Application of statistical models to geoelectric variations with a long electrode span to detect anomalous changes

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Abstract

We examined two techniques for eliminating components induced by variations of the geomagnetic field to accurately and quickly detect anomalous changes in the geoelectric field, which would enable us to identify crustal signals. One method is based on a multiple regression model, where any geoelectric variation is presented as a linear combination of the past, present, and future values of geomagnetic variations. The induced geoelectric variation is estimated as a convolution of the geomagnetic variations and the parameters of the obtained regression model. The other method uses BAYTAP-G, by which the observed geoelectric data are separated into four components: 1) tidal, 2) electromagnetically induced, 3) trend, and 4) irregular components. Signals due to volcanic and/or seismic activity may be detected since the trend and the irregular component indicate variations of the self-potential of the crust and/or noise, provided that the amplitudes exceed that of the typical variation. The geomagnetic field at the Kakioka Magnetic Observatory was used as associated data for both methods. These methods were applied to geoelectric variations in the Numazu group, which are contaminated by artificial noise but show anomalous changes. The multiple regression method can apparently eliminate daily variations and telluric storms and can clarify anomalous changes that are not obvious in the original data. However, the gain and phase characteristics calculated from the estimated parameters of the model do not yield information on the underground resistivity structure since the estimated impulse responses do not correctly reflect relationships between the inducing geomagnetic field and the induced geoelectric field due to the presence of excessive artificial noise. BAYTAP-G separates daily variations due to artificial noise as the tidal component and the responses to geomagnetic variations. Anomalous changes are identified in the trend and the irregular component.

We investigated the relationship of the tidal component of geoelectric variations estimated by BAYTAP-G with the tidal current and the tide. The correlation between the tidal component of geoelectric variations and tidal currents could not be clarified since simultaneous data of tidal currents with geoelectric variations were not available. Temporal variations of the amplitudes of geoelectric variations of KSM-MTO and tides at OAR for O_1 and M_2 constituents were not correlated despite their high coherencies.

1. INTRODUCTION

Many researchers currently think that some changes in the geoelectric field are related to crustal activities such as earthquake occurrence. There are two different ways by which crustal activity may bring about changes in the geoelectric field: (1) a process within the earth creates a source of the geoelectric field; (2) a process within the earth changes the conductivity,

leading to changes in the response of the earth to geomagnetic variations. The conductivity (or resistivity) of the earth itself is directly measurable and many attempts to detect crustal signals have been reported (e.g., Mazzella and Morrison, 1974; Yamazaki, 1975; Fitterman and Madden, 1977; Searls et al., 1978; Morrison et al., 1979; Qian, 1984/1985; Sumitomo and Noritomi, 1986). Whatever the mechanism, such changes in the geoelectric field should appear as "anomalous changes". Many investigators maintain that

anomalous changes in the geoelectric field observed before earthquakes were precursors (e.g., Myachkin et al., 1972; Corwin and Morrison, 1977; Koyama and Honkura, 1978; Varotsos and Alexopoulos, 1984a,b; Miyakoshi, 1986). However, those anomalous changes may not be true precursors for the following reasons: (1) the geoelectric potential between the electrode and the soil is likely to be unstable in the method used (particularly due to precipitation); (2) geoelectric data can be easily contaminated by artificial noise due to, for example, industrial activities and electric railways; (3) most short-period fluctuations in the geoelectric field are caused by electromagnetic induction within the earth, i.e., by geomagnetic variations of primarily external origin. Nevertheless, as far as the attempts to detect crustal signals in the geoelectric field reported so far are concerned, no real exact separation of the effect of induction due to variations of the geomagnetic field has been performed. On the other hand, experimental results have indicated that variations in stress, streaming potential, and other factors could create variations in the geoelectric potential of the earth (e.g., Ishido and Mizutani, 1981; Bishop, 1981; Sobolev et al., 1982; Baird and Kennan, 1985) and that the conductivity of rock samples depends on pressure through changes of the water content in the cracks and pores (Brace et al., 1965; Brace and Orange, 1968). Therefore, some of those "anomalous changes" reported so far may have been genuine precursors, although that is difficult to prove.

