Surface-Consistent Residual Statics by Stack Optimization

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Introduction

The conventional perception of the surface-consistent residual statics problem, is of an overdetermined and underconstrained problem of solving for the set of parameters that satisfy, in a least squares sense, a larger set of equations. The parameters are the surface, offset and structure statics. The equations are cross-correlation picks of relative shifts between seismic traces. An alternative approach, suggested to me by Jon Claerbout, is that the statics are the set of parameters that will best correct the data. Best should be defined as a quantitative measure that is a function of the statics. These functions may be used: the power or entropy of the stack or migrated section; the semblance of unstacked data; continuity of events on the stack; or some combination of them. We are interested in finding the multidimensional point at which the absolute maximum occurs. The power of the stack was chosen as the function to be optimized, for practical reasons. The structure term, which is usually found but not applied in conventional methods, is not solved for. When applied to real data, this method of estimating residual statics by stack optimization yields very encouraging results.

The static shift is part of the more general surface-consistent phase deconvolution. Applying the optimization approach here will yield a method for partial phase deconvolution without phase unwrapping. So far, I have not yet applied this generalization, promoted by Francis Muir, to seismic data.

Automatic statics by stack power optimization

Suppose trace x_t is the last trace in a common midpoint gather to be stacked. We would like to find that time shift to apply to x_t, before we add it to the rest of the stack, s_t, that will maximize the power of summed trace.

$$\begin{aligned}\textbf{Power}(\Delta t) &= \sum_t (x_{t-\Delta t} + y_t)^2 \\ &= \sum_t x_t^2 + \sum_t y_t^2 + 2\sum x_t y_{t-\Delta t} \\ &= \textbf{constant} + \textbf{cross correlation}\end{aligned}$$

Maximizing the power is, therefore, equivalent to maximizing the cross correlation. This can be efficiently done by iterative search: To estimate a shot consistent shift, the shot profile is cross-correlated to the relevant part of the stack and the maximum is picked. This is done for every shot and every geophone, and repeated until convergence is achieved. The stacked traces, serving as pilot traces, are improved as the statics estimate improves. The data are available in the iterations that follow so, unlike conventional statics methods, errors that may be done in the nonlinear pick can be corrected. In optimization theory, this method is in the category of line search methods; the variables are sequently searched for the extremum. This method shows a robust in ability to recover from early errors. Another advantage of this method is that the structure and residual NMO terms are kept out of the game: these terms are not pursued because they are not applied. The residual NMO may be found by a second round of velocity analysis after the statics are corrected.

Optimization by successive line search is prone to local extrema, which may cause the familiar cycle skip problem of cross-correlation picks. When filtering the estimated statics, the power drops for the short run but climbs again, in the subsequent iterations, hopefully without the cycle skips. Using running medians as suggested by Francis Muir, was effective in extracting cycle skips. This "glitches extractor" was used occasionally, not in every iteration; letting the subsequent iterations repair the damage.

Another motivation for filtering is that the most powerful stack and the best stack are assumed to coincide only for practical reasons. The filtering biases the solution towards other measures of quality, like lateral continuity, without actually computing the lateral continuity. For example, in certain recording geometries the geophones enter the stack at every other midpoint. Estimating the statics of every geophone independently produces discontinuous events. Filtering out the nyquist component improves the continuity although the power is reduced. Null space components such as wavelengths much bigger than the cable, were cleaned out too.

When the problems caused by local extrema are more severe, other maxima can be found by using the same algorithm with different starting points. If this is repeated many times there is a good chance of arriving at the absolute maxima. If local maxima are a plague, an algorithm like Dan Rothman's annealing (also discussed in this report) may help.

In practice, so far filtering was sufficient to clean the cycle skips that occurred in the early iterations.

Real data examples

The method was applied to two vibroseis lines. One was high quality, flat reflectors. The other was more problematic: it has geophone-midpoint decoupled geometry, dipping reflectors and a poor signal-to-noise ratio due to ground roll. Both lines show positive results except up shallow of the poor quality data (Figures 1 and 2). These results confirm the assumption of surface-consistency assumption because the statics were estimated in a narrow time window down deep but applied at all times with positive effect. The estimated shot-geophone-station statics (Figures 3 and 4) show reasonable match for the poor quality and perfect match for the good quality data.

