiking deconvolution ϕ_w.

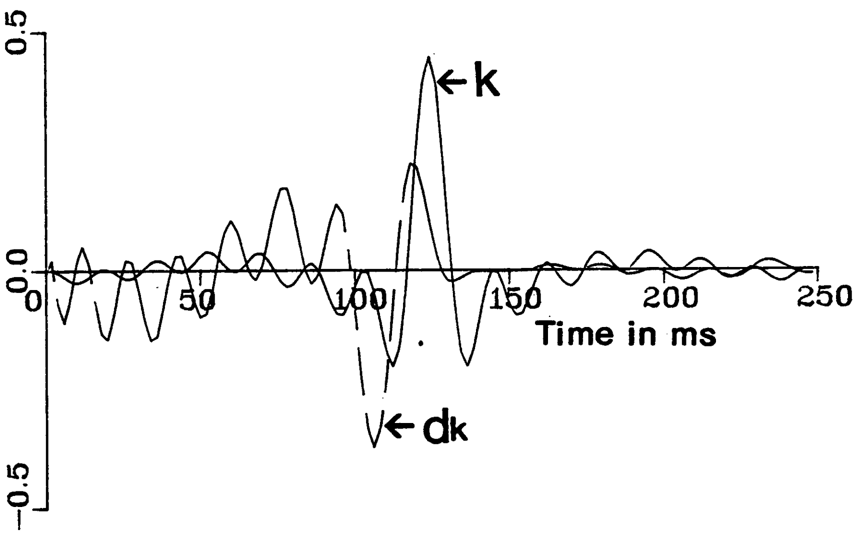

Figure 21. Klauder wavelet k and spiking deconvolution d_k with 0.5 % additive white noise.

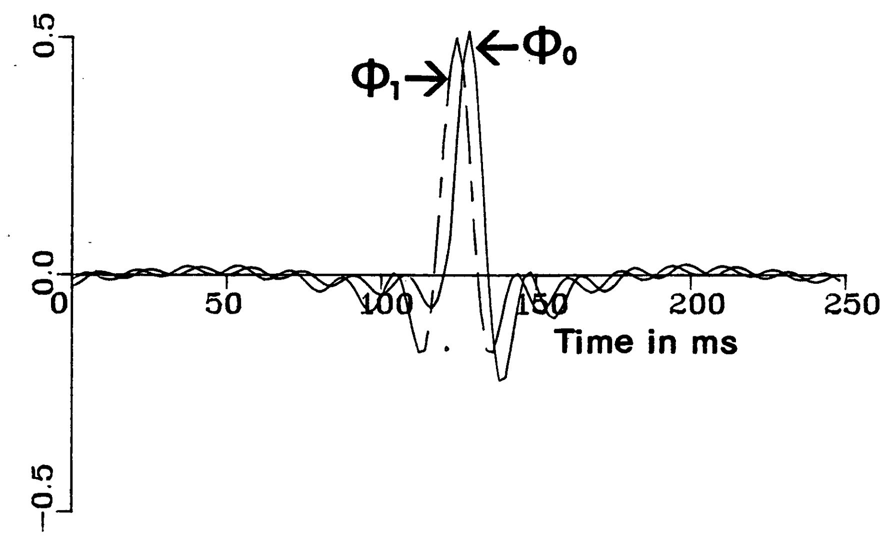

Figure 22. Phase compensation of deconvolved-Kláuder wavelet d_k with and without 0.5 % additive white noise (ϕ_1, ϕ_0).

Seismic source	Klauder wavelet	Vaporchoc signature	Watergun signature
CC value after deconvolution	0.265	0.877	0.517
CC value after phase compensation	0.947	0.999	0.934

Table 1. Correlation coefficient between spike and both output of spiking deconvolution and output after phase compensation for three types of nonminimum-phase wavelets

Klauder wavelet, these results are superimposed and shown (ϕ_1 and ϕ_0) in figure 22. Although ϕ_1 obtained adding 0.5 % white noise is not so sharp spike which seems to be the effect by 0.5 % white noise addition, it appears at the correct location and its waveform is nearly symmetric. On the other hand, ϕ_0 which is generated without 0.5 % additive white noise has phase-distorted waveform. This demonstrates that the phase compensator should contain the same amount of additive white noise as that of W-L deconvolution operator in order to compensate for phase distortion introduced by W-L deconvolution.

Inverse Attenuation Filter

In order to correct the time variance of the seismic data, which is introduced by time-variant earth's attenuation, the time-variant inverse attenuation filter must be applied to the seismic data before deconvolution. The time-variant attenuation filter and its inverse filter are also obtained by making use of the Wiener transform, as described by Hato and Sengbush (1986). This algorithm is based on attenuation being a minimum-phase filter.

Attenuation studies by McDonal et al (1958) show that the linear law given by $\ln[A(f;x)] = \alpha f x$ holds, where x is the distance travelled and α is the characteristic attenuation constant for earth material through which the seismic wave has travelled. Wuenschel (1965) used McDonal et al's experimental data and showed that the causal filter due to Futterman (1962) predicted accurately the far field pulse waveform from the near field pulse waveform.

The powerful validity of the Wiener transform for generating minimum-phase attenuation filters using McDonal et al's data and their linear law is demonstrated here. The far-field pulse waveform after 399.7 feet of vertical travel is estimated by applying to the near-field pulse waveform both minimum-phase attenuation filter calculated by Wiener transform and zero-phase attenuation filter. The results are superimposed on the observed far-field pulse waveform (fig. 23), and show that the minimum-phase attenuation filter predicts the attenuated pulse waveform much more precisely than does the zero-phase filter. The attenuation constant that gave the best estimate, 1.40×10^{-5}, was obtained by finding the maximum CC value between observed far-field pulse waveform and predicted far-field pulse waveform. The CC values were computed for attenuation constants ranging from 0.88×10^{-5} to 1.88×10^{-5} (fig. 24). McDonal's estimate of the attenuation constant, 1.38×10^{-5}, is also indicated.

Phase velocity with respect to frequency V(f) was computed by using

$$V(f) = \frac{2\pi f X}{\theta_m(f) + 2\pi f T}, \tag{12}$$

where x is distance traveled, T is difference in onset times, and $\theta_m(f)$ is minimum phase lag of the attenuation filter. The result shown in figure 25 compares favorably with those obtained by Wuenschel.

In the optimal deconvolution which will be described in the next chapter, the algorithm for generating inverse attenuation filter will be used. This algorithm is summarized as follows:

1) Estimate the time-variant amplitude spectrum of the attenuation filter [A(f;τ)] from the seismic data,

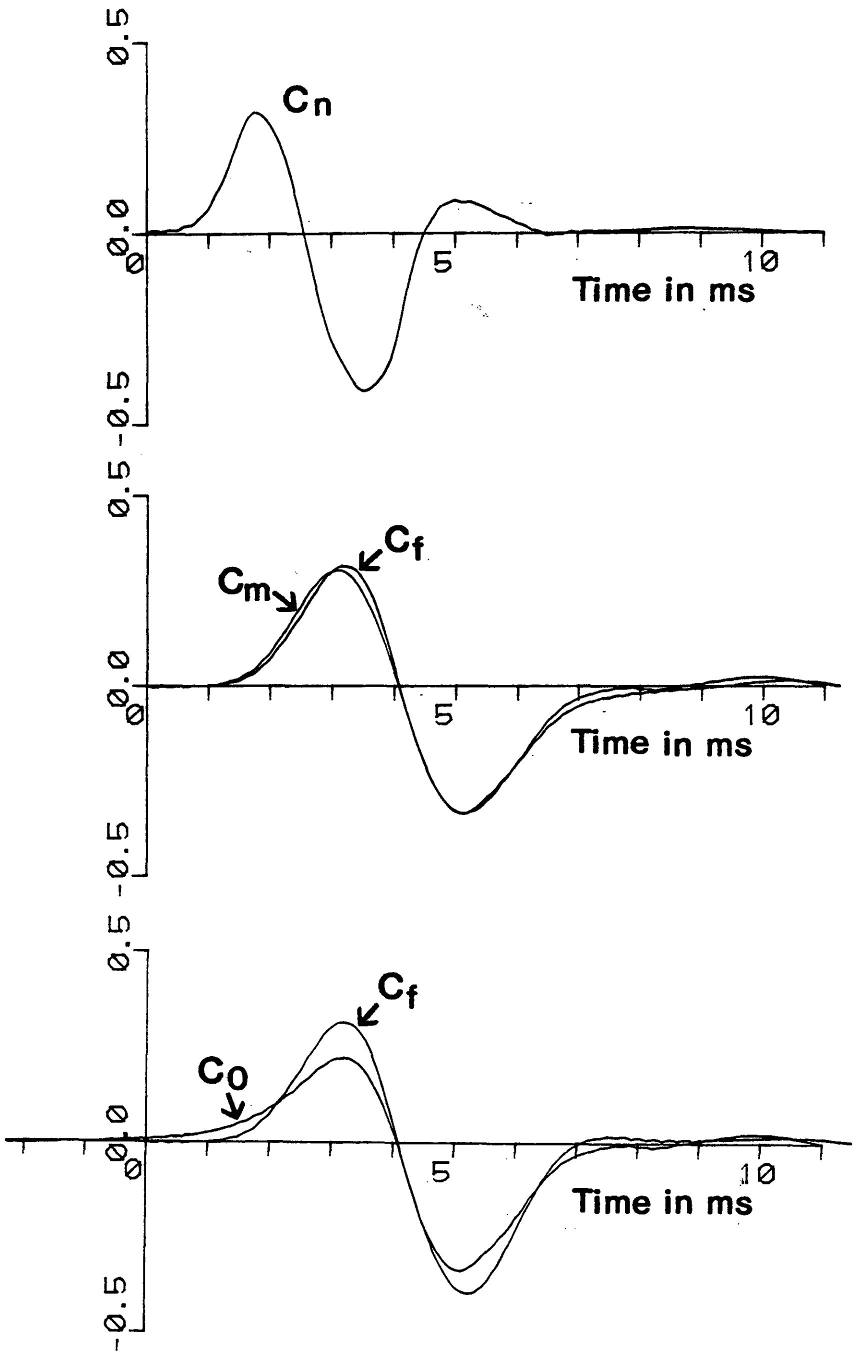

Figure 23. Observed far-field pulse (c_f) and predicted pulses (c_m and c_0) obtained by applying minimum-phase and zero-phase attenuation filter to observed near-field pulse (c_n).

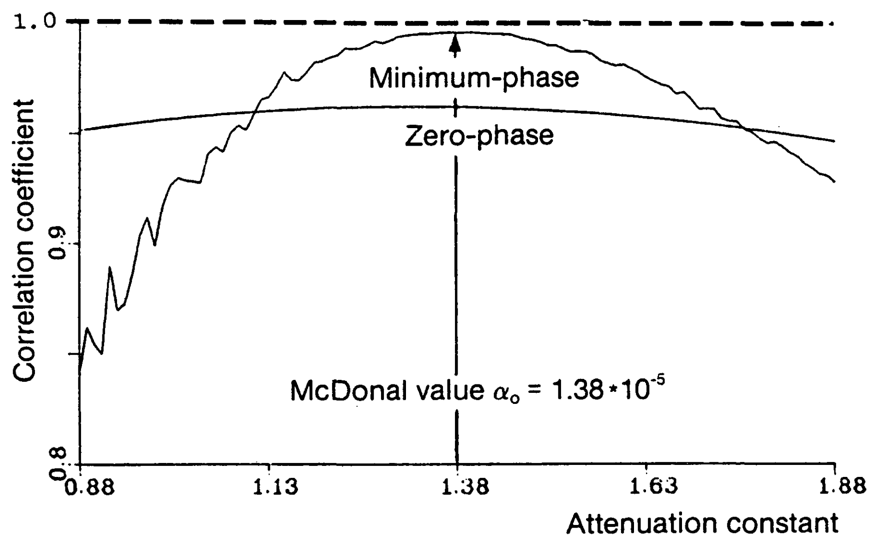

Figure 24. Correlation coefficient between observed pulse and predicted pulse by changing attenuation constant.

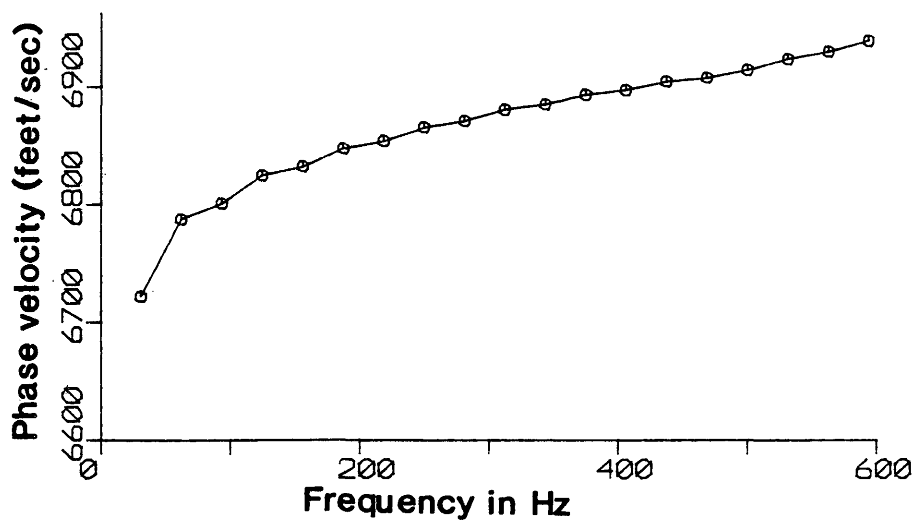

Figure 25. Phase velocity vs frequency calculated by using optimized attenuation filter from McDonal et al's experimental data.

where time-variance is indicated by record time τ.

2) Compute the time-variant zero-phase attenuation filter $a_0(t;\tau)$ using the inverse Fourier transform.

3) Compute the time-variant inverse of the minimum-phase equivalent, a_m^{-1}, using the Wiener transform, $W(a_0) = a_m^{-1}$.

4) Apply the time-variant inverse to the data to compensate for attenuation.

OPTIMAL DECONVOLUTION

Optimal Deconvolution

According to the facts criticized in the former chapter, in order to simplify and unify complicated problems and then to build the optimal deconvolution for all kinds of seismic data, a time-variant (written as TV) inverse attenuation filter followed by phase-compensated spiking deconvolution is proposed, which is called S-H deconvolution hereafter. The processing steps are summarized as follows:

1) To suppress the noise as much as possible before applying deconvolution,
2) To apply the TV inverse attenuation filter to the seismic data in order to correct for time variance,
3) To apply W-L spiking deconvolution without additive white noise,
4) To apply the allpass phase compensator to the spiking-deconvolved data in order to compensate for phase distortion introduced by applying W-L spiking deconvolution to nonminimum-phase data,
5) To apply the bandlimited desired seismic pulse to phase-compensated spiking-deconvolved data.

The schematic diagram of S-H deconvolution is shown in figure 26.

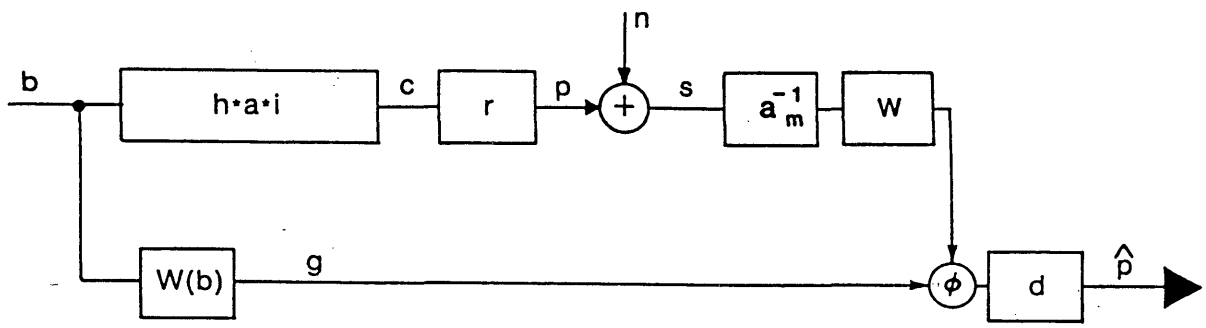

Figure 26. Schematic diagram of S-H deconvolution.

