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ON THE MAGNETOTELLURIC IMPULSE RESPONSE AT THE NURMIJÄRVI OBSERVATORY

by

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Abstract

Geomagnetic 2 s values were recorded at the Nurmijärvi Geophysical Observatory for some days in June 1983, and simultaneous electric values were collected at a noise-free place about 3 km from the observatory. The data were analysed by selecting all events which could be used in the determination of the impedance tensor and the impulse response. Polar diagrams of the impedance tensor are presented. The structure of the resistivity of the earth seems to be complex (three-dimensional) at Nurmijärvi, which is shown by the fact that the diagonal elements of the impedance tensor are large. The nondiagonal ones being not opposite numbers also imply deviations from lateral uniformity. The resistivity of the earth is high since the apparent resistivity has values in the order of 1000 Ωm. In this paper, the prediction of the electric field using magnetic data and the computed impulse response is also discussed, and it is shown that the predicted and recorded electric fields correspond to each other very well at Nurmijärvi.

1. *Introduction*

A Polish-Finnish study was started in 1982 in which the induction contribution to geomagnetic variations recorded at the Nurmijärvi Geophysical Observatory (60°30′34″ N, 24°39′20″ E) in southern Finland is investigated. The analyses of geomagnetic variation data collected at Nurmijärvi and in its surroundings (distance about 30 km) in June 1982 showed that the variations are spatially homogeneous at the array used for periods ranging from 300 s to 2000 s (Jankowski *et al.*, 1986). But a regional induction anomaly is implied by big induction vectors, *i.e.*, the scale length of the anomaly is larger than the dimensions of the array. A complex structure of the conductivity of the earth in Finland is indicated *e.g.* by (Hjelt *et al.*, 1986).

Besides magnetic variations, each geomagnetic observatory should also record the electric (or telluric) field to obtain information of possible local induction effects. In the frequency domain, the horizontal electric field is connected to the horizontal magnetic variations by transfer functions which are elements of the impedance tensor. We believe that each observatory should have knowledge of its transfer functions. The tensor can be inverted, and if the observatory is located in an area having a nearly one-dimensional conductivity distribution in the earth, information of the geology below the observatory is obtained. Anyway, in all cases the impedance tensor implies some qualitative knowledge about the structure of the earth.

Thus, the recordings of geomagnetic variations mentioned above were supplemented by magnetotelluric recordings at Nurmijärvi for some days in June 1983. In fact, the electric measurements were impossible to be made at the observatory because of man-made disturbances, and they were carried out at Löytlammi about 3 km north of the observatory. The distance 3 km does not play any role because magnetic variations are homogeneous at distances of even 30 km around the Nurmijärvi Observatory (*cf.* above). So we consider Löytlammi to »belong» to the observatory and regard both electric and magnetic measurements as having been made at the same place.

2. *Experimental data*

A TPM (torsion photoelectronic magnetometer) made in Poland was used for the magnetic measurements. The telluric recordings were performed with the normal electrode method. The measurements were made in the short period part of the spectrum. Digital 2 s mean values were collected to be used in analyses; analog curves were produced just for checking. The accuracy of the final digital data was 0.1 nT and 0.1 mV/km. Fig. 1 shows an example of the plotting of the digital data for an interval 20 minutes in length.

