Research on maximum level noise contaminated of remote reference magnetotelluric measurements using synthesized data

Zhang Gang*, Meng Fansong, Wang Jianzhong, Ding Mingtao
School of Environment and Resource, Southwest University of Science and Technology, Mianyang 621010, China
zg@swust.edu.cn

Abstract. Determining magnetotelluric impedance precisely and accurately is fundamental to valid inversion and geological interpretation. This study aims to determine the minimum value of signal-to-noise ratio (SNR) which maintains the effectiveness of remote reference technique. Results of standard time series simulation, addition of different Gaussian noises to obtain the different SNR time series, and analysis of the intermediate data, such as polarization direction, correlation coefficient, and impedance tensor, show that when the SNR value is larger than 23.5743, the polarization direction disorder at morphology and a smooth and accurate sounding carve value can be obtained. At this condition, the correlation coefficient value of nearly complete segments between the base and remote station is larger than 0.9, and impedance tensor Zxy presents only one aggregation, which meet the natural magnetotelluric signal characteristic.

1. Introduction
The magnetotelluric sounding method is an important method for the investigation of the electrical structure of the crust and upper mantle. Obtaining accurate tensor impedance estimation is fundamental to magnetotelluric measurement. Remote reference magnetotellurics is an effective method to eliminate noncorrelated noises (Gamble et al., 1979; Clarke et al., 1983; Chave and Thomson, 1989; Ritter et al., 1998; Oettinger et al., 2001; Shalivahan et al., 2006; Muñoz and Ritter, 2013). Gamble et al. (1979) analyzed the error associated with remote reference and found that the variances decrease as the number of measurements (N) contained in the average powers increases. Egbert (1997) developed a robust multivariate errors-in-variables estimator, which can automatically estimate incoherent noise levels. Kappler (2012) identified the time series spikes according to intersite comparison within each window and then replaced the flagged windows with Wiener filtering coincident data in clean channels. Through this method, he obtained a smooth transfer function.

In practice, the following equation can be used to solve various impedance elements:

\[
Z_y = \frac{S_{E,R_i}S_{H,R_i} - S_{E,R_j}S_{H,R_j}}{S_{H,R_i}S_{H,R_i} - S_{H,R_j}S_{H,R_j}}
\]  

(1)

Among them, \(S_{E,R_i}\) is the summation of cross power spectra in the \(E_i\) and \(R_i\) channels, \(i\) and \(j\) represent the \(x\) and \(y\) directions, \(E\) and \(H\) are the electric and magnetic fields of the base station,
respectively, and \( R \) is the reference station channel field. The electric field unit is \( mV/km \), and the magnetic field unit is \( nT \).

Using impedance-apparent resistivity and impedance phase equations, the final apparent resistivity and impedance phase is finally obtained.

\[
\rho_j = 0.2T \left| Z_{ij} \right|^2, \quad \phi_j = \frac{180}{\pi} \cdot \arctan \left( \frac{\text{imag}(Z_{ij})}{\text{real}(Z_{ij})} \right),
\]

where \( \rho_j \) and \( \phi_j \) represent the apparent resistivity (ohm per meter) and impedance phase (degree), respectively, in the \( x \) and \( y \) directions.

Under ideal condition, remote reference processing can obtain the accurate estimation as expressed by Equation (1). However, with the development of industrial technology, electromagnetic noise increases in severity around the collect stations, and thus it cannot meet the criteria that cross power spectrum between the noise existed at base station and the signal existed at remote station equal 0. Consequently, obtaining an accurate estimation of the station is difficult. This finding raises the question of how a strong noise at a base station can remote reference recover for useful data or sounding curves. Thus, this paper mainly discusses how noise at different intensities contaminates the signal and varied the results will be and compute how much noise the signal contaminated. It can also recover the sounding curves and obtain the maximum level of noise from which remote reference can recover useful data.

2. Experiment

We simulate two 100 ohm-m homogeneous half-space time series from EMTF software package (Egbert, 1997). The parameter settings are the same in this paper to exclude various influential factors. For example, the time series length of each data segment is four times of the maximum period, the overlap rate of each adjacent segment is 0.3, and the correlation coefficient of \( E \) and \( H \) channel is used to screen data. Remote reference estimation (Egbert, 1997) is implemented. Threshold value of the correlation coefficient for base stations \( H \) and \( E \) (\( EHCoh \)) and that for remote stations \( H_R \) and \( E_R \) (\( EHRRCoh \)) is 0.9.

The Gaussian noises of different intensities are added to the original \( Hy \) channel time series to obtain different signal-to-noise ratio (SNR) signals, the SNR is the ratio of specific parameters (signal) and nonspecific parameters (noise). This approach is necessary for the identification of the maximum level of noise contaminated by the base station. New SNRs are 3.0027, 10.4093, 15.0807, 20.0282, 22.0199, and 23.5743 dB, which are obtained by adding different intensities Gaussian noise to the \( Hy \) time series channel. Figure 1 provides the intermediate result data of the remote reference magnetotellurics under different SNRs.