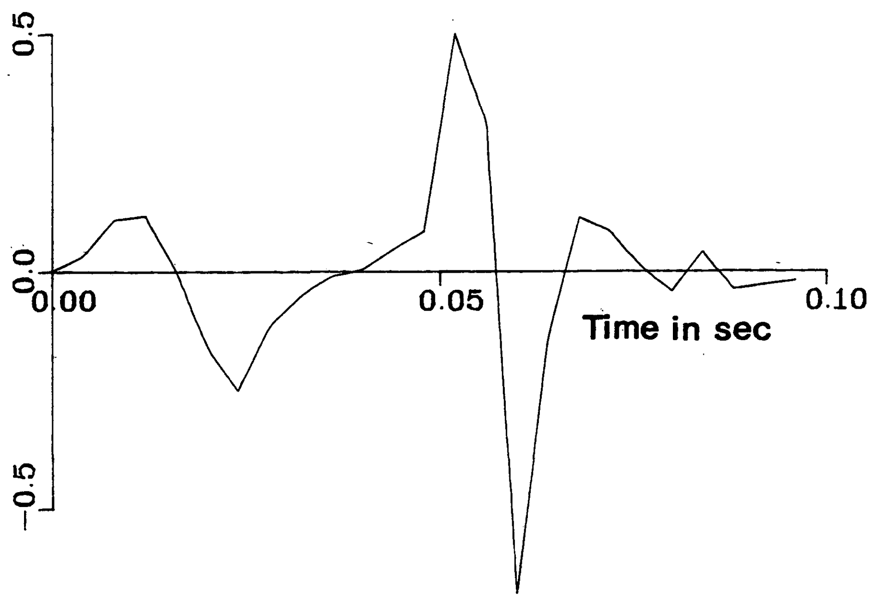

Figure 27. Resampled (2 msec to 4 msec) watergun signature.

Convolutional Model

The seismic trace can be expressed as the following convolutional model,

$$s = r * b * h * i * a + n, \tag{13}$$

where r is reflectivity, b is the known source wavelet (nonminimum phase), h is due to ghosts and reverberations (minimum phase), i is the instrument response (nonminimum phase), a is TV earth's attenuation filter (minimum phase) and n is additive natural noise.

In general, a nonminimum-phase character of the instrument response will be easily corrected to the minimum-phase character because the instrument response is usually well-known. In addition, minimum-phase filtering effects do not introduce any problem in the W-L deconvolution if additive noise is not applied. Therefore the convolutional model of the seismic data can be simplified as follows:

$$s = r * b * a + n. \tag{14}$$

At the first step, the TV inverse attenuation filter a^{-1} is applied to correct the time variance of the seismic data,

$$s * a^{-1} = r * b * a * a^{-1} + n * a^{-1}. \tag{15}$$

At the second step, W-L spiking deconvolution is applied, which converts all filters to the inverses of their minimum-phase equivalents,

$$s * a^{-1} * w = r * b * b_m^{-1} + n * a^{-1} * b_m^{-1}. \tag{16}$$

At the third step, the allpass phase compensator g, which is convolution of b with W(b), is correlated with the seismic trace,

$$s * a^{-1} * w \,\phi\, g = r * b * b_m^{-1} \,\phi\, g + n * a^{-1} * b_m^{-1} \,\phi\, g, \qquad (17)$$

where ϕ is crosscorrelation operation.

At the final step, the desired seismic pulse, the d-filter, is convolved with the seismic trace to bandlimit the noise,

$$s * a^{-1} * w \,\phi\, g * d = r * d + n * a^{-1} * b_m^{-1} \,\phi\, g * d. \qquad (18)$$

Simulation Using Dense Reflectivity and Watergun Signature

To study the performance of S-H deconvolution for nonminimum-phase data, the computer simulation was done using a watergun signature, which is the SODERA S-80 watergun signature resampled by 4 msec (fig. 27), and a dense reflectivity function (fig. 28), which is generated from well data.

The desired seismic pulse was designed as 45 points in length and 4 msec sampling and its frequency band is trapezoidal specified by 5/6 and 60/65 Hz (fig. 29).

The amplitude spectrum of the attenuation filter is assumed as $\exp(-\alpha f V \tau)$, where α is the attenuation constant, τ is two-way travel time, V is an average velocity at time

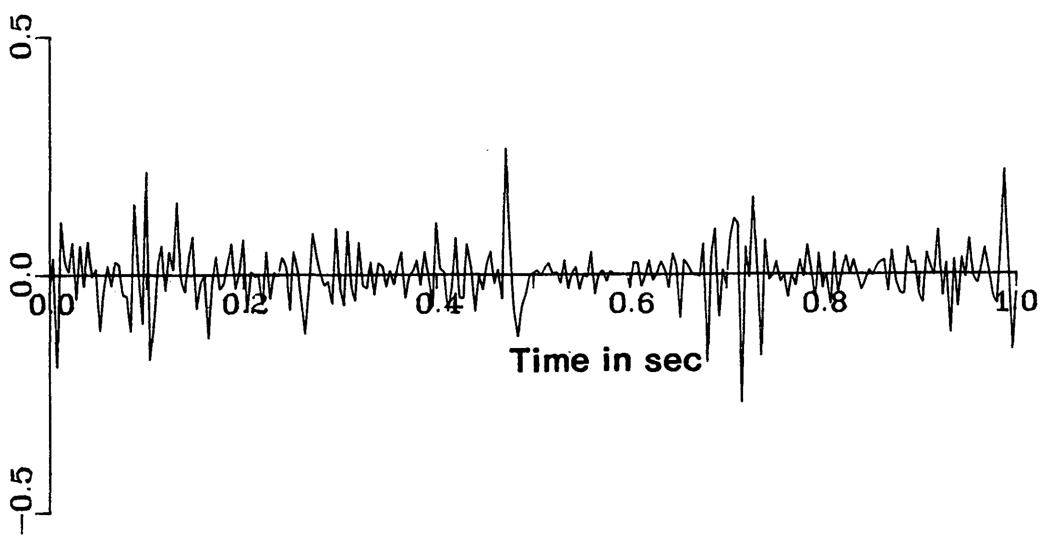

Figure 28. Reflectivity function for dense model.

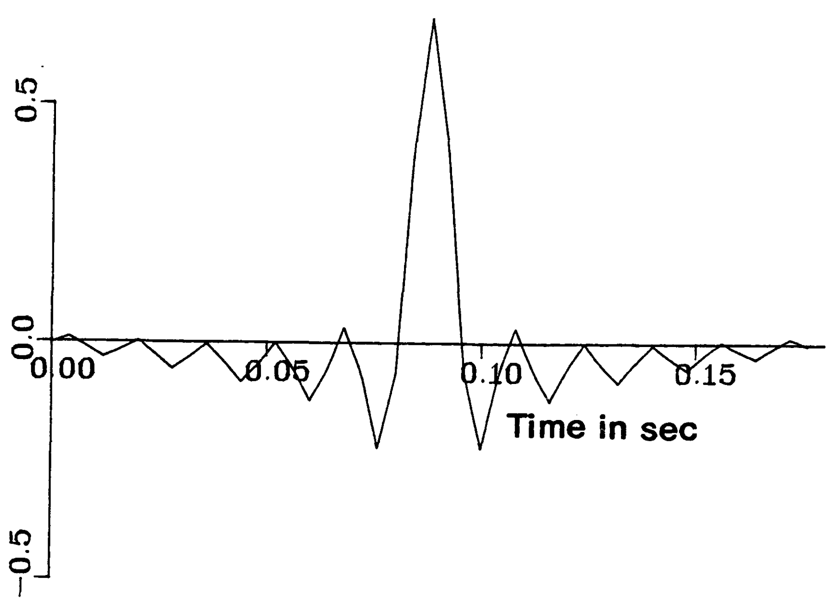

Figure 29. Desired seismic pulse (d-filter)

τ, and f is frequency in Hertz. In this simulation, the attenuation filter and inverse attenuation filter were designed as 32 points with 4 msec sampling rate.

Three attenuation cases are considered, with 0.02, 0.05, and 0.1 used as the attenuation constant for low attenuation, moderate attenuation, and high attenuation case, respectively. Velocity V is always assumed 1.0 in each attenuation case.

The amplitude spectrum of TV attenuation filter and of TV inverse attenuation filter at two different reference times (τ = 0.5 and 1.0) in case of moderate attenuation are shown in figure 30 and 31. A zero-phase attenuation filter (a_0), a minimum-phase attenuation filter (a_m), and a minimum-phase inverse attenuation filter (a_m^{-1}) at two different reference times (τ = 0.5 and 1.0) in case of moderate attenuation are shown in figure 32 and 33, respectively.

When doing computer simulation, four different types of deconvolution, spiking deconvolution (called SP deconvolution in tables) with and without additive white noise, gapped deconvolution (called GP deconvolution in tables), and S-H deconvolution were applied to both natural noise-free and 3 % natural noise-added dense watergun model traces for the following attenuation cases: 1) low attenuation, 2) moderate attenuation, and 3) high

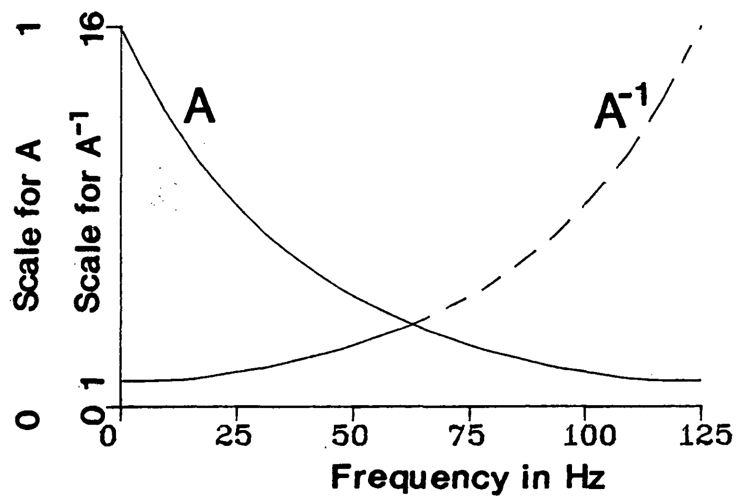

Figure 30. Amplitude spectrum of attenuation and inverse attenuation filter at 0.5 sec (α=0.05) (A and A^{-1}).

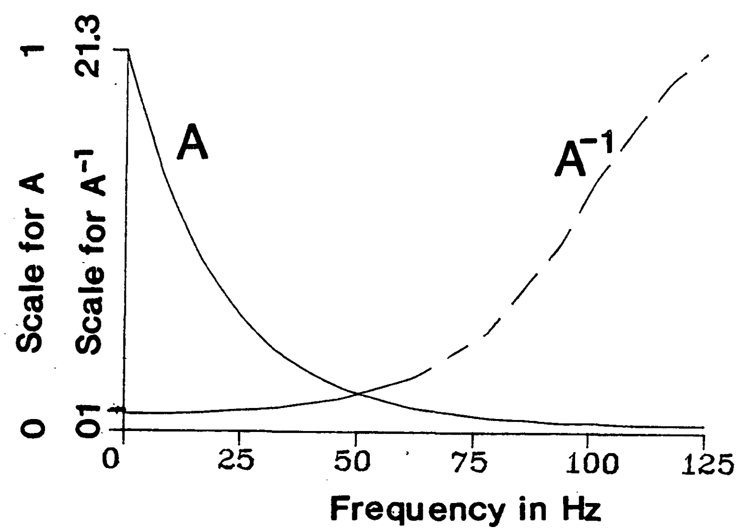

Figure 31. Amplitude spectrum of attenuation and inverse attenuation filter at 1.0 sec (α=0.05) (A and A^{-1}).

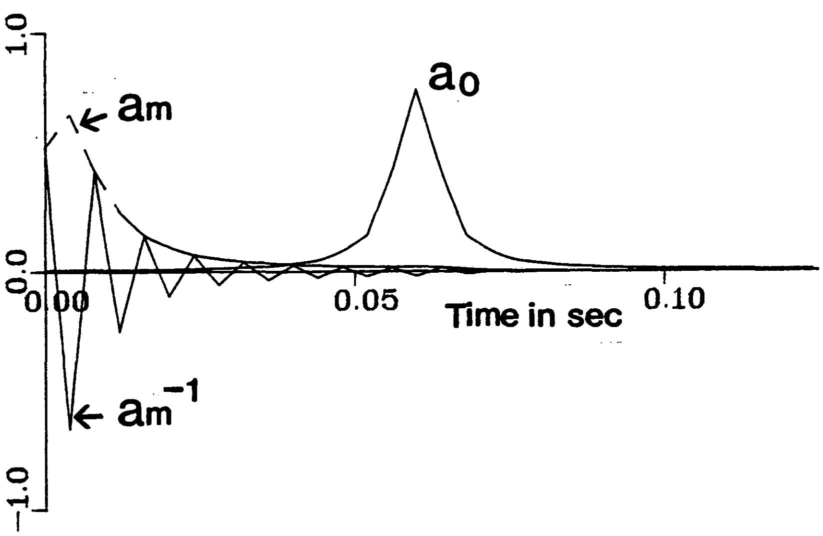

Figure 32. Zero-, minimum-, and inverse minimum-phase attenuation filter at 0.5 sec (α=0.05) (a_0,a_m,a_m^{-1}).

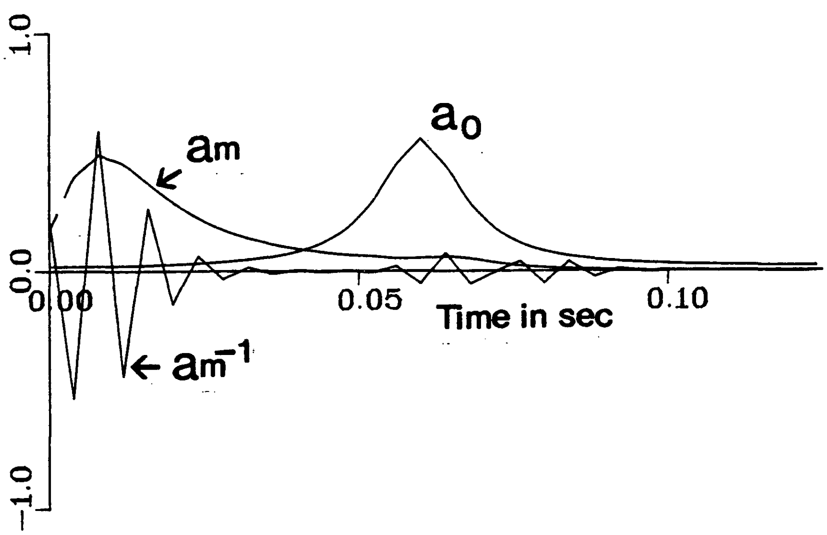

Figure 33. Zero-,minimum-, and inverse minimum-phase attenuation filter at 1.0 sec (α=0.05) (a_0,a_m,a_m^{-1}).

attenuation. Additive natural noise is obtained from a pseudo-Gaussian random number generator and shown in figure 34. After deconvolution, the d-filter was applied and some selected output traces will be displayed.

The desired output trace, which is the convolution of reflectivity with d-filter, is shown in figure 35 and remarkable reflection events are seen at 0.45 seconds and at 0.7 seconds (arrows mark E1 and E2).

In order to study the effect of various deconvolution methods on TV attenuated data without applying the TV inverse attenuation filter, no deconvolution, which is generated by applying only the d-filter, spiking deconvolution without and with 5 % white noise, gapped deconvolution with 10 points gap, and S-H deconvolution were applied to the dense watergun model trace ($r*b*a(\tau)$), which was TV attenuated by using moderate attenuation constant ($\alpha=0.05$), with and without 3 % additive natural noise. The output of each deconvolution in the natural noise-free case convolved with the d-filter is shown in figures 36 through 40. As can be seen in figure 40, output of S-H deconvolution has relatively well-recovered reflection events (E1 and E2). On the other hand, outputs of other deconvolutions have large phase shift and severe waveform distortion.