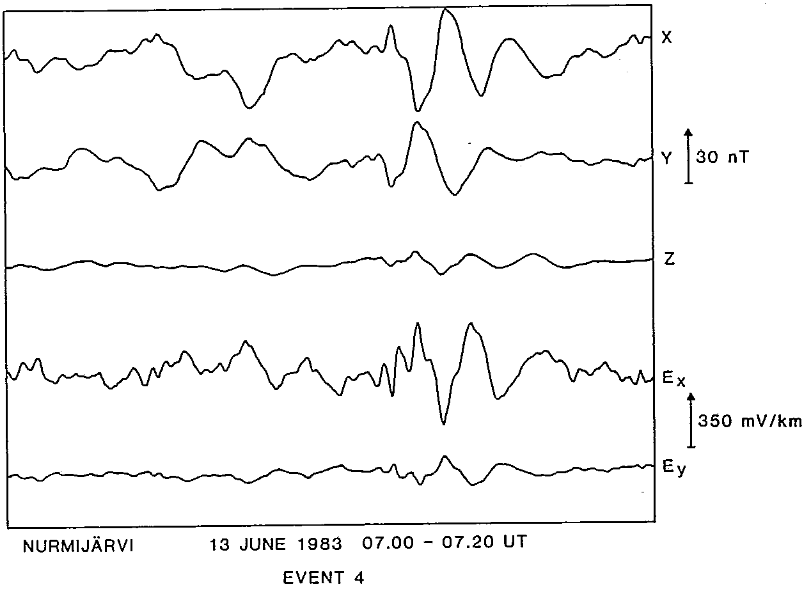


Fig. 1. Magnetotelluric event of 20 minutes recorded at the Nurmijärvi Observatory (magnetic) and at Löytlammi 3 km north of the observatory (telluric). X, Y and Z denote the north, east and downward vertical geomagnetic components, respectively. E_x and E_y are the electric north and east components.

3. *Impedance tensor calculation*

The impedance tensor, $\boldsymbol{Z}$, which is a 2x2 matrix, is defined by the formula

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \tag{1}$$

where E_x, E_y and H_x, H_y denote the Fourier transforms of perpendicular horizontal components of the electric and magnetic field intensities, respectively (*e.g.* Kaufman and Keller, 1981, p. 434).

An apparent resistivity $\rho_{aij}(\omega)$ can be assigned to the nondiagonal elements $Z_{ij} = Z_{ij}(\omega)$ by the formula

$$\rho_{aij}(\omega) = \frac{|Z_{ij}(\omega)|^2}{\omega\mu} \qquad (i,j = x,y;\ i \neq j) \tag{2}$$

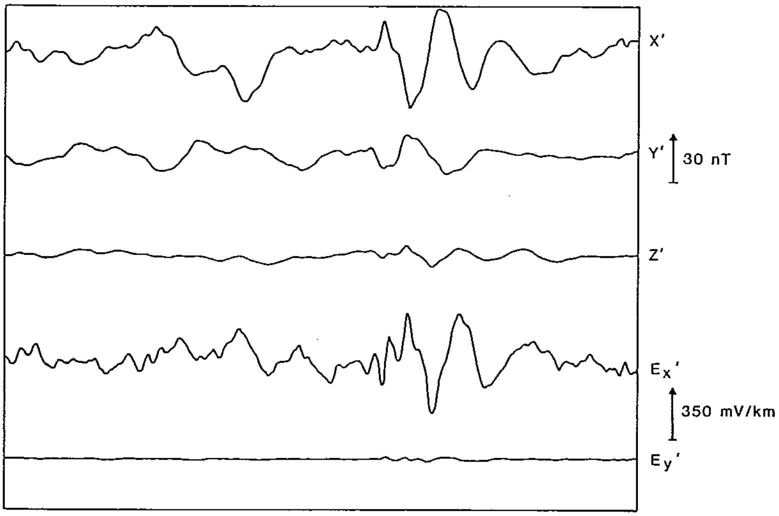
where ω is the angular frequency in question (= 2π/period) and μ is the permeability of the earth.

For the determination of the impedance tensor and the apparent resistivities at the Nurmijärvi Observatory, we selected twelve events of 20 minutes from the data (see Fig. 1), and the computations were made by a computer program based on the method developed by (Wielądek and Ernst, 1977). The program works in the time domain using the linear least-square method. The quality of the data was good making the error limits small in the computations.

The diagonal elements of the impedance tensor are of the same order of magnitude as the nondiagonal ones, which means that the structure of the conductivity of the earth is three-dimensional. In one direction the apparent resistivity has values in the order of thoudands of Ωm, but in another direction there are values in the order of only tens to hundreds of Ωm. Some further analysis of the impedance tensor will be described in Section 5. A more detailed investigation neglected in this paper would require the determination of values of the »skewness» and the »tipper» (Kaufman and Keller, 1981, pp. 483...484).

