Estimation of the earth impulse response of MTEM in very noisy environment

Wenwei Zhang,Qingyun Di , Da Lei
Institute of Geology and Geophysics,
Chinese Academy of Science
Beijing 100029, China
wwzhang0421@163.com

***Abstract*—we demonstrate how several tools, such as stacking, cross correlation, digital filtering, significantly attenuate the correlated and uncorrelated noise encountered during the estimation of the earth impulse response of multi-transient electromagnetic survey. This study focuses on processing of correlated cultural noise using digital recursive filtering. We also applied this to process the data observed from the MTEM single-line survey conducted over an underground hydrocarbon reservoir.**

Keywords—multitransient eletromagnetic; the earth impulse response; digital recursive filter; stacking;cross correlaiton

I. INTRODUCTION

The multitransient electromagnetic (MTEM) method distinguishes itself from the electromagnetic family by recording both input current, usually pseudo random binary sequences (PRBS), and the received voltages, and it also recovers the earth impulse response. This allows a manner similar to seismic data processing to be used to process electromagnetic data [1-5].

The MTEM method deploys a bi-pole current source and several inline bi-pole receivers for measuring voltages, as illustrated in Fig. 1. The earth is assumed to be a linear and time-invariant system modeled by convolution. However, aperiodic and periodic noise is often present in almost all observation data, so the received voltage can be expressed by the convolution of the input current and the earth impulse response, plus aperiodic or periodic noise.

$$v(t)=I(t)*g(t)+n_a(t)+n_p(t) \quad (1)$$

where, v(t) is the measured voltage, I(t) is the measured input current, g(t) is the earth impulse response, $n_a(t)$ is the aperiodic noise, and $n_p(t)$ is the periodic noise.

Our objective is to estimate the earth impulse response from noisy received voltages. Szarka gave a comprehensive review of man-made electromagnetic noise in the Earth [6]. In some cases, sporadic noise caused by some sudden events are also recorded as bad traces which must be isolated since its amplitude deviates far from the average signal level. Watt and Bednar introduced the so-called alpha-trimmed mean to eliminate bad seismic traces [7]. Ruchkemann systematically compared different stacking methods [8]. Strack gave a detailed account of the tool chain for compensating for the distortion of the LOTEM signal caused by aperiodic and periodic noise [9-10].

Furthermore, periodic noise from the electric power and human activities sometimes dominates the observed data so that it is difficult to recover the earth impulse response. Wright and Ziolkowski classified the noise in MTEM measurements and described techniques for suppression of noise in real data [11]. They exploited the polarity of current source to eliminate the electric power noise. However, the PRBS input current has no stable polarity switch relation between two traces, which is called a run in PRBS. In addition, one entire period of PRBS is not a short time due to requirement of the chip frequency and the size of PRBS in order to receive effective voltages when the cultural noise maybe varies, and therefore it is inconvenient to restrict a period of PRBS exactly equal to the multiple of the period of the cultural noise. In this abstract, we present a chain of methods, especially digital recursive filter (after Strack), to attenuate the noise, and then applied it to real data, after which we estimated the earth impulse response from measured MTEM data.

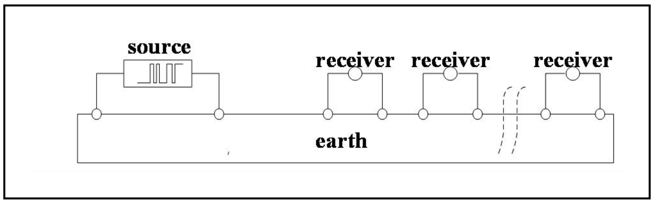

Fig. 1. The MTEM survey filed setup

II. DATA PROCESSING METHOD

A. Correlation

To lay the mathematical foundation of the cross correlation estimation of the earth impulse response, we first reformulate (1) using integral formation without considering noise.