The same deconvolutions were also applied to TV

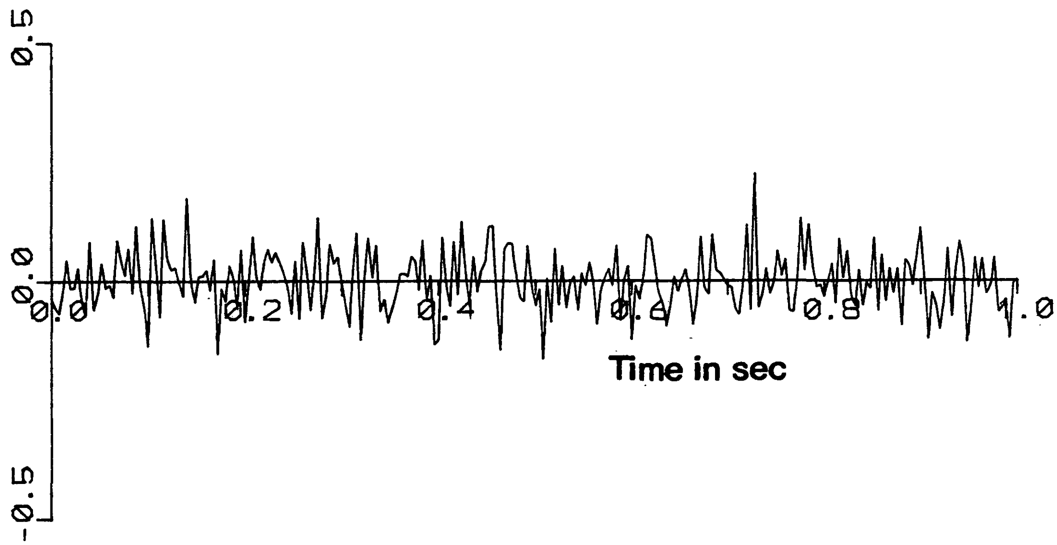

Figure 34. Additive natural noise.

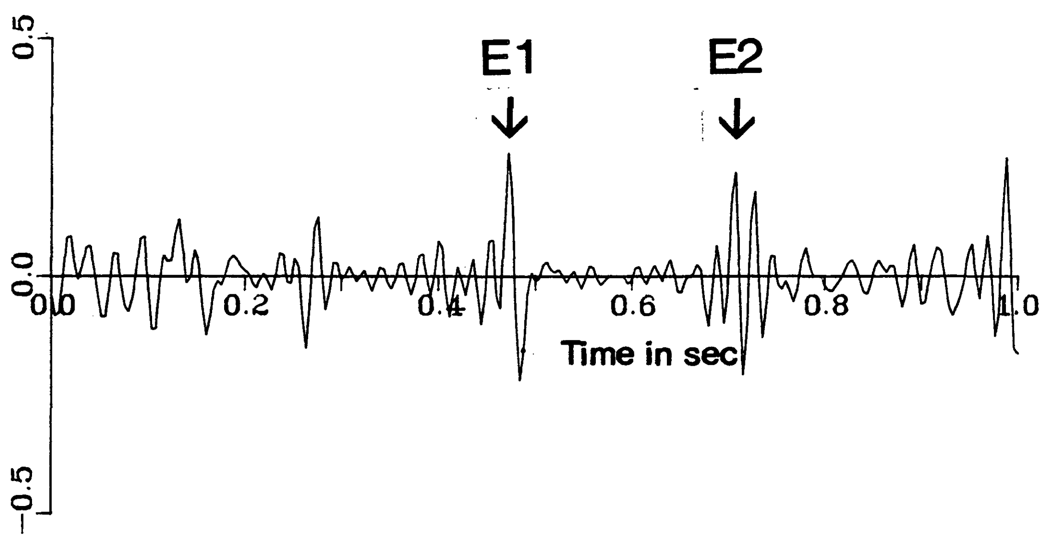

Figure 35. Desired output of dense watergun model.

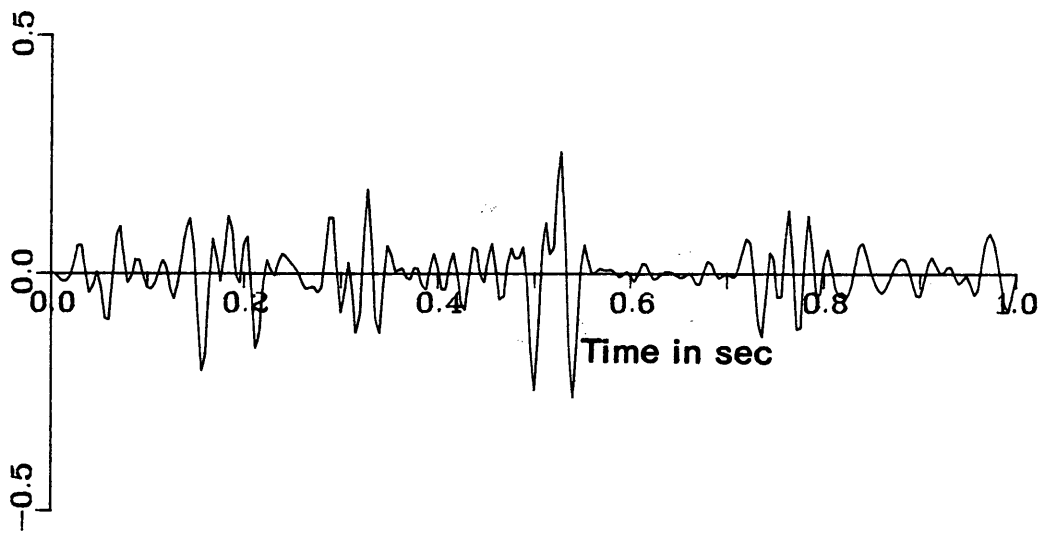

Figure 36. No deconvolution output for TV attenuated dense watergun model.

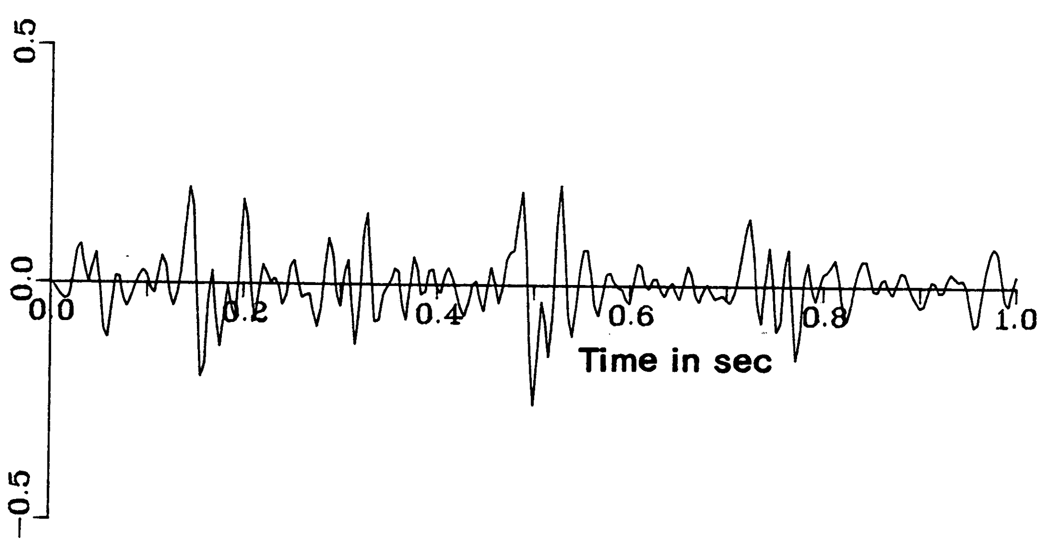

Figure 37. Spiking deconvolution for TV attenuated dense watergun model.

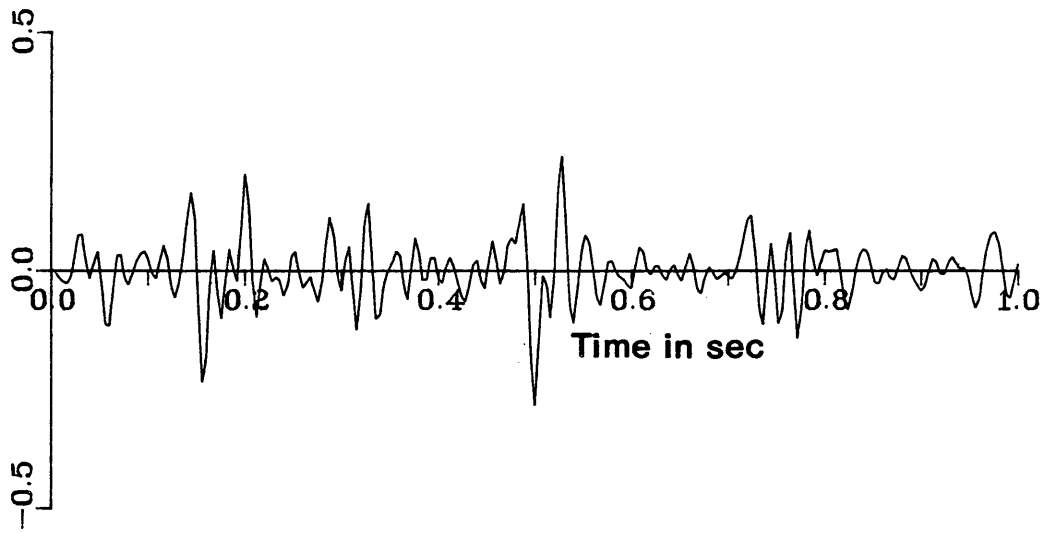

Figure 38. Spiking deconvolution with 5 % additive white noise for TV attenuated dense watergun model.

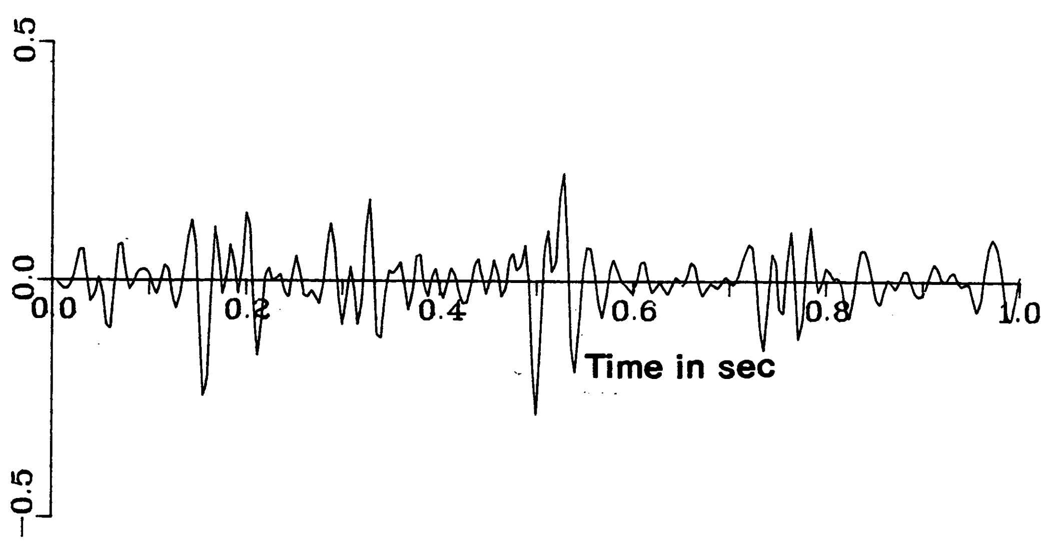

Figure 39. Gapped deconvolution (gap = 10 points) for TV attenuated dense watergun model.

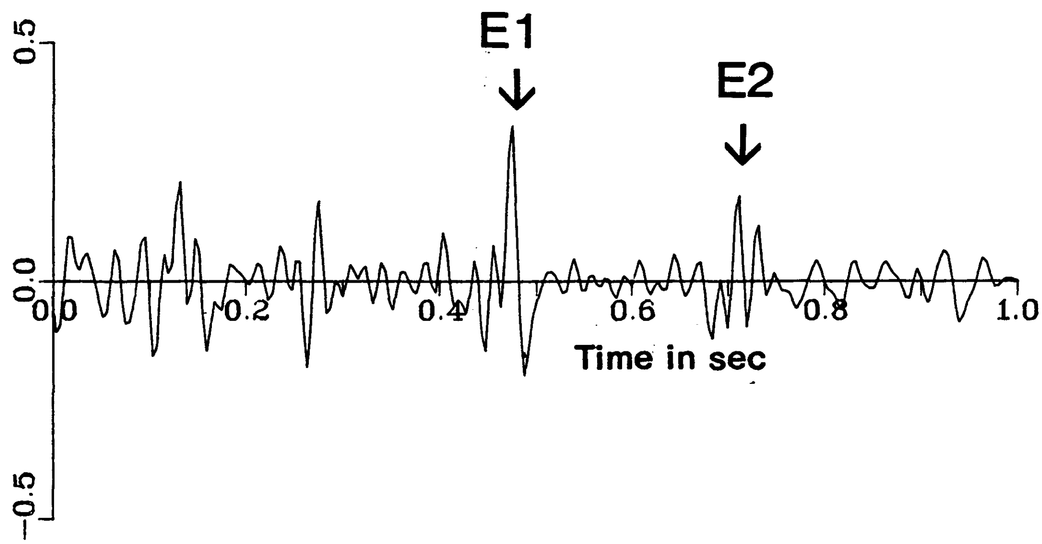

Figure 40. S-H deconvolution for TV attenuated dense watergun model.

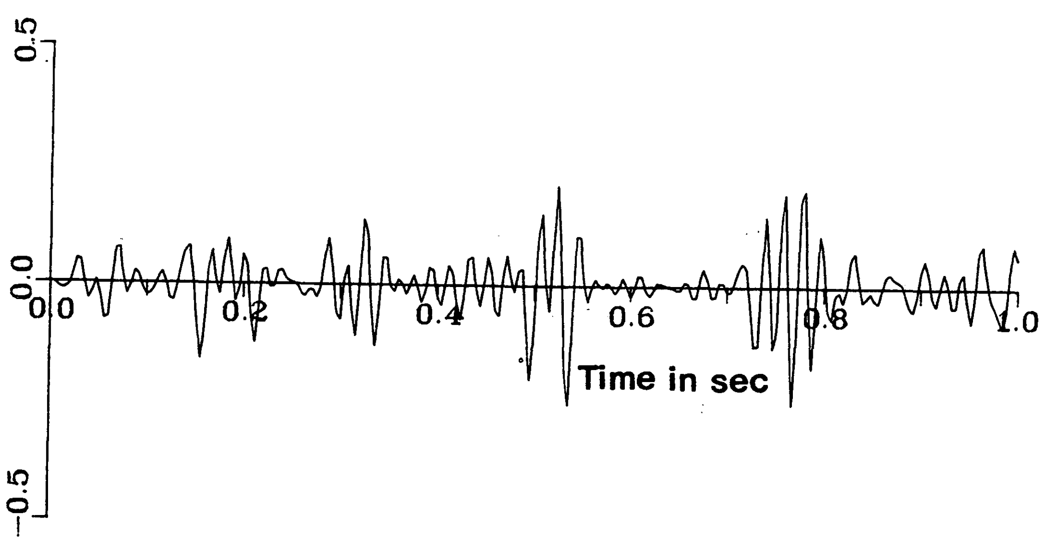

Figure 41. No deconvolution output for TV inverse-attenuated dense watergun model.

inverse-attenuated dense watergun model trace $((r*b*a(\tau)*a^{-1}(\tau))$ with and without 3 % additive natural noise. Each output in the natural noise-free case convolved with the d-filter are shown in figures 41 through 45. As in the previous simulation, only S-H deconvolution can recover reflection events E1 and E2 for TV inverse-attenuated trace.