4. *Polarization of the electric field*

Analysis of the recordings and of the polar diagrams of the impedance tensor (see Section 5) indicated that the electric field might be linearly polarized. To



NURMIJÄRVI 13 JUNE 1983 07.00 - 07.20 UT
EVENT 4 AFTER ROTATION

Fig. 2. The event of Fig. 1 shown in a coordinate system that is obtained from the original system by a rotation of 16° around the vertical axis (the z-axis). As viewed from above, the rotation is made counterclockwise, *i.e.* from the north towards the west (see Figures 3–5).

check this possibility, the coordinate system, whose x-, y- and z-directions were originally northwards, eastwards and downwards, respectively, was rotated around the z-axis. A plotting of the data after rotation (Fig. 2) shows that linear polarization exists. The angle was determined by the least-square method and is 16° from the north towards the west, and it is shown in Figures 3–5.

5. *Polar diagrams of the impedance tensor*

Generally the impedance tensor varies when the axes along which the field components are measured are rotated. These changes can be illustrated by so-called polar diagrams that represent the absolute values of the tensor elements as functions of the rotation polar angle. The formulas for the rotation of the impedance tensor are given *e.g.* by (KAUFMAN and KELLER 1981, p. 483).

In a one-dimensional case the diagonal elements of the impedance tensor are zero for all angles θ, and the polar diagrams for the nondiagonal elements are circles. This is true for all periods and at all points. At a two-dimensional structure

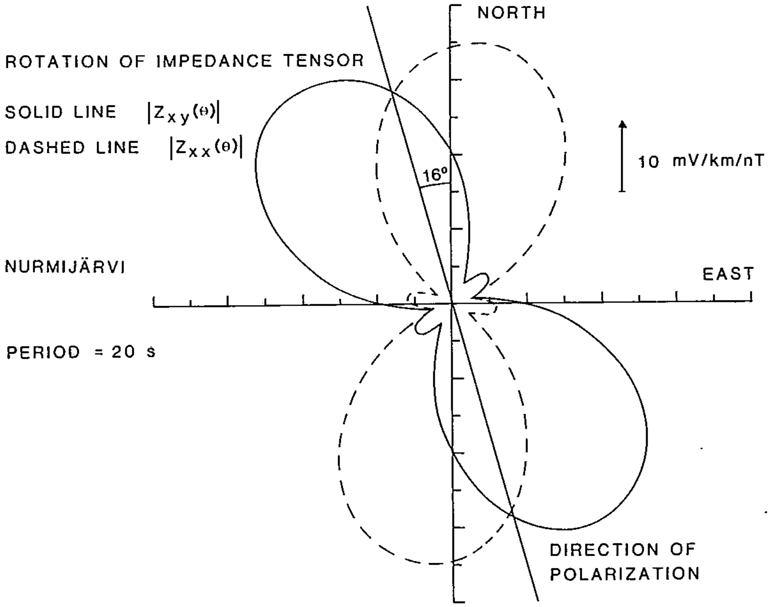


Fig. 3. Polar diagram of the impedance tensor at the Nurmijärvi Observatory for the period of 20 s. The straight line shows the direction of the linear polarization of the electric field.

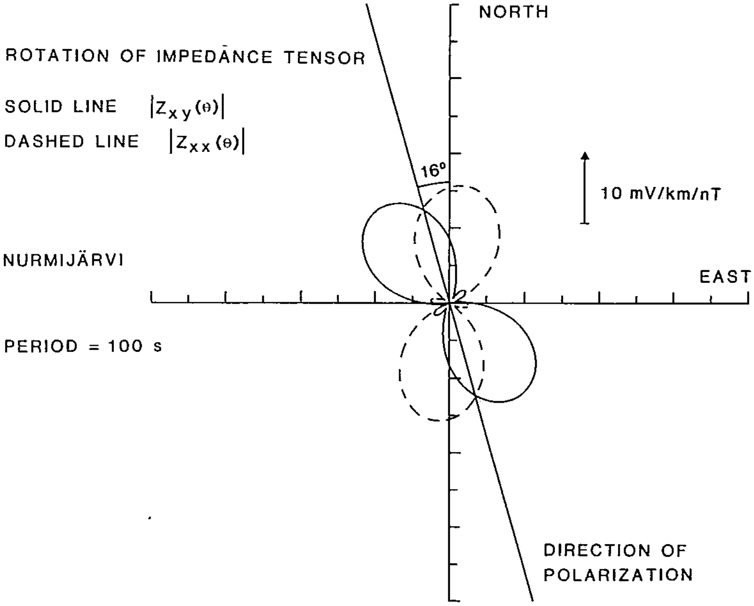


Fig. 4. Similar to Fig. 3 but for the period of 100 s.

