

Geomagnetic vertical transfer function revealed from multi-interval geomagnetic data*

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Abstract The geomagnetic vertical transfer functions (VTFs) are useful to constrain the conductivity structure in the deep Earth. In this study, we propose an approach of estimating the geomagnetic VTFs in the wide period range from the multi-interval geomagnetic data. Applying the above method to the different interval (such as one-second, one-minute, one-hour) data from some geomagnetic observatories in China, we obtain the corresponding VTFs in the wide period range from 64 s to 9,830,400 s. In order to evaluate the possible ocean effect on different observatories, we make close investigations of the real geomagnetic induction vectors at QZH, SYG and XIC observatories. The results indicate that the ocean effect is clear at the coastal observatory like QZH. However, the ocean effect tends to decrease for the inland observatories (such as SYG and XIC) with the increasing distance from the coast.

Keywords: geomagnetic vertical transfer function; geomagnetic induction vector; ocean effect

1 Introduction

The geomagnetic vertical transfer functions (VTFs) has been widely used on the study of the electrical conductivity anomaly in the Earth's deep interior by using the geomagnetic deep sounding method (Kanda and Ogawa, 2014; Wang et al., 2014; Püthe et al., 2015). In the magnetotelluric (MT) method, the geomagnetic VTFs (also called “tippers”) are used to perform a joint inversion with MT impedance tensor, which gives a superior image of the horizontal anomalies with low electrical resistivity in the crust and mantle (Campányà et al., 2016; Ye et al., 2018). In addition, the time change of VTFs is found to be

associated with the earthquake (Chen et al., 2006). Since the pioneering work of Parkinson (1959), simulated data collection of one-hour, one-minute and one-second interval types have been calculated to obtain the VTFs in the period range of $\sim 10^3$ – 10^5 s. However, with the access of accurate digital geomagnetic data in China, there are few applications of the geomagnetic VTFs in the recent years (Li et al., 2005; Gong et al., 2015, 2017; Wang and Huang, 2016).

In the period spectrum between a few minutes and a few days, the geomagnetic field are affected by diurnal variation, magnetic storms and bays. The well-known geomagnetic “ocean effect” (Parkinson, 1962), the real geomagnetic induction vector at the coastal observatories point towards the nearest deep ocean, is significant among magnetic storms and substorms (Parkinson and Jones, 1979). However, the diurnal variation and its higher harmonics related to the ocean tide are regarded as noises in estimating the geomagnetic VTFs in the period range of 10^4 – 10^5 s (Shimizu et al., 2011). Moreover, the geomagnetic VTFs are generally excluded data with periods longer than 10^5 s to avoid violating the plane-wave approximation (Wang et al., 2014). Therefore, it is very important to estimate the reliable VTFs in a wide period range to understand these effects.

In this study, we propose an approach to estimate the geomagnetic VTFs from multi-interval geomagnetic data. By restructuring, the reliable VTFs in a wide period range are obtained. We then discuss the ocean effect on the real geomagnetic induction vectors at some observatories in China.

2 Data and processing

The relationship between the vertical component z and horizontal components (x , y) of the geomagnetic field at a given observatory can be written as (Schmucker, 1973):

$$z(\omega) = Ax(\omega) + By(\omega) \quad (1)$$

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where ω is the angular frequency, and the three components of the geomagnetic field are in the frequency domain. The geomagnetic VTFs are frequency-dependent complex quantities, represented here as A and B . The real geomagnetic induction vector is defined as $(-A_r, -B_r)$ following the Parkinson convention that the real geomagnetic induction vectors point towards the electrical conductors (Schmucker, 1970). In this work, segments of z , x and y are taken to estimate the geomagnetic VTFs by using the robust estimation code BIRRP (Chave and Thomson, 2004).

Geomagnetic raw data accompanied with the spikes and jumps were first identified and processed by the trained observers using single-site checking and multi-site checking methods (Deng and Luo, 2009), which were then synchronized to the Geomagnetic Network of China for multiple rounds of checking. The pre-processed data would be reprocessed and stored if they were over-processed or unprocessed, which ensures the quality of the geomagnetic pre-processed data to some extent (Wang et al., 2010). We collected the multi-interval geomagnetic pre-processed data from the Geomagnetic Network of China to estimate the geomagnetic VTFs in a wide period range. In the data processing, we further deleted the abnormal observations (the absolute value of the first-derivative of the geomagnetic data large than 50) from the pre-processed data. For the successive abnormal observations with the number less than 120, we filled the gap by linear interpolation with a uniform sampling rate of one sample per hour, and we did not fill the gaps otherwise. Thus, the quality of the processed data are assured to obtain the reliable geomagnetic VTFs.