In order to show the superiority of S-H deconvolution quantitatively, the CC value and relative time shift between the desired output and each deconvolution output convolved with d-filter were calculated for the following 4 different types of inputs; with and without TV inverse attenuation filter, and with and without 3 % natural noise. These results are tabulated on tables 2 through 5. The value inside parenthesis indicates the relative time shift (in samples) of the deconvolution output with respect to the desired output.

In the natural noise-free case without TV inverse attenuation filter (table 2), S-H deconvolution has the largest CC values, 0.66 and 0.52, for moderate and high attenuation, respectively. For low attenuation, the CC value of no deconvolution is 0.75 and largest, but its output has large time shift (13); on the other hand, the CC value of S-H deconvolution is 0.73 and it has no time shift. In the 3 % natural noise-added case without TV inverse attenuation filter (table 3), the same results are also

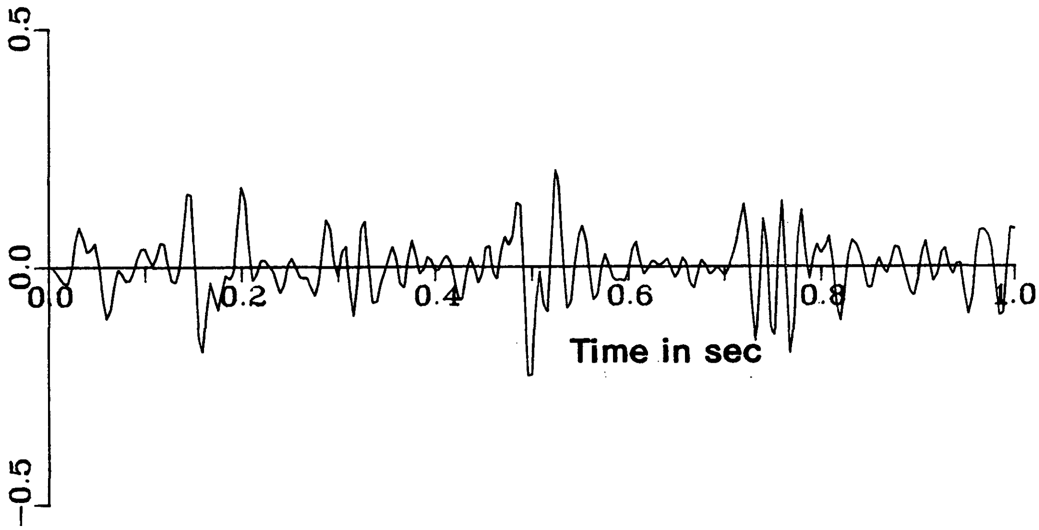

Figure 42. Spiking deconvolution for TV inverse-attenuated dense watergun model.

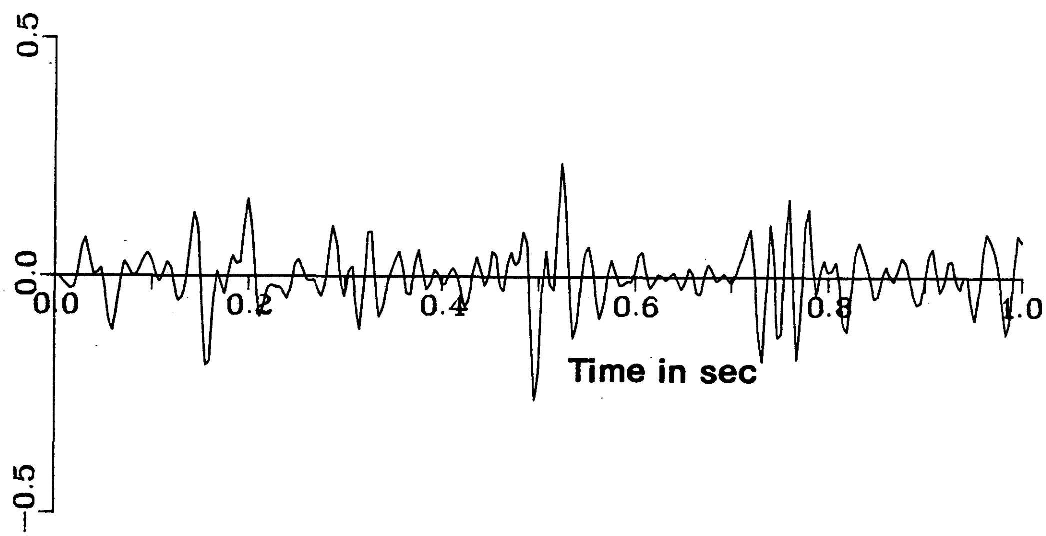

Figure 43. Spiking deconvolution with 5 % noise for TV inverse-attenuated dense watergun model.

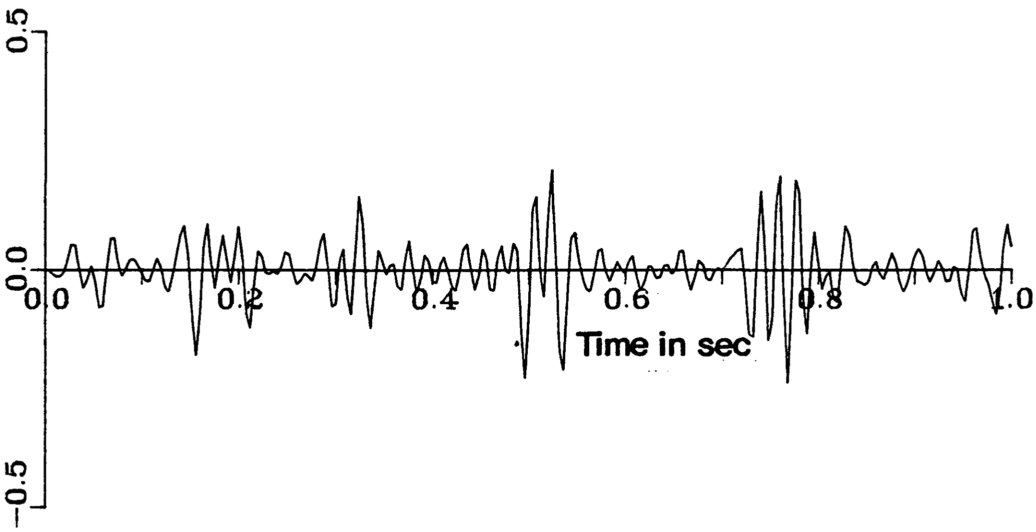

Figure 44. Gapped deconvolution (gap=10 points) for TV inverse-attenuated dense watergun model.

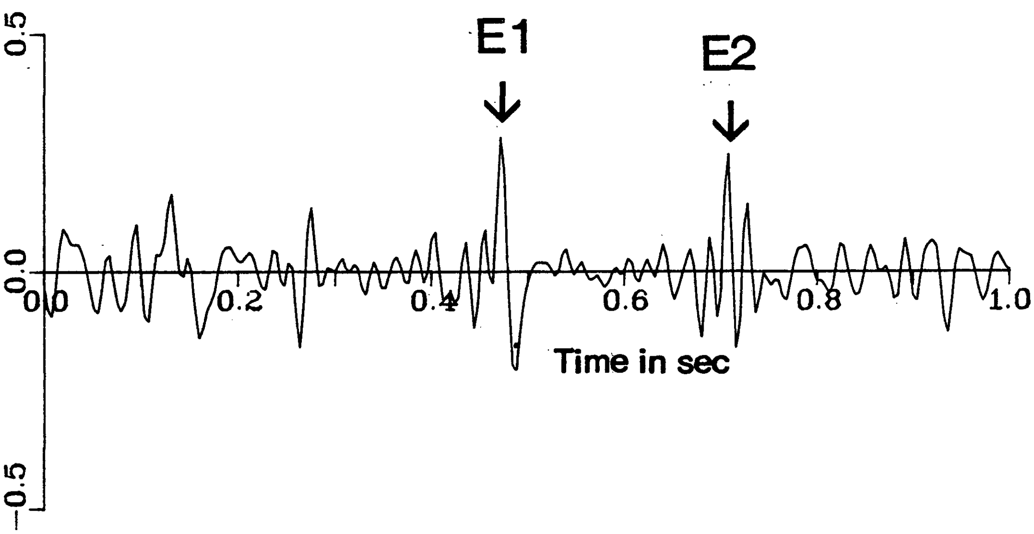

Figure 45. S-H deconvolution for TV inverse-attenuated dense watergun model.

Attenuation constant	0.02	0.05	0.1
No deconvolution	0.75 (13)	0.64 (14)	0.51 (14)
SP deconvolution	0.50 (4)	0.45 (4)	0.35 (4)
SP deconvolution with 5 % noise	0.61 (13)	0.45 (4)	0.34 (14)
GP deconvolution (gap=10 points)	0.71 (13)	0.54 (14)	0.43 (14)
S-H deconvolution	0.71 (0)	0.66 (1)	0.52 (1)

Table 2. Correlation coefficient between desired output and each deconvolution output without TV inverse attenuation filter for dense watergun model without natural noise

Attenuation constant	0.02	0.05	0.1
No deconvolution	0.75	0.64	0.51
	(13)	(14)	(14)
SP deconvolution	0.50	0.45	0.35
	(4)	(4)	(4)
SP deconvolution with 5 % noise	0.62	0.45	0.34
	(13)	(14)	(14)
GP deconvolution (gap=10 points)	0.71	0.54	0.43
	(13)	(14)	(14)
S-H deconvolution	0.73	0.65	0.53
	(0)	(1)	(1)

Table 3. Correlation coefficient between desired output and each deconvolution without TV inverse attenuation filter for dense watergun model with 3 % natural noise.

Attenuation constant	0.02	0.05	0.1
No deconvolution	0.75 (13)	0.76 (13)	0.75 (13)
SP deconvolution	0.56 (13)	0.56 (13)	0.56 (13)
SP deconvolution with 5 % noise	0.67 (13)	0.67 (13)	0.67 (13)
GP deconvolution (gap=10 points)	0.72 (13)	0.72 (13)	0.71 (13)
S-H deconvolution	0.85 (0)	0.85 (0)	0.85 (0)

Table 4. Correlation coefficient between desired output and each deconvolution output with TV inverse attenuation filter for dense watergun model without natural noise.

Attenuation constant	0.02	0.05	0.1
No deconvolution	0.75 (13)	0.75 (13)	0.74 (13)
SP deconvolution	0.56 (13)	0.53 (13)	0.55 (13)
SP deconvolution with 5 % noise	0.68 (13)	0.67 (13)	0.67 (13)
GP deconvolution (gap=10 points)	0.72 (13)	0.72 (13)	0.71 (13)
S-H deconvolution	0.85 (0)	0.83 (0)	0.84 (0)

Table 5. Correlation coefficient between desired output and each deconvolution output with TV inverse attenuation filter for dense watergun model with 3 % natural noise.

obtained. All other deconvolutions have large time shift. Gapped deconvolution, which has been often used as deconvolution of nonminimum-phase data, has small CC value and large time shift value (14) for moderate and high attenuation cases.

In both the natural noise-free and noise-added cases, inclusion of the TV inverse attenuation filter increases the CC value of S-H deconvolution for each attenuation case; the value is always greater than 0.83 and time shift is always zero (table 4 and 5). The CC values of all other deconvolutions also increase due to the TV inverse attenuation filter, but they still have large phase distortion.

From these results, it is realized that S-H deconvolution always gives the best result even if time variance in the data was not compensated by applying the TV inverse attenuation filter.

Mismatched Attenuation Constant

In the former section, TV inverse attenuation filter was always designed by using matched attenuation constant used in TV attenuation filtering. However, it is difficult to estimate the exact attenuation constant from the real seismic data in practical seismology.

In this section, using the same data used in the dense watergun model, the same deconvolution processes were applied to the TV attenuated trace ($\alpha=0.05$) by changing the attenuation constant ($\alpha=0.025$ for underestimation case and $\alpha=0.1$ for overestimation case) in the TV inverse attenuation filter. The CC value between the desired output and each deconvolution output convolved with d-filter are presented in table 6.

In the overestimation case, the CC value of S-H deconvolution is 0.68 and is not largest but only S-H deconvolution has no time shift. On the other hand, in the underestimation case, S-H deconvolution has the largest CC value, 0.73, and its time shift value is 0.

Outputs of S-H deconvolution by overestimating and underestimating the attenuation constant are shown in figure 46 and 48, respectively. In order to compare performance of SH deconvolution visually, spiking deconvolution was applied to the same overestimation and underestimation trace and these output are shown in figure 47 and 49, respectively.

S-H deconvolution recovers event E1 relatively well in the overestimation case, and recovers both events E1 and E2 well in case of underestimation. On the other hand, spiking deconvolution does not restore both events, especially in the overestimation case. In the output of spiking deconvolution in the underestimation case, some wave packets can be recognized at times close to reflection

Attenuation constant	0.05	0.05
Inverse attenuation constant	0.1	0.025
No deconvolution	0.72 (13)	0.51 (12)
SP deconvolution	0.48 (4)	0.59 (13)
SP deconvolution with 5 % noise	0.59 (13)	0.60 (13)
GP deconvolution (gap=10 points)	0.68 (13)	0.57 (12)
S-H deconvolution	0.68 (0)	0.73 (0)

Table 6. Correlation coefficient between desired output and each deconvolution output for dense watergun model without natural noise by underestimated and overestimated attenuation constant.

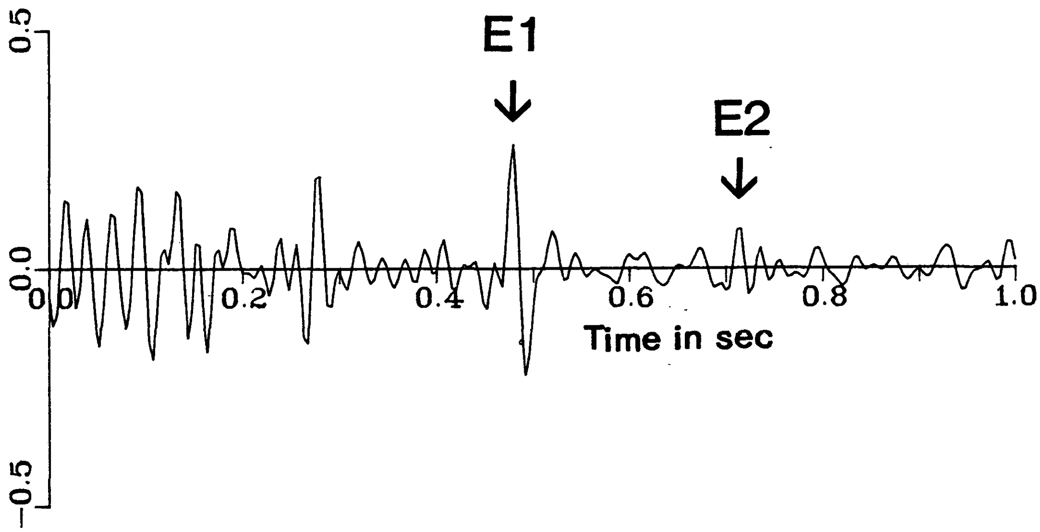

Figure 46. S-H deconvolution for dense watergun model by overestimated attenuation constant.