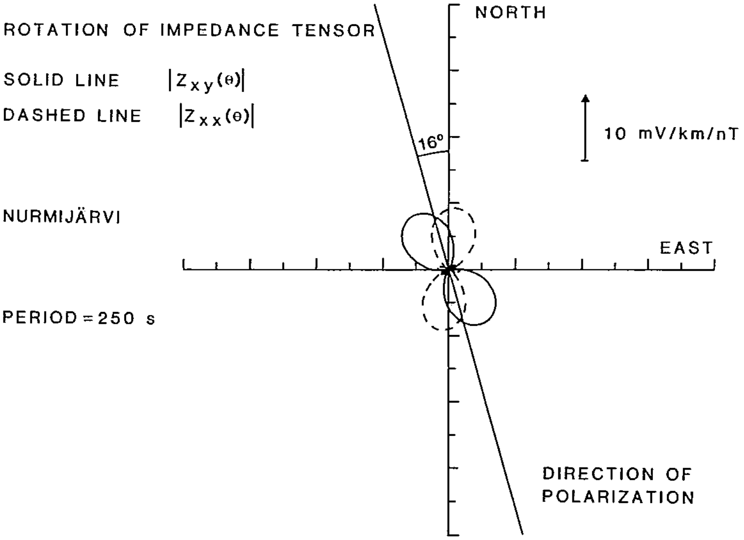


Fig. 5. Similar to Fig. 3 but for the period of 250 s.

there exists a direction where for each point and each period the diagonal elements of the impedance tensor are zero. Our polar diagrams (Figures 3–5) show that the distribution of the conductivity of the earth is three-dimensional at Nurmijärvi, and it is too complicated for a quantitative interpretation here. As mentioned in Section 4, the direction of the polarization of the electric field is also shown in Figures 3–5.

6. *Prediction of the electric field*

The horizontal electric field components can be obtained in the time domain by a convolution of the impulse response functions $a(t)$, $b(t)$, $c(t)$ and $d(t)$ and the horizontal magnetic variation:

$$E_x(t) = \int_0^\infty a(u) X(t-u)\,du + \int_0^\infty b(u)\,Y(t-u)\,du \tag{3}$$

and

$$E_y(t) = \int_0^\infty c(u) X(t-u)\,du + \int_0^\infty d(u)\,Y(t-u)\,du \tag{4}$$

Referring to Section 3, it is clear that the impulse response and the impedance tensor are related to each other by a Fourier transform. Note that the ***B*** field with components X and Y is used in equations (3) and (4) instead the ***H*** field included in formula (1).

In practice in numerical calculations, we use the formulas

$$E_{xj} = \sum_{k=-N_0}^{N_1} a_k X_{j-k} + \sum_{k=-N_0}^{N_1} b_k Y_{j-k} \tag{5}$$

and

$$E_{yj} = \sum_{k=-N_0}^{N_1} c_k X_{j-k} + \sum_{k=-N_0}^{N_1} d_k Y_{j-k} \tag{6}$$

The coefficients a_k, b_k, c_k and d_k of the impulse response were calculated by our computer program (see Section 3 and WIELĄDEK and ERNST, 1977). The reason for using $-N_0$ instead of zero is that the present data represent a finite range of frequencies, and the transfer function is thus also cut. In this case the impulse response can have a non-zero value for a negative argument. We used the values $N_0 = 3$ and $N_1 = 27$. Values of the impulse response coefficients at Nurmijärvi are

Table I. Values of the impulse response coefficients at the Nurmijärvi Observatory.