Surface-Consistent Phase Deconvolution by Stack Optimization

Near surface irregularities are usually not a goal of reflection seismology. However, they do change the seismic wavelet that is passed through them. Their effect, along with the source signature and receiver response, is the target of deconvolution and statics correction. It is important to remove these near surface effects before stacking, afterwards they can be neither estimated nor applied.

In general the near surface may be nonlinear. I assume that these nonlinearities are negligible, and that the near surface is a linear, time-invariant, filter that can be described by a transfer function.

Most deconvolution methods assume a minimum-phase transfer function. This assumption is clearly wrong for mixed phase vibroseis data. For the near surface, the static shift is

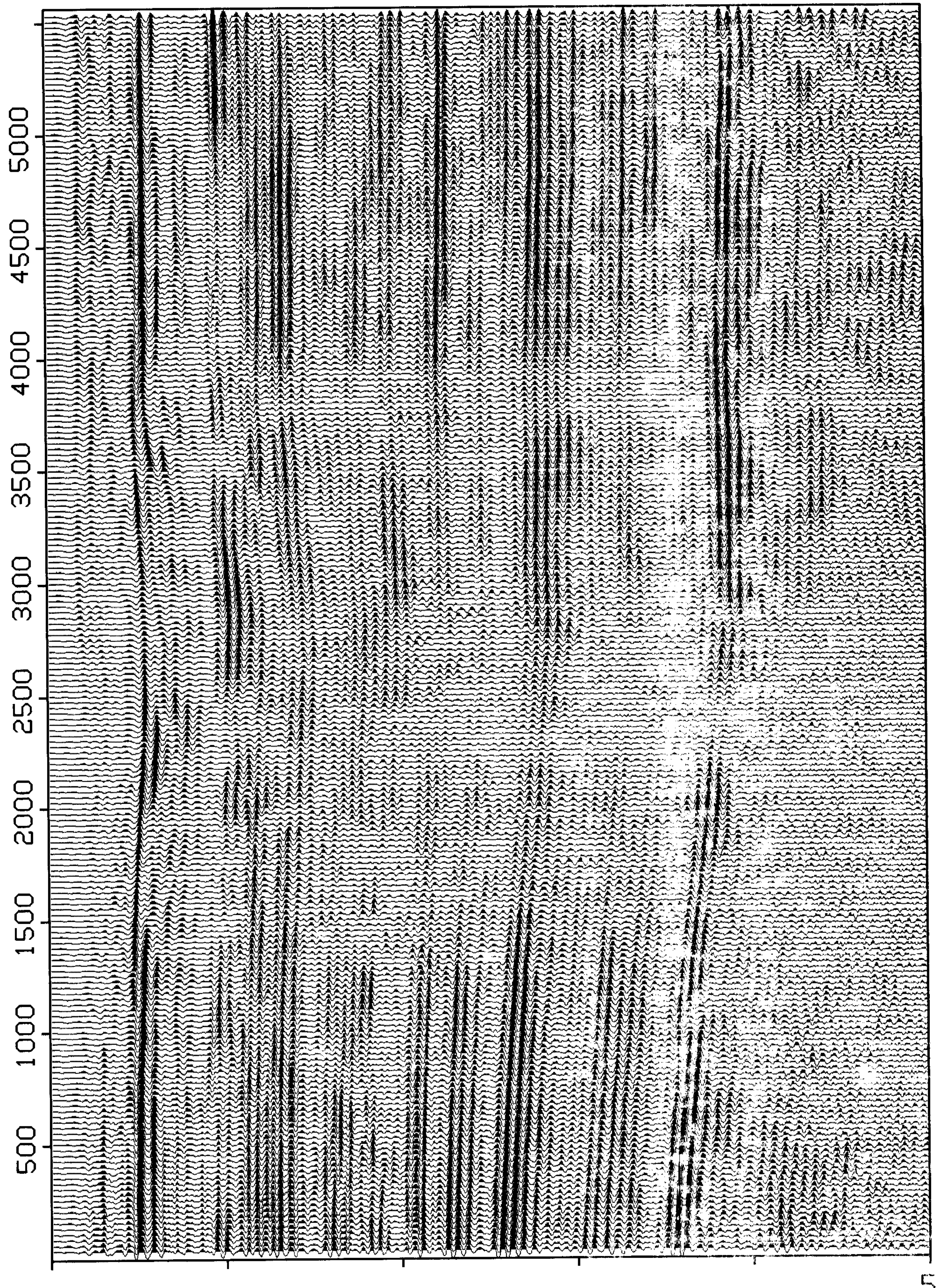

FIG. 1a. Stacked high-quality data without statics correction.

