Physics of the Earth and Planetary Interiors, 52 (1988) 30–40
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Processing of noisy magnetotelluric data using digital filters and additional data selection criteria *

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(Received August 31, 1987)

Fontes, S.L., Harinarayana, T., Dawes, G.J.K. and Hutton, V.R.S., 1988. Processing of noisy magnetotelluric data using digital filters and additional data selection criteria. Phys. Earth Planet Inter., 52: 30–40.

Although the magnetotelluric (MT) method is known to be effective and fast in probing the electrical conductivity structure of the Earth at crustal depths, the results are often degraded by industrial and cultural noise. To obtain reliable processed results for modelling, it is first necessary to extract or select the natural signals from the contaminated time series.

Various noise-reduction techniques based on digital filters are discussed with special reference to persistent noise signals, e.g. from power lines, DC-operated railways and electrical fences. Both previously suggested techniques (delay-line and notch filtering) and two other procedures (maximum entropy extension and deconvolution filtering) are applied to both synthetic data and to field observations from southern Scotland and the Italian Alps. Better quality data sets and more geophysically acceptable Earth models are shown to result.

Noise of a more intermittent nature has recently been observed in MT observations near the development site of the geothermal power station on Milos, Greece. Large highly coherent electromagnetic field signals were observed to coincide with the opening and closure of the valves on the test wells. In this case, meaningful apparent resistivity curves could be obtained from an undisturbed subset of the previously accepted data, which had been selected mainly on the basis of signal power.

Delay-line filtering is shown to be superior to notch filtering in eliminating non-sinusoidal noise, while both the MEM extension and the window deconvolution techniques are found to be useful in spike removal.

These studies illustrate that use of an automatic data selection procedure should only be undertaken with great care in areas where the cultural noise is high. In such cases, continuous time-domain monitoring of the MT signals is recommended. The appropriate techniques of noise reduction can then be applied.

1. Introduction

Man-made noise in certain regions can be a major obstacle to the effective application of the MT method in studies of the electrical structure of the Earth's crust. Noise is that portion of the measured electric and magnetic data that is neither induced nor homogeneously induced, and which therefore does not fulfil the plane wave assumption required by the magnetotelluric method. The non-induced part exists in the recordings of both magnetic and electric fields, the noise in the magnetic field being independent of that in the electric field, i.e. incoherent or random MT noise. Noise due to inhomogeneous induction is essentially that of a nearby source (i.e. < 3 skin-depths away) and therefore the electric and magnetic fields are related to each other, i.e. coherent noise. Both categories of noise may occur either singly or in combination, exhibiting variable amplitude and

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* Paper presented at the 8th Workshop on Electromagnetic Induction in the Earth and Moon, 1986, Neuchatel, Switzerland.

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0031-9201/88/$03.50

frequency of occurrence, and they may be generated by a great number of sources.

Incoherent noise may sometimes have its origin in the data acquisition system itself, may be caused by moving vehicles which produce magnetic disturbance or arise from natural disturbances such as wind or microseismic activity. Several workers have assessed the biasing of the transfer function estimations introduced by incoherent noise (Sims et al., 1971; Goubau et al., 1978; Pedersen and Svennekjaer, 1984). If severe surface distortions are not present, and some care is exercised during acquisition and processing of data contaminated only by random noise in a single-site study, one can generally get an interpretable set of resistivity and phase curves.

Coherent noise in MT signals is due to various sources and the literature concerned with the problems caused by these noise sources is considerable. The noise signatures of various man-made disturbances have been reviewed by Herman (1979). The stray currents observable in the vicinity of DC-operated railways and their influence in masking the natural electromagnetic signals have been discussed by Kovaleskiy et al. (1961). Jones and Geldart (1967), Chaize and Lavergne (1970), Linington (1974), Yanagihara (1977), etc. Besides the railway noise problem, Adam et al. (1986) have reported on their experience of various other noisy signals in magnetotelluric data recorded in the highly resistive and mountainous Eastern Alps. These include signals from an unbalanced power network and from pipeline anticorrosion currents. A recent comprehensive review of man-made electromagnetic noise sources has been given by Szarka (1986).

Processing of MT signals degraded by coherent noise poses a formidable task as the natural and man-made signals are indistinguishable. With the advent of more sophisticated acquisition systems possessing comprehensive real-time analysis capabilities, a clear indication of the presence of coherent noise may only be noticed after data processing, e.g. the apparent resistivity and phase curves may exhibit unrealistic slopes or provide unreasonable Earth models. Nevertheless, on scrutiny of the original time series the noisy segments or spikes may be located on amplitude considerations, if the noise amplitude is considerably higher than the natural signals. The discussion which follows is restricted to this situation. It is useful to distinguish between two types of coherent noise according to whether it occurs regarly or irregularly.

