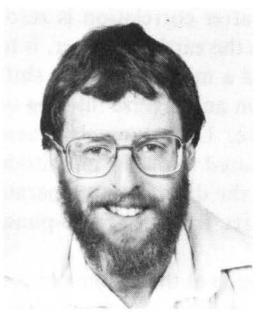
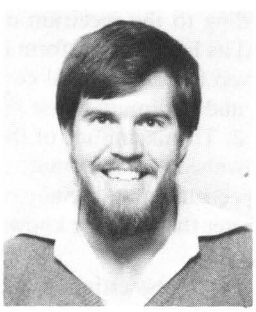


Michael Sexton obtained his BSc(Hons) degree in geophysics from the University of Melbourne in 1973. He then worked for the Hawaii Institute of Geophysics as a research assistant in marine seismic refraction studies until joining the Geophysical Branch of the Bureau of Mineral Resources in 1976. He worked in the Antarctic Observatory Group first as Observer at Macquarie Island in 1977, and then at Mawson, Antarctica in 1979. In 1980 he joined the seismic group where he worked on the Central Eromanga Basin Project. In January 1985 he began work in the BMR seismic processing centre.

M. J. Sexton, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601.



Kevin Wake-Dyster obtained his BSc(Hons) degree in Geophysics from the University of Adelaide in 1974. He joined Exploration Logging of Australia and worked on well-site surveys mainly on the North-west Shelf before joining the Geophysical Branch of the Bureau of Mineral Resources in 1976. He worked in the Antarctic Observatory Group first as observer at Mawson, Antarctica in 1977, and then at Macquarie Island in 1979. In 1980 he joined the seismic group where he worked on the Central Eromanga Basin Project. In 1984 he was Party Leader on the South-East Queensland and Clarence-Moreton Basin Seismic Projects.

K. Wake-Dyster, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601.

Some issues in vibrator data processing

Cameron B. Wason and Mark J. Potts

Summary

Recent improvements in vibrator control, such as the use of phase and amplitude control of ground force, require that some of the issues relating to vibrator data processing be reviewed. One central issue concerns the polarity of processed vibrator data as compared to processed dynamite data. At the field processing stage, alternate methods of correlation that include conventional zero-phase correlation, zero-phase inverse filtering, and minimum-phase inverse filtering are compared to determine their compatability with subsequent steps of wavelet estimation and inverse filtering or deconvolution. This issue is shown to be of particular importance when nonlinear sweeps are used. Conventional correlation is shown to be responsible for causing deconvolution to induce different phase shifts on the data when different spectral pre-emphasis sweeps or methods are used. Techniques for avoiding this problem are reviewed.

Vibrator system control and polarity convention

For many years vibrators have been controlled in accordance with an SEG polarity convention that specifies the phase of the vibrator baseplate motion with respect to the pilot. The polarity convention stated that 'the recorded pilot signal shall lead the recorded baseplate velocity detector by 90 degrees.' Stated in an alternate way, this convention requires that the baseplate acceleration be in phase with the pilot signal. More recently it has been shown that by controlling the vibrator ground force, better control of the phase of the far-field signal is achieved. Figure 1 shows the far-field acceleration recorded down a test hole and correlated with the pilot when three types of control are used, viz groundforce control, baseplate acceleration control, and reaction-mass acceleration control. Clearly, the most zero-phase result has been achieved with groundforce control. In this experiment ground force was defined as a compressive force; the control in Fig. 1 was such that the pilot signal and the compressive ground force were polarity-reversed.

Phase and polarity control, however, represent only part of the requirement. During processing, deconvolution will invariably be used to enhance the resolution of the data and, in this case, it is important to know what happened to the amplitude of the signal because deconvolution gets all its 'steering signals' from the amplitude spectrum. Recent advances in vibrator control now allow amplitude to be controlled with comparable response and precision as has been possible with phase control.

This leads to the recommendation that the polarity convention be changed to state that the pilot signal and the negative of the compressive ground force be in phase. This change would yield fairly similar results to the current baseplate velocity convention but would provide for the more accurate ground-force control of phase and amplitude.

Nonlinear sweeps and deconvolution

There is a trend in the industry toward use of nonlinear sweeps, especially those which pre-emphasize high-frequency signals. This is beneficial because high frequencies are more severely attenuated, particularly in the near surface. The intent of such nonlinear sweeps is to improve the signal-to-noise ratio of recovered data. It is our intention to point out the confusion that can be created for subsequent deconvolution when these signals are conventionally match-filtered (correlated).

