CSEG JOURNAL, V. 8, NO. 1 (DEC., 1972) P. 41-53, 15 FIGS.

SIGNATURE DECONVOLUTION FOR MARINE SEISMIC REFLECTION SURVEYS†

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"Signature Deconvolution", an adaptation of spiking deconvolution, is investigated. The results indicate that it is a reliable and effective method for bubble-pulse removal in marine seismic. The method requires that a clear record of the "signature" of the source function including bubble-pulses be available, if this is not available it may possibly be modeled, and then used.

INTRODUCTION

A problem commonly encountered in the acquisition of marine seismic data from explosive sources, is that of secondary pulses generated by the oscillating gas bubble remaining after the primary explosion has taken place. Such secondary pulses may obscure the data after the first arrivals, and can make interpretation extremely difficult. Figure 1 illustrates such bubble-pulse trains, in this instance the data is from an air-gun; as is easily seen the bubble-pulse train has obscured a considerable amount of primary data.

Recordings of bubble-pulses vary in amplitude, duration and frequency with the type of explosive source used. Dynamite sources are perhaps the most thoroughly investigated of the available sources, and it has been found (Cole, 1965) that the bubble pulse period is dependent upon the charge size and the depth at which it is fired.

The relationship is $T = KW^{1/3}/(D+33)^{5/6}$

where T is the period (in seconds) of the first bubble pulse.

K is an empirical constant (4.35 for dynamite).

D is the depth (in feet) at firing.

W is the weight of the charge (in pounds).

Subsequent oscillations follow a similar relationship: $T_n = 0.56 \frac{(r_n QW)^{1/3}}{Z_n^{5/6}}$ $\quad Z_n = d_n + 33$

Where n is the index indicating the n^{th} oscillation

Q is the initial (primary) detonation energy

r_n is the energy ratio; of the n^{th} bounce to the primary bubble energy.

d_n is the depth, at the n^{th} oscillation.

The qualitative behaviour of other types of sources is similar. There appears to be no published account of theoretical relationships for other types of sources however. Further research is necessary to establish formulae, similar to those for dynamite, which will be applicable to other types of sources. The behaviour of such bubble pulses is quite complex and their periodicities are of course not constant. This is a characteristic of bubble-pulses and can make predictive type deconvolution quite difficult for short periods. There remains then, the problem of removal of bubble-effects from marine seismic data, and we shall see that it is not necessary to have detailed theoretical knowledge of the behaviour of the bubble-pulse to be able to remove it. We should mention that there are a number of seismic methods available which produce a single pulse (Goldberg, 1972; Kramer *et al.*,

†Manuscript received by Editor October 6, 1972.

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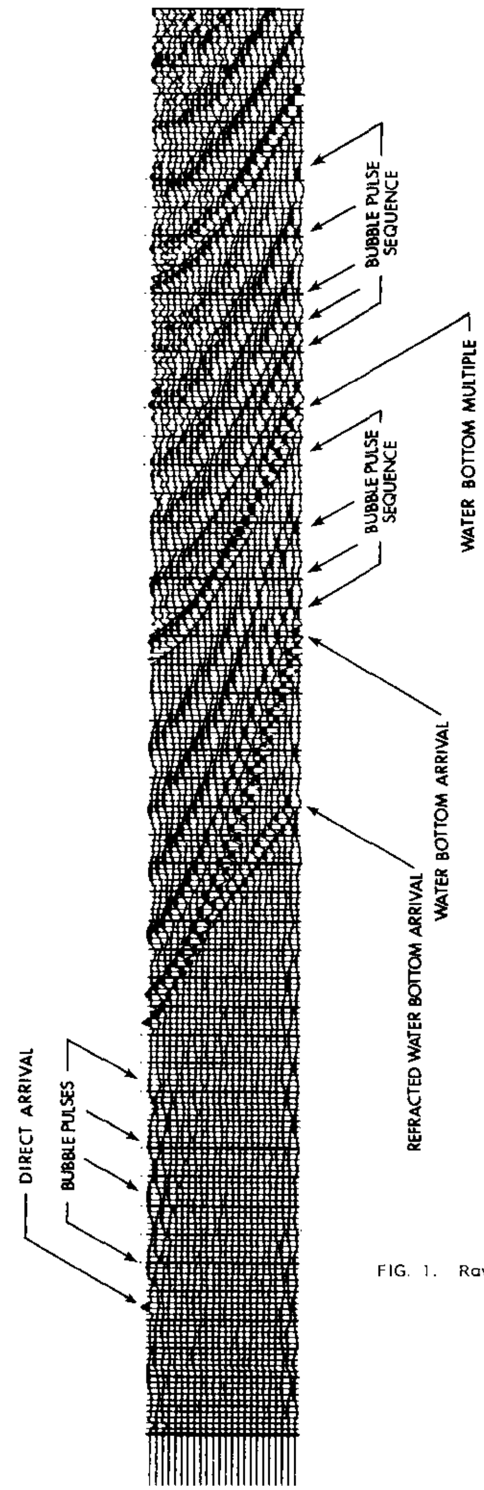


FIG. 1. Raw record illustrating bubble pulses.

1968) and for these there are no bubble effects; however for surveys made before the advent of such techniques, or for surveys which have not made use of them, the problem remains.

THE SIGNATURE DECONVOLUTION METHOD

If, as shown, in Figure 2, we can assume that the recording configuration is such that it allows sufficient time for the direct arrival to come in well before the first reflected or refracted arrival, then we can regard the initial pulse together with its subsequent bubble-pulse train as the effective "signature" of the particular source used, (provided it is not severly contaminated by noise). Such a "signature" may then be treated as the wavelet which we wish to deconvolve from the data. The most common implementation of such a deconvolution is by means of a least-square-energy-error inverse operator designed by the Wiener-Levinson algorithm (Rice, 1962; Ford and Hearne, 1966; Robinson, 1967).