The analyzed period is 9.5137 s, the period band of which ranges from 4 s to 256 s, and the time window length at each segment is set to four times of the maximum period. Thus, each time series segment at the period band is 1,024 s (4*256 s). The overlapping ratio for each adjacent segment is set to 0.3. The first column in Figure 1 represents the polarization direction of the magnetic field (Weckmann et al., 2005), the second column represents the correlation coefficient between the base and remote stations at \( Hy \) channel (\( Cor_{H_h,H_y,R} \)), and the last column represents the scatter of the impedance tensor \( Z_{xy} \). The horizontal and vertical axes represent the real and image parts of the tensor, respectively.

First, we analyze the standard time series without any noise (the 9th row of Figure 1). The magnetic field polarization direction is in disorder, the \( Cor_{H_h,H_y,R} \) value is high and nearly 1, and the impedance tensor \( Z_{xy} \) presents only one aggregation around \((5, -5)\). At the worst condition in this experiment, the magnetic field polarization direction at most contaminated data (SNR = 3.0027) displays good consistency. This result is inconsistent with the unordered law of natural
magnetotelluric signal polarization direction (Weckmann et al., 2005), and $Cor_{Hy\&Hy_{_R}}$ is approximately 0.3, which does not meet the high correlation of natural magnetotelluric signal characteristic. At increasing SNRs, the magnetic field polarization becomes increasingly disordered, and the $Cor_{Hy\&Hy_{_R}}$ value increases. Given the lack of quantitative assessing criteria, judging the degree of disorder in magnetic field polarization is difficult. Therefore, $Cor_{Hy\&Hy_{_R}}$ is more suitable for the estimation of the degree of contaminated time series. When $SNR = 22.0199$, approximately half of the correlation coefficient of the data segments is $Cor_{Hy\&Hy_{_R}} \geq 0.9$, and when SNR reaches 23.5743, nearly all the correlation coefficient of the data segment is $Cor_{Hy\&Hy_{_R}} \geq 0.9$, indicating that nearly the entire data meet a criterion of data screening. Thus, the entire data is included in the subsequent calculation.

The time series with different SNRs has different sounding curves (Figure 2). Morphologically, the higher the SNR time series is, the larger the number of the rectified curves is. At the lowest SNR ($SNR = 3.0027$), the sounding curve processed with RR in the x-y direction is considerably distorted. As the SNR value of the Hy channel increases in the time series, the apparent resistivity and impedance phase curves become increasingly smooth. When the SNR reaches 23.5743, it obtains a good curve in the same manner as the original data without noise. The data from the simulation time series show that different SNR time series obtain different sounding curves, intermediate data, including polarization direction, Hy channel correlation coefficient between base and remote stations, and impedance tensor $Z_{xy}$. Furthermore, the apparent resistivity and impedance phase data show that remote reference processing can obtain a reasonable result when the SNR of the time series is 23.5743.

The synthesized data experiment show that the minimum value of the time series SNR is 23.5743 at the base station. However, when the SNR is below 23.5743, accurately obtaining a transfer function is difficult.
Figure 1. Intermediate data with remote reference magnetotelluric method (period $T=9.5137s$). a. Polarization direction of the magnetic field (Weckmann et al., 2005). Horizontal axe represents the data segment index. b. Correlation coefficient between the base and remote stations at the Hy channel ($\text{Cor}_{\text{Hy}_B, \text{Hy}_R}$). Horizontal axe represents the data segment index. c. Scatter of the impedance tensor $Z_{xy}$. Horizontal and vertical axes represent the real and image parts of the tensor, respectively.
Figure 2. Hy channel time series is added to different noise intensities, and different processing results are obtained. The x-y direction of apparent resistivity and impedance phase is shown.

3. Conclusions
This paper describes the improvement effects of remote reference magnetotellurics on the sounding curves through processing of different SNR synthesized data. The intermediate data, such as polarization direction, correlation coefficient between base and remote stations at magnetic channel, impedance tensor, apparent resistivity, and impedance phase are analyzed to study the maximum noise level of the contaminated time series. The following conclusions are obtained:

1. Remote reference processing can improve the quality of the sounding curve. However, for noncorrelated noises with different SNRs, remote reference magnetotellurics perform differently on the sounding curve. Under a high SNR condition, remote reference magnetotellurics can recover the sounding curve well. By contrast, under a low SNR condition, remote reference magnetotellurics has a limited capability with regard to enhancing the quality of the sounding curve.

2. The synthesized data experiment show that the minimum value of the time series SNR is about 23.5743 at the base station. However, when the SNR is below about 23.5743, accurately obtaining a transfer function is difficult.

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