The general objective of the present study is the assessment of the effectiveness of various digital filtering techniques to remove regular and irregular coherent noise from the recorded magnetotelluric signals. The analysis is performed both on synthetic data and on noisy field data recorded in three different regions: Asiago in northern Italy, Craik in southern Scotland and Milos in Greece. The results of the analysis are presented in the three following sections. Firstly, the reductions of regular coherent noise by the application of notch or delay-line filters are compared. Secondly, coherent 'spike' noise signals of regular or irregular character are detected on amplitude grounds and reduced by two distinct approaches. In one, the data set is divided into 'contaminated' and 'uncontaminated' segments and the uncontaminated segments are extended to replace the contaminated segments, by means of the maximum entropy method. The second approach assumes that the data set is convolved with a combination of rectangular windows such that the contamination by 'spike' noise is reduced. The resulting spectral distortion is attenuated by a deconvolution operation. These procedures are applied to data recorded in Asiago, Northern Italy and Craik in southern Scotland.

Finally, MT data recorded in 1985 at a few stations on Milos, Greece exhibited such a high disturbance level that only careful selection of subsets of data has provided meaningful impedance values.

2. Regular coherent noise

Usually, MT field data acquisition systems incorporate notch filters that remove with varying levels of success the 50 Hz (or 60 Hz) noise and its harmonics from power lines. The main concern here is with the regular coherent noise that has not been eliminated during acquisition time. Such

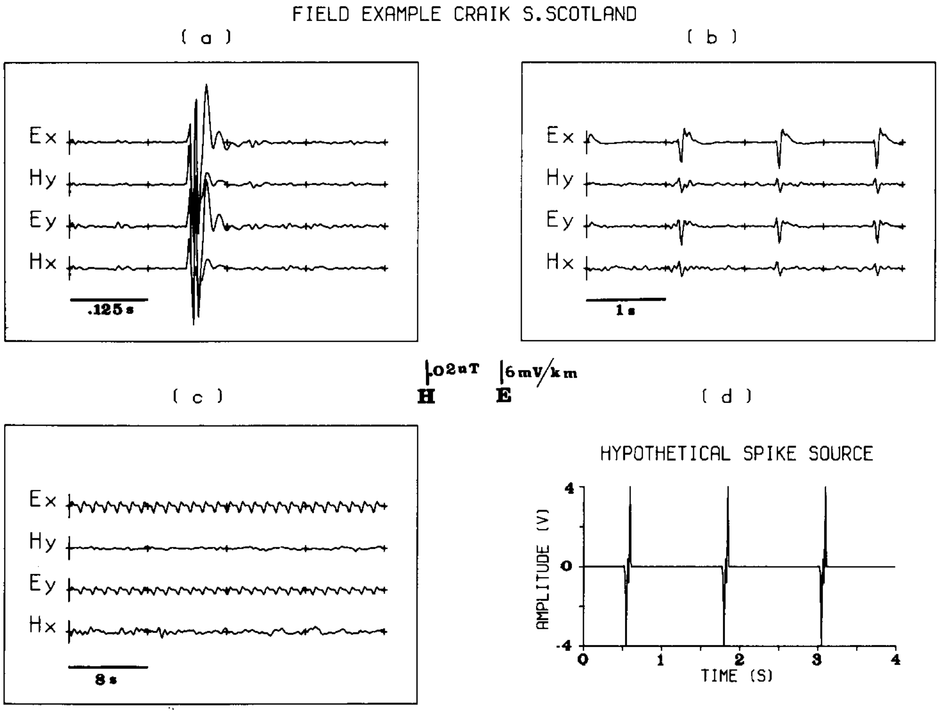


Fig. 1. Field example of regular noise recorded in Craik, Southern Scotland for three consecutive frequency bands. Magnetic (nT) and electric (mV/Km^{-1}) signals are bandpass filtered (6-pole Butterworth low-pass and 2-pole butterworth high-pass) and are shown in data windows consisting of 256 samples per channel. (a) Data window for band 0 (128–16 Hz). (c) Data window for band 1 (16–2 Hz). (c) Data window for band 2 (2–0.125 Hz). (d) Hypothetical spike source signal of 0.8 Hz repeat frequency that emulates the noise waveforms observed at the three bands.

noise is highly coherent and since in-field data selection is generally based on minimum coherency levels (Pedersen, 1986), apparently excellent MT responses result as shown in examples observed in data sets recorded in Scotland and Italy. In the Scottish example, shown in Fig. 1(a)–(c), a source with repeat frequency of 0.8 Hz observed in three different frequency bands covering the range 128–0.125 Hz has been later attributed to electrified cattle fences. In this latter case the current pulse has produced, as a result of the bandpass filters (6-pole Butterworth low-pass and 2-pole Butterworth high-pass filters) of the MT instrumentation, a random character in band 0 (cut-off frequencies 128–16 Hz; Fig. 1(a)) and a remarkably periodic signal in bands 1 (16–2 Hz; Fig. 1(b) and 2 (2–0.125 Hz; Fig. 1(c)). Note the correspondence between Fig. 1(b) and a hypothetical spike source in Fig. 1(d). In Italy, a predominantly 100 Hz noise appears to be rectified mains frequency. No hardware provision had been made for removal of 50 Hz even harmonics in this study. This example is discussed later.

To reduce such regular coherent noise, two digital filtering techniques have been used; the notch and delay-line filters.