Figure 3* illustrates the type of signature which one may record from an air-gun, this particular set was made using a 300 cubic inch PAR air-gun with a wave-shaping kit (to attenuate bubbles) and is quite typical. The waveshaping kit has caused attenuation of the bubble-pulses as compared with the primary pulse, but the temporal extent is greater and their amplitudes do not decay as rapidly as when there is no waveshaping kit present. The sequence shown is a set of near-trace recordings from a seismic profile. The signatures can be seen to be relatively constant in form except for some noise interference. A good

*All data in this paper is .004 second sample rate.

Ray path 1 is the ghosted arrival.

Ray path 2 is the direct arrival, the signature.

Ray path 3 is the water bottom reflected arrival.

Z_w — depth of water

Z_s = depth of shot

Z_g = depth of geophones

D = offset from shot receiver

In practice the ghosted arrival is not separable from the direct arrival, so that the signature actually includes the ghosted arrival. The appearance of ghost plus direct is as shown below;

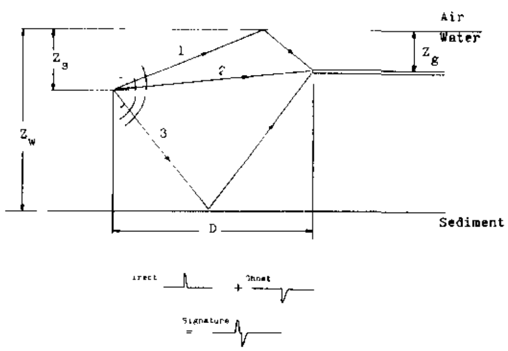


FIG. 2 Ray path diagram for typical marine

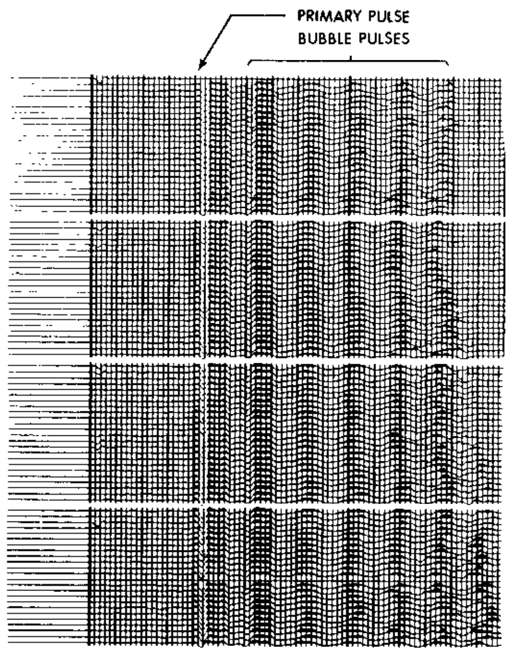


FIG. 3. Typical suite of air-gun signatures.

estimate of the noise free signature can be obtained by stacking several of them together and using this stacked signature to design the deconvolution operator. Figure 4 shows a typical seismic marine section and the interference of the bubble pulses can be clearly seen.

The procedure used to remove the bubble effects was as follows. An autocorrelation was taken of each trace of a record such as that shown in Figure 5A from 0.0 to 1.0 sec. in order to record the periodicities occurring in it. The resultant autocorrelation record is shown in Figure 5B in which it can be seen that there are strong periodicities due to the bubble-pulse train. The near trace only of the same record was autocorrelated and the resultant output smoothed with a cosine taper function. In Figure 6 can be seen a typical near-trace signature in detail, and in Figure 7 the cosine smoothed autocorrelation. The set of autocorrelation coefficients so produced was then used to design (via the Wiener-Levinson Algorithm) the inverse operator seen in Figure 8, which was used to filter the data and collapse the signature to a single minimum-delay pulse. The power spectrum of such an inverse operator is shown in Figure 9. The result of filtering the record of Figure 5A with such an operator is seen in Figure 5C and the autocorrelation of that output is seen in Figure 5D. The periodicities which were evident in Figure 5B have been effectively removed. In the case of the signature of Figure 6 the filtered output is shown in Figure 10. Inspection of Figure 12 shows that the spectrum of the signature is now very much whiter.

The process of deconvolution amplifies high frequencies in contrast with the original data and it is usual therefore to filter the output from the deconvolution process with a bandpass filter of the same bandwidth as the original data. Figure 5C is the resultant output of the deconvolution process and it can be seen that we have