Stable and reliable data are necessary to detect anomalous geoelectric changes of precursory signals and to identify small signals as precisely as possible. Thus, observation of the geoelectric field with lines as long as a few tens of kilometers was carried out using the telephone facilities of the Nippon Telegraph and Telephone Company (NTT) (Takayama and Mori, 1990). The cables connecting the grounded earths at NTT repeater stations in the Kanto and Tokai regions were used for the observation. The results were very promising (Takayama and Mori, 1990). This observation method has two advantages. One is that the contact electric potential between the electrode and the soil is very stable, since the installation depth of the electrode exceeds 5 meters and the contact resistance between the electrode and the soil is less than 2 ohms. The stability of the contact potential was confirmed by the observed geoelectric fields. The second advantage is that the base lengths of the observation, ten to several tens of kilometers, are 10 to 100 times longer than those for other ordinary observations in Japan. Most of the observed geoelectric variations caused by geophysical phenomena are thought to increase in proportion to the length of the observation lines, while the contact

potential and artificial electric noise do not depend on it. Therefore, we can expect to get a high signal-to-noise ratio by using long-spaced electrodes.

Without any treatment of the data, anomalous changes can be detected only when their amplitude exceeds that of the induced component. Therefore, it is necessary to separate the effect of the electromagnetic induction to improve the detectability of anomalous changes so that we can identify crustal signals. There are two different approaches to do this, i.e. in the frequency and time domains. Chouliaras and Rasmussen (1988) developed a method of using magnetotelluric impedance tensor analysis in the frequency domain. The method was applied to geoelectric observations in Greece (Chouliaras and Rasmussen, 1988; Hadjioannou et al., 1993). It is difficult to estimate the impedance tensor over long periods due to the limitation of data length in the method based on spectral analysis, in which the data must be multiplied by a window to make the spectra and impedance smooth in the frequency domain. Consequently, the method in the frequency domain may not correctly separate the induced geoelectric variations in the low frequency range. We developed two alternative methods to eliminate the effects of induction by external geomagnetic variations and applied them to detect anomalous geoelectric changes in the above-mentioned high-quality data. These two new methods involve the use of statistical models in the time domain; a multiple regression model in one and BAYTAP-G (e.g., Ishiguro, 1981) in the other. The method based on a multiple regression model subtracts the effects of geomagnetic variation, allowing quasi-real-time detection of the self-potential associated with crustal activities. The "anomalous changes" in the geoelectric field so far reported can be classified into two types, a slow change with a long duration and a quick change. Therefore, it is expedient to further separate the part of the geoelectric field that is not caused by induction or tides into two components, slow and quick variations. The method using BAYTAP-G is useful to analyze the observed geoelectric field in reference to the two types of "anomalous changes".

Tidal components were distinguished in the geoelectric data obtained by utilizing the NTT telephone facilities after eliminating variations induced by geomagnetic variations of external origin with statistical models (Takayama and Mori, 1987; Ozima et al., 1989). The tidal component data in the Numazu group included predominant variations of S_1 and its harmonics due to artificial noise with daily variations. In contrast, geoelectric variations in the Mito group were not affected by artificial noise and the tidal component had peaks at O_1 and M_2 constituents. Brown and Woods (1971) asserted that the abnormal size of the lunar semi-

diurnal component and the significant correlation in both phase and amplitude between the earth potential and the local tides clearly demonstrate a strong tidal influence on the earth potential gradient at Aberystwyth, which is 2 km inland. Johnston et al. (1983) found M_2 peaks in the amplitude spectra of the total force of the geomagnetic field along the San Andreas fault and attributed them to inhomogeneous tidally generated current systems in and around the fault system. The direct evidence of this was obtained from telluric data measured both parallel and perpendicular to the fault zone in central California. It is possible that the tidal component is related to ocean tides to some extent since the observation network in the Mito group is located within 10 to 30 km of the Pacific Ocean. We investigated the relationships of the obtained tidal component in geoelectric variations in the Mito group with tidal currents and tides.

