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On the Use of Fast Registrations of Observatories as a Reference for Magnetotelluric Measurements

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Abstract

Surprisingly, some records of geomagnetic variations measured in observatories are able to support magnetotellurics, a geophysical branch relatively far away from investigations of the magnetic field itself. Magnetotellurics is an electromagnetic induction method to study the solid Earth. The way it can benefit from geomagnetic observatories is outlined here.

1. Variation Measurements at Observatories

The continuous measurement and recording of variations of the Earth's magnetic field is a fundamental task of geomagnetic observatories. The data obtained thereby serve, on the one hand, to investigate the external field itself, and on the other hand, they are taken into account during the evaluation of absolute measurements.

The international standard of the INTERMAGNET network (St.-Louis 2004) demands a registration of the components X, Y, and Z carried out with a sampling interval of not less than 10 seconds to cover these variations. Interestingly, some observatories are able to provide a more densely sampled registration. E.g. Niemegk and Belsk carry out continuous variation measurements in the framework of their daily work that result in a steadily available one-second registration. In special cases, a still much higher sampling rate of 100 Hz is reached, i.e. if the observatory performs a monitoring of the Schumann Resonance phenomenon, as it is done in Nagycenk, Hornsund, and Belsk, (see Neska *et al*. 2007, this volume).

Now it turned out that such variation data can serve another purpose beside the ones they are designed for. They are able to support magnetotelluric measurements in a situation that is fatal for them. This possibility will be illustrated below.

2. Magnetotellurics

A broad introduction of this field is beyond the scope of this paper. It can be found in textbooks like (Zhdanov *et al.* 1994). However, features that are essential to our topic will be described in the following.

2.1 Some basics

Magnetotellurics is a geophysical method targeted on the investigation of the electric conductivity of the Earth's crust and mantle. Thereby it contributes to solid Earth studies, since different electric conductivities allow to draw conclusions about different underlying rocks and their state. E.g., sediments saturated with saline water are better conductors than not-weathered, not-porous crystalline rocks like granite. Other examples for good conductors in terms of geology are partially or completely molten rocks and some minerals like graphite and sulfides. Furthermore, the conductivity of a rock depends highly on its temperature. Hence, a model of the conductivity distribution in the subsurface (which magnetotellurics intends to find by numerical modeling) gives answers on geological, tectonic, and petrophysical questions about the region of interest.

Such a conductivity model is based on information obtained from variations of the natural electromagnetic field via the induction equation. This works as follows: The given region is covered by a network of magnetotelluric stations. Each of them measures field variation of five components, the horizontal electric ones in north and east direction (E_x and E_y) and three magnetic ones in north, east, and vertical direction (B_x, B_y, B_z). See Fig. 1 for an example record demonstrating the similarity, i.e. correlation or coherency, between certain components caused by electromagnetic induction. The registration can have rather varying parameters and instrumentation depending on the depth range one is interested in. So shallow studies use fast sampling rates in the Hz to kHz range, short recording durations of several hours, and induction coils to measure the magnetic channels. In contrast, deep studies work with a sampling interval in the second range, they last several weeks, and they use, in general, fluxgate magnetometers to measure B_x, B_y, and B_z.

During the data processing, all time series are Fourier-transformed to the frequency domain, and the so-called transfer functions between several field components are calculated. So the impedance tensor **Z** transforms (B_x, B_y) into (E_x, E_y)

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} , \tag{1}$$

and the induction arrow (A, B) connects (B_x, B_y) with B_z:

$$(B_z) = (A \;\; B) \begin{pmatrix} B_x \\ B_y \end{pmatrix} . \tag{2}$$

Both transfer functions are complex functions of frequency or, which is equivalent, of period T. Usually, the impedance at a certain station is plotted in form of apparent resistivity and phase and the induction arrow in form of a vector with components *A* in North and *B* in East direction (see Fig. 3).

The above-mentioned transfer functions contain the desired conductivity information under the condition that the underlying mechanism of their generation is electromagnetic induction, indeed. This includes that the so-called far-field condition is fulfilled, i.e. the source of the magnetic variations must be so far away that the latter comes as a plane wave to the study area. For natural variations this is generally met in mid latitudes.