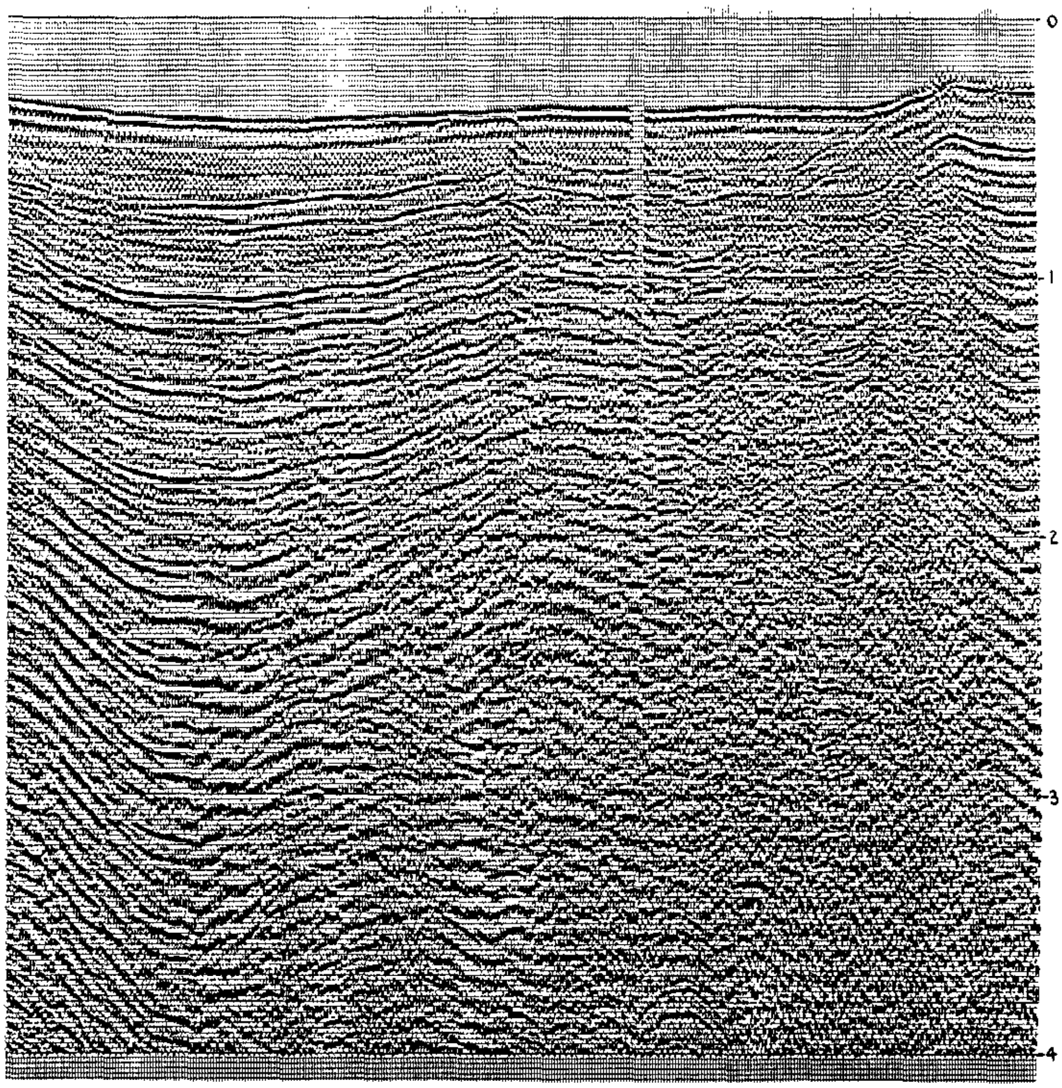


FIG. 4. Marine sixfold stack section showing bubble pulse effects.

sharpened the data as well as having removed the bubble pulse effect. In terms of spiking deconvolution the design of the operator was optimum for the design gate used, since we were able to use the signature uncontaminated with primaries, multiples etc. as would be the case with land data or shallow water marine data. The increased resolution obtained from such a process as that described has been used to advantage in the determination of velocity functions of both primaries and multiples.

The result of a sixfold stack of marine data prior to the application of the signature deconvolution, is illustrated by Figure 13. The same data restacked after use of signature deconvolution is seen in Figure 14. It is evident that the data has been effectively debubbled in the deep part of the section and is also somewhat better resolved in the early part. No attempt was made in this example to remove the water bottom multiple. As a further example the data shown in Figure 4 was also debubbled