2.1. *The notch filter*

The notch filter is well known to geophysicists involved in acquisition and processing of data. The outline that follows is based on the discussion by Kanasewich (1981, pp. 247–252). The description of its digital formulation may easily be given in the z domain. Let

$$z = e^{-iw} \tag{1}$$

Each point on the unit circle $|z| = 1$ represents an infinitely long sinusoidal oscillation with frequency $f = w/2\pi$, w being the angular frequency. The z transform of the notch filter impulse response can be written as

$$W(z) = G(z - z_z)(z - z_z^*)/(z - z_p)(z - z_p^*) \tag{2}$$

where z_z is the point on the unitary circle associated with the frequency to be rejected, z_z^* is its complex conjugate; z_z and z_z^* are the 'zeros' of eq. (2). Parameter z_p is a point of radius r_p located just outside the unitary circle and z_p^* is its complex conjugate; in eq. 2 z_p and z_p^* are the 'poles'. Parameter G is a constant for normalizing the filter response gain to unity for a particular frequency, usually the Nyquist frequency.

The value chosen for r_p gives a compromise between sharpness of the filter and length of the impulse response. Thus if r_p is very close to 1 (say $r_p = 1.001$) the filter produces a very sharp cut-off response, but it requires a signal of long duration for the filter to become effective.

2.2. *The delay-line filter*

The delay-line filter (or Comb filter) was first applied to MT data by Schnegg and Fischer (1980). Its impulse response in the z domain is

$$W(z) = 1 - z^n \tag{3}$$

which has n zeros equally spaced on the unitary circle at locations given by

$$z_j = e^{i2\pi j/n} \qquad j = 0, 1, 2, \ldots, (n-1) \tag{4}$$

z_0 corresponds to the fundamental frequency to be filtered, e.g. 50 Hz, and $z_1, \ldots, z_n$ are all the higher harmonics up to the Nyquist frequency. The corresponding linear difference equation for this filter is

$$y(t) = x(t) - x(t - n) \tag{5}$$

where $x(t)$ is the sampled signal at the time t.

It is easily verified that $W(z)$ in eq. 3 has variable amplitude with its maximum value reaching 2 at all the frequencies midway between two harmonics (or zeros of $W(z)$). Fortunately, this undesirable behaviour does not lead to a serious problem when this filter is applied to MT data, as both magnetic and electric signals (or their spectra) are equally affected.

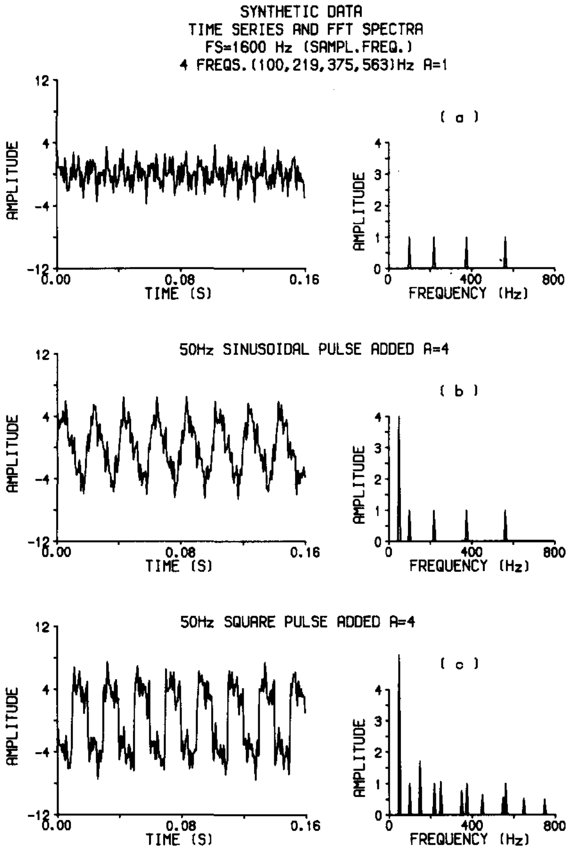


Fig. 2. (a) Synthetic example of 'pure' signal (time series and FFT spectrum) sampled at 1600 Hz and composed of four unitary amplitude (arbitrary units) sinusoids of frequencies 100, 219, 375 and 563 Hz. (b) Same signal as (a) superposed by a 50 Hz sinusoidal 'noise' of amplitude four times that of each individual sinusoid. (c) Same signal as (a) superposed by a 50 Hz square pulse 'noise' of amplitude four times that of each individual sinusoid.

2.3. *Applications*

A comparison of notch and delay-line filtering techniques applied to a synthetic sinusoidal signal sampled at 1600 Hz and composed of four unitary amplitude sinusoids of frequencies 100, 219, 375 and 563 Hz is presented in Figs. 2 and 3. The signal and its FFT spectrum are given in Fig. 2(a). In Fig. 2(b) the same signal corrupted by a 50 Hz sinusoidal noise of amplitude four times that of each individual sinusoid, and its respective spectrum are shown. The same synthetic signal as before but 'corrupted' by non-sinusoidal noise and