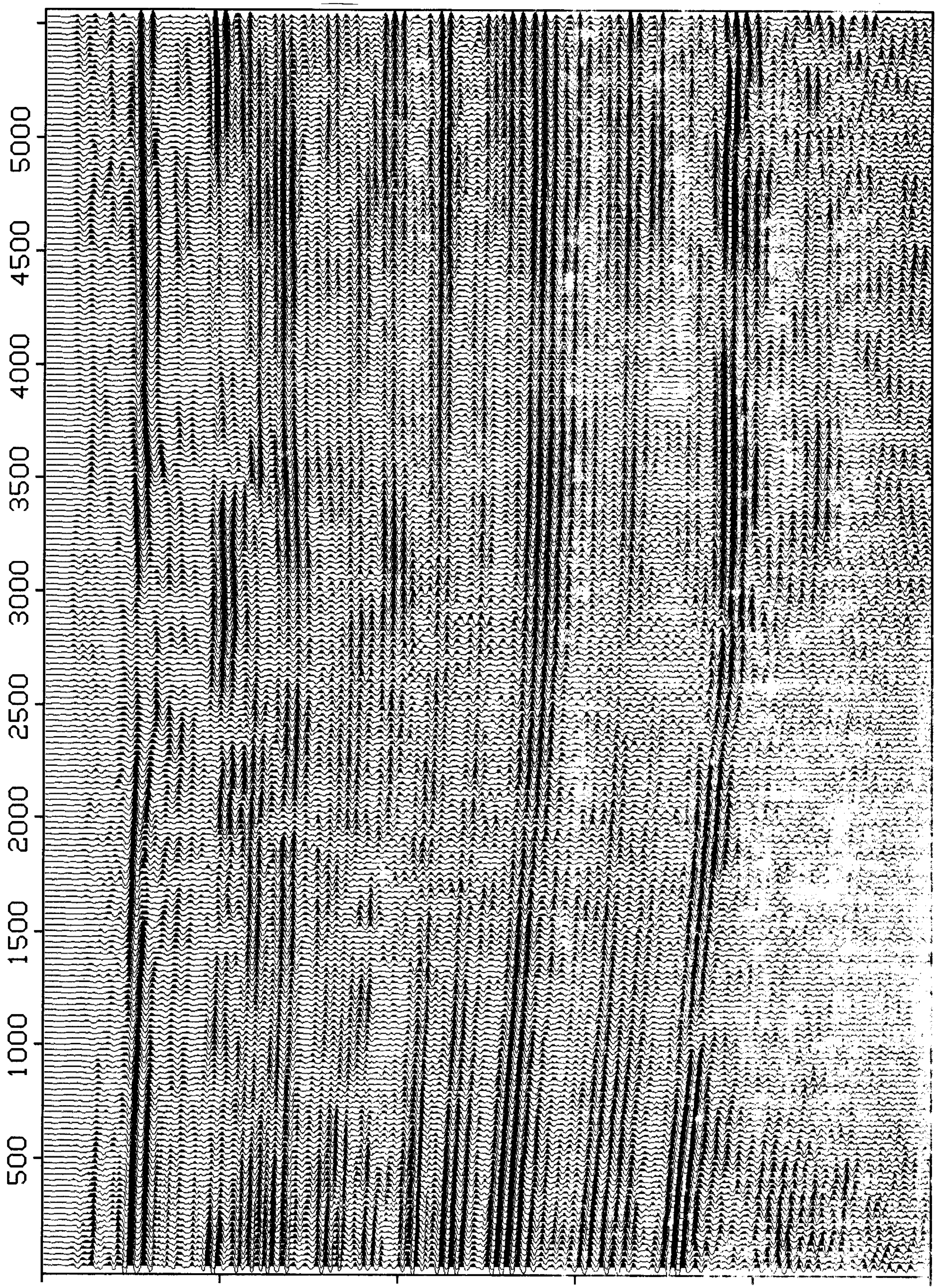

FIG. 1b. With correction. The statics were estimated at the time window of 3.5 to 4 seconds.