In many cases nonlinear sweeps are correlated against 'flat' sweeps. The result is that the data, after correlation, is left with an implicitly nonwhite originating function. If the data had been correlated against similar nonlinear sweeps, the data would have an even more exaggerated spectral pre-emphasis, although with no change in the resulting wavelet's phase. If the data were collected with a linear sweep source and match-filtered, a flat spectral shape results, again with no difference in phase. Hence, correlation of linear and nonlinear sweep data present unequal spectral shapes to subsequent deconvolution, implying different phase and causing the different outputs from deconvolution to mistie.

It is shown that inverse filtering, as opposed to correlation, alleviates these changes in the wavelet caused by sweep pre-emphasis. In all cases inverse filtering produces a 'correlated' signal with a flat spectrum (except for minimum-phase attenuation effects of absorption, ghosts, etc.). The benefit of the nonlinear sweep shows up as an increase in the signal-to-noise ratio of the data, not merely in spectral pre-emphasis of the correlated shot record with its subsequent confusing effect on deconvolution.

Having established that inverse filtering produces a spectrum which is insensitive to sweep pre-emphasis, whereas normal correlation does not, we are then led to considering compatibility between the process and the subsequent deconvolution. Even when correlation is performed on data shot with a flat sweep, the subsequent data is mixed phase. This occurs because the source wavelet itself has a limited spectrum (being fairly flat over the limits of the sweep and rapidly attenuating beyond it), but the phase after correlation is zero. The influence of propagation through the earth, however, is to produce attenuation of the signal and a minimum phase shift to the signal, which wavelet estimation and inverse filtering or deconvolution is intended to remove. Unfortunately, these signal estimation procedures, being based upon the amplitude spectrum (or its autocorrelogram) of the data cannot separate the minimum-phase propagation parts from the zero-phase sweep parts.

One method of avoiding this confusion at the deconvolution stage is to inverse-filter the data and insert a minimum-phase component approximately corresponding to the spectrum of the sweep. If the pilot signal is $p(t)$ and its Fourier transform is $P(w)$, mathematical operations involved in conventional correlation, zero-phase inverse filtering, and minimum-phase inverse filtering are summarized in Fig. 2. The magnitude of the constant, c, in the minimum-phase inversion is important. It controls the behaviour of the phase spectrum in the vicinity of the cutoff of the sweep and is a parameter that must be known to the subsequent deconvolution step.

The wavelet estimation and inversion process estimates the spectrum of the signal and, after addition of matched noise corresponding to the constant c, estimates a wavelet that is jointly the effect of the now minimum-phase source and the minimum-phase propagation effects of the earth. The exact phase propagation effects of the earth cannot be estimated, even in the pass band of the signal when the signal pass band is not complete. This is because the phase of a minimum-phase process is the Hilbert transform of the entire spectral effect, which is not available to us with vibrator data. This can be accommodated to some degree by spectral shaping using an assumed model. This complete process can be termed inverse filtering with minimum-phase output (IFMPO).

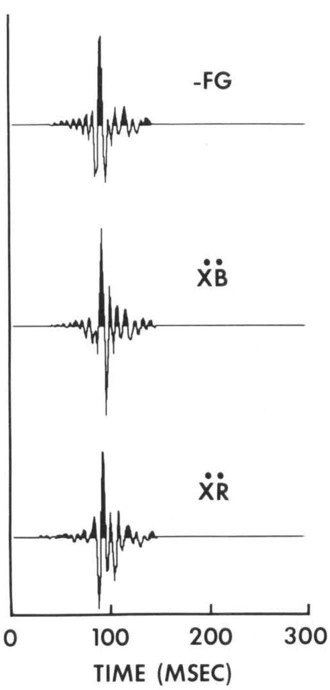


Fig 1 Cross-correlation of pilot and filtered 500-foot downhole accelerometer (X3/TR-4 Vibrator, 8–180 Hz, 6s).

	Operator	Autocorrelated Signal
Conventional Correlation	$P^*(w)$	$P(w)\,P^*(w)$
Zero-Phase Inverse Filtering	$\dfrac{P^*(w)}{P(w)\,P^*(w) + c}$	$\dfrac{P(w)\,P^*(w)}{P(w)\,P^*(w) + c}$
Minimum-Phase Inverse Filtering	$\dfrac{P^*(w)\,e^{-i\phi(w)}}{P(w)\,P^*(w) + c}$	$\dfrac{P(w)\,P^*(w)\,e^{-i\phi(w)}}{P(w)\,P^*(w) + c}$

$\phi(w)$ is the minimum phase associated with the autocorrelated signal.

Fig 2 Various types of sweep-collapse operators.