$$v(t)=\int I(t-\tau)g(\tau)d\tau \quad (2)$$

From Backus-Gilbert solution to linear inverse problem, we can express the discrete estimate of the earth impulse response, namely g'(t), in the form of

$$g'(i) = \sum_j b_{ij} v(j) \quad (3)$$

i.e., a discrete kernel operating on the discretized observations of the received voltage. Substituting (2) into (3), we obtain

$$g'(i) = \int s(i,\tau) g(\tau) d\tau \quad (4)$$

with the definition of the function

$$s(i,\tau) = \sum_j b_{ij} I(j-\tau) \quad (5)$$

If s(i,τ) is equal to the Dirac delta function δ(i-τ), the discrete estimation g'(i) is identically equal to the earth impulse response. In (5), let b_{ij}= I(j-i), the shift of input current, then s(i,τ) is the auto correction of the input current, which is approximately a train of impulses when PRBS current is transmitted in the MTEM survey. In this case, we can estimate the earth impulse response from discretized received voltages by substituting shifted input current for discrete kernel within (3), and then we have

$$g'(i) = \sum_j I(j-i) v(j) \quad (6)$$

which is the cross correlation between the input current and received voltage. For the irrelevancy between the input current and random noise with periodic cultural noise, the corrections between them vanish and (6) gives a good estimation of the earth impulse response from noisy received voltages.

This result we derivate above is similar to that of Ziolkowski who had based his work on Wiener deconvolution [12]. Treitel and Lines gave a comprehensive description of the relation of linear inversion and deconvolution [13].

B. Stacking

We transmit quite a few numbers of periods of PRBS for one source, up to 250 in some cases. When we calculate cross correlation power, we break the acquired data into several segments and perform correlative calculation between the input current and received voltage, and then stack these correlations by selective stacking which can reduce the sporadic noise significantly by rejecting jamming, which deviates by more than two multiples of the preliminary standard deviation away from the preliminary mean, as well as random noise. We can also stack the measured input current and received voltage in advance before calculating correlations to eliminate sporadic peaks.

C. Digital Recursive Filter

Cultural noise in measurement is complex and nonstationary, however, there is still residual correlated components left in the cross correlation between the input current and received voltages, which may be very powerful and can be reduced further by digital recursive filtering.

Therefore, we have designed a filter, which not only reject cultural noise but also cause negligible amplitude distortion for other frequency components of the measured data. Filters with this property are referred to as notch filters.

For the sake of simplicity, we first consider a system function with only a first-order zero at z_n corresponding to our rejection frequency, we have

$$H(z) = z - z_n \quad (7)$$

where, H(z) is the Z-transform of the impulse response and is defined as

$$H(z) = \sum_{i=0}^{\infty} h(n) z^n \quad (8)$$

As seen in Fig. 2, the addition of complex numbers agrees with triangle rule. On the unit circle, the amplitude response for numerical radian frequency ω is determined by the distance of the point $z=e^{-jw}$ and the zero $z_n=(\alpha,\beta)$. The corresponding phase is measured by the rotation angle so that the direction vector of the point $z=e^{-jw}$ coincides with the sum vector. This filter above does not only reduce the frequency ω, but it also attenuates other frequencies. Obviously, its amplitude response along the unit circle increases with increase in the distance from the zero point and reaches its maximum value at the opposite end of the diameter passing the zero point. To get around this problem, we add another first-order pole z_p which is so close to the zero point that the amplitude response for frequencies other than rejection frequency is almost equal to one. Of course, this pole is still outside the unit circle so in order to make system the stationary. Dc is the point (1, 0) and Nyquist frequency is (-1, 0) respectively, for which both we also want the amplitude responses to be equal to one. That is, the distance from point (1, 0) to zero and that to the pole remain the same, so is the point (-1, 0). By triangle rule, we have