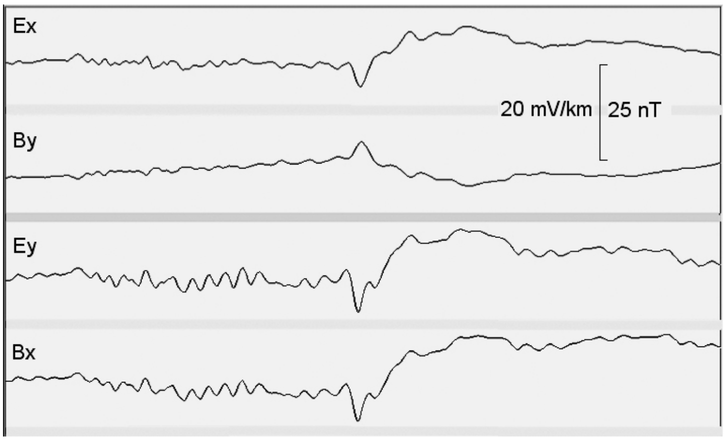

Fig. 1. Horizontal electric and magnetic channels recorded by a magnetotelluric station with a 2 s sampling interval. The length of time series is 25 min, the visible pulsations are mainly pc2 and pc3. The induction-caused similarity between perpendicular E and B components is significant.

2.2 The correlated noise problem

However, if there is registered an artificial electromagnetic signal from a near-by source, this basic requirement of magnetotellurics is not accomplished. When doing magnetotelluric measurements in Poland, one faces such a situation in the proximity of electrified railways, which are run with direct current (DC) here. The start-up peaks of the moving trains are clearly visible in the time series in Fig. 2, destroying the harmony of the pc2 and pc3 pulsations expected in the given time range. Nevertheless, these peaks are correlated between different field components. This fact leads to the term “correlated noise” for such a kind of disturbances. Correlated noise is a big problem for the magnetotelluric method, because such features will enter the transfer functions due to their coherent nature, if affected time series are processed. This means, that a part of the impedances and induction arrows will be dominated by the railway disturbances which do not fulfill the far-field condition. Thereby, the latter will distort the conductivity information obtained at the given station. Figure 3, left-hand side, shows such distorted transfer functions of a station at a distance of 25 km from a DC railway. The distortions are always characteristic: they misleadingly suggest the presence of a bad conductor beneath the railway.

Fortunately, there is a method rescuing the magnetotelluric approach in such a correlated-noise situation.

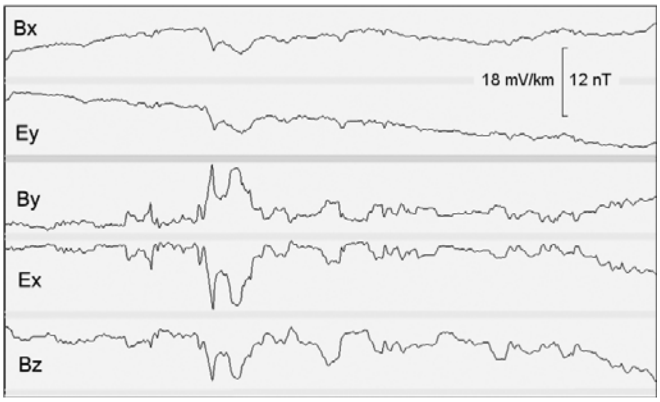

Fig. 2. Time series (34 min) recorded by a station 7 km off a DC railway. The peaked, angular structures are not natural, but due to the railway. Note the coherency between channels.