The geomagnetic VTFs at 16 discrete periods in the range of 64–10,923 s were calculated from one-second instantaneous data for one year. The geomagnetic VTFs at 22 discrete periods from 960 s to 655360 s were obtained from one-minute interval data with three-year length. Hourly mean values of long time-series (over 18 years) were collected to estimate the VTFs at 16 discrete periods in the range between 57,600 s to 9,830,400 s. Therefore, we derived the VTFs in the wide period range of 64–9,830,400 s with two overlap period regions, R_1 and R_2 (Figure 1). In this paper, we only show the real part of VTFs, hereinafter referred as VTFRs, which we are interested in.

In Figure 1, the VTFRs at the last two periods from one-second instantaneous data are less stable with the relatively bigger error bars than the VTFRs at their adjacent period from one-minute interval data in R_1 . That is the reason why we need to use the geomagnetic VTFRs from multi-interval geomagnetic data to restructure the VTFRs, instead of these less reliable values in the overlap

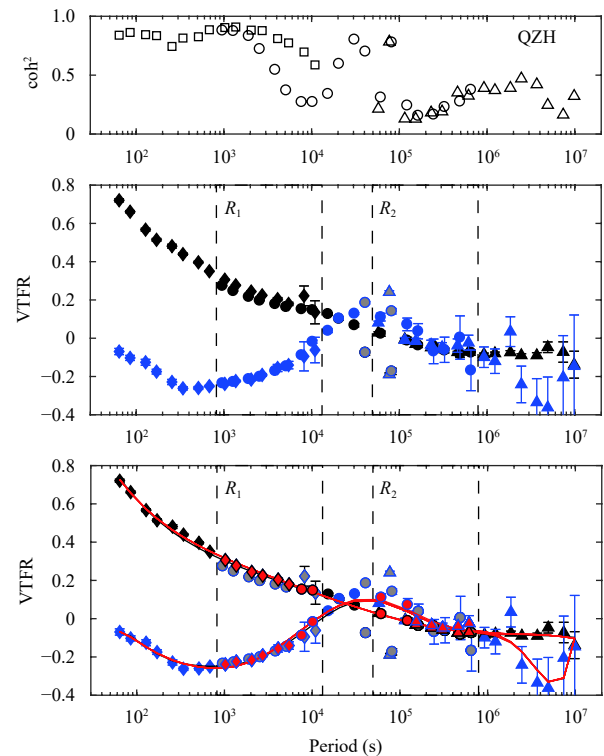


Figure 1 Geomagnetic VTFRs (middle and bottom panels) and squared coherencies (top panel) at QZH estimated from multi-interval geomagnetic data, one-second (diamonds), one-minute (circles) and one-hour (triangles). Black and blue colors are for the A_r and B_r , respectively. The two dashed boxes denote the overlap period regions, R_1 and R_2 . The abnormal VTFRs are represented as grey circles and triangles in the middle panel. In the bottom panel, black curves are the iteration results to fit the geomagnetic VTFRs except the ones marked as “0” in the loops. Two reds curves are the final results of the fitting. In R_1 and R_2 , the geomagnetic VTFRs in red are chosen to be more reliable

period regions. Moreover, it is obvious that geomagnetic VTFRs at the periods of around one day and half of the day are abnormal. Therefore, restructuring the VTFRs from multi-interval geomagnetic data is significantly important to obtain the reliable geomagnetic VTFRs in the wide period range. The procedure below describes how we restructure the geomagnetic VTFRs in detail.

Step 1: All the geomagnetic VTFRs were assumed to be defined and marked with “1”. Abnormal A_r at some periods were deleted if their first-derivatives exceed the threshold, which is set for each observatory, as well as B_r . These values (grey circles and triangles in the middle panel of Figure 1) often appear around the periods of one day and half of the day. We renewed the label of such abnormal A_r or B_r with “0” and removed them.

Step 2: Fit all the A_r marked with “1” by using a multivariate curve, as well as the B_r marked with “1”,

which remained the relatively reliable VTFRs in a wide period range on a large scale.