k	a_k	b_k	c_k	d_k
−3	0.14	−0.20	−0.24	−0.01
−2	1.55	1.65	0.47	0.01
−1	−3.96	−1.61	−1.90	−0.96
0	−29.59	−16.27	9.65	4.79
1	18.08	6.53	−2.38	−0.70
2	0.74	2.90	−2.20	−1.22
3	2.45	1.39	0.07	−0.17
4	2.28	1.90	−0.86	−0.01
5	−0.60	−0.79	0.13	−0.34
6	1.44	0.66	−0.40	0.32
7	0.15	0.31	−0.27	−0.46
8	0.48	0.25	0.26	0.09
9	0.45	0.35	−0.62	−0.23
10	−0.48	−0.25	0.44	0.14
11	0.56	0.24	−0.11	0.04
12	0.27	0.24	−0.19	−0.14
13	0.16	0.12	0.03	0.01
14	0.14	0.14	−0.14	−0.03
15	−0.02	0.02	0.06	−0.02
16	0.08	0.07	−0.06	0.01
17	0.05	0.07	−0.04	−0.04
18	0.04	0.06	0.04	0.01
19	0.04	0.06	−0.07	−0.03
20	−0.01	0.03	0.02	0.00

shown in Table I. Coefficients corresponding to k larger than 20 are omitted in the table because they are practically zero.

Based on formulas (5) and (6) and Table I, predictions for the electric field were calculated. As indicated in Section 3, twelve 20 min events were used in the computation of the coefficients of the impulse response. The criterion in the selection of these events was only a high magnetic activity, so the selection was quite objective and the events can be considered representative. The error limits of the results are also small. Hence the impulse response obtained is considered generally valid, *i.e.* independent of the particular events, and the same events can be used for studies of the accuracy of the predicted electric field. Strictly speaking however, it is, of course, only a question of the accuracy of the determination of the impulse response that is connected with the particular events.

An example of the prediction is shown in Figures 6 and 7. The predicted electric field corresponds very well to the recorded one. It means that it is not necessary

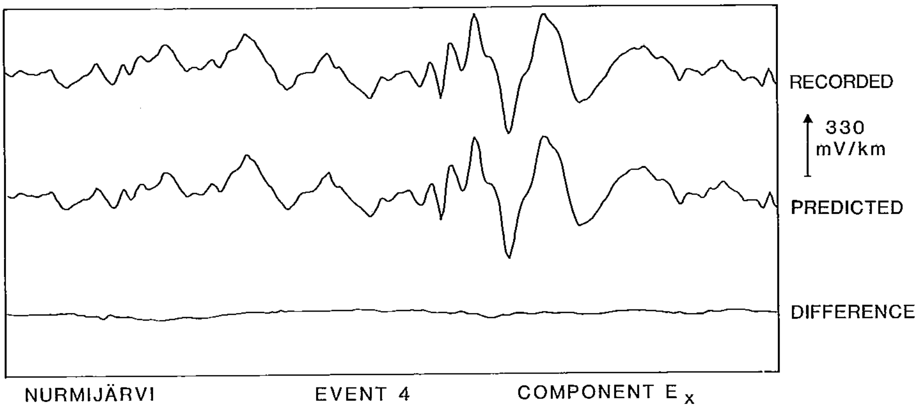


Fig. 6. The recorded and the predicted electric north component E_x of the event shown in Fig. 1. The predicted curve for E_x was obtained by convoluting the computed impulse response functions with the recorded magnetic north and east components. The difference between the recorded and predicted E_x curves is also shown. The whole time interval included in the figure is 18 minutes, *i.e.* the length of the event (20 min) minus the length of the impulse response (2 min).