$$|1-z_n|/|1-z_p| = |(1+z_n| \; |1+z_p| \quad (9)$$

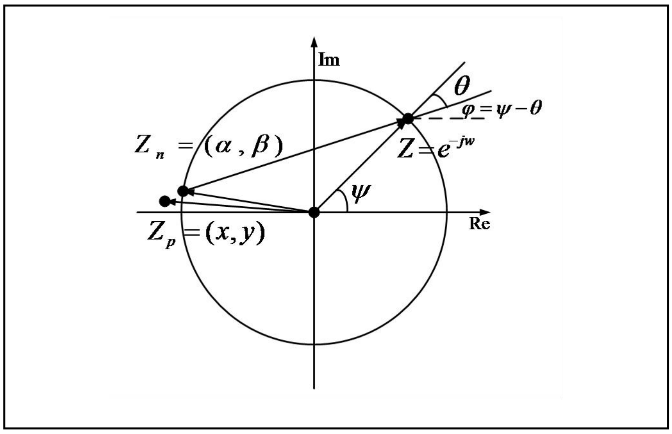

Fig. 2. Geometrical illustration of frequency response of singleton-zero system

In (9), the left term is the amplitude response of dc, and the right term is amplitude response of the Nyquist frequency. As shown in Fig. 2, if we set $z_n=(\alpha,\beta)$, $z_p=(x,y)$, and $x=\gamma\alpha$, and substitute them into (5), we obtain

$$\gamma=|1-z_p|\hat{}2/|1-z_n|\hat{}2 \qquad (10)$$

$$x\hat{}2+y\hat{}2=2\gamma-1 \qquad (11)$$

where γ is a factor controlling the distance of the zero and the pole. In practice, if we want to get a real output when the input is real, we require zeros and poles of the system function to appear as complex-conjugate pairs, which gives a two-order recursive notch filter with amplitude normalized for gain 1,

$$H(z)=\gamma\,(z-z_n)(z-z_n^*)/(z-z_p)(z-z_p^*) \qquad (12)$$

reformulated into,

$$H(z)=\gamma\,(z\hat{}2-2\alpha z+1)/(z\hat{}2-2\alpha\gamma z+2\gamma-1) \qquad (13)$$

We know that multiplication with z indicates a delay by one step in the time domain. Therefore, the recursive formula in the time domain becomes

$$y(n)=1/(2\gamma-1)(\gamma x(n)-2\alpha\gamma x(n-1)+\gamma x(n-1)+2\alpha\gamma y(n-1)-y(n-2)) \qquad (14)$$

We choose γ to be almost equal to 1, such as 1.02 or even lesser, α to be cosine of the rejection frequency divided by sampling frequency and times 2π, that is,

$$\alpha=\cos(2\pi f_0/f_s) \qquad (15)$$

In order to eliminate the phase shift caused by the recursive filter, the filter is applied twice to the data, first in the forward, and then in the reverse direction. That is, first the input is filtered, then the output is time-reversed and filtered again, and finally the new output is time-reversed to get the final result.

III. Examples

We conducted a MTEM single-line survey over an underground hydrocarbon reservoir and deployed a 300-m inline bipole current source and thirty 50-m inline potential receivers along the 6-km survey line. A typical estimation of the earth impulse response is showed in Fig. 3, the up right and left is the measured input current and very noisy received voltage (only part of the entire signal for clarity of plot), respectively. The lower left is the auto correlation which is almost a Dirac delta function, while the lower right is the cross correlation that is the estimation of the earth impulse response and is free of noise. The initial peak of the cross correlation is the air wave traveling through the air from the transmitter to the receiver.

Stacking is able to suppress noise effectively, as illustrated in Fig. 4. From the bottom to top, the number of stacking increases from 1 to 20. Noise is suppressed significantly when the number is more than 10, but larger stacking number has little effect. For different noise levels, number of stacking is a compromise between efficiency and data quality. The number of samples per segment also influences the result, as depicted by Fig. 5. It should be noted that more samples provide more information but also with more noise, so longer signal does not always imply better estimation, the result of 20 periods per segment is worse than that of 10 periods per segment.