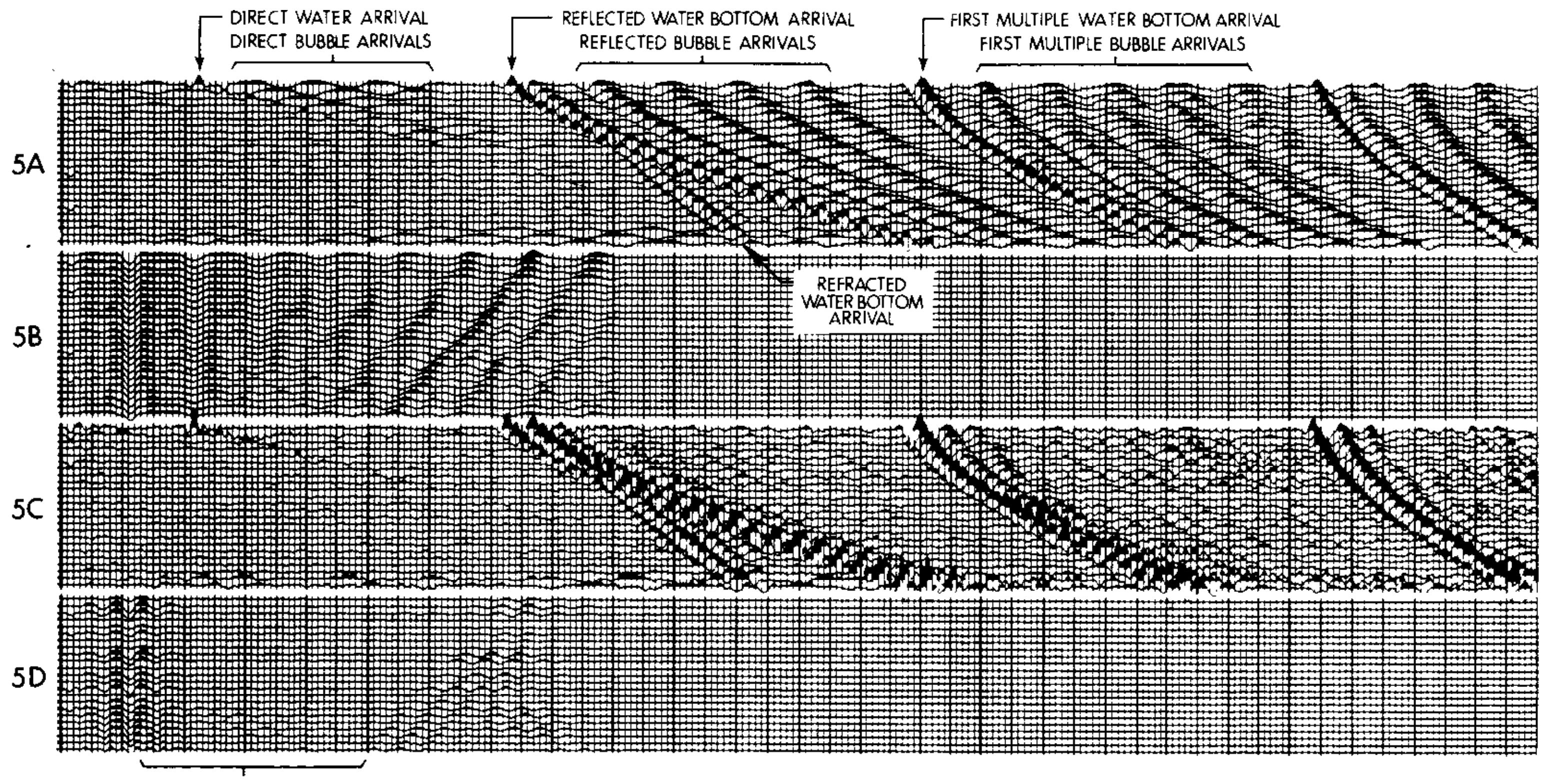


FIG. 5. A. Raw record. B. Autocorrelation of *raw* record over gate 0.0 - 1.0 second, note strong bubble pulse periodicities. C. Record after application of signature decon; operator design gate 0.190 - 0.710 seconds on near trace. D. Autocorrelation after signature decon over gate 0.0 - 1.0 seconds; bubble pulse effect removed.

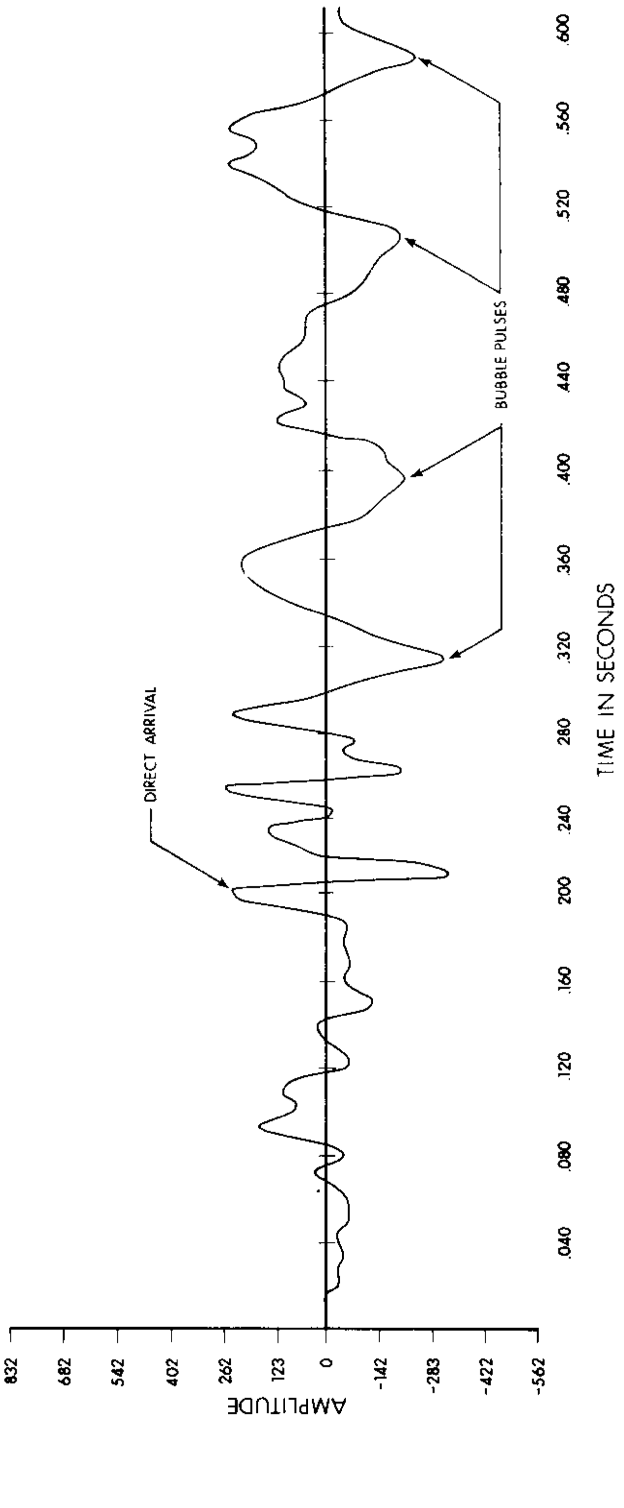


FIG. 6. Raw signature (near trace)