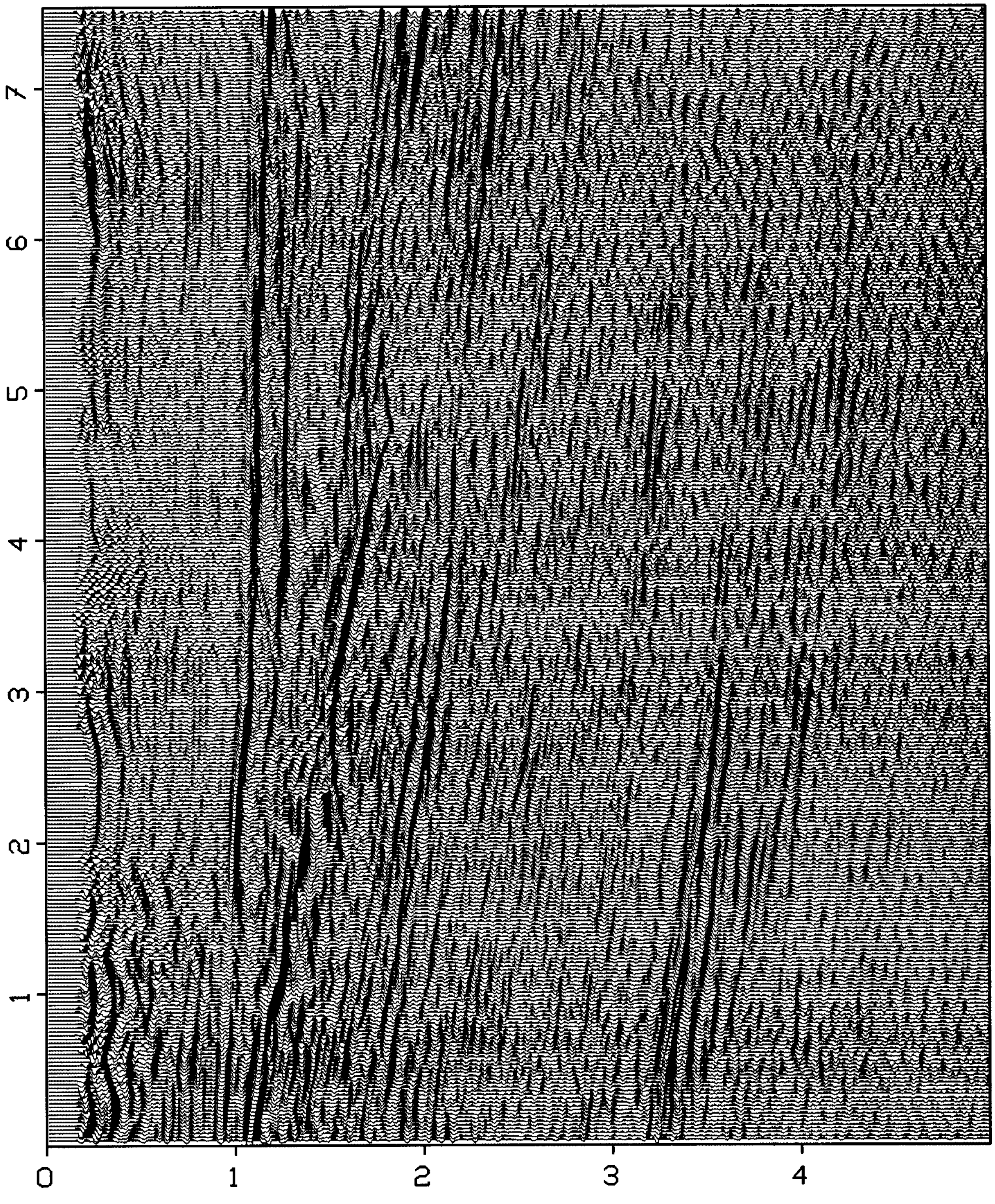

FIG. 2a. Stacked problematic data without statics correction.