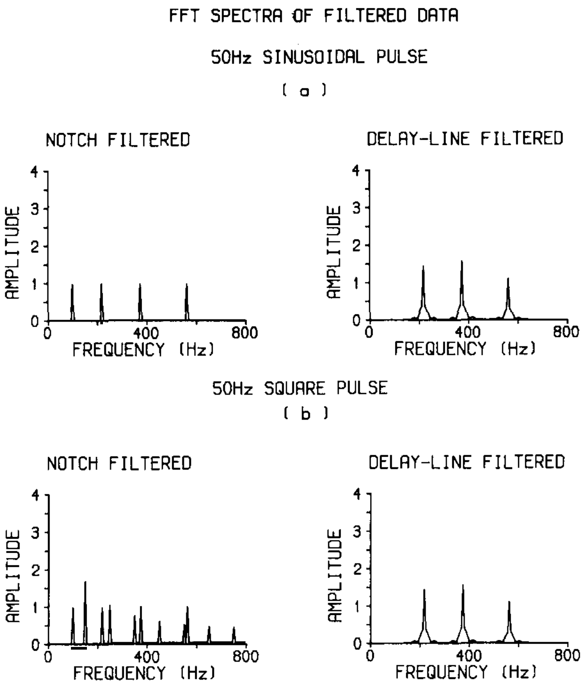


Fig. 3. Comparison of digital filtering for 50 Hz noise by notch and delay-line. (a) FFT spectra of 50 Hz sinusoidal 'noise' filtered by notch and delay-line. (b) FFT spectra of 50 Hz square pulse 'noise' filtered by notch and delay-line.

its spectrum are shown in Fig. 2(c). It is shown that unlike the 50 Hz sinusoidal noise, the 50 Hz non-sinusoidal noise resulted in a spectrum presenting several 50 Hz odd harmonics. The spectra resulting from the application of both the notch and the delay-line filters to the 50 Hz sinusoidal noise added signal are shown in Fig. 3(a). From these examples, it is clear that the notch filter is more effective in removing pure sinusoidal noise from the data (in this case a 50 Hz signal with no harmonics), while the delay-line filter may remove 'good' components of signal along with the noise, e.g. the 100 Hz sinusoid has been removed in this particular example. In Fig. 3(b) the spectra resulting from the application of both the notch and the delay-line filters to the signal 'corrupted' by non-sinusoidal noise are presented. In this situation the delay-line filter appears to be more effective than the notch filter in removing the non-sinusoidal noise. Note, however, that the 100 Hz is again absent and that the spectral components have their amplitudes changed as a result of the variable gain response for the delay-line filter mentioned earlier in Section 2.2.

The application of the delay-line filter to real data is shown in Fig. 4(a), (b). A dominant regular 100 Hz coherent noise signal of amplitude > 100 mV/km^{-1} in the electric channels completely masks the natural signal in data recorded in Asiago, northern Italy (Fig. 4(a)). The delay-line filtered data window (256 samples per channel) corresponding to Fig. 4(a) is shown in Fig 4(b). The respective rotationally invariant apparent resistivity and phase curves obtained after processing 60 data windows are shown in Fig. 4(c). The effect of filtering in the (512–64 Hz) band results in continuity of the MT response with the values found for the undisturbed adjacent frequency band.

3. Irregular coherent noise

Irregularly occurring coherent noise in recorded MT signals is only recognizable if its amplitude exceeds the natural signal. The primary difficulty in this situation is the establishment of a discrimination level between good signal and noise. Therefore, whatever criterion is adopted, the detection of noise-contaminated segments of a data window must be based on amplitude levels. In the present study, each data window has been subdivided in such a way that 16 partial variances have been estimated and highly coherent segments with unexpectedly high variance values have been disregarded. As gaps result in some data windows, two approaches have been examined for processing these particular data windows; use of the maximum entropy method for extending good data to the rejected segments and use of a window deconvolution scheme.

3.1. The maximum entropy extension

The maximum entropy method (MEM) was proposed by Burg (1967) and since then has been utilized as an important tool in spectral analysis. Its improved spectral resolution compared to most traditional methods is well known, more especially when periods of interest are comparable to data sample lengths. In the present study, the potentiality of MEM as a predictive technique is explored. In fact, the potentiality of this technique has already been investigated on synthetic data by Ulrych and Clayton (1976). Wiggins and Miller (1972) have successfully applied a predictive noise reduction technique derived from Burg's method to seismological data. The scheme proposed differs in some aspects from the Wiggins and Miller technique and the steps necessary for its implementation are outlined here. Consider a non-deterministic time series

$$s_t \qquad t = 1, \dots, n$$

Then

$$s_t = \sum_{k=0}^{\infty} a_k e_{t-k} \tag{6}$$

is its infinite moving average (MA) representation, where $a_0 = 1$ and e_t is a white noise process.

Whether or not a_t is a minimum delay wavelet, it is always possible to convert an MA process to an autoregressive process (AR) (Robinson, 1964, 1967)

$$s_t = \sum_{k=0}^{\infty} p_k s_{t-k} + e_t \tag{7}$$

the main advantage being that AR parameters are easier to estimate (Ulrych and Clayton, 1976). For practical applications the number of parameters to be estimated must be finite and the forward prediction error (EF) may be written as

$$EF_t = \sum_{k=0}^{M} a_k S_{t-k} \quad a_0 = 1$$
$$a_i = -p_i, \; i = 1, \dots, M \tag{8}$$