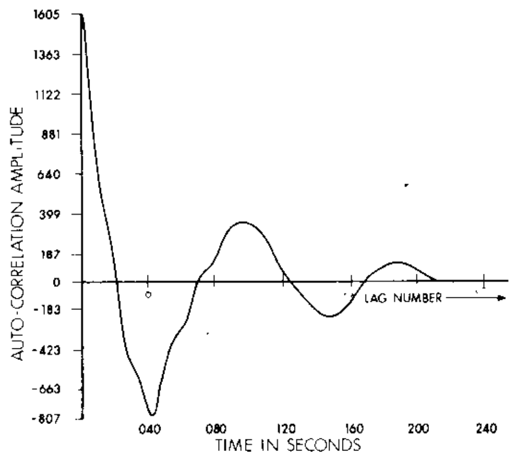
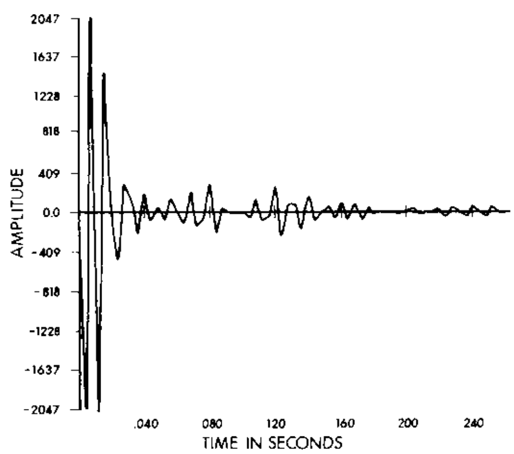


FIG. 7. Cosine smoothed auto-correlation of the signature from 0 - 650 Ms on original trace.

FIG. 8. Operator designed from cosine smoothed auto-correlation of signature.



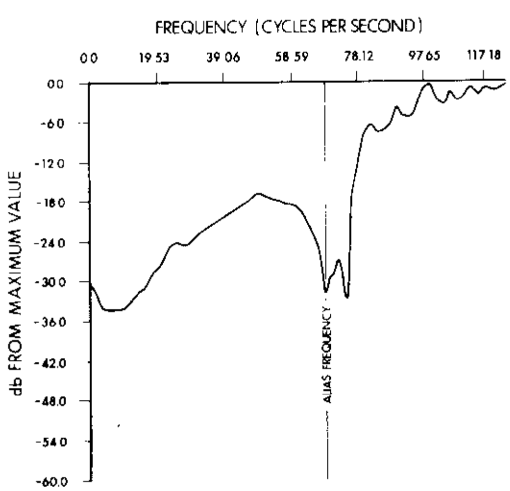


FIG. 9. Spectrum of the inverse filter.

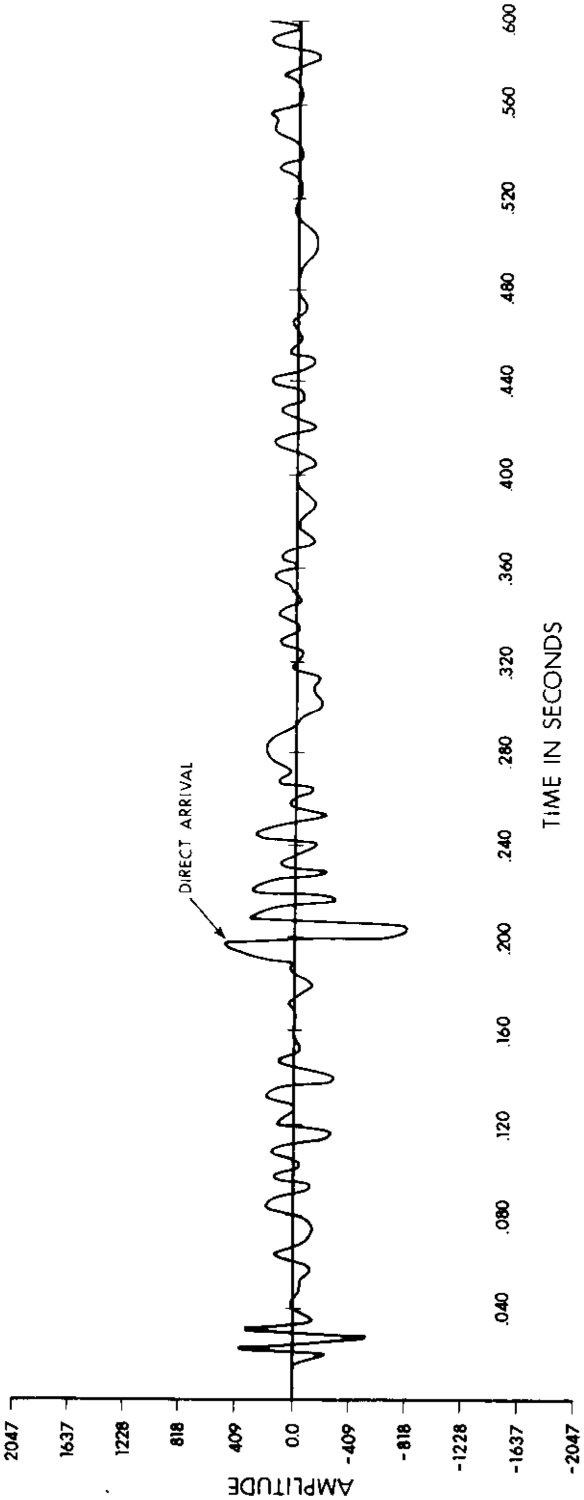


FIG. 10. Signature after decon.

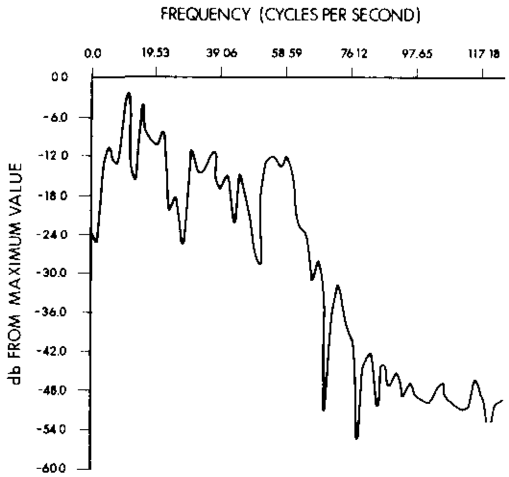


FIG. 11. Power spectrum of signature before decon.

in the same way and the result is shown in Figure 15.