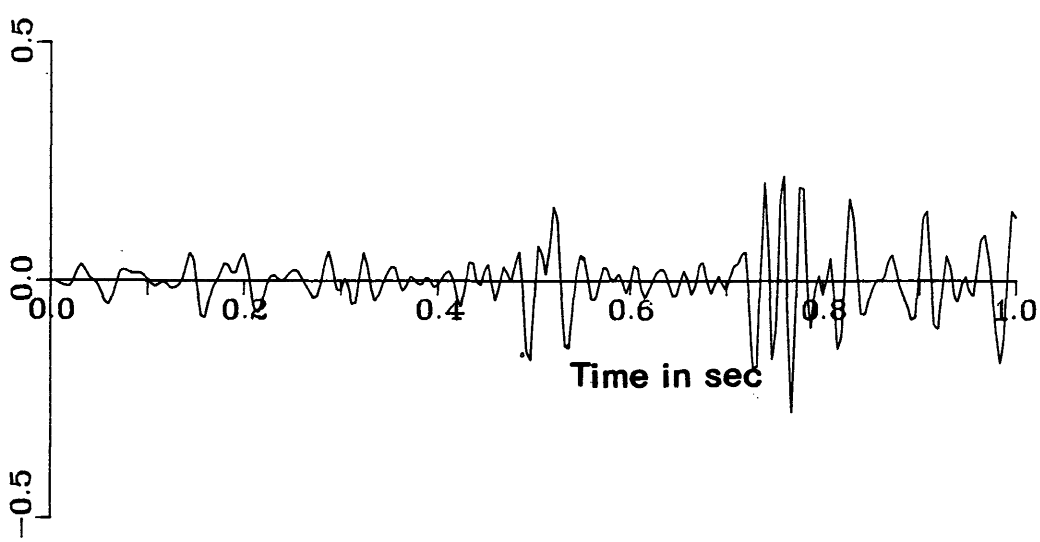

Figure 47. Spiking deconvolution for dense watergun model by overestimated attenuation constant.

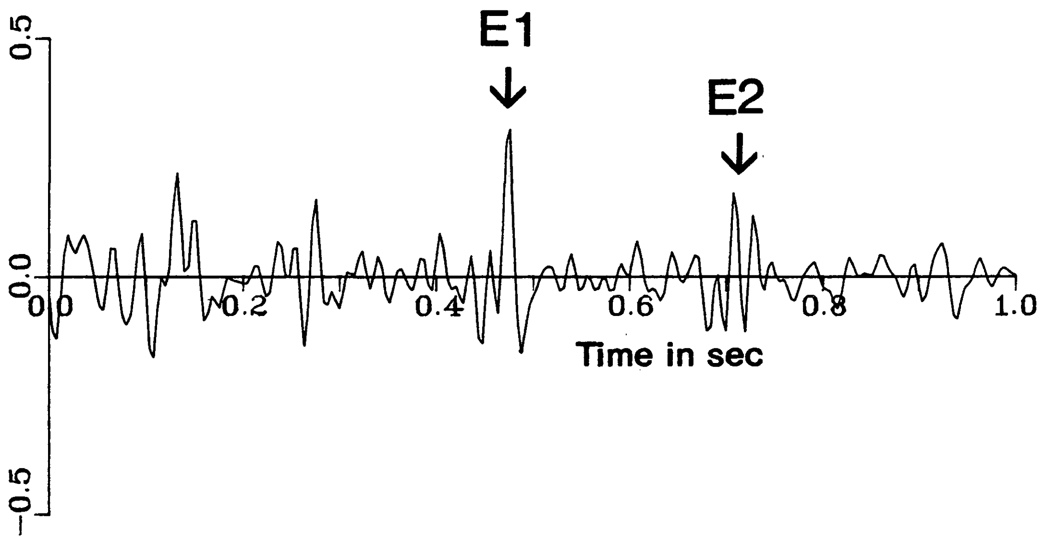

Figure 48. S-H deconvolution for dense watergun model by underestimated attenuation constant.

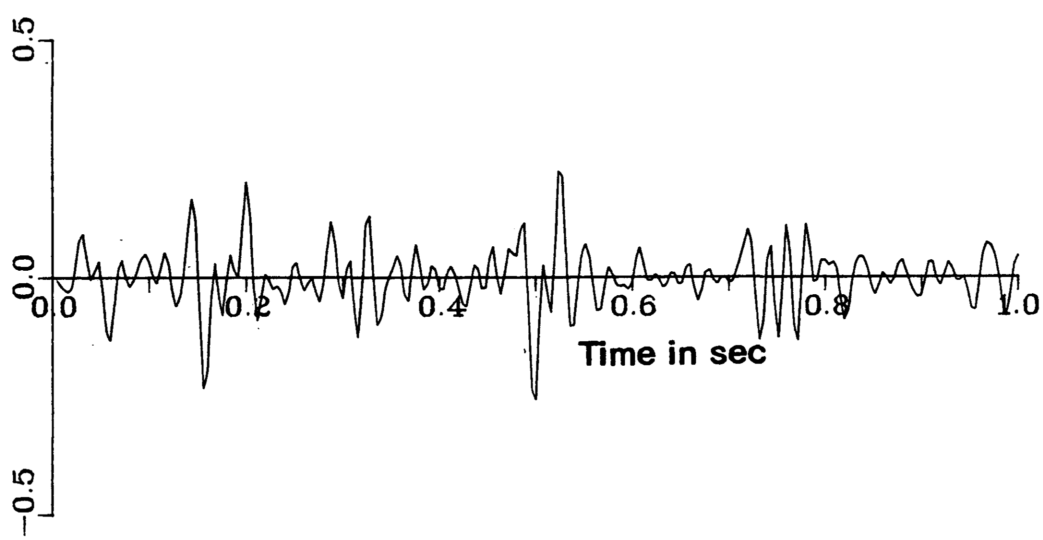

Figure 49. Spiking deconvolution for dense watergun model by underestimated attenuation constant.

events E1 and E2, but their waveforms are distorted or oscillating.

From these results, S-H deconvolution still holds its high performance even when using a mismatched attenuation constant in TV inverse attenuation filtering.

Simulation Using Sparse Reflectivity and Klauder Wavelet

To study applicability of S-H deconvolution to other type of source signature, the same deconvolutions used in former simulation and R-J deconvolution were applied to a TV attenuated Klauder wavelet seismic model consisting of sparse reflectivity and Klauder wavelet with and without TV inverse attenuation filter for the high attenuation case (α=0.1). The CC value and relative time shift between desired output and each deconvolution output convolved with d-filter were calculated for each case and is listed in table 7.

Desired output and output of no deconvolution application are shown in figures 50 and 51, respectively. Outputs of spiking deconvolution with and without 5 % additive noise, gapped deconvolution, R-J deconvolution, and S-H deconvolution are shown in figures 52 through 56. Although S-H deconvolution and R-J deconvolution keep better performance than that others in case of no application of TV inverse attenuation filter, the second reflection event

Inverse attenuation filter	WITHOUT	WITH
No deconvolution	0.63 (1)	0.99 (0)
SP deconvolution	0.56 (-155)	0.66 (-1)
SP deconvolution with 5 % noise	0.57 (0)	0.81 (-1)
GP deconvolution (gap=10 points)	0.63 (1)	0.98 (0)
R-J deconvolution	0.68 (0)	0.99 (0)
S-H deconvolution	0.68 (0)	0.99 (0)

Table 7. Correlation coefficient between desired output and each deconvolution with and without TV inverse attenuation filter for sparse Klauder wavelet model without natural noise (High attenuation case)

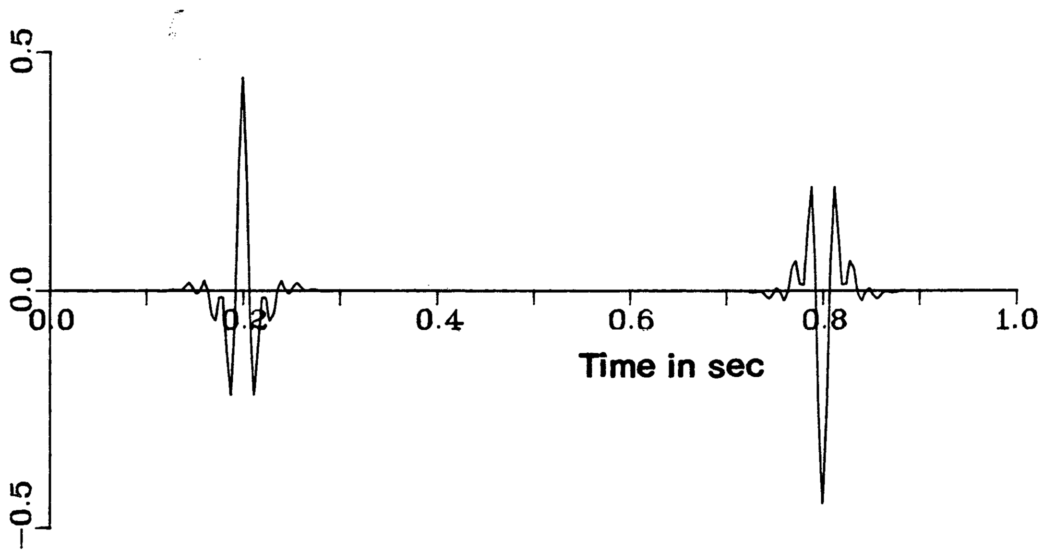

Figure 50. Desired output for sparse Klauder wavelet model.

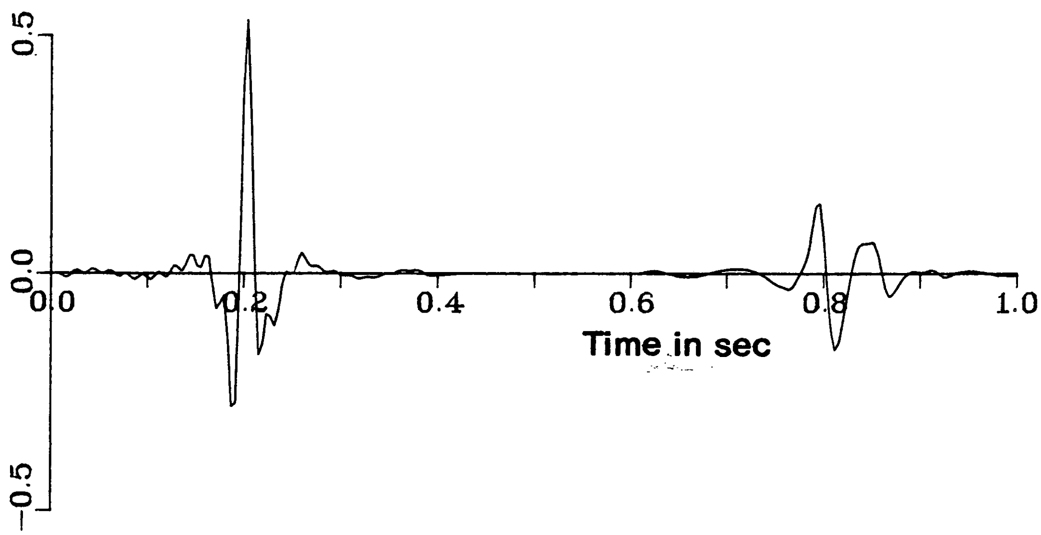

Figure 51. No deconvolution for TV attenuated sparse Klauder wavelet model.

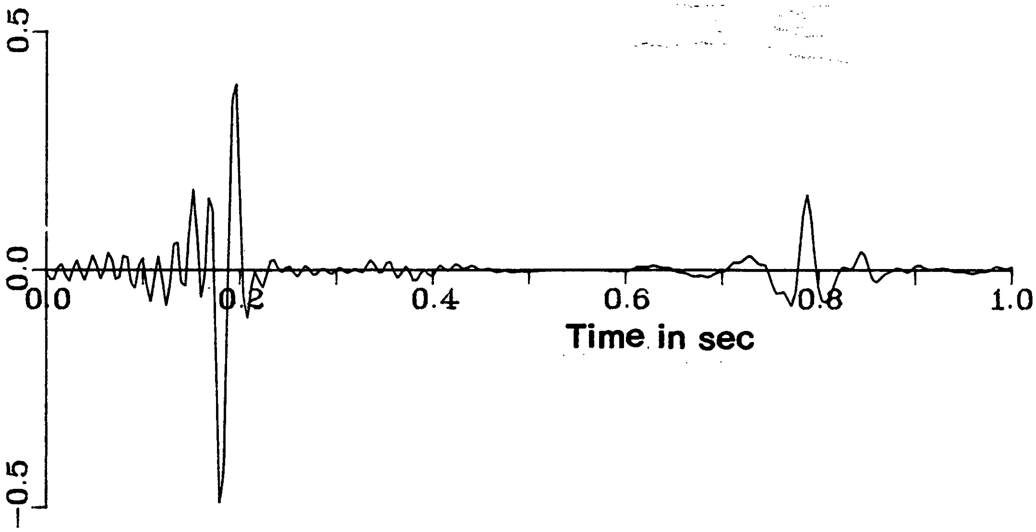

Figure 52. Spiking deconvolution for TV attenuated sparse Klauder wavelet model.

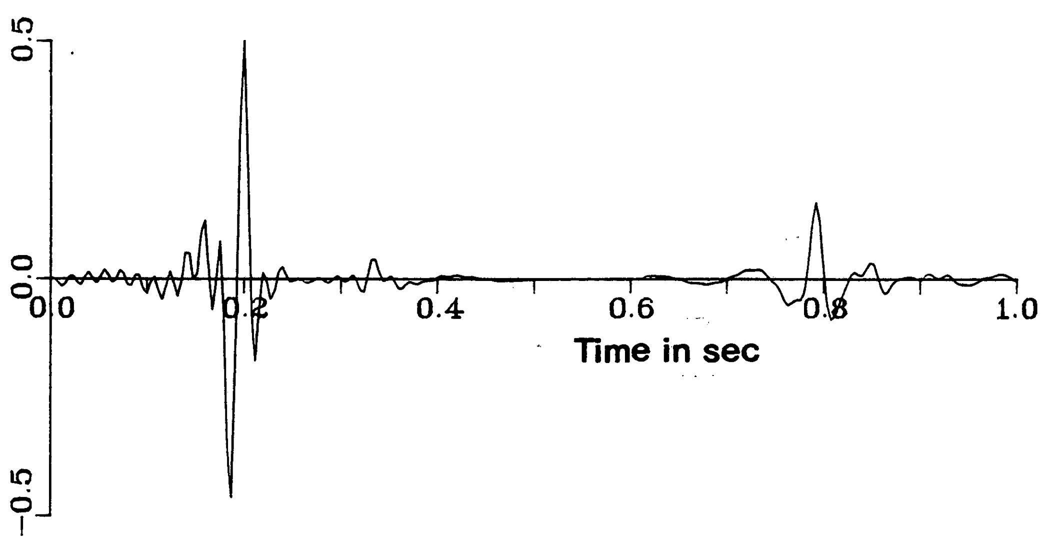

Figure 53. Spiking deconvolution with 5 % additive white noise for TV attenuated sparse Klauder wavelet model.

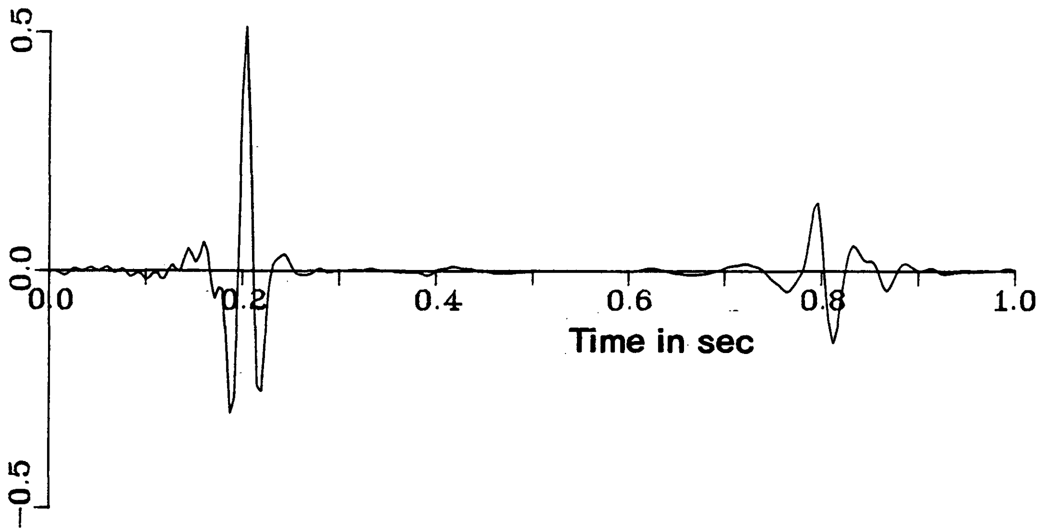

Figure 54. Gapped deconvolution (gap=10 points) for TV attenuated sparse Klauder wavelet model.