Step 3: In order to choose the more reliable VTFRs in R_1 , the i th geomagnetic VTFR at some period from one-second interval data was compared with the counterpart at its adjacent period from one-minute interval data in the form,

$$E_i = (|A_r^m - A_r^o| + |B_r^m - B_r^o|)_{\text{sec}} - (|A_r^m - A_r^o| + |B_r^m - B_r^o|)_{\text{min}} \quad (2)$$

where the superscript o and m denote the observed value and the fitted one at the same period, respectively. The subscript sec and min represent the values from different data interval types at two adjacent periods. If the i th E was greater than zero, it means that the geomagnetic VTFR from one-minute interval data is closer to the fitted value than the other. We then marked the i th R_1 with “M”, and marked the i th R_1 with “S” otherwise ($0 \leq i \leq g$, where g is the number of the geomagnetic VTFRs from one-second interval data in R_1).

Step 4: If the labels of R_1 started with the k ($1 \leq k \leq g$) consecutive “S” and the rest of labels consecutive “M” in an ascending order of periods, the subprocedure within R_1

stopped. It is obvious that more number of sections yields more reliable geomagnetic VTFRs with less uncertainties if the different interval data are all of comparable quality through the whole interval of data length. Such judgement standard is defined according to this conventional understanding, that is, the geomagnetic VTFR from one-second interval data at long period with relatively big error may be less reliable than the VTFR from one-minute interval data at its adjacent period since the three-year data from one-minute interval has more sections than one-year data from one-second interval data. Therefore, we chose the k geomagnetic VTFRs from one-second interval data and the $(g-k)$ geomagnetic VTFRs from one-minute interval data, and the other geomagnetic VTFRs in R_1 were marked with “0”.

Step 5: Otherwise, in R_1 , the $(g-j+1)$ th ($1 \leq j \leq g$) label of the geomagnetic VTFR from one-second interval data were updated with “0” if the $(g-j+1)$ th R_1 were marked with “M”, which would not be involved in the next fitting. Then go to step 2. In each iteration, the $(g-j+1)$ th geomagnetic VTFR was not chosen to join the fit until the judgement standard met. The flowchart shows the

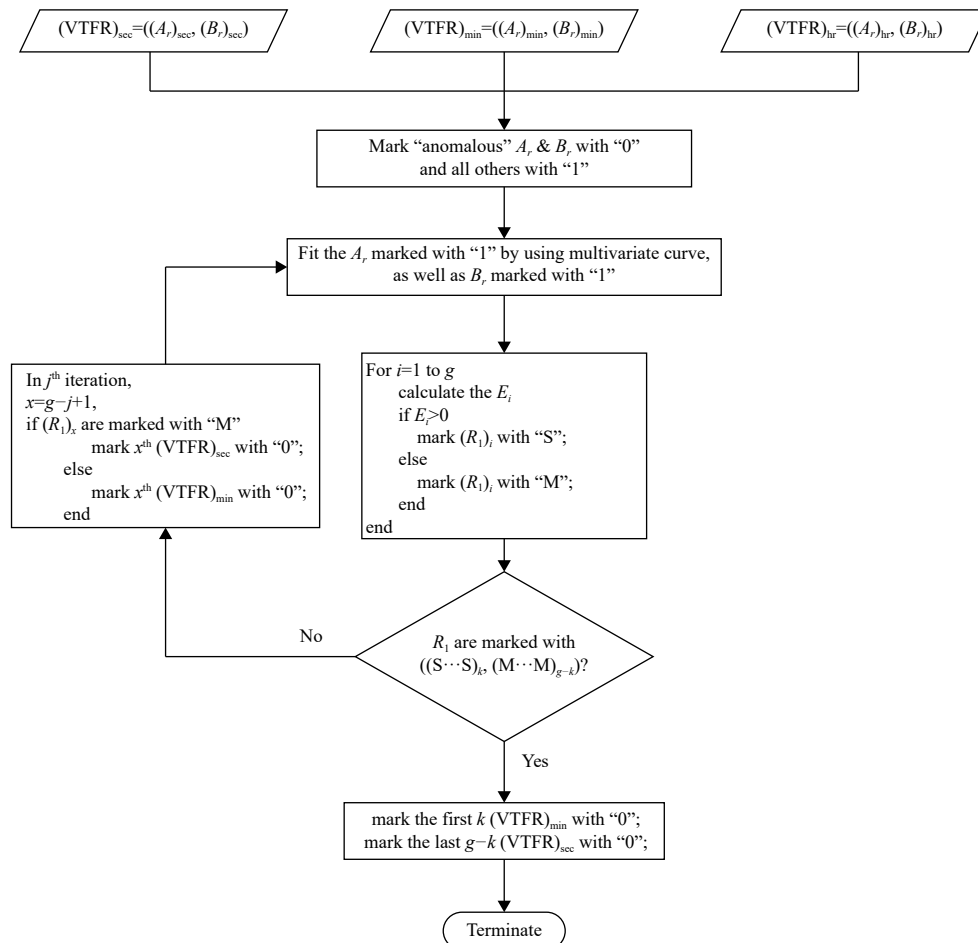


Figure 2 Flowchart describing the algorithm to restructure the geomagnetic VTFRs in the overlap period range R_1

subprocedure below (Figure 2).