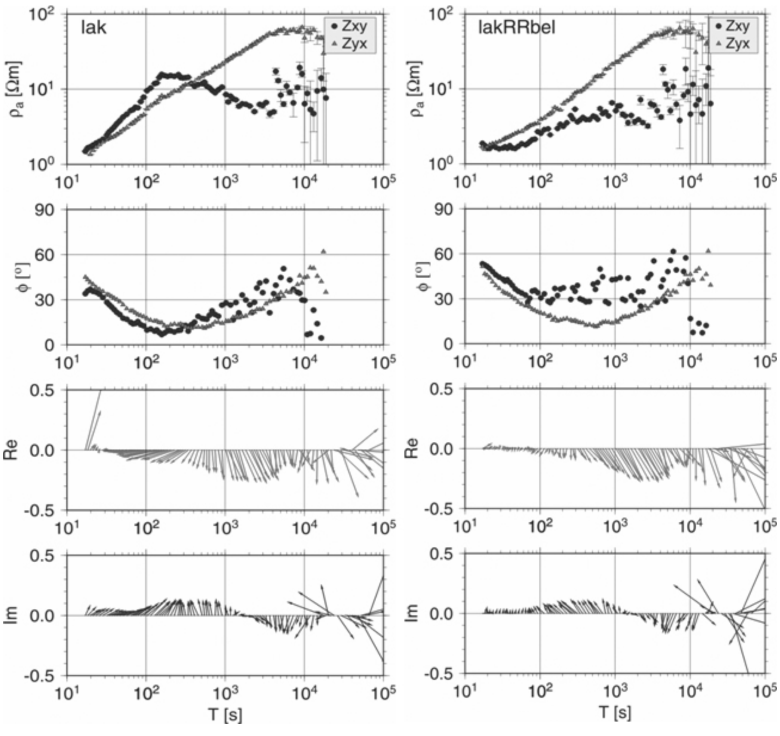

Fig. 3. Magnetotelluric transfer functions of a station affected by correlated noise 25 km off a railway. Left-hand side processed without, right-hand side with Belsk observatory records as reference data. The upper two panels show apparent resistivity and phase of the off-diagonal elements of the impedance tensor, the lower ones real and imaginary induction arrows. Note that there are artificial features (enhanced resistivity and decreased phase in Z_{xy}, too long induction arrows) in the transfer functions without Remote Reference at periods below 1000 s.

2.3 The Remote Reference technique

The method to suppress the influence of correlated noise on transfer functions is called Remote Reference technique, introduced by Gamble *et al*. (1979). The most important task of this processing approach, the distinction between natural signal and artificial noise, is solved by means of a simple fact: The artificial noise decays within a relatively short distance to its source; in my experience with the Polish sedimentary basin, it is not traceable much farther than 100 km from the railway. In contrast, the natural magnetic variations are correlated over several hundred kilometers in mid latitudes, as can be seen in Fig. 4.

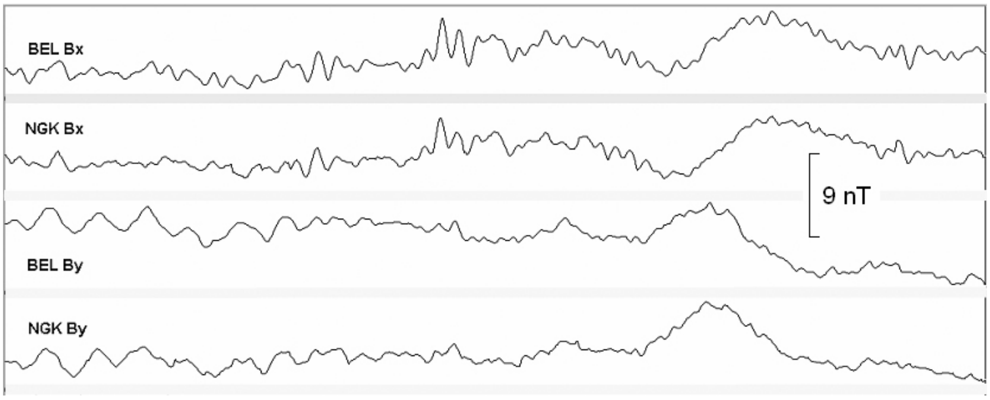

Fig. 4. Natural magnetic pulsations are correlated over several hundred kilometers: In spite of the distance of 560 km between Niemegk and Belsk, their horizontal records look similarly. Length of time series 25 min.

So, when comparing time series of a local station affected by railway disturbances and a some hundred kilometers remote reference station, the natural variations will be correlated between both sites and the railway noise will not. Hence, synchronously recorded horizontal magnetic time series of a remote reference station are included into the processing in the following way: To obtain, e.g., Z_{xy} in general, one must take a number of spectral values of the field components E_x, B_x, and B_y at the same frequency and apply the least-square solution:

$$Z_{xy} = \frac{[E_x^* B_x][B_y^* B_y] - [E_x^* B_y][B_x^* B_y]}{[B_x^* B_x][B_y^* B_y] - [B_x^* B_y][B_y^* B_x]}, \tag{3}$$

where [] indicates the average of the spectra in between and A^* the complex conjugate of A. The solution for the Remote Reference technique looks as follows

$$Z_{xy}^R = \frac{[E_x^* B_x^R][B_y^* B_y^R] - [E_x^* B_y^R][B_x^* B_y^R]}{[B_x^* B_x^R][B_y^* B_y^R] - [B_x^* B_y^R][B_y^* B_x^R]}, \tag{4}$$

where a superscript ^{R} indicates spectra of the reference station.

Due to the cross spectra between local and remote data it is provided that only features correlated between both sites, i.e. natural variations, can enter the result, whereas the railway noise is suppressed. Let it be noted that features in the reference data caused via induction by the subsurface of the remote site do not enter the local transfer functions, since the remote spectra appear quasi in the enumerator and the denominator of Eq. (4) and are thereby cancelled down. It remains just the benefit from the averaged cross spectra which removes the influence of correlated noise in the local time series. Figure 3, right-hand side, shows transfer functions of a railway-affected station, which have been corrected by the Remote Reference technique.

A more detailed discussion of magnetotelluric data processing including the Remote Reference technique can be found in (Neska 2006).