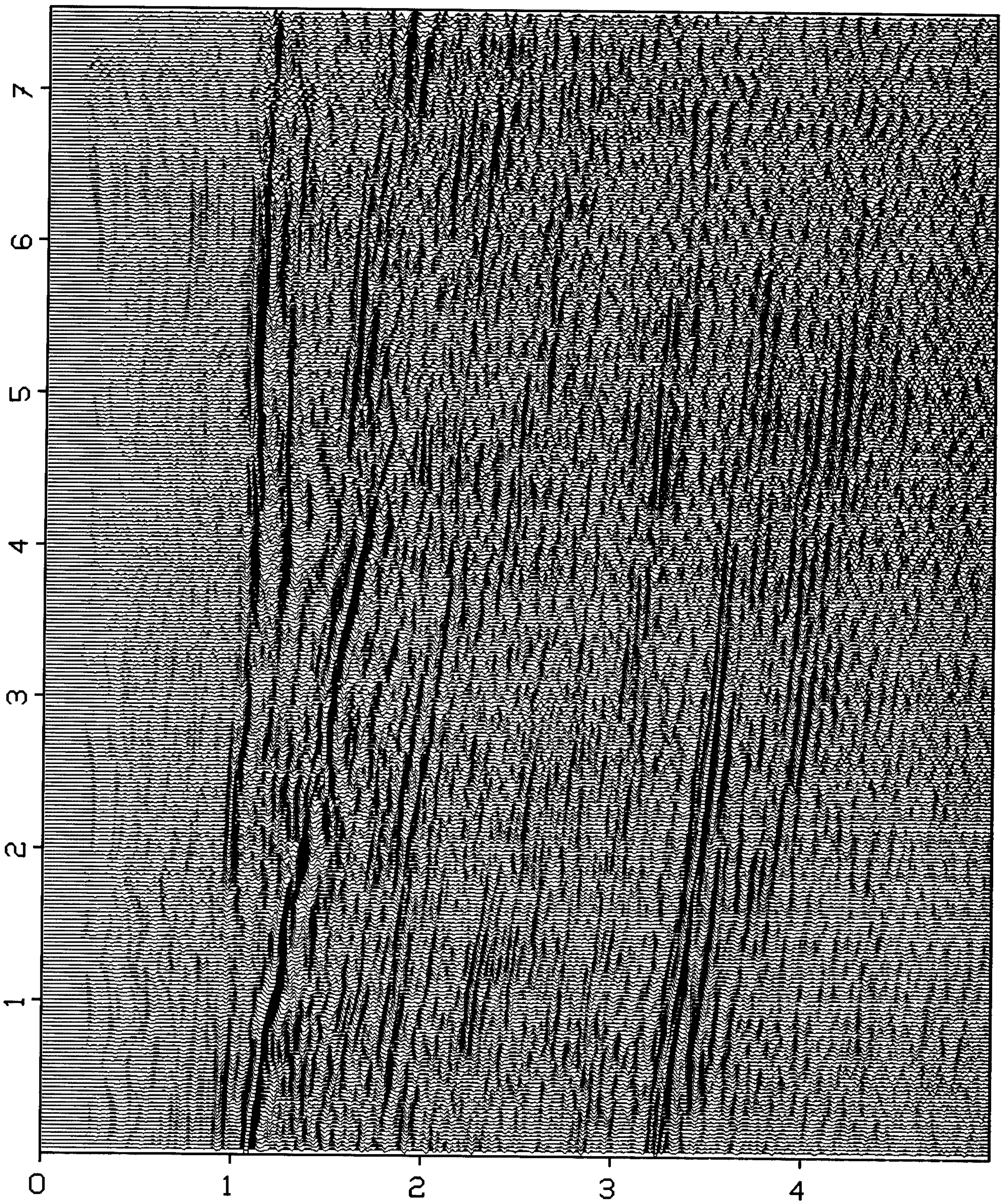

FIG. 2b. With correction. The statics were estimated at the time window of 3 to 3.5 seconds.