In some cases, residual cultural noise is correlated to the input current so that it resides in the cross correlation of the input current and the received voltage, which can be notched by digital recursive filter. Fig. 6 shows the real data example .The up left is one of the thirty cross correlations that is almost the 50Hz cultural noise, the result obtained when we applied notch to up left correlation is that it sits up right, the lower left is the stacking of the thirty notched correlation, and the lower right one is the smooth version of the lower left one.

IV. Conclusion

We have seen how a Backus-Gilbert inversion leads to the cross correlation estimation of the earth impulse response. In MTEM survey we choose appropriate chip frequency of PRBS generating impulsive-like auto correlation to give good estimation. We derived a two-order recursive notches filter to eliminate correlated cultural noise. These techniques were applied into real MTEM data and good results are obtained.

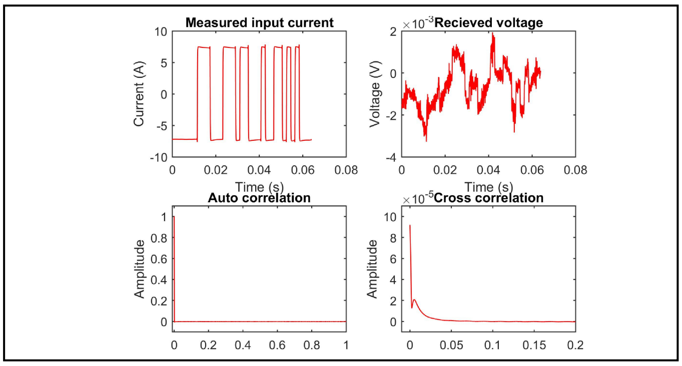

Fig. 3. Cross correlation estimation of the earth impulse

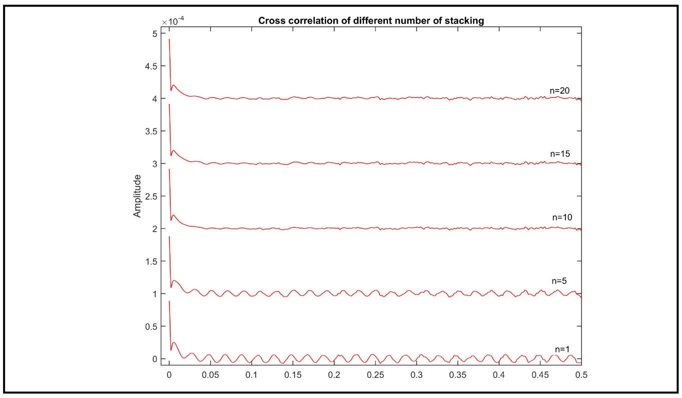

Fig. 4. Cross correlation with different number of stacking

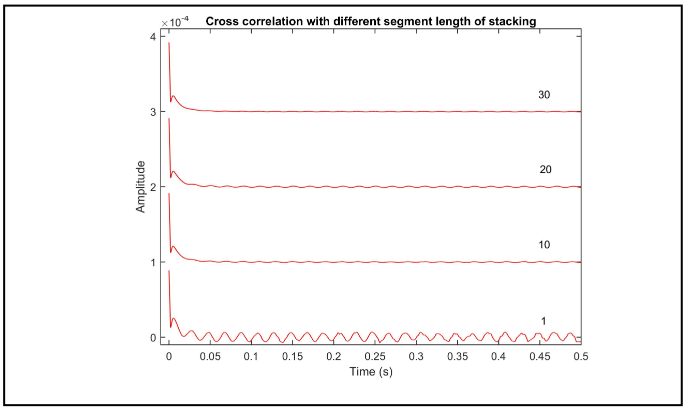

Fig. 5. Cross correlation with different number of samples per segment

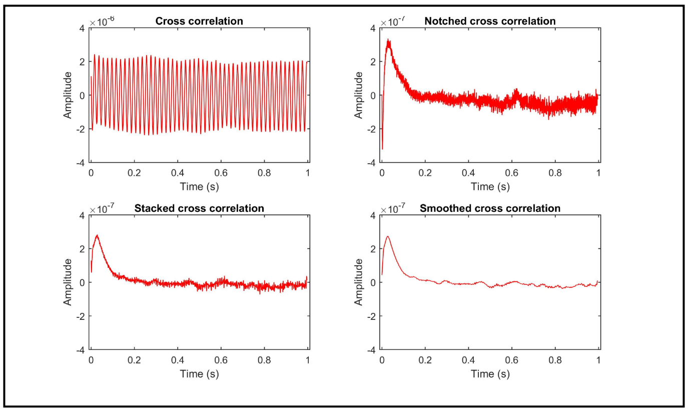

Fig. 6. Cross correlation with notching

ACKNOWLEDGMENT

We thank all the staff and students and who had participated in the field work for data acquisition and the major national scientific research and equipment development project for sponsoring this research. We also thank Dr. Fayemi and Dr. Zou Ya Fei for helping to review the abstract.

REFERENCES

[1] A. Hördt, P. Andrieux, F.M. Neubauer, H. Rüter, K. Vozoff, "A first attempt at monitoring underground gas storage by means of time-lapse multichannel transient electromagnetics," Geophysical Prospecting, vol48, pp. 489-509, 2000.