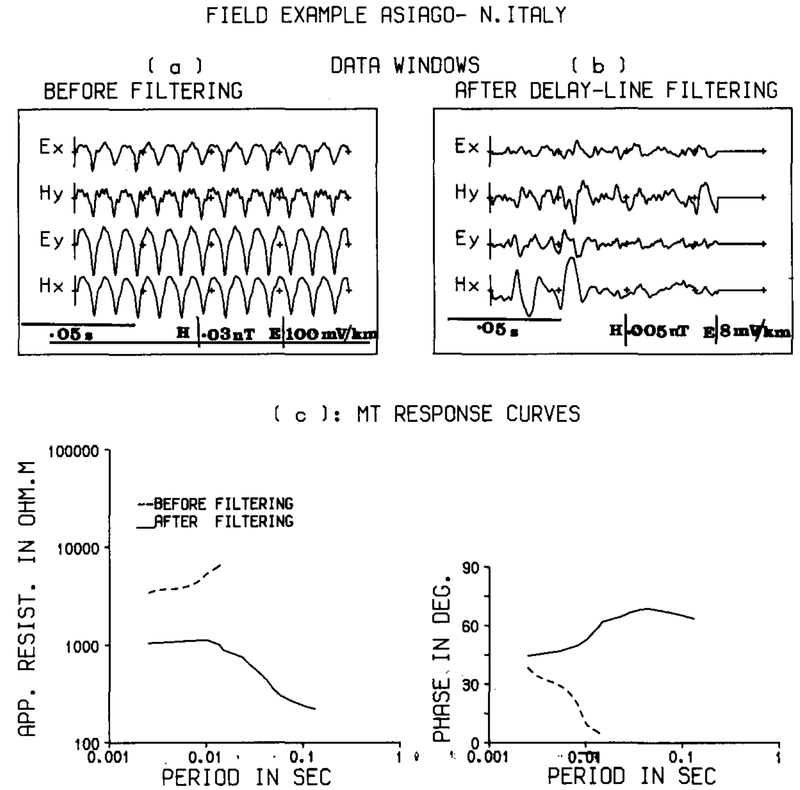


Fig. 4. Field example of regular coherent noise on MT data recorded in Asiago, northern Italy. (a) Magnetic (nT) and electric (mV km^{-1}) signals for a recorded data window. (b) Same data window after delay-line filtering. Note the different amplitude scales used for the electric and magnetic signals. (c) MT response curves (averaging of 60 data windows) for the invariant before and after application of delay-line filtering (100–200 Hz).

and the backward prediction error (EB) as

$$EB_t = \sum_{k=0}^{M} a_k S_{t+k} \tag{9}$$

The noise reduction scheme based on the MEM extension of good segments of a data window is undertaken through the following steps:

(1) noise-contaminated segments are rejected, the criterion being a partial variance exceeding 3–4 times the average variance for the particular site;

(2) EF_t and EB_t are estimated for the non-contaminated subsets of a data window using the Burg algorithm and the Akaike final prediction error criterion (Akaike, 1969) for controlling the order of the process M;

(3) the gaps in the data window are filled with values obtained by averaged forward and backward predictions;

(4) transfer functions of 'cleaned' data windows are estimated in the frequency domain in the conventional way.

3.2. *The window deconvolution technique*

In this scheme the gaps created by the deletion of the noisy segments are not filled, i.e. zero signal level is assumed. It implies that the signal s_t is multiplied by a window W_t

$$W_t \begin{array}{ll} = 1 & \text{noise-free data} \\ = 0 & \text{noise-contaminated data} \end{array} \tag{10}$$

or in the frequency domain

$$S_w(w) = S(w) * W(w)$$

with power spectra representation

$$PS_w(w) = PS(w) * PW(w) \tag{11}$$

The distortion introduced by the W_t can be attenuated by deconvolving $PS_w(w)$ with $PW^{-1}(w)$

$$PS_w(w) * PW^{-1}(w) \tag{12}$$

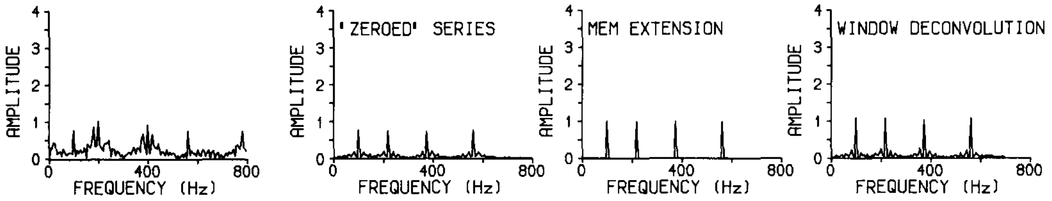
The inverse $PW^{-1}(w)$ can be calculated by means of a spiking filter operations as described by Robinson (1967). Spiking filter computer routines are available in Silvia and Robinson (1979).