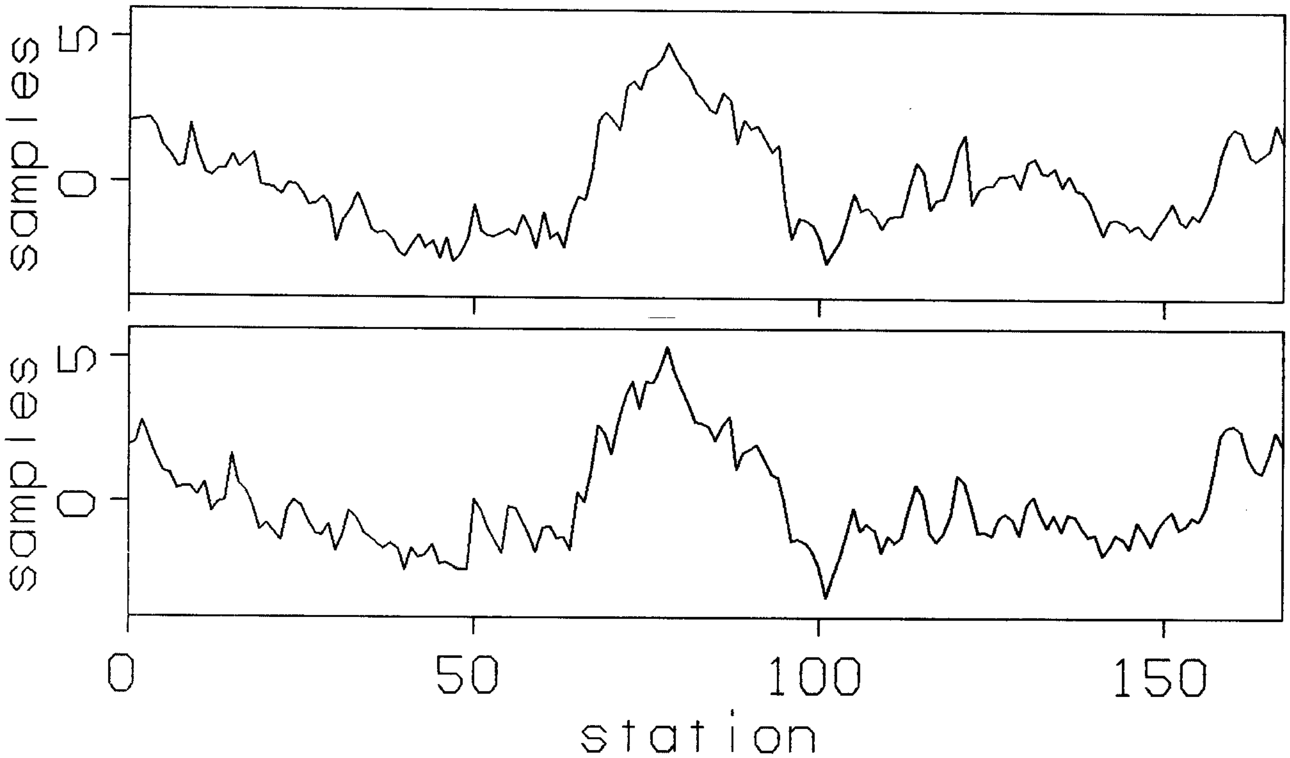

FIG. 3. Station statics estimation for the high quality data. Geophones are above and shots, below.

linear phase, not minimum, and there probably is more near-surface phase that needs correction. Whether the assumption of minimum phase is right or not, prediction-error-filter, or any other deconvolution method that uses only the amplitude spectrum is valid. Gibson and Larner (1983) noted that the residual phase can be corrected after deconvolution.

The shot and receiver phase can be corrected after stacking but the surface-consistent phase correction should be done before stack. If the deconvolution is done with Larry Morley's method (Morley and Claerbout, 1983), the residual phase is likely to be surface-consistent. The phase correction after amplitude spectrum deconvolution, is the sum of the near-surface phase and the minimum phase of the prediction error operator. An offset dependent term can correct for the angle dependent reflection coefficient. In general, all this does not reduce exactly to the linear phase correction of the residual static.

Straightforward generalization of Morley's method to phase deconvolution faces the painful problem of phase unwrapping. Chuck Sword (1983) found a way to avoid phase unwrapping by working the opposite way: wrapping the parameter instead of unwrapping the equation. However, he used the conventional perception of overdetermined system. The phase deconvolution can be done instead, as an optimization problem: by looking for the set