3. Observatories as Remote Reference Stations

From the above description, it becomes clear that under certain conditions, observatory records can play the role of reference data for magnetotelluric measurements. These conditions are mainly connected with the sampling rate of both observatory and magnetotelluric registration, and with the distance between observatory and magnetotelluric sites. The sampling rates should not be very different from each other; in the ideal case they are equal. If the observatory samples faster, it is also easy to deal with: the data must be just low-pass filtered and resampled to the magnetotelluric rate. If conversely the observatory samples slower, the magnetotelluric data have to be adapted in the same way to the observatory rate, which would, however, lead to a loss of information from the highest frequencies. For the example shown in Fig. 3, the one-second registration of Belsk Observatory has been adapted to the two-second sampling of the field measurement.

Figure 5 demonstrates that even more "exotic" measurements carried out in observatories can have an application that supports other geophysical fields. In this case, a relatively high-frequency magnetotelluric record was concerned by correlated noise. Amongst others, it contains a band sampled with 64 Hz. It could be subjected to a Remote Reference processing using horizontal magnetic variation data which have been measured with a 100 Hz sampling rate in Belsk. The reason for recording such data steadily is the observation of the Schumann Resonance phenomenon at the observatory, cf. (Neska *et al.* 2007). The comparison of Z_{xy} results processed with and without Remote Reference in Fig. 5 shows that the former leads to vanishing correlated-noise features which are visible in the first.

Concerning the question of distance, it has to be stated that observatory and station network must be remote enough to avoid being within the reach of the same emitter of correlated noise, e.g. the same DC railway. It is on the other hand intuitively clear that the possible distance is not unlimited for the coherency of the natural magnetic variations is a condition *sine qua non*. However, in my experiments I did not reach that limit, I can only confirm that a distance of about 500 km did not cause any problems in Remote Reference processing. The statement that natural variations are correlated over several hundred kilometers in mid-latitudes stems from Schmucker (1984).

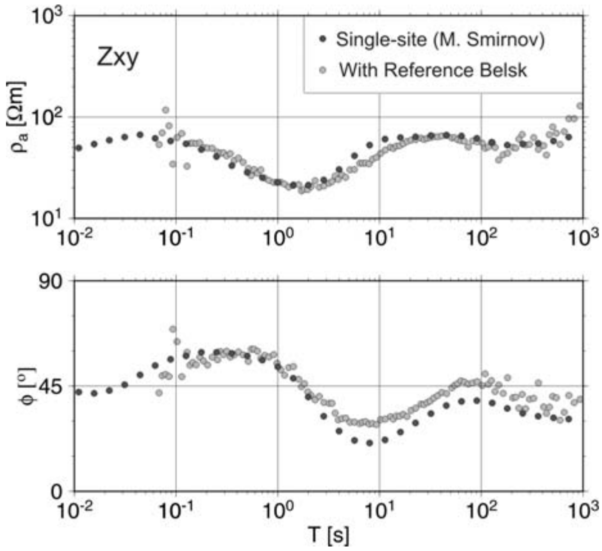

Fig. 5. An application of Remote Reference at higher frequencies with data from Belsk. Local data has been measured by V. Červ, the observatory-station distance is 350 km. Apparent resistivity and phase of impedance tensor element Z_{xy} show correlated-noise features around 10 s, when processed without reference (single-site, done by M. Smirnov).

It has to be emphasized that the absence of uncorrelated (i.e. local) noise in the remote reference data is not demanded for the success of processing. Such a noise (which can hardly be kept away from Mid-European observatories) does not endanger the ability of the Remote Reference technique to compensate for correlated noise in the local site. However, if such a remote noise is strong compared to the natural signal, it can lead to somewhat scattered sounding curves, as it can be seen in Fig. 3, right-hand side.

Concluding, I would like to illustrate what meaning the availability of observatory data can have for people carrying out a magnetotelluric field campaign. When measuring in areas affected by correlated noise like Poland, it is absolutely necessary to have a Remote Reference station. If not counting on observatories, the magnetotelluric worker has to provide this station on his own. This means that one instrument is blocked for this role during the entire campaign. Furthermore, it costs a notable effort regarding staff and transportation to install and maintain such a station, since it must be in a certain distance from the rest of the network as mentioned above. Finally, field stations are less secure than observatories; they are endangered by bad weather, animals, and in worst case, by vandalism and theft, so one cannot be sure to get uninterrupted data from it. In contrast, using observatory records guarantees continuous, steadily available data from a sufficient distance without additional measurement effort for the magnetotelluric worker.

From this point of view it would be desirable that magnetic observatories provide also variation records sampled faster than with a ten-second interval.

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