The geomagnetic VTFRs in R_2 were performed with the same subprocedure as steps 2–5. Finally, we obtained the restructured geomagnetic VTFRs in the wide period range.

3 VTFRs and the real geomagnetic induction vectors

In order to evaluate the possible ocean effect on different observatories, the geomagnetic VTFRs and the corresponding real geomagnetic induction vectors at QZH, SYG and XIC are plotted in Figures 3–5 by applying the approach given in Section 2. It is a generally understanding that the real geomagnetic induction vector points towards the regional conductor (Parkinson, 1959; Schmucker, 1973; Wang et al., 2014). For the coastal observatory QZH, the directions of the real geomagnetic induction vectors at periods of 64–8192 s point to south (southeast). The amplitudes of the real geomagnetic induction vectors at QZH tend to decrease with the increasing periods. However, the orientations of the real geomagnetic induction vectors at SYG change from southeast to north at periods between 64 s and 8192 s (Figure 4). At XIC, the amplitudes of the real geomagnetic induction vectors at the first two periods are almost 0, and the real geomagnetic induction vectors point to southwest with the increasing periods (Figure 5). Note that the spatial distribution of the observatories used in this paper is shown in Figure 6, with the relevant information given in Table A1.

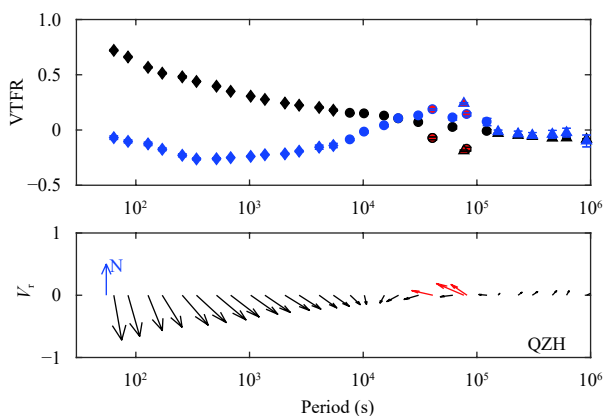


Figure 3 The geomagnetic VTFRs (top) and the real geomagnetic induction vectors (bottom) at QZH. The length of the arrow denotes the amplitude of the vector, and the direction of the arrow is the orientation of the vector. The blue arrow points to north. In the top panel, the abnormal geomagnetic VTFRs are in red. In the bottom panel, the corresponding abnormal real geomagnetic induction vectors are plotted as red arrows

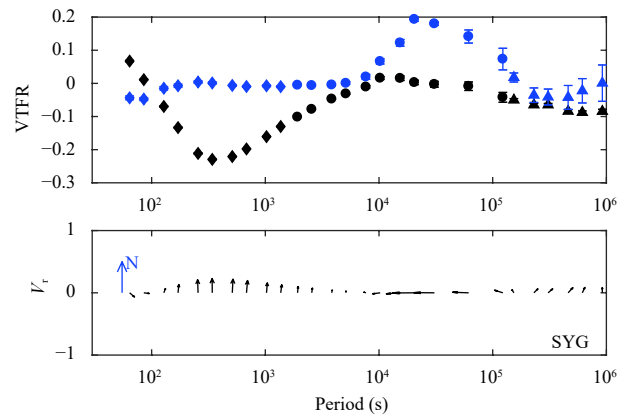


Figure 4 The geomagnetic VTFRs (top) and the real geomagnetic induction vectors (bottom) at SYG. The length of the arrow denotes the amplitude of the vector, and the direction of the arrow is the orientation of the vector. The blue vector points to north

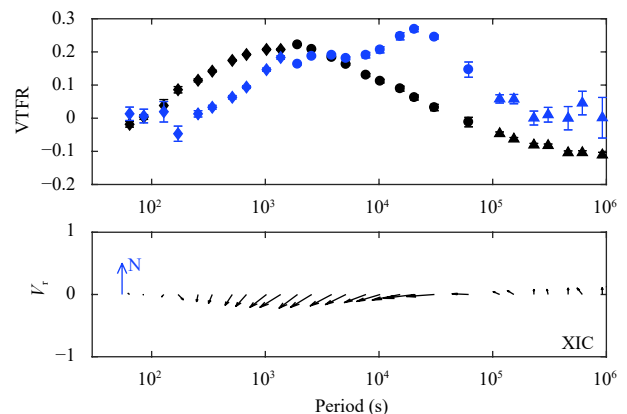


Figure 5 The geomagnetic VTFRs (top) and the real geomagnetic induction vectors (bottom) at XIC. The length of the arrow denotes the amplitude of the vector, and the direction of the arrow is the orientation of the vector. The blue vector points to north