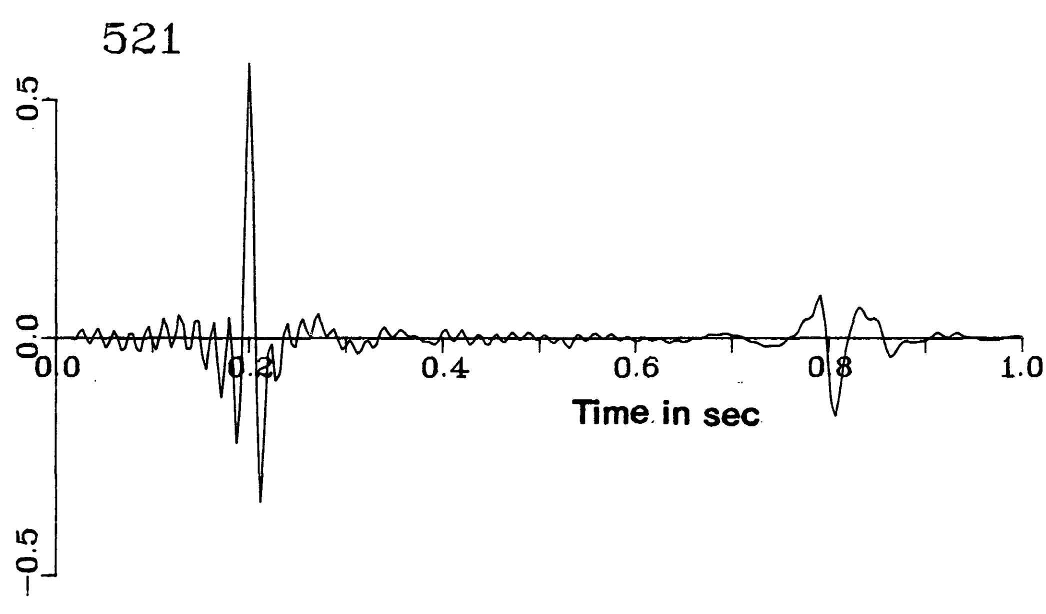

Figure 55. R-J deconvolution for TV attenuated sparse Klauder wavelet model.

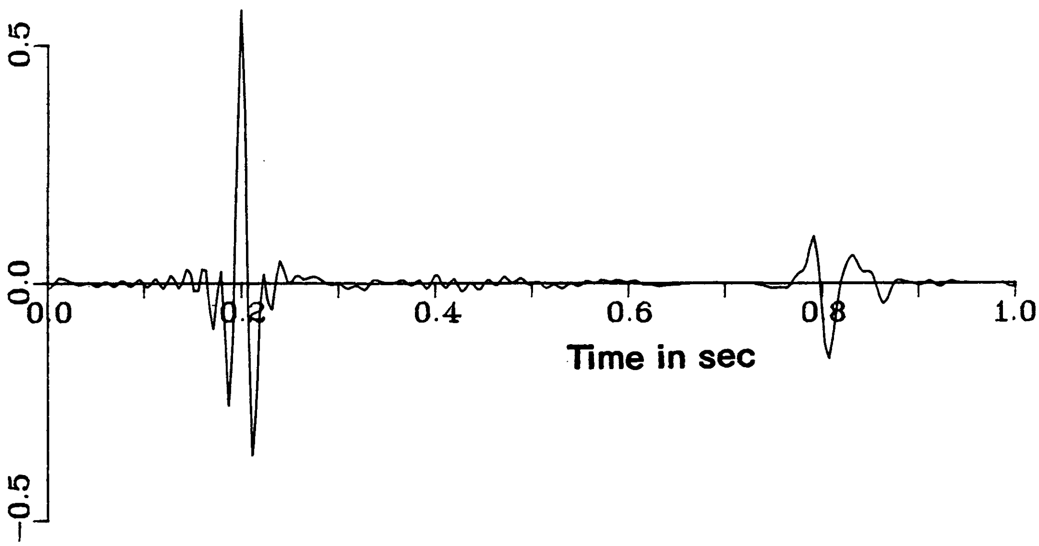

Figure 56. S-H deconvolution for TV attenuated sparse Klauder wavelet model.

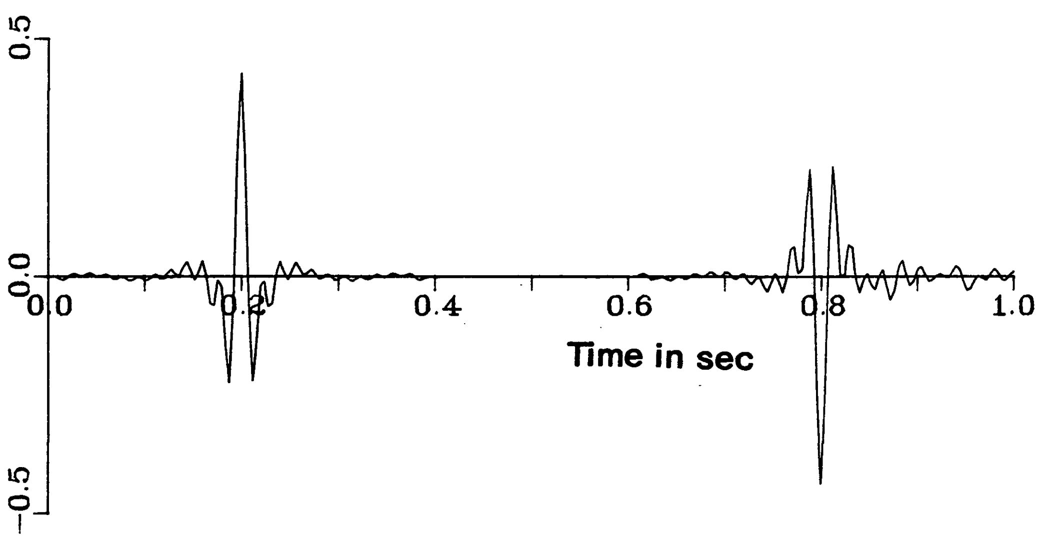

Figure 57. No deconvolution for TV inverse attenuated sparse Klauder wavelet model.

is not restored sufficiently.

On the other hand, by applying TV inverse attenuation filter before deconvolution, all deconvolution performances, including no deconvolution output (fig. 57) are nearly perfect, except for spiking deconvolution (table 7). This is due to the special characteristic of Klauder wavelets whose amplitude spectra are originally whitened. That is to say, within the specific frequency band of interest, this input trace is already spectral whitened before applying deconvolution. Furthermore, the d-filter which has flat amplitude spectrum does not distort amplitude spectrum of trace if its frequency band is the same as that of Klauder wavelet. From these facts, though S-H deconvolution does work well for Klauder wavelet model, no deconvolution need to be applied.

However, in practical seismology, there are many factors, which distort well-whitened Klauder wavelet spectrum, such as instrument response in land surveys and multiples and ghosts in marine surveys. In such cases, S-H deconvolution is needed and will hold its performance on real seismic data.

FUTURE WORK

Following topics can be considered to be future studies:

1) more detailed simulation for various nonminimum-phase data, including Vibroseis wavelets, by considering other filtering factors such as instrumental response,

2) determination of exact attenuation constant from real data by spectral analysis for exact compensation of time variance,

3) more detailed quantitative investigation of the influence of additive natural noise on the deconvolution results,

4) application of S-H deconvolution to real seismic data.

CONCLUSIONS

1) Validity of the Wiener transform for simplification and unification of processing various types of seismic data was proved.

2) Necessity of additive white noise on Wiener-Hopf equation was denied by showing various results of data processing without additive white noise.

3) S-H deconvolution, which is time-variant inverse attenuation filtering followed by phase-compensated spiking deconvolution, always has the highest performance for nonminimum-phase data.

4) S-H deconvolution without time-variant inverse attenuation filter also works well for nonminimum-phase data.

5) S-H deconvolution has wide tolerance for underestimation and overestimation of the attenuation constant for time-variant inverse attenuation filter.

6) S-H deconvolution is qualified as the deconvolution technique which always gives the highest performance when applied to any type seismic source data.

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APPENDIX A

HILBERT TRANSFORM

The Hilbert transform has been used as a minimum phase converter. Real and imaginary parts of Fourier transforms of causal function are related by the Hilbert transform. Furthermore, when the causal function has minimum phase, its phase spectrum is connected with the logarithm of the amplitude spectrum through the Hilbert transform. Therefore, a minimum-phase equivalent to a nonminimum-phase wavelet can be obtained by making use of this relationship. However, unlike the minimum mean-square error criterion with the Wiener transform, the Hilbert transform does not guarantee optimality in minimum-phase conversion.

Minimum phase conversion by the Hilbert transform is as follows:

1. Compute the amplitude spectrum by Fourier transform,
2. Take the logarithm of the amplitude spectrum,
3. Generate the minimum-phase spectrum by applying the Hilbert transform to the logarithmic amplitude spectrum (this process can be carried out by circular convolution of Hilbert operator with logarithmic amplitude spectrum),
4. Apply the inverse Fourier transform to amplitude spectrum

and minimum-phase spectrum,

5. Extract real part of inverse Fourier-transformed data.

APPENDIX B

Z-TRANSFORM

In digital processing, any stable function can be expressed by Z-transform. Suppose e^{-jwt} to be z, when the function has minimum phase, all zeros of its Z-transform are located outside the unit circle on Z plane. On the other hand, some zeros or all zeros are located inside the unit circle in case of mixed phase and maximum phase, respectively. Therefore, if the exact coordinates of zeros inside the unit circle are known, they can be moved outside the unit circle by computing the conjugate reciprocal value of each zero, and the exact minimum-phase equivalent can be obtained. However, minimum-phase conversion by Z-transform is not practical due to extreme difficulty of finding roots of high-order polynomial.

Jenkins and Traumb (1970) showed one numerical technique for finding zeros of high-order polynomials.

APPENDIX C

CORRELATION COEFFICIENT

The correlation coefficient is an estimator of similarity between two functions. This value is defined as follows;

$$CC_{gh} = \frac{\mathrm{Max}\left[\Phi_{gh}(\tau)\right]}{\sqrt{\Phi_{g(0)}\Phi_{h(0)}}} ,$$

where $\phi_g(0)$ and $\phi_h(0)$ are values at the origin of the autocorrelation of functions g and h, which corresponds to the total energy of function g and h, respectively, and $\phi_{gh}(\tau)$ is crosscorrelation of g and h.

$CC_{gh} = 1$ means the same waveforms independent of amplitude and time shift. When $CC_{gh} = -1$, the waveforms are the same and polarity is reversed. $CC_{gh} = 0$ means uncorrelated waveforms. The shift τ_d at which the absolute value of ϕ_{gh} is the maximum is a measure of linear phase shift of h(t) with respect to g(t). So, the pair CC_{gh} and τ_d measures the waveform similarity.