LIMITATIONS OF THE METHOD

The technique depends upon a clear record of the signature. If this is not available then the method cannot be readily applied, this would be the case if an entire line was shot in very shallow water. It might be possible to design a pulse synthetically if sufficient information were available from the manufacturer of the explosive source. In the event that the signature is available on only a portion of a line and provided the entire line was shot at constant gun depth and offset a good estimate for an operator, appropriate for use on the entire line is made possible by first stacking the signatures from the deepest part of the line. Such an operator was in fact used in the generation of the stack of Figure 13. It is sometimes necessary to use an operator which is as long as the bubble pulse train. However, in most cases it is sufficient to design from only the first two bubbles.

CONCLUSIONS

Signature deconvolution, an adapation of spiking deconvolution, may be used for the effective removal of bubble pulse effects from marine seismic data. The method allows for greater resolution in the data due to its pulse compression effect (provided

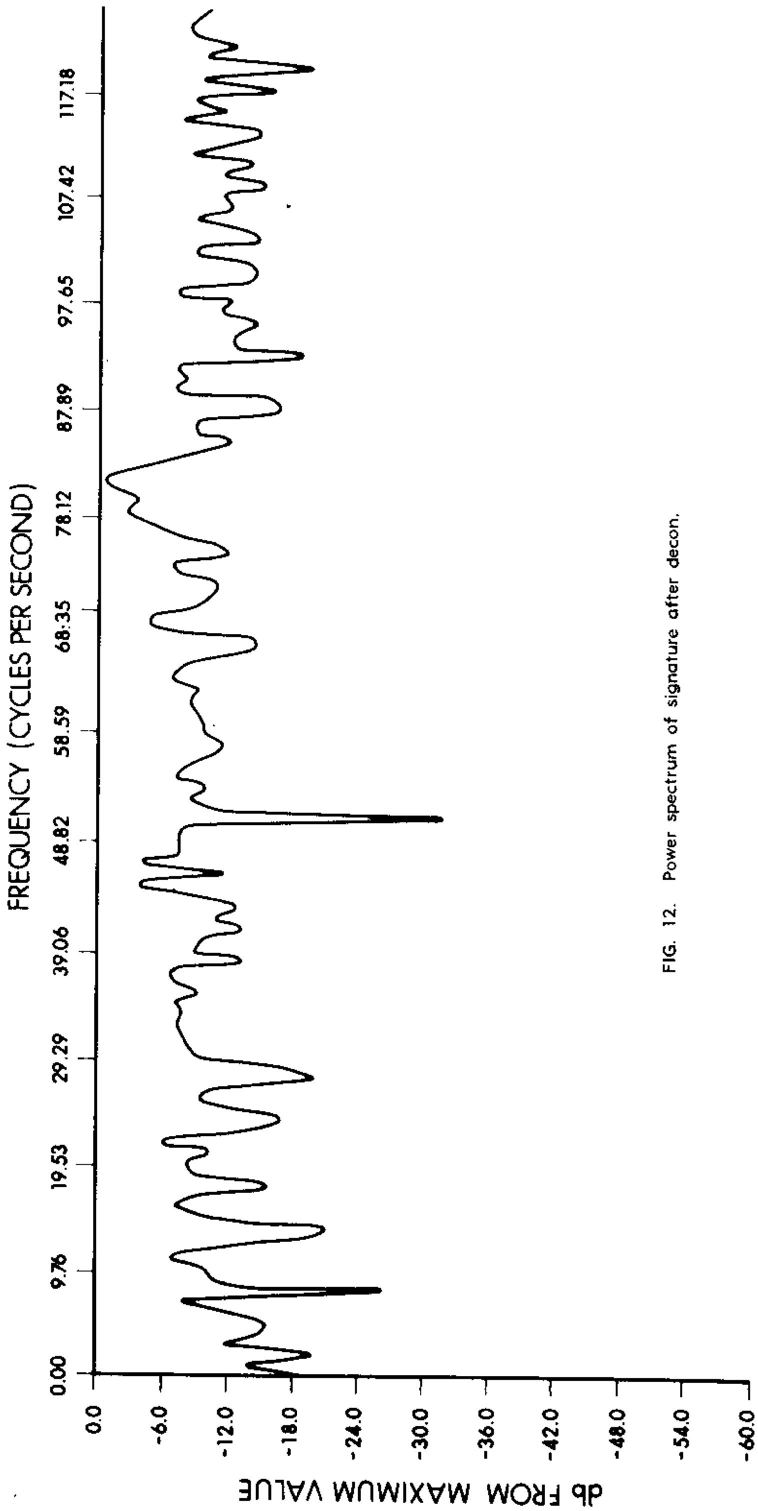


FIG. 12. Power spectrum of signature after decon.