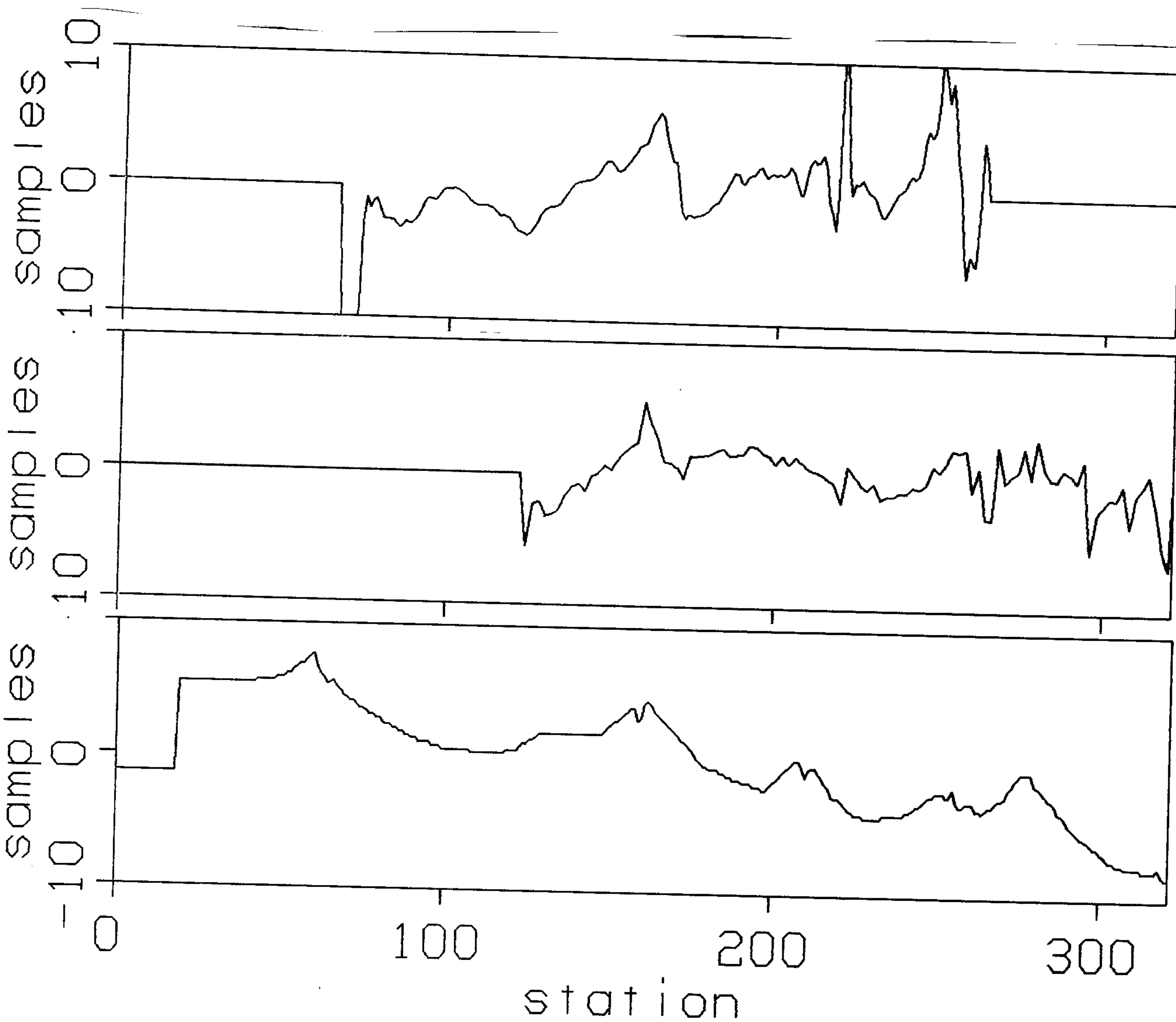

FIG. 4. Station statics estimation for the poor quality data. Geophones are above, shots are in the center, field statics (which were not applied) are below.

of parameters that will maximize the quality of the result, no phase unwrapping is needed. Solving for the phase at all frequencies will result in an overwhelming number of parameters. To keep things in control we can solve for a limited degrees of freedom obtained, this is obtained by expanding the phase $\Phi(\omega)$ to a truncated series in the frequency ω. the phase is odd function of frequency because the operator is real. The phase can be described by

$$\Phi(\omega,p) = \sum_n \Phi_n(\omega,p) = \sum_n \varphi_n(p)\, sgn(\omega) \left|\omega\right|^n$$

where p is a parameter index, e.g. shot index. The n term has a phase delay

$$\tau_p \equiv \frac{\Phi_n}{\omega} = \varphi_n \left|\omega\right|^{n-1}$$

and a group delay

$$\tau_g \equiv \frac{\partial \Phi_n}{\partial \omega} = \begin{cases} (n-1)\varphi_n \omega^{n-1} & \text{for } n \text{ odd} \\ (n-1)\varphi_n \left|\omega\right|^{n-1} + \varphi_n \omega^n \delta(\omega) & \text{for } n \text{ even} \end{cases}$$

The group delays are causal if φ_n is positive.