APPENDIX D

PROGRAMES FOR COMPUTER SIMULATION FOR OTIMAL DECONOLUTION

HOPREP : PREPARATION STEP
HOAFIL : INVERSE ATTENUATION APPLICATION
HODCON : DECONVOLUTION STEP

```
C     *****************************************
C     *       PROGRAM : HOPREP                *
C     *****************************************
      DIMENSION      DFILT(125),RREF(600),DREF(600),PULSE(250),
     .               SEIS(600),W1(1000),AFILT(512),TREF(600)
      REAL           NREF(600),KREF(600),IREF(600),KAREF(600),
     .               NLEVEL,KLAUD(250)
      CHARACTER*12   DATAN1,DATAN2,DATAN3,DATAN4,DATAN5,DATAN6
      CHARACTER*1    ANS,Y,N
      DATA           Y/'Y'/,N/'N'/
C
C---- PARAMETER DECISION
C
      IRMS   =1
      IFIRST =2
      IMAX   =3
      IKLAUD =0
      IDFILT =0
      IRREF  =0
      IDREF  =0
      INREF  =0
      IKREF  =0
      IPULSE =0
      IIREF  =0
      IKAREF =0
      ISEIS  =0
C
C---- PROCESS SELECTION
C
1     WRITE(6,*) 'Do you generate source wavelet (r) ? (Y/N)'
      READ(5,10) ANS
10    FORMAT(A1)
      IF(ANS.EQ.N) GOTO 101
C
C---- SOURCE WAVELET GENERATION ---- k(t)
C
      WRITE(6,*) 'XXXXX SOURCE WAVELET k GENERATION XXXXX'
      WRITE(6,*) '      Enter data file name to read'
      READ(5,12) DATAN1
      WRITE(6,*) '      Enter data format (1/2)'
      READ(5,*)  IFORM
      WRITE(6,*) '      Enter length in point'
```

```
      READ(5,*)  LENGK
      WRITE(6,*) '      Enter sampling rate in sec'
      READ(5,*)  DELT
C
      OPEN (UNIT=9,FILE=DATAN1,STATUS='UNKNOWN')
      DO 25 I=1,LENGK
      IF(IFORM.EQ.1) READ(9,26) KLAUD(I)
      IF(IFORM.EQ.2) READ(9,27) KLAUD(I)
26    FORMAT( 1X,F15.7)
27    FORMAT(16X,F15.7)
25    CONTINUE
      CLOSE (UNIT=9)
C
      OPEN (UNIT=10,FILE='SOURCE.FIL',STATUS='UNKNOWN')
      CALL NORM85(KLAUD,LENGK,1,LENGK,IRMS)
      DO 40 I=1,LENGK
      T=(I-1)*DELT
      WRITE(10,*) T,KLAUD(I)
40    CONTINUE
      IKLAUD=1
      CLOSE (UNIT=10)
C
C---- PROCESS SELECTION
C
101   WRITE(6,*) 'Do you generate reflectivity (r) ? (Y/N)'
      READ(5,110) ANS
110   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 201
C
C---- REFLECTIVITY GENERATION ----- r(t)
C
      WRITE(6,*) 'XXXXX REFLECTIVITY r GENERATION XXXXX'
      WRITE(6,*) '      Enter (DATA FILE NAME)'
      READ(5,12) DATAN1
12    FORMAT(A12)
      WRITE(6,*) '      Enter (ISTART,LENGTH,DELT,DATA FORMAT (1/2))'
      READ(5,*) ISTART,LENG,DELT,IFORM
C
      OPEN (UNIT=10,FILE=DATAN1,      STATUS='OLD')
      OPEN (UNIT=11,FILE='RREF.FIL'  ,STATUS='UNKNOWN')
C
      IF(ISTART.EQ.1) GOTO 135
      IEND=ISTART-1      ! This loop is dummy read
      DO 130 I=1,IEND
      READ(10,*) A,B
130   CONTINUE
135   CONTINUE
C
      DO 140 I=1,LENG
      IF(IFORM.EQ.1) READ(10,141) RREF(I)
```

```
      IF(IFORM.EQ.2) READ(10,142) RREF(I)
141   FORMAT( 1X,F15.7)
142   FORMAT(16X,F15.7)
140   CONTINUE
C     ! Remove bias from reflectivity
      SUM=0.0
      DO 145 I=1,LENG
      SUM=SUM+RREF(I)
145   CONTINUE
      AVE=SUM/FLOAT(LENG)
      DO 146 I=1,LENG
      RREF(I)=RREF(I)-AVE
146   CONTINUE
C
      CALL NORM85(RREF,LENG,1,LENG,IRMS)
C
      DO 150 I=1,LENG
      T=(I-1)*DELT
      WRITE(11,*) T,RREF(I)
150   CONTINUE
      IRREF=1
      CLOSE (UNIT=10)
      CLOSE (UNIT=11)
C
C---- PROCESS SELECTION
C
201   WRITE(6,*) 'Do you generate d-filter (d) ? (Y/N)'
      READ(5,210) ANS
210   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 301
C
C---- DESIGN OF DESIRED FILTER ---- d(t)
C
      WRITE(6,*) 'XXXXX DESIRED PULSE d GENERATION XXXXX'
      WRITE(6,*) '      Enter (LENGD,DELT,F1,F2,F3,F4,IHAM)'
      READ(5,*) LENGD,DELT,F1,F2,F3,F4,IHAM
C
      CALL FILT86(DFILT,LENGD,DELT,F1,F2,F3,F4,IHAM,1)
C
      OPEN (UNIT=10,FILE='DFILT.FIL',STATUS='UNKNOWN')
      CALL NORM85(DFILT,LENGD,1,LENGD,IRMS)
      DO 240 I=1,LENGD
      T=(I-1)*DELT
      WRITE(10,*) T,DFILT(I)
240   CONTINUE
      IDFILT=1
      CLOSE (UNIT=10)
C
C---- PROCESS SELECTION
C
```

```
301   WRITE(6,*) 'Do you generate desired output trace (r*d) ? (Y/N)'
      READ(5,310) ANS
310   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 401
C
C---- DESIRED OUTPUT TRACE GENERATION ---- r(t)*d(t)
C
      WRITE(6,*) 'XXXXX DESIRED OUTPUT TRACE r*d GENERATION XXXXX'
      WRITE(6,*) '      Enter (LENG,DELT--REFLECTIVITY)'
      READ(5,*) LENG,DELT
      WRITE(6,*) '      Enter (LENGD,DELTD--DESIRED FILTER)'
      READ(5,*) LENGD,DELTD
C
      OPEN (UNIT=10,FILE='RREF.FIL'  ,STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE='DFILT.FIL' ,STATUS='UNKNOWN')
      OPEN (UNIT=12,FILE='DREF.FIL'  ,STATUS='UNKNOWN')
C
      DO 330 I=1,LENG
      READ(10,331) RREF(I)
331   FORMAT(16X,F15.7)
330   CONTINUE
      DO 335 I=1,LENGD
      READ(11,336) DFILT(I)
336   FORMAT(16X,F15.7)
335   CONTINUE
C
      LENGDH=LENGD/2
      LENGW =LENG + LENGD -1
      CALL ZERO85(W1,1000)
      CALL MOVE85(RREF,W1(LENGDH+1),LENG)
C
      CALL CORR85(W1,LENGW,DFILT,LENGD,DREF,LENG)
      CALL NORM85(DREF,LENG,1,LENG,IRMS)
C
      DO 340 I=1,LENG
      T=(I-1)*DELT
      WRITE(12,*) T,DREF(I)
340   CONTINUE
      IDREF=1
      CLOSE (UNIT=10)
      CLOSE (UNIT=11)
      CLOSE (UNIT=12)
C
C---- PROCESS SELECTION
C
401   WRITE(6,*) 'Do you generate psuedo random noise (n) ? (Y/N)'
      READ(5,410) ANS
410   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 501
C
```

```
C---- NATURAL NOISE SERIES GENERATION ---- n(t)
C
      WRITE(6,*) 'XXXXX NATURAL NOISE n GENERATION XXXXX'
      WRITE(6,*) '      Enter (LENG,DELT)'
      READ(5,*) LENG,DELT
C
      CALL RAND85(NREF,LENG,0.0,1.0)
      CALL NORM85(NREF,LENG,1,LENG,IRMS)
C
      OPEN (UNIT=10,FILE='NREF.FIL',STATUS='UNKNOWN')
      DO 430 I=1,LENG
      T=(I-1)*DELT
      WRITE(10,*) T,NREF(I)
430   CONTINUE
      INREF=1
      CLOSE (UNIT=10)
C
C---- PROCESS SELECTION
C
501   WRITE(6,*) 'Do you generate r*k trace ? (Y/N)'
      READ(5,510) ANS
510   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 601
C
C---- r(t)*k*t TRACE GENERATION
C
      WRITE(6,*) 'XXXXX r*k TRACE GENERATION XXXXX'
      WRITE(6,*) '      Enter (LENG,DELT) -- REFLEVCTIVITY'
      READ(5,*) LENG,DELT
      WRITE(6,*) '      Enter (LENGK) -- SOURCE WAVELET'
      READ(5,*) LENGK
      WRITE(6,*) '      Enter source wavelet type (0:zero-phase)'
      READ(5,*) ITYPE
C
      OPEN (UNIT=10,FILE='RREF.FIL'  ,STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE='SOURCE.FIL',STATUS='UNKNOWN')
      OPEN (UNIT=12,FILE='KREF.FIL'  ,STATUS='UNKNOWN')
C
      DO 530 I=1,LENG
      READ(10,531) RREF(I)
531   FORMAT(16X,F15.7)
530   CONTINUE
      DO 540 I=1,LENGK
      READ(11,541) KLAUD(I)
541   FORMAT(16X,F15.7)
540   CONTINUE
C
      IF(ITYPE.EQ.0) GOTO 545
      IF(ITYPE.NE.0) GOTO 546
545   CONTINUE
```

```
      LENGKH=LENGK/2
      LENGW =LENG + LENGK -1
      CALL ZERO85(W1,1000)
      CALL MOVE85(RREF,W1(LENGKH+1),LENG)
      CALL CORR85(W1,LENGW,KLAUD,LENGK,KREF,LENG)
      GOTO 549
C
546   CONTINUE
      CALL CONV85(RREF,LENG,KLAUD,LENGK,KREF,LENG)
C
549   CONTINUE
      CALL NORM85(KREF,LENG,1,LENG,IRMS)
C
      DO 550 I=1,LENG
      T=(I-1)*DELT
      WRITE(12,*) T,KREF(I)
550   CONTINUE
      IKREF=1
      CLOSE (UNIT=10)
      CLOSE (UNIT=11)
      CLOSE (UNIT=12)
C
C---- PROCESS SELECTION
C
601   WRITE(6,*) 'Do you convolve another pulse (i) with r*k ? (y/n)'
      READ(5,605) ANS
605   FORMAT(A1)
      IF(ANS.EQ.N) GOTO 701
C
C---- NOISELESS i-convolved SEISMIC TRACE GENERATION -- r*k*i
C
      WRITE(6,*) 'XXXXX TRACE r*k*i GENERARION XXXXX'
      WRITE(6,*) '      Enter (LENG,DELT(sec)) -- r*k TRACE'
      READ(5,*)  LENG,DELT
      WRITE(6,*) '      Enter file name of filter i'
      READ(5,12) DATAN1
      WRITE(6,*) '      Enter data file (i) format (1/2)'
      READ(5,*)  IFORM
      WRITE(6,*) '      Enter filter type (0:zero-phase)'
      READ(5,*)  IITYPE
      WRITE(6,*) '      Enter filter (i) length'
      READ(5,*)  LENGI
C
      OPEN (UNIT= 9,FILE='KREF.FIL' ,STATUS='UNKNOWN')
      OPEN (UNIT=10,FILE=DATAN1     ,STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE='IREF.FIL' ,STATUS='UNKNOWN')
      OPEN (UNIT=12,FILE='PULSE.FIL',STATUS='UNKNOWN')
C
      DO 630 I=1,LENG
      READ( 9,631) KREF(I)
```

```
631    FORMAT(16X,F15.7)
630    CONTINUE
       DO 640 I=1,LENGI
       IF(IFORM.EQ.1) READ(10,641) PULSE(I)
       IF(IFORM.EQ.2) READ(10,642) PULSE(I)
641    FORMAT( 1X,F15.7)
642    FORMAT(16X,F15.7)
640    CONTINUE
C
C---- CONVOLUTION OF PULSE (I) WITH KREF
C
       IF(IITYPE.EQ.0) GOTO 651
       IF(IITYPE.NE.0) GOTO 652
651    CONTINUE
       LENGIH  = LENGI/2
       LENGIW  = LENG+LENGI-1
       CALL ZERO85(W1,1000)
       CALL MOVE85(KREF,W1(LENGIH+1),LENG)
       CALL CORR85(W1,LENGIW,PULSE,LENGI,IREF,LENG)
       GOTO 660
C
652    CONTINUE
       CALL CONV85(KREF,LENG,PULSE,LENGI,IREF,LENG)
C
660    CONTINUE
       CALL NORM85(IREF,LENG,1,LENG,IRMS)
C
C---- STORE DATA ON IREF.FIL & PULSE FORM ON PULSE.FIL
C
       DO 670 I=1,LENG
       T=(I-1)*DELT
       WRITE(11,*) T,IREF(I)
670    CONTINUE
       DO 680 I=1,LENGI
       T=(I-1)*DELT
       WRITE(12,*) T,PULSE(I)
680    CONTINUE
       IIREF =1
       IPULSE=1
       CLOSE (UNIT= 9)
       CLOSE (UNIT=10)
       CLOSE (UNIT=11)
       CLOSE (UNIT=12)
C
C---- PROCESS SELECTION
C
701    CONTINUE
       WRITE(6,*) 'Do you generate attenuated trace (r*k*i*a) ? (Y/N)'
       READ(5,710) ANS
710    FORMAT(A1)
```

```
      IF(ANS.EQ.N) GOTO 801
C
C---- Attenuated SEISMIC TRACE GENERATION -- r(t)*k(t)*i(t)*a(t)
C
      WRITE(6,*) 'XXXXX Attenuated TRACE r*k*i*a GENERATION XXXXX'
      WRITE(6,*) '      Enter input type (1:r*k,2:r*k*i)'
      READ(5,*) ITYPE
      WRITE(6,*) '      Enter (LENG,DELT) of input trace'
      READ(5,*) LENG,DELT
      WRITE(6,*) '      Enter length of attenuation filter'
      READ(5,*) LENGA
      WRITE(6,*) '      Enter attenuation constant'
      READ(5,*) ALFA
      WRITE(6,*) '      Enter velocity (constant)'
      READ(5,*) VEL
      WRITE(6,*) '      Enter reference time (tau) in sec'
      READ(5,*) TAU
      IF(TAU.EQ.0.0) ITV=1
      IF(TAU.NE.0.0) ITV=0
C
      IF(ITYPE.EQ.2) OPEN (UNIT=10,FILE='IREF.FIL' ,STATUS='UNKNOWN')
                     OPEN (UNIT=11,FILE='KAREF.FIL',STATUS='UNKNOWN')
C
      DO 730 I=1,LENG
      READ(10,731) TREF(I)  ! store data in temporary file TREF
731   FORMAT(16X,F15.7)
730   CONTINUE
C
C---- APPLICATION OF ATTENUATION FILTER ACCORDING TO ITV
C
      IF(ITV.EQ.0) GOTO 760
C------------ GENERATION OF ATTENUATION FILTER AT EACH TIME POINT
      DO 750 I=1,LENG
      TAU=(I-1)*DELT
      CALL ATTEN86(AFILT,DELT,LENGA,TAU,VEL,ALFA,1)
      CALL PCONV86(TREF,LENG,I,AFILT,LENGA,Z)
      KAREF(I)=Z
750   CONTINUE
      GOTO 770
C------------   GENERATION OF TIME-INVARIANT ATTENUATION FILTER & APPLY
760   CONTINUE
      CALL ATTEN86(AFILT,DELT,LENGA,TAU,VEL,ALFA,1)
      CALL CONV85(TREF,LENG,AFILT,LENGA,KAREF,LENG)
C
770   CONTINUE
      CALL NORM85(KAREF,LENG,1,LENG,IRMS)
C
      DO 790 I=1,LENG
      T=(I-1)*DELT
      WRITE(11,*) T,KAREF(I)
```

```
 790   CONTINUE
 C
       IKAREF=1
       CLOSE (UNIT=10)
       CLOSE (UNIT=11)
 C
 C---- PROCESS SELECTION
 C
 801   WRITE(6,*) 'Do you generate seismic trace (r*k*i*a+N*n) ? (Y/N)'
       READ(5,810) ANS
 810   FORMAT(A1)
       IF(ANS.EQ.N) GOTO 901
 C
 C---- SEISMIC TRACE GENERATION ---- r(t)*k(t)*i(t)*a(t) + N*n(t)
 C
       WRITE(6,*) 'XXXXX SEISMIC TRACE r*k*i*a+N*n GENERATION XXXXX'
       WRITE(6,*) '      Enter (LENG,DELT,NOISE LEVEL)'
       READ(5,*) LENG,DELT,NLEVEL
 C
       OPEN (UNIT=10,FILE='KAREF.FIL',STATUS='UNKNOWN')
       OPEN (UNIT=11,FILE='NREF.FIL' ,STATUS='UNKNOWN')
       OPEN (UNIT=12,FILE='SEIS.FIL' ,STATUS='UNKNOWN')
 C
       DO 830 I=1,LENG
       READ(10,831) KAREF(I)
       READ(11,831) NREF(I)
 831   FORMAT(16X,F15.7)
 830   CONTINUE
 C
       DO 840 I=1,LENG
       SEIS(I)=KAREF(I) + NLEVEL*NREF(I)
 840   CONTINUE
 C
       CALL NORM85(SEIS,LENG,1,LENG,IRMS)
 C
       DO 850 I=1,LENG
       T=(I-1)*DELT
       WRITE(12,*) T,SEIS(I)
 850   CONTINUE
 C
       ISEIS=1
       CLOSE (UNIT=10)
       CLOSE (UNIT=11)
       CLOSE (UNIT=12)
       WRITE(6,*) 'XXXXX HOPREP PROGRAM COMPLETE XXXXX'
       STOP
       END
 C     ******************************************
 C     *       PROGRAM : HOAFIL                 *
 C     ******************************************
```

```
      DIMENSION         DATAIN(1250),DATAOUT(1250),AFILT(513)
      REAL              IFILT(513)
      CHARACTER*12      DATAN1,DATAN2,DATAN3
      CHARACTER*1       ANS,N
      DATA              N/'N'/