3.3. *Applications*

In Fig. 5, application of both the MEM extension and the window deconvolution techniques are demonstrated for the same synthetic data used in the examples of Section 2.3, considering two distinct levels of contamination by spike noise. The

SPIKE CONTAMINATED TIME SERIES- SPECTRA BEFORE AND AFTER SPIKE REMOVAL

(a) 25% OF SERIES CONTAMINATED WITH SPIKES



(b) 35% OF SERIES CONTAMINATED WITH SPIKES

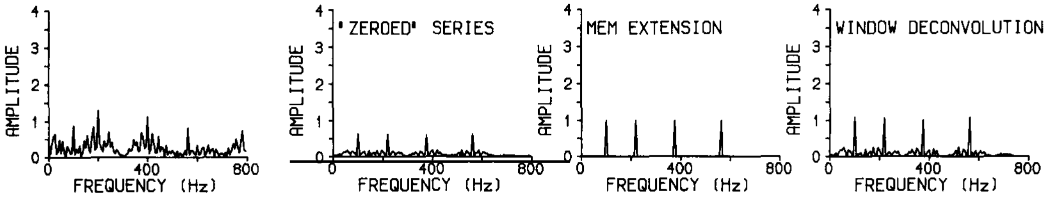


Fig. 5. Application of MEM extension and window deconvolution techniques to the same synthetic signal as Fig. 2a in which 25 and 35% of its length is contaminated by spike 'noise' signals of irregular occurrence. (a) FFT spectrum of spike added time series (25% case), and the FFT spectra after spike removal by 'zeroed' series, MEM extension and window deconvolution techniques. (b) Same as (a) for 35% spike noise added.

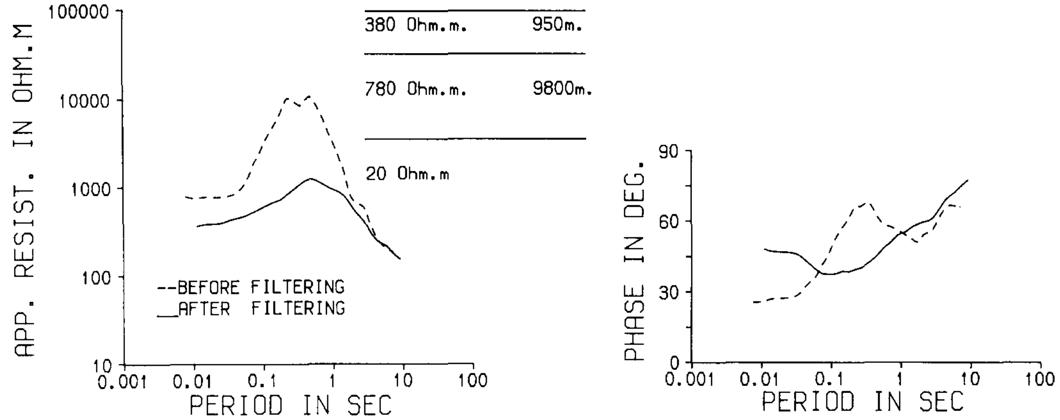


Fig. 6. Field results recorded in Craik, South Scotland before and after the application of the MEM extension technique (1–100 Hz) and delay-line filtering (0.1–1 Hz): MT response curves and 1 – D model for the filtered response.

FFT spectrum for the series in which 25% of its length is contaminated by irregularly occurring spike noise is given in Fig. 5(a). This figure also shows the FFT spectrum estimated for the time series with spike segments replaced by zeros (the 'zeroed' series) and the spectra obtained after spike removal by the MEM extension and the window deconvolution techniques. Similarly, the results for the 35% contaminated signals are given in Fig. 5(b). From comparison of spectra given in Fig. 5, one can see that the MEM extension technique recovers the FFT amplitudes of the original series (Fig. 2(a)) for both levels of contamination. While the window deconvolution technique can recover the peaks amplitudes when compared with the 'zeroed' series spectrum, it does not remove completely the additional noise in other portions of the spectrum.

An application of these techniques to field observations recorded in Craik, Southern Scotland is illustrated in Fig. 6(a). Rotationally invariant apparent resistivity and phase curves before and after application of the MEM extension technique (1–128 Hz) and delay-line filtering (0.125–2 Hz) are presented. The improvement achieved, especially in the frequency range 1/16–1 s, in which nearly 30% of each data window is corrupted by noise, is clearly demonstrated. In Fig. 7, the MEM extension and the window deconvolution techniques are compared for field data from Asiago,

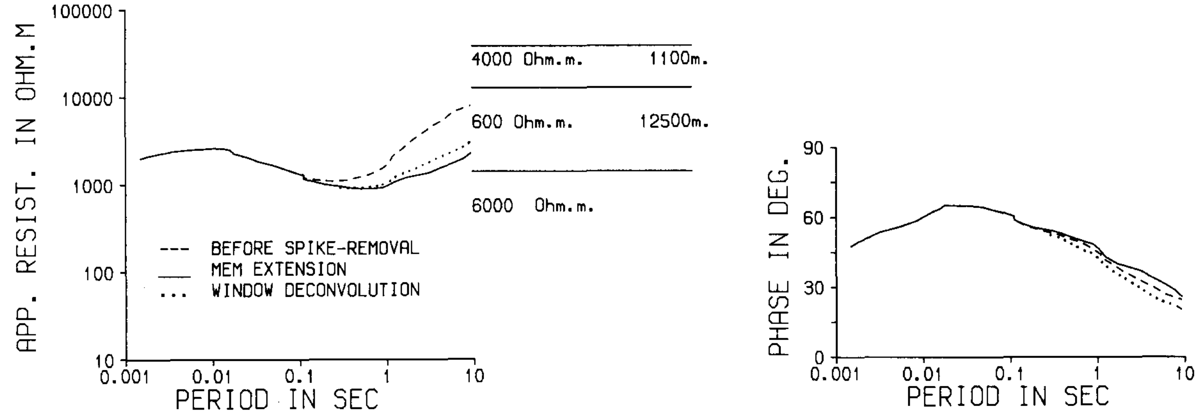


Fig. 7. Field results recorded in Asiago, North Italy before and after the application of the MEM extension and window deconvolution techniques (0.1–5 Hz): MT response curves and 1 D model for the filtered response.

northern Italy. The noise source was found to be leakage currents to ground from the DC electric railway system. This affects a large area of the very resistive Alps (Schnegg et al., 1986). The comparison of results for the two techniques when applied to field data shows that they are equally efficient.