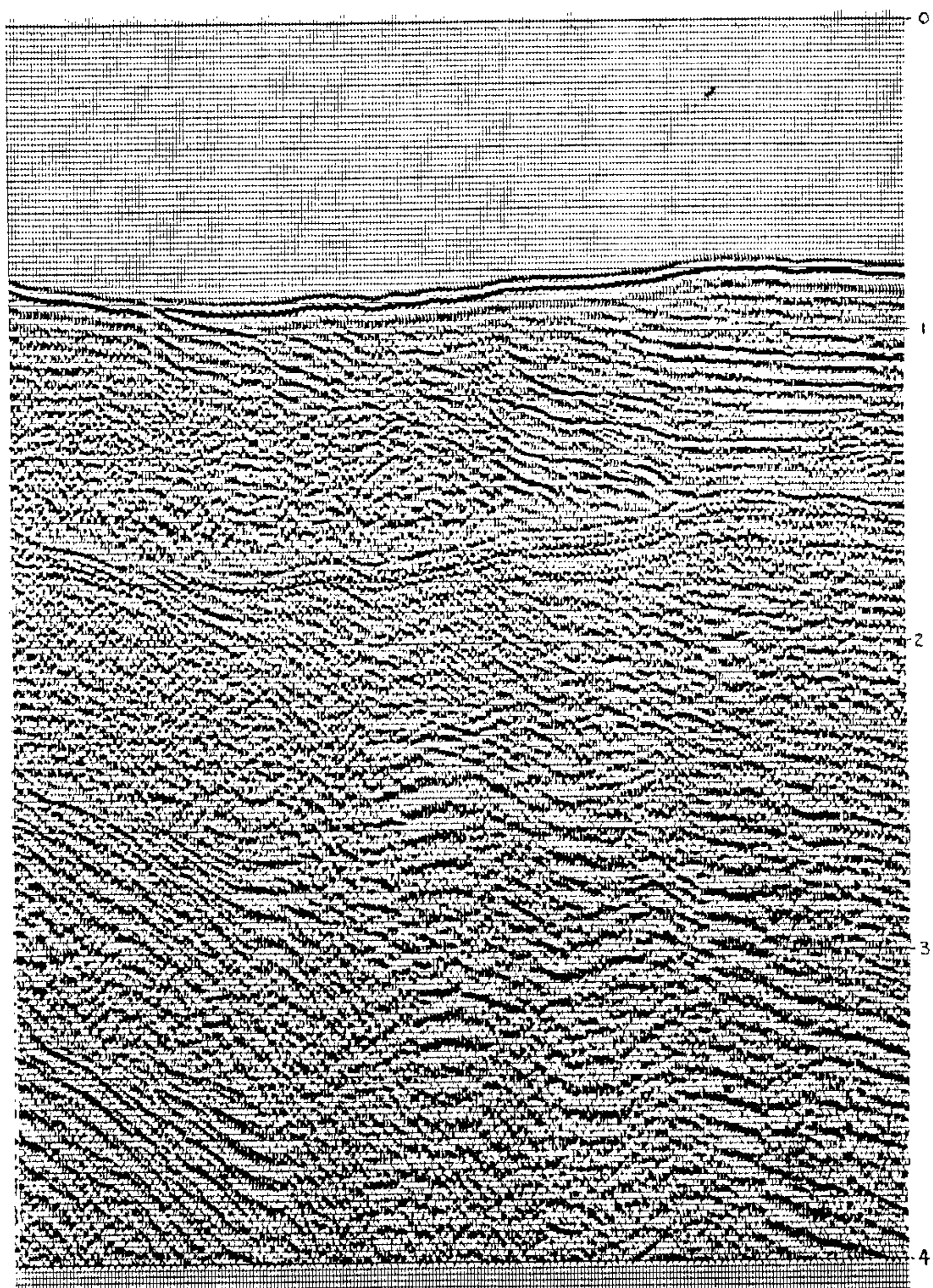


FIG. 13. Sixfold stack showing bubble pulse interference.