The $n=1$ term is the nondispersive static shift $\varphi_1 = \Delta t$. This term time-shifts without changing the wavelet appearance.

The $n=0$ term is the bulk phase correction. The operator

$$e^{i\varphi_0 sgn(\omega)} = \cos\varphi_0 + i \sin\varphi_0\, sgn(\omega) \subset \cos\varphi_0 \delta(t) + \sin\varphi_0 H$$

where H is the Hilbert transform operator. This term does not shift the envelope, but it changes the wavelet. The analytic signal $f(t)+iH[f(t)]$ is rotated by the angle φ_0 in the complex plane, before the real part is taken.

The $n=2$ term,

$$F_2(\omega) = \exp[i\, \varphi_2 sgn(\omega) \left|\omega\right|^2]$$

transforms to

$$f_2(t) = \frac{\cos\alpha^2}{\sqrt{\varphi_2}}\left[\sqrt{\frac{\pi}{2}} - 2\int_0^\alpha \cos x^2 dx\right] + \frac{\sin\alpha^2}{\sqrt{\varphi_2}}\left[\sqrt{\frac{\pi}{2}} - 2\int_0^\alpha \sin x^2 dx\right]$$

where $\alpha = \frac{t}{2\sqrt{\varphi_2}}$. $f_2(t)$ is shown in Figure 5.

Conclusions

Approaching the residual statics as an optimization problem gives very good results. The method is economical and robust. In tests, so far, local extrema were not a problem. The same approach may be applied to generalized partial phase deconvolution.

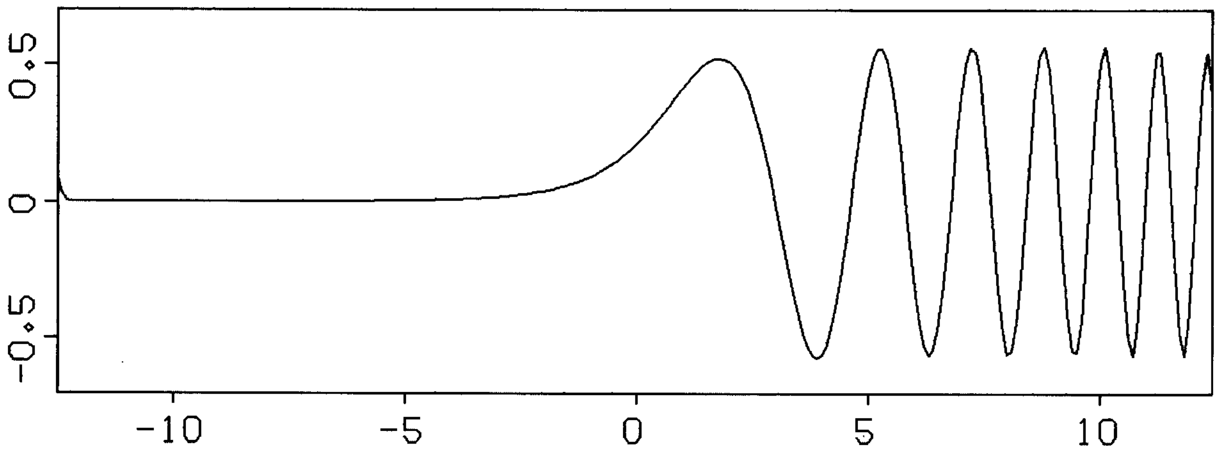

FIG. 5. The $n=2$ term

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REFERENCES

Gibson B., and Larner K., 1982. Predictive deconvolution and the zero phase source, presented at the 52nd SEG meeting, Dallas.

Morley, L.C. and Claerbout J.F., 1983. Predictive deconvolution in shot-receiver space, Geophysics v. 48 p. 515-531.

Sword C., 1983. The generalized frequency-dependent surface-consistent statics problem, SEP-35, p. 19-41.

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