[2] D. Wright, A. Ziolkowski, B. Hobbs, "Hydrocarbon detection and monitoring with a multicomponent transient electromagnetic (MTEM) survey," The Leading Edge, vol 21, pp. 852-864, 2002 Ziolkowski, Anton

[3] B. Hobbs, A. Ziolkowski, D. Wright, "Multi-Transient Electromagnetics (MTEM) – controlled source equipment for subsurface resistivity investigation,", 18th IAGA WG 1.2 on Electormagneitc Induction in the Earth, 2006

[4] A. Ziolkowski, B. Hobbs, G. Dawes, D. Wright, "True Amplitude Transient Electromagnetic System Response Measurement," patent, WO2006/114561 A2, 2006

[5] D. Wright, A. Ziolkowski, B. Hobbs, "Multitransient Electromagnetic Demonstration Survey in France," Geophysics, vol72, no. 4, pp. F197-F209, 2007

[6] L. Szarka, "Geophysical aspects of man-made electomagnetic noise in the earth- A review," Surveys in Geophysics, vol 9, no. 3, pp. 287-318, 1988.

[7] T. Watt, J.B. Bednar, "Role of the Alpha-Timmed Mean in Combining and Analyzing Seismic Common-Depth-Point Gathers," Expanded Abstracts: 53rd annual meeting, Society of Exploration Geophysics, pp. 276-277, 1983.

[8] C.P. Ruckemann, "Comparison of Stacking Methods Regarding Processing and Computing of Geoscinefific of Depth data," GEOProcessing: The 4th Internatinal Conference on Advanced Geographic Information Systems, Application, and Services, 2012.

[9] K.M. Strack, T. H. Hanstein, H. N. Eilenz, "LOMTEM data processing for ares with high cultral noise levels," Physics of the Earth and Planetary Interiors, vol 53, pp. 261-269, 1989

[10] K.M. Strack, "Exploration with deep transient electromagnetics," in Motheds in Geoehcmiestry and Geophysics, Asmterdam-London-New York-Tokyo Elseier, 1992

[11] D. Wright, A. Ziolkowski, "Suppression of Noise in MTEM data," SEG San Antonio Annual Meeting, pp. 583-587, 2007

[12] A. Ziolkowski, "Wiener estimation of the Green's function," Geophysics, vol. 78, no. 5, pp. W31-W44, 2013

[13] S. Treitel, L. R. Lines, "Linear inverse theory and deconvolution", Geophysics, pp. 1153-1159, 198