C
C---- PARAMETER
C
      IRMS  =1
      IFIRST=2
      IMAX  =3
      IPRED =1
      PNOIS =0.
C
C---- START MESSEGE
C
      WRITE(6,*) 'XXXXX HOAFIL START (INVERSE ATTENUATION FILTER) XXXXX'
1     WRITE(6,*) '      Enter input data file name'
      READ(5,12) DATAN1
12    FORMAT(A12)
      WRITE(6,*) '      Enter output data file name'
      READ(5,12) DATAN2
      WRITE(6,*) '      Enter data length in points'
      READ(5,*) LENG
      WRITE(6,*) '      Enter sampling rate in sec'
      READ(5,*) DELT
C
      WRITE(6,*) '      Enter inverse attenuation filter length'
      READ(5,*) LENGA
      WRITE(6,*) '      Enter attenuation constant (positive)'
      READ(5,*) ALFA
      WRITE(6,*) '      Enter velocity (constant)'
      READ(5,*) VEL
C
      WRITE(6,*) '      Enter reference time (tau) in sec'
      READ(5,*) TAU
C
C---- OPEN 11,12
C
      OPEN (UNIT=10,FILE=DATAN1      ,STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE=DATAN2      ,STATUS='UNKNOWN')
C
C---- READ DATA FROM FILES
C
      DO 100 I=1,LENG
      READ(10,101) DATAIN(I)
101   FORMAT(16X,F15.7)
100   CONTINUE
C------ CHECK TIME VARIANT OR TIME INVARIANT
      IF(TAU.EQ.0.0) GOTO 200
```

```
      IF(TAU.NE.0.0) GOTO 210
C
C---- GENEARTION OF INVERSE ATTENUATION FILTER & APPLICATION
C
200   CONTINUE          ! Time-variant inverse attenuation
      DO 1000 I=1,LENG
      TAU=(I-1)*DELT
      CALL ATTEN86(AFILT,DELT,LENGA,TAU,VEL,ALFA,1)
      CALL WTRAN86(AFILT,IFILT,LENGA,IPRED,PNOIS)
      CALL MNORM86(AFILT,LENGA,IFILT,LENGA) ! Matched normalization
      CALL PCONV86(DATAIN,LENG,I,IFILT,LENGA,Z)
      DATAOUT(I)=Z
 1000 CONTINUE
      GOTO 1500
C
210   CONTINUE          ! Time-invariant inverse attenuation
      CALL ATTEN86(AFILT,DELT,LENGA,TAU,VEL,ALFA,1)
      CALL WTRAN86(AFILT,IFILT,LENGA,IPRED,PNOIS)
      CALL CONV85(DATAIN,LENG,IFILT,LENGA,DATAOUT,LENG)
C
C---- NORMALIZATION AND DATA OUTPUT
C
1500  CONTINUE
      CALL NORM85(DATAOUT,LENG,1,LENG,IRMS)
      DO 2000 I=1,LENG
      T=(I-1)*DELT
      WRITE(11,*) T,DATAOUT(I)
2000  CONTINUE
C
C----  CLOSE FILES
C
      CLOSE (UNIT=10)
      CLOSE (UNIT=11)
      WRITE(6,*) 'XXXXX HOAFIL COMPLETE XXXXX'
      STOP
      END
C     ******************************************
C     *       PROGRAM : HODCON                 *
C     ******************************************
      DIMENSION      SPDCON(1200),ZPDCON(1200),RJDCON(1200),
     .               SHDCON(1200),W1(2048),W2(2048),W3(2048),
     .               WAPCO(1024),WORK(2048)
      DIMENSION      DREF(1200),DFIL(600),SEIS(1200)
      REAL           KLAUD(600),NODCON(1200)
      COMPLEX        COMP(2048)
      CHARACTER*12   DATAN1,DATAN2,DATAN3,DATAN4,DATAN5,DATAN6
      CHARACTER*1    ANS,Y,N
      DATA           Y/'Y'/,N/'N'/
      IRMS  =1
      IFIRST=2
```

```
      IMAX  =3
      IDIST =1
      IPULSE=0
C
C---- START MESSAGE & SELECTION OF DECONVOLUTION PROCESS
C
1     WRITE(6,*) 'XXXXX START HODCON XXXXX'
C
      WRITE(6,*) '      Enter name of input data'
      READ(5,12) DATAN1
      WRITE(6,*) '      Enter name of desired output (DREF.FIL)'
      READ(5,12) DATAN2
      WRITE(6,*) '      Enter name of source wavelet (SOURCE.FIL)'
      READ(5,12) DATAN3
      WRITE(6,*) '      Enter source wavelet type (0:zero-phase)'
      READ(5,*)  IZERO
      WRITE(6,*) '      Enter source wavelet length in points'
      READ(5,*)  LENGK
      WRITE(6,*)'      Enter name of desired seismic pulse(DFILT.FIL)'
      READ(5,12) DATAN4
      WRITE(6,*) '      Enter length of desired seismic pulse'
      READ(5,*)  LENGD
      WRITE(6,*) '      Enter data length to treat'
      READ(5,*)  LENG
      WRITE(6,*) '      Enter sampling rate in sec.'
      READ(5,*)  DELT
11    FORMAT(A1)
12    FORMAT(A12)
C
C---- SOME INTERNAL PARAMETERS DEFINITION
C
      LENGDH=LENGD/2
      LENGDW=LENG+LENGD-1
      LENGKH=LENGK/2
      LENGKW=LENG+LENGK-1
C
C---- OPEN DATA FILE & READ DATA
C
      OPEN (UNIT=10,FILE=DATAN1,STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE=DATAN2,STATUS='UNKNOWN')
      OPEN (UNIT=12,FILE=DATAN3,STATUS='UNKNOWN')
      OPEN (UNIT=13,FILE=DATAN4,STATUS='UNKNOWN')
C
      DO 50 I=1,LENG
      READ(10,51) SEIS(I)
      READ(11,51) DREF(I)
51    FORMAT(16X,F15.7)
50    CONTINUE
C
      DO 60 I=1,LENGK
```

```
      READ(12,61) KLAUD(I)
61    FORMAT(16X,F15.7)
60    CONTINUE
C
      DO 70 I=1,LENGD
      READ(13,71) DFIL(I)
71    FORMAT(16X,F15.7)
70    CONTINUE
C
C---- OPEN FILE AND READ DATA REQUIRED
C
2     WRITE(6,10)
10    FORMAT(1H0, '       SELCT DECONVOLUTION TYPE'    /
     .               '    0: NO DECONVOLUTION'/
     .               '    1: PREDICTIVE DECONVOLUTION'   /
     .               '    4: RISTOW-JURCZYK DECONVOLUTIN'/
     .               '    6: SENGBUSH-HATO DECONVOLUTION' )
      READ(5,*) ITYPE
      IF(ITYPE.EQ.0) GOTO  500
      IF(ITYPE.EQ.1) GOTO 1000
      IF(ITYPE.EQ.4) GOTO 4000
      IF(ITYPE.EQ.6) GOTO 5000
      WRITE(6,*) '***** DECONVOLUTION TYPE ERROR TYPE (Y:RETRY,N:STOP)'
      READ(5,100) ANS
100   FORMAT(A1)
      IF(ANS.EQ.Y) GOTO 2
      STOP
C     ****************************************************
C             NO DECONVOLUTION (JUST APPLY d-FILTER)
C     ****************************************************
500   CONTINUE
      WRITE(6,*) 'XXXXX NO DECONVOLUTION START XXXXX'
      WRITE(6,*) '      Enter output data file name'
      READ(5,12) DATAN5
C
C---- APPLY d-FILTER
C
      CALL ZERO85(WORK,LENGDW)
      CALL MOVE85(SEIS,WORK(LENGDH+1),LENG)
      CALL CORR85(WORK,LENGDW,DFIL,LENGD,NODCON,LENG)
      CALL NORM85(NODCON,LENG,1,LENG,IRMS)
C
C---- COMPUTE RMS AND CC VALUE
C
      IFIX=0
      CALL SIMLR86(CC,ISHIFT,CCFIX,IFIX,NODCON,LENG,DREF,LENG)
      CALL DEVI85(DEVI,NODCON,DREF,LENG)
      WRITE(6,*) '      RMS ERROR = ',DEVI
      WRITE(6,*) '      CC VALUE  = ',CC,'  ISHIFT = ',ISHIFT
C
```

```
C---- STORE DATA ON #15
C
      OPEN (UNIT=15,FILE=DATAN5,STATUS='UNKNOWN')
      DO 530 I=1,LENG
      T=(I-1)*DELT
      WRITE(15,*) T,NODCON(I)
530   CONTINUE
      CLOSE (UNIT=15)
C
C---- END
C
      WRITE(6,*) '      Do you continue to work ? (Y/N)'
      READ(5,12) ANS
      IF(ANS.EQ.Y) GOTO 2
      GOTO 9000
C     ****************************************
C             PREDICTIVE DECONVOLUTION
C     ****************************************
1000  CONTINUE
      WRITE(6,*) 'XXXXX PREDICTIVE DECONVOLUTION START XXXXX'
      WRITE(6,*) '      Enter output data file name'
      READ(5,12) DATAN5
      WRITE(6,*) '      Enter design gate start point'
      READ(5,*)  ISTART
      WRITE(6,*) '      Enter design gate length'
      READ(5,*)  LWIN
      WRITE(6,*) '      Enter W-L equation order'
      READ(5,*)  NOP
      WRITE(6,*) '      Enter prediction points (1: spiking)'
      READ(5,*)  IPRED
      WRITE(6,*) '      Enter additive white noise level (%)'
      READ(5,*)  PNOIS
C
      PNOIS=PNOIS/100.
C
C---- DECONVOLUTION APPLICATION
C
      CALL PDCON86(SEIS,SPDCON,LENG,ISTART,LWIN,NOP,IPRED,PNOIS)
C
C---- APPLY d-FILTER
C
      CALL ZERO85(WORK,LENGDW)
      CALL MOVE85(SPDCON,WORK(LENGDH+1),LENG)
      CALL CORR85(WORK,LENGDW,DFIL,LENGD,SPDCON,LENG)
      CALL NORM85(SPDCON,LENG,1,LENG,IRMS)
C
C---- COMPUTE RMS ERROR AND CC VALUE
C
      IFIX=0
      CALL SIMLR86(CC,ISHIFT,CCFIX,IFIX,SPDCON,LENG,DREF,LENG)
```

```
      CALL DEVI85(DEVI,SPDCON,DREF,LENG)
      WRITE(6,*) '      RMS ERROR = ',DEVI
      WRITE(6,*) '      CC VALUE  = ',CC,'  ISHIFT = ',ISHIFT
C
C---- WRITE SPIKING DECONVOLVED DATA ON UNIT-15
C
      OPEN (UNIT=15,FILE=DATAN5,STATUS='UNKNOWN')
      DO 1240 I=1,LENG
      T=(I-1)*DELT
      WRITE(15,*) T,SPDCON(I)
1240  CONTINUE
      CLOSE (UNIT=15)
C
C---- END
C
      WRITE(6,*) '     Do you continue to work ? (Y/N)'
      READ(5,12) ANS
      IF(ANS.EQ.Y) GOTO 2
      GOTO 9000
C     ***************************************
C             R-J DECONVOLUTION
C     ***************************************
4000 CONTINUE
      IF(IZERO.EQ.0) GOTO 4010
      WRITE(6,*) '      Source is not zero-phase, try again'
      GOTO 2
4010  CONTINUE
      WRITE(6,*) 'XXXXX START R-J or G-L DECONVOLUTION START XXXXX'
      WRITE(6,*) '      Enter output data file name'
      READ(5,12) DATAN5
      WRITE(6,*) '      Enter noise level (%) on deconvolution'
      READ(5,*)  PNOIS1
      WRITE(6,*) '      Enter noise level (%) on phase compensator'
      READ(5,*)  PNOIS2
      WRITE(6,*) '      Enter design gate start point'
      READ(5,*)  ISTART
      WRITE(6,*) '      Enter design gate length'
      READ(5,*)  LWIN
      WRITE(6,*) '      Enter W-L equation order'
      READ(5,*)  NOP
C
C---- DECONVOLUTION (R-J) ----- 1-ST STEP (SPIKING DECONVOLUTION)
C
      IPRED=1
      PNOIS1=PNOIS1/100.
      PNOIS2=PNOIS2/100.
      CALL PDCON86(SEIS,W1,LENG,ISTART,LWIN,NOP,IPRED,PNOIS1)
C
C---- GENERATE MINI-PHASE EQUIVALENT OF KLAUDER WAVELET----- 2-ND STEP
C
```

```
      CALL WTRAN86(KLAUD,W2,LENGK,IDIST,PNOIS2)
      CALL WTRAN86(W2   ,W3,LENGK,IDIST,PNOIS2)
C
C---- COVOLUTION OF MINI-PHASE EQUIVALENT WITH SPIKING DECONVOLVED DATA
C
      CALL CONV85(W1,LENG,W3,LENGK,RJDCON,LENG)
C
C---- WRITE RJDCON ON UNIT-15
C
      OPEN (UNIT=15,FILE=DATAN5,STATUS='UNKNOWN')
      CALL NORM85(RJDCON,LENG,1,LENG,IRMS)
      DO 4400 I=1,LENG
      T=(I-1)*DELT
      WRITE(15,*) T,RJDCON(I)
4400  CONTINUE
      CLOSE (UNIT=15)
C
C---- APPLY d-FILTER AND COMPUTE RMS ERROR, CC VALUE
C
      CALL ZERO85(WORK,LENGDW)
      CALL MOVE85(RJDCON,WORK(LENGDH+1),LENG)
      CALL CORR85(WORK,LENGDW,DFIL,LENGD,RJDCON,LENG)
      CALL NORM85(RJDCON,LENG,1,LENG,IRMS)
C
C---- COMPUTE RMS ERROR AND  CC VALUE
C
      IFIX=0
      CALL SIMLR86(CC,ISHIFT,CCFIX,IFIX,RJDCON,LENG,DREF,LENG)
      CALL DEVI85(DEVI,RJDCON,DREF,LENG)
C
      WRITE(6,*) '      RMS ERROR = ',DEVI
      WRITE(6,*) '      CC  VALUE = ',CC,'  ISHIFT = ',ISHIFT
C
C---- END
C
      WRITE(6,*) '     Do you continue to work ? (Y)'
      READ(5,12) ANS
      IF(ANS.EQ.Y) GOTO 2
      GOTO 9000


C     *****************************************
C             SH- DECONVOLUTION
C     *****************************************
5000  CONTINUE
      WRITE(6,*) 'XXXXX START S-H DECONVOLUTION XXXXX'
      WRITE(6,*) '      Enter output data file name'
      READ(5,12) DATAN5
      WRITE(6,*) '      Enter design gate start point'
      READ(5,*)  ISTART
```

```
      WRITE(6,*) '      Enter design gate length'
      READ(5,*)  LWIN
      WRITE(6,*) '      Enter W-L equation order'
      READ(5,*)  NOP
      WRITE(6,*) '      Enter noise level (%) on phase compensator'
      READ(5,*)  PNOISE
C
C---- SPIKING DECONVOLUTION STAGE
C
      IPRED =1
      PNOISD=0.0
      CALL PDCON86(SEIS,W1,LENG,ISTART,LWIN,NOP,IPRED,PNOISD)
C
C---- PHASE COMPENSATOR GENERATION
C
      LENGW =LENG+LENGKH
      LENGF =LENG+LENGK-1
C
      PNOISE=PNOISE/100.
      CALL WTRAN86(KLAUD,WORK,LENGK,IPRED,PNOISE)
      CALL CONV85(KLAUD,LENGK,WORK,LENGK,WAPCO,LENGK)
C
C---- APPLICATION OF PHASE COMPENSATOR BY CONSIDERING SOURCE TYPE
C
      IF(IZERO.EQ.0) GOTO 5201
      IF(IZERO.NE.0) GOTO 5202
C
5201 CONTINUE
      CALL ZERO85(WORK,LENGKW)
      CALL MOVE85(W1,WORK(LENGKH+1),LENG)
      CALL CORR85(WORK,LENGKW,WAPCO,LENGK,SHDCON,LENG)
      GOTO 5300
C
5202  CONTINUE
      CALL ZERO85(WORK,LENGKW)
      CALL MOVE85(W1,WORK,LENG)
      CALL CORR85(WORK,LENGKW,WAPCO,LENGK,SHDCON,LENG)
C
5300  CONTINUE
      CALL NORM85(SHDCON,LENG,1,LENG,IRMS)
C
C---- APPLY d-FILTER
C
      CALL ZERO85(WORK,LENGDW)
      CALL MOVE85(SHDCON,WORK(LENGDH+1),LENG)
      CALL CORR85(WORK,LENGDW,DFIL,LENGD,SHDCON,LENG)
      CALL NORM85(SHDCON,LENG,1,LENG,IRMS)
C
C---- WRITE ON 15
C
```

```
      OPEN (UNIT=15,FILE=DATAN5,STATUS='UNKNOWN')
      DO 5400 I=1,LENG
      T=(I-1)*DELT
      WRITE(15,*) T,SHDCON(I)
5400  CONTINUE
      CLOSE (UNIT=15)
C
C---- RMS ERROR COMPUTE
C
      IFIX=0
      CALL SIMLR86(CC,ISHIFT,CCFIX,IFIX,SHDCON,LENG,DREF,LENG)
      CALL DEVI85(DEVI,SHDCON,DREF,LENG)
      WRITE(6,*) '      RMS ERROR = ',DEVI
      WRITE(6,*) '      CC VALUE  = ',CC,' ISHIFT = ',ISHIFT
C
C---- END
C
      WRITE(6,*) '      Do you continue to work ? (Y)'
      READ(5,12) ANS
      IF(ANS.EQ.Y) GOTO 2
9000  CONTINUE
C
C---- COMPLETION
C
      CLOSE (UNIT=10)
      CLOSE (UNIT=11)
      CLOSE (UNIT=12)
      CLOSE (UNIT=13)
      WRITE(6,*) '     Do you want to continue this program ? (Y)'
      READ(5,12) ANS
      IF(ANS.EQ.Y) GOTO 1
      CLOSE (UNIT=99)
      WRITE(6,*) 'XXXXX HODCON PROGRAM COMPLETE XXXXX'
      STOP
      END
```