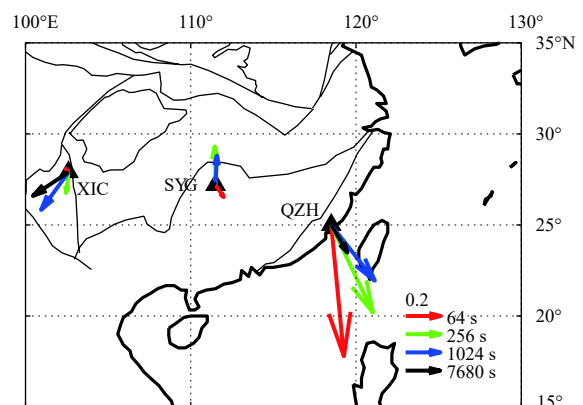


Figure 6 The amplitudes and orientations for the real geomagnetic induction vectors at the periods (64 s, 256 s, 1,024 s, 7,680 s) at QZH, SYG and XIC represented by the length and direction of the arrows. The number on arrows indicates the scale of the vectors

4 Discussion and conclusions

Figure 6 shows the amplitudes and orientations for the real geomagnetic induction vectors at the periods of 64 s, 256 s, 1,024 s and 7,680 s at QZH, SYG and XIC. For QZH and SYG, the real geomagnetic induction vectors at period of 64 s point towards the conductive sea, which is affected by the electrical conductivity distribution of land and ocean, called geomagnetic “ocean effect” (Parkinson, 1962). The orientations of the real geomagnetic induction vectors at QZH vary slightly in the period range from 64 s to 8,192 s in Figure 3, indicating that the real geomagnetic induction vectors at the observatory near the coast has the ocean effect in a wide period range. The real geomagnetic induction vectors for the inland observatories (SYG and XIC) at the periods larger than 256 s do not point towards the conductive sea (Figure 6), which may be mainly affected by the local lateral variations in the electrical resistivity. Moreover, it is clear that the amplitudes of the real geomagnetic induction vectors decrease from the southeast coast to the inland, and the rate may depend on the geological nature of the continent (Parkinson and Jones, 1979). Thus, the ocean effect tends to decrease for the inland observatories with the increasing distance from the coast.

As shown in Figure 1, the geomagnetic VTFRs at period longer than 10^4 s have relatively low squared coherency, which may be caused by not fulfilling the plane wave assumption. Our approach recognizes the geomagnetic VTFRs at periods of 40,960 s, 76,800 s and 81,920 s as distinctly abnormal values (marked as red circles and triangles in Figure 3), and the corresponding real geomagnetic induction vectors at these periods tend to have a significant westward component (red arrows in Figure 3).

Appendix

Table A1 Relevant information of the three observatories used in this paper.

Code	Latitude (°N)	Longitude (°E)	Data interval type	Data duration
QZH	25.0	118.5	1 second	2018
			1 minute	2016–2018
			1 hour	1983–2018
SYG	27.2	111.5	1 second	2018
			1 minute	2016–2018
			1 hour	1983–2018
XIC	27.9	102.6	1 second	2018
			1 minute	2016–2018
			1 hour	1995–2018

They are removed from the observed geomagnetic VTFRs and not involved into the restructuring. These abnormal geomagnetic VTFRs may be ascribed to the “source-field”, mainly solar Sq variation and its higher harmonics (Lizaralde et al., 1995; Baba et al., 2010; Shimizu et al., 2011).

In summary, we obtain the reliable geomagnetic VTFRs in the period range of 64–9,830,400 s based on the multi-interval geomagnetic data by applying the method of restructuring. For the coastal observatory, the ocean effect is clear in the period range of 64–8,192 s, while for the inland observatory, the effect of ocean is just obvious at the short periods. In addition, with the increasing distance from the coast, the decreasing amplitudes of the real geomagnetic induction vectors are obvious, indicating that the ocean effect decreases for the inland observatories.

It is of significant importance to constrain the lateral variation of the electrical resistivity structure with the geomagnetic VTFRs in the wide period range. To achieve a more accurate electrical conductivity model beneath China, 3-D inversion of the geomagnetic VTFRs is necessary.

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