4. Data selection

The noise-reducing techniques discussed above are not effective when severe conditions of irregular coherent noise are present. This statement is well exemplified by the AMT data recorded in Milos, Greece. Indeed, large highly coherent magnetic and electric signals were observed in measurements surrounding the development site of the Milos geothermal power station. From inspection of data windows from the most disturbed site (Fig. 8(b)), it is obvious that the signals are not natural, but the actual waveform of the noise source required examination of the signals prior to filtering by the real-time MT system used in this study. For this purpose, simultaneous chart re-

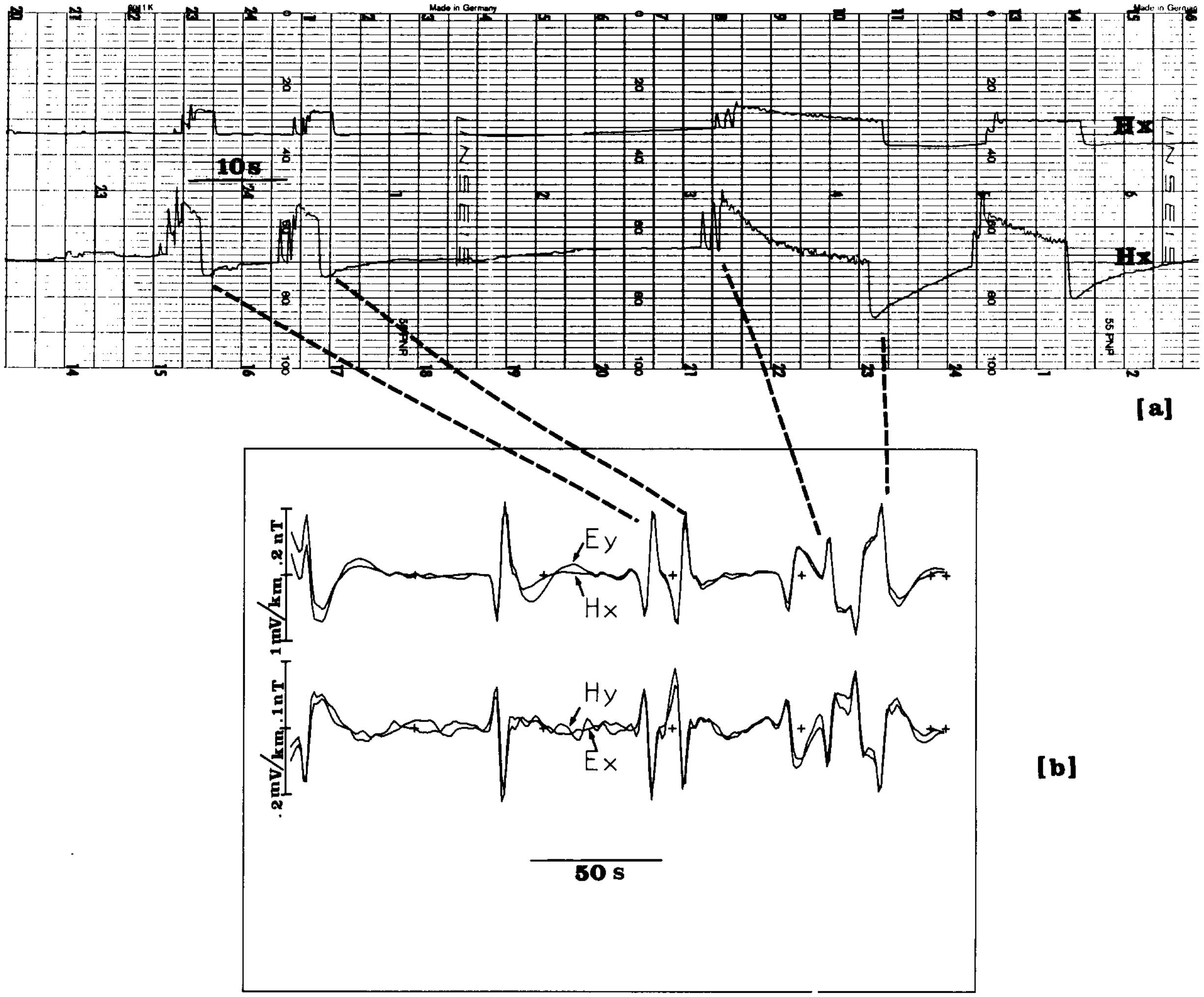


Fig. 8. Field data recorded on Milos, Greece showing the effect of opening and closure of the geothermal power station test wells. (a) Chart recording of the magnetic signal in the magnetic north direction (Hx) at two stages prior to filtering of the MT acquisition system. (b) Simultaneously recorded noisy data window (orthogonal magnetic and electric signals overlapped) in the frequency range 0.1–0.125 Hz.