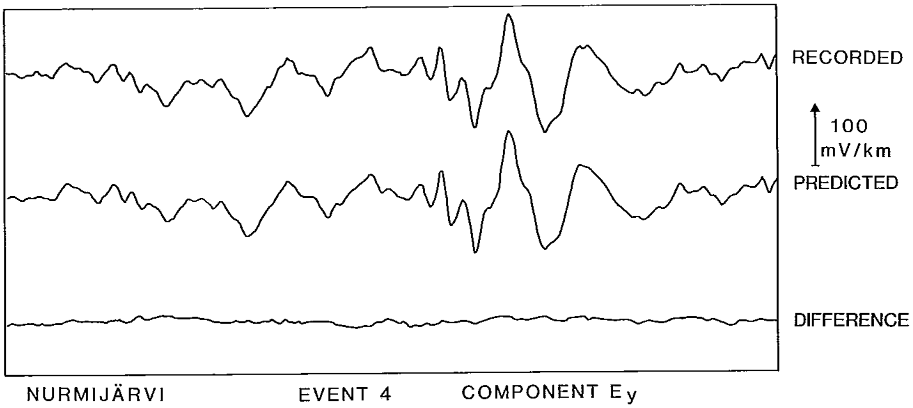
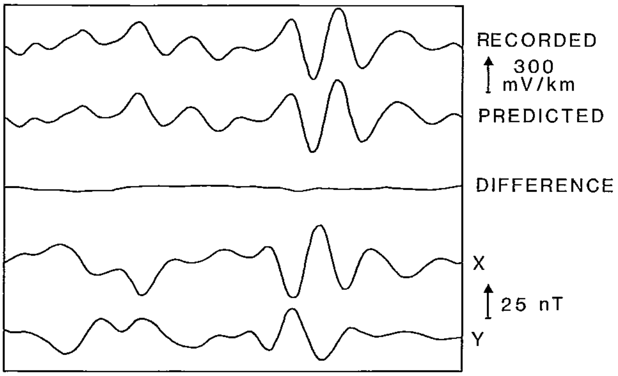


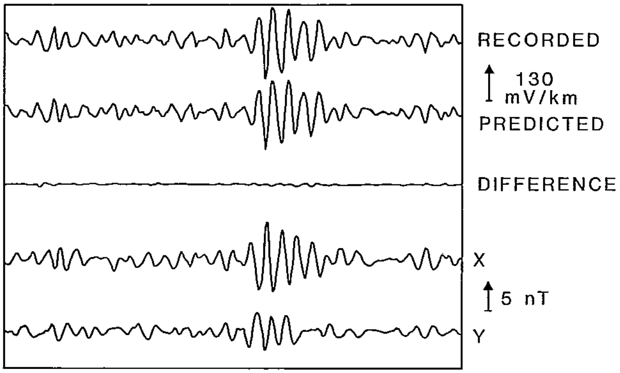
Fig. 7. Similar to Fig. 6 but for the electric east component E_y.

to measure the electric field at Nurmijärvi because we can compute it from magnetic variations. This conclusion is obviously also valid for other observatories.

To know better how the prediction works for the shortest periods where the amplitudes are smaller, we made numerical filtration of the data before the prediction. An example of the results is shown in Fig. 8, in which the longest



NURMIJÄRVI EVENT 4 COMPONENT E_X
AFTER LOW-PASS FILTERING



NURMIJÄRVI EVENT 4 COMPONENT E_X
AFTER HIGH-PASS FILTERING

Fig. 8. Similar to Fig. 6 but two different treatments are included now: one with low-pass and the other with high-pass filtering of the data. The filtered magnetic north X and east Y components are also shown.

periods (low pass filtering) and the shortest periods (high pass filtering) are considered separately. The prediction is good in both cases.

7. *Conclusions*

Magnetotelluric measurements were carried out at the Nurmijärvi Observatory for some days in June 1983. The short period part of the spectrum (10...800 s) was used.

The polar diagrams of the impedance tensor computed from the data have a very complicated pattern which cannot be explained by a two-dimensional model.

The electric field is linearly polarized, and the condition that the electric and magnetic fields are perpendicular is not satisfied. Anyway even in this case, the relation between the horizontal electric and magnetic components can be determined with high accuracy. It allows us to calculate the electric components using the convolution of the magnetic ones with the impulse response, and the error is insignificant then, as can be concluded from Figures 6–8.

A magnetotelluric sounding just at the Nurmijärvi Observatory is, of course, not sufficient for conclusions of the conductivity distribution in the observatory area, since the distribution is very complicated. Also computations of apparent resistivity values may be misleading if one tries to interpret them as real conductivities.

The main purpose of the present short paper is the discussion of the impulse response, which in our opinion, should be determined at every geomagnetic observatory. If magnetic variations are recorded at an observatory and the impulse response is known, it is not necessary to perform electric recording permanently.

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