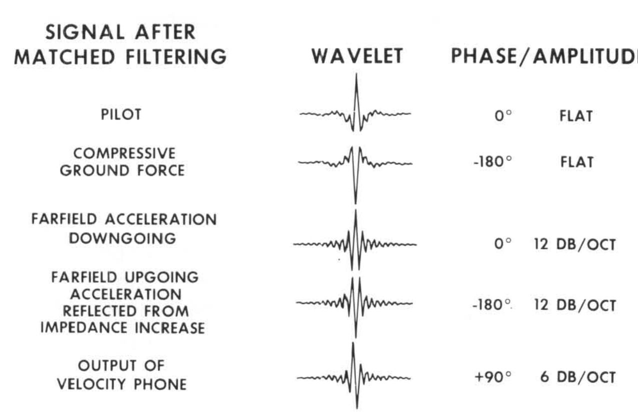


Fig 3 Tracking the vibrator signal from source to recorder.

Polarity of deconvolved vibrator data

Returning to the issue of polarity, it is best understood by following the vibrator's signal through the earth, recording, and deconvolution systems. If the compressive ground force phase and amplitude are controlled to be polarity-reversed with respect to the pilot and to have the same flat spectrum as the pilot, phase and amplitude of the signal propagated in a lossless earth then recorded into a velocity phone can be traced as shown in Fig. 3. J. Sallas in 1982 showed that the far-field down-going acceleration is in antiphase with the compressive ground force and has a 12 dB/octave rising spectrum. Hence, it is in phase with the pilot. After reflection at a positive impedance change, the phase of the up-going acceleration signal reverses because of the direction change, but the amplitude spectrum remains the same. When sensed by a velocity phone connected according to SEG polarity convention, the phase will lag an additional 90° because of the integration implicit in going from acceleration to velocity and the spectrum will rise at only 6 dB/octave. Hence, the signal is −270, or +90° with respect to the pilot with a rising spectrum.

Processing of the recorded signal progresses from this point as shown in Fig. 4. Inverse-filtering with minimum-phase output, which is based on the pilot signal, has no knowledge of the recorded spectral shape. Thus, output of IFMPO is still +90° and 6 dB/octave. In fact, except for the significant absence of amplitude definition outside the sweep band, the output of conventional, zero-phase correlation would also result in the same minimum-phase wavelet in this case. The phase estimation of deconvolution would be based on the rising 6 dB/octave spectrum, which implies +90° phase. Hence, after deconvolution the reflected wavelet will be zero phase with respect to the pilot and have a flat spectrum. It will be shown that in similarly tracking the wavelet for impulsive-source data that a reflected wavelet with a flat spectrum, but a phase of −180° would be obtained.

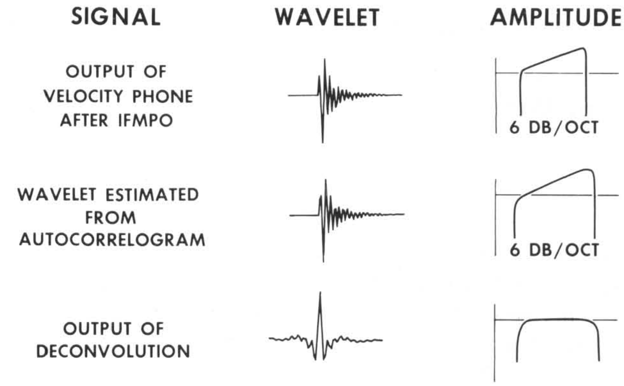
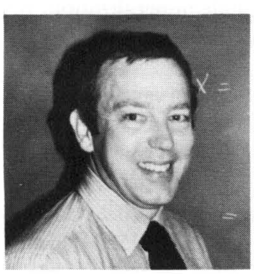


Fig 4 Tracking the recorded vibrator signal through deconvolution.



Cam Wason received the BE degree in electrical engineering in 1959 and the MEngSc degree in electronics in 1960, both from the University of Queensland, Brisbane. From 1960 to 1965 he was a Research Scientist with the Weapons Research Establishment working on telemetry and control systems. From 1965 to 1973 he worked with EMI, England, in millimeter wave radar design and then with Texas Instruments in Dallas on various NASA programs in remote sensing and satellite communication. In 1973 he transferred to Geophysical Service Inc as Manager of Geophysical Research. He is a member of SEG and is a Texas Instruments Senior Fellow.

C. B. Wason, Geophysical Service Inc., PO Box 106 North Ryde, NSW 2113.

Mark Potts received his PhD in Geochemistry from Washington University (St Louis) in 1971. During 1971 and 1972, he worked at the Geochemisches Institut in Göttingen, West Germany. From 1973 to the present he has worked in a progression of positions with GSI, including Manager of the Airborne Geophysics Group (radiometrics and magnetics) and Wavelet-Processing Research Group. He is a member of the SEG and GSA.

M. J. Potts, Geophysical Service Inc., PO Box 106, North Ryde, NSW 2113.