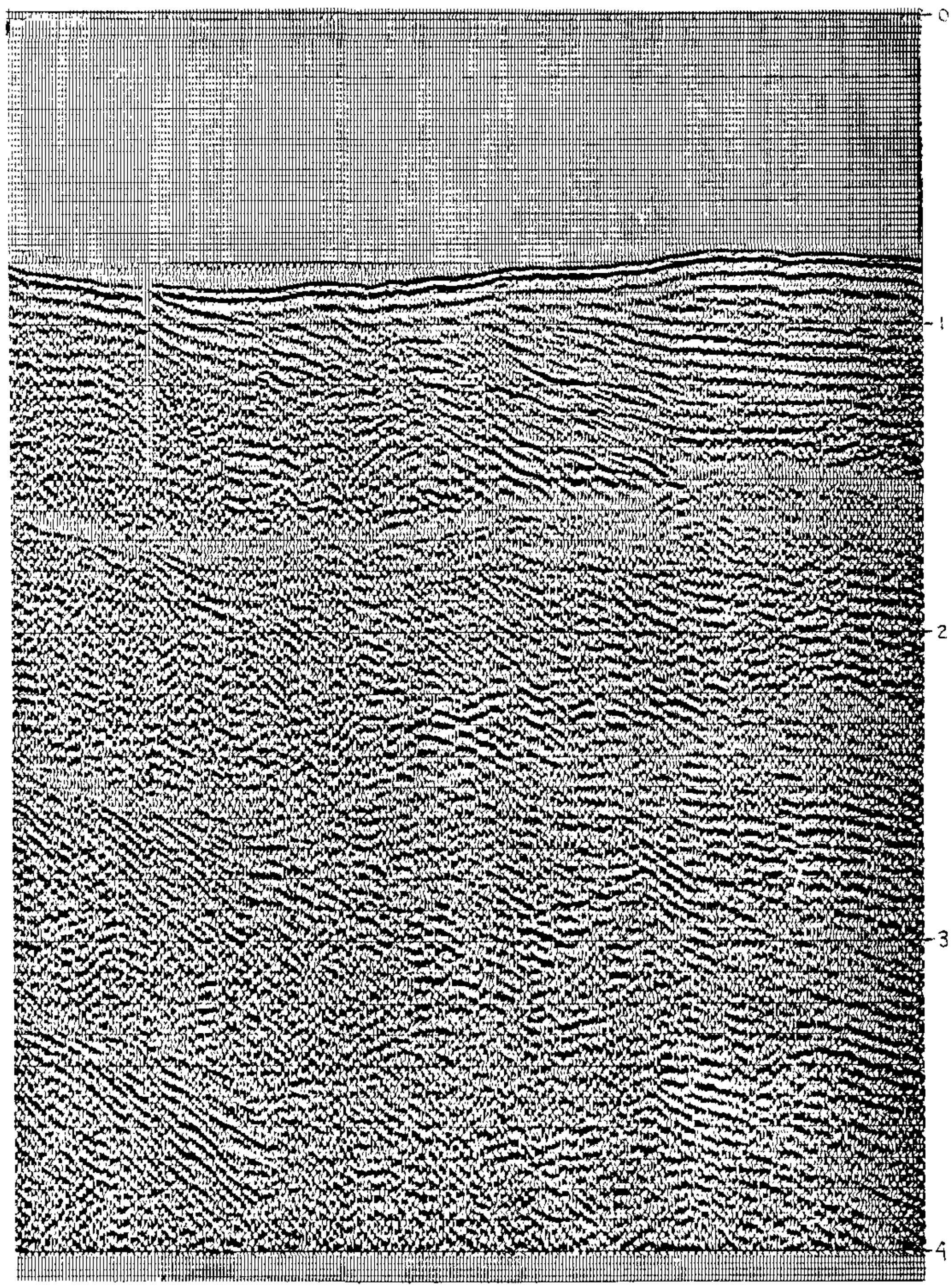


FIG 14 Sixfold stack of data in Fig 13 after Signature Deconvolution.

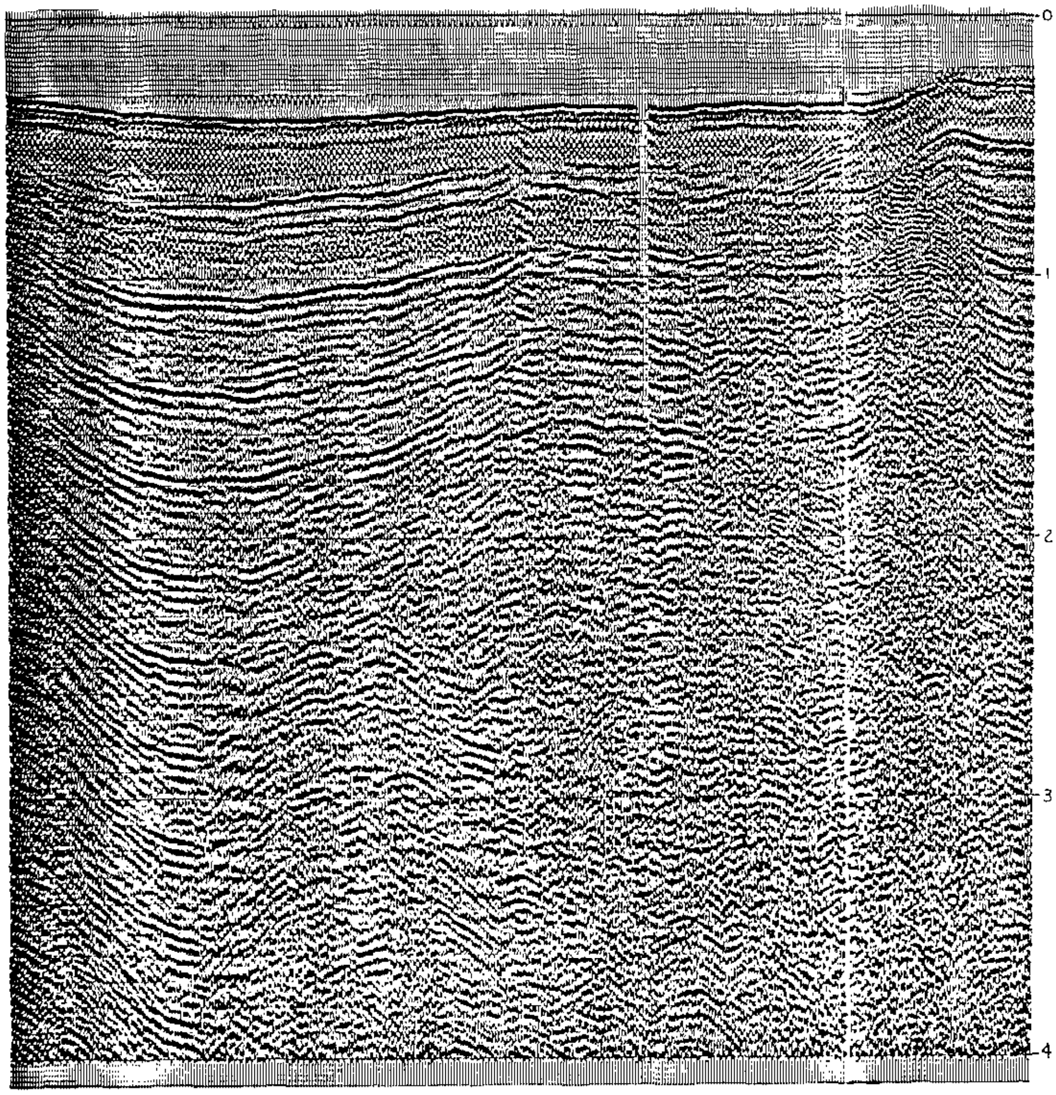


FIG. 15. Sixfold stack of the data of Fig. 4 after Signature Deconvolution

the signal to noise ratio of the raw data is reasonable). The application of this method can be expected to give improved velocity determination for both primary and multiple arrivals. The process is currently being used on a production basis for data which has severe bubble problems not amenable to predictive deconvolution techniques.

ACKNOWLEDGEMENTS

The author wishes to thank Digital Technology (Calgary) Ltd., for permission to publish the results of this investigation, and also the management of KenQuest Exploration for permission to use the examples presented throughout this paper.

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