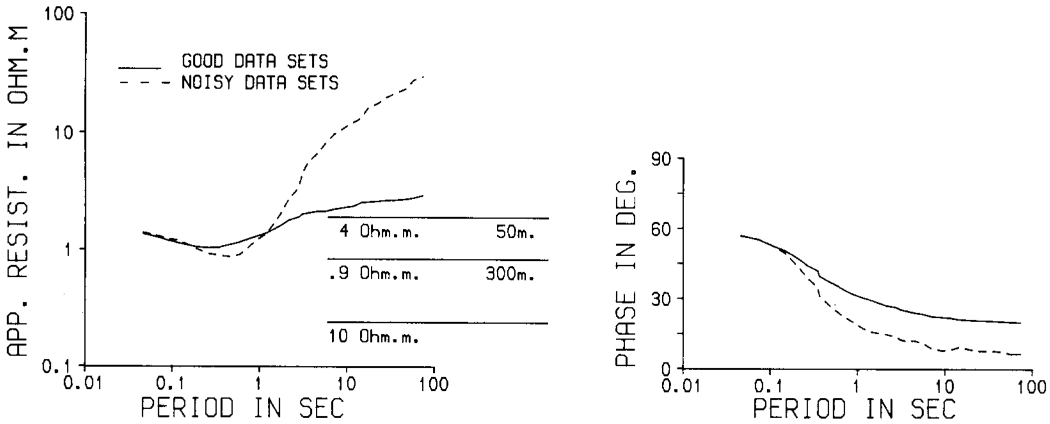


Fig. 9. Field results recorded on Milos, Greece, before and after data selection: MT response curves and 1 – D model for the selected data.

cording of the sensor outputs (Fig. 8(a)) made the identification of the stepwise character of the noise possible. Correspondence between the opening and closure of the valves of the test wells and the recorded noise had also been noted during the fieldwork itself.

Fortunately, owing to the intermittent character of this noise source, it was possible in this case to scrutinize all recorded data windows and to perform a window by window analysis in order to attempt the separation of good and corrupted data. The invariant apparent resistivity and phase curves derived from both 'noisy' and 'good' data windows for the most disturbed site are presented in Fig. 9. They show a significant difference between the responses of the two data sets. The same process was repeated for three other sites, where the same noise problem existed to a lesser extent. These yielded data sets and 1 D models that are in agreement with available borehole information (Dawes, 1985).

5. Discussion

When man-made noise reaches high levels, as observed in data sets from southern Scotland, Northern Italy and Greece, the notch filters normally incorporated in MT data acquisition systems are inadequate since large amplitude non-sinusoidal noise sources can produce very high-order harmonics in the data. Additional notch filters could be included either in the acquisition systems, or alternatively, be applied to the data during processing. The latter option should only be considered when hardware limitations have resulted in inadequate notch filtering. Otherwise the data resolution may be reduced considerably owing to limitations in the dynamic range of the recording device.

The delay-line filter has been shown to be more effective than the notch filter since the main noise source frequency and all its harmonics (odd and even) are completely eliminated. Unlike the notch filter, which is applied either to analog or digital signals, delay-line filtering is more generally applicable to digital signals. It thus appears advantageous to incorporate an optional delay-line filter in real-time data analysis.

In frequency domain processing of MT data, the presence of a single spike noise can contaminate the whole spectrum. Simply deleting the spikes can cause leakage from this portion to the uncontaminated portion of the data set. The maximum entropy method used as a predictive technique has been applied to this problem. When applied to field data of which > 30% have been contaminated by spike noise, the technique has proved effective in producing acceptable resistivity and phase curves.

The window deconvolution technique presented in this study attenuates the noise effects simply by deleting the noise-contaminated segments of a data window. The application of this technique to synthetic and field data showed that it was in good agreement with the MEM extension technique, although it does not represent a significant improvement when compared with the simple replacement of the spike segments by zero. The only advantage is ease of implementation in the data processing.

For MT data, acquired by a real-time system that uses coherency as one of the data acceptance criteria and badly contaminated by coherent noise of an intermittent nature, the selection of subsets of data windows is essential. As an example of this situation, data recorded on Milos have been shown to yield Earth models compatible with borehole data.

No claim is made that all man-made noise can be eliminated by the techniques discussed, nor is it guaranteed that all the superposed noise has been removed from the field examples presented in this study. Filtering itself may introduce noise and should thus always be applied with great care. The case studies discussed in this paper show that automatic data acquisition alone is not advisable in areas affected by high cultural electric noise as it can yield misleading results. In such cases, continuous time-domain monitoring of the unfiltered MT signals, e.g. using a chart recorder, is also necessary. The appropriate noise-reduction technique can then be applied.

Acknowledgments

One of the authors (S.L.F.) wishes to thank the Brazilian Research Council (CNPq) and another (T.H) the Association of Commonwealth Universities for providing financial assistance in the form of scholarships. The authors are thankful to Dr. A.G. Jones, Ottawa for useful discussions during his visit to Edinburgh University in July, 1986.

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