2. ELIMINATION OF THE GEOELECTRIC FIELD INDUCED BY GEOMAGNETIC VARIATIONS

It is necessary to eliminate the effect of electromagnetic induction from the observed geoelectric data to improve the detectability of subtle signals due to crustal activities in the geoelectric field. We developed practical methods to eliminate induction components by using external geomagnetic variations. The methods are based on statistical models in the time domain. One method exploits a multiple regression model and the other utilizes BAYTAP-G (e.g., Ishiguro, 1981). The latter was originally developed to analyze tidal data. The former is an extension of conventional regression models, in which it is generally assumed that the regressand is expressed by a linear combination of regressors. As regressors, the autoregressive model uses the same kind of past data as the regressand, while the usual regression model uses a different kind of data at the same time point. The multiple regression model employed in this study uses different kind of time series data for the regressand and regressors, that is, geoelectric and geomagnetic variations, respectively. It is usually difficult to objectively determine the proper order of the model when applying regression models. We used the *AIC* (Akaike Information Criterion, Akaike, 1973) and the *ABIC* (Akaike Bayesian Information Criterion, Akaike, 1980), which is an extension of the *AIC*, to solve this problem. The *AIC* and *ABIC* are indicators of the poorness of model fitting. Therefore, the lower the value, the better the model.

2.1 Multiple Regression Method

2.1.1 Method

We obtain the following relationship between perpendicular components of periodic geoelectric

variations E and geomagnetic variations B with the period T for an electromagnetically uniform and isotropic semi-infinite medium:

$$\frac{E}{B} \propto \sqrt{\frac{\rho}{\mu T}} \exp\left(\frac{\pi}{4}i\right), \quad (1)$$

where μ and ρ are the permeability and resistivity of the medium. As shown in the above relation, the phase of the geoelectric variation is ahead by $\pi/4$ against the geomagnetic variation and the amplitude ratio is proportional to $1/\sqrt{T}$. Since the geoelectric field is linearly related to the geomagnetic field, geoelectric variation between two electrodes $E(t)$ at time t can be practically expressed as a finite linear combination of the past, present, and future values of the northward component $X(t)$ and the eastward component $Y(t)$ of the geomagnetic variation as follows:

$$E(t) = \sum_{m=-L}^K \{a(m) \cdot X(t-m) + b(m) \cdot Y(t-m)\} + c + \varepsilon(t), \quad (2)$$

where $a(m)$ and $b(m)$ represent the impulse response coefficients of the geoelectric field for the geomagnetic variations and c is a constant. The time series $\varepsilon(t)$ is a part of $E(t)$ uncorrelated with the geomagnetic variation. The parameters $a(m)$, $b(m)$, ($m = -L, \dots, K$), and c are determined by the maximum likelihood method (the least squares method). Parameters K and L are determined so as to minimize the *AIC*, which is defined as follows:

$$AIC = 2 \times (\text{maximum log likelihood of the model}) + 2 \times (\text{number of free parameters of the model}). \quad (3)$$

In this case,

$$AIC = N(\log 2\pi + 1) + N \log \sigma^2 + 2(2(K+L+1)+2), \quad (4)$$

where N is the number of data and σ^2 represents the variance of $\varepsilon(t)$ in equation (2). The number of parameters of the model should be less than 2 to $3\sqrt{N}$ (Sakamoto et al., 1986). The lower the *AIC* value, the better the model. It is the difference in the *AIC* values that matters and not the actual values themselves. If the difference of *AIC*s for different models is larger than 1 ~ 2, then the difference is considered to be significant (Sakamoto et al., 1986). The parameters K and L are lag numbers (time). Negative m implies that we can refer to the advanced associated data (associated data of the future) in the equation (2). The *AIC* value is significantly decreased by the use of the associated data of the future. This may be explained by the fact that the phase of the geoelectric field is ahead of that of the geomagnetic field by $\pi/4$. We chose a set of parameters, K and L , to minimize the *AIC* value. Thus, the induced field is estimated as a convolution of the geomagnetic variations

and the parameters $a(m)$ and $b(m)$.

2.1.2 Application to the geoelectric field in the Numazu group

Takayama and Mori (1987) applied the multiple regression method to hourly mean values of the geoelectric field in the Mito group, whose short-period variations are mostly induced by geomagnetic variations. In this section, we investigate how the method works when it is applied to geoelectric variations in the Numazu group, which are contaminated with substantial artificial noise due to electric railways supplied with direct-current power and many factories (Takayama and Mori, 1990), and compare the result with that for the Mito group. The geomagnetic variations at KAK were used as the inducing geomagnetic field in the data analyses for both the Numazu and Mito groups. The network in the Mito group is very close to KAK, while the network in the Numazu group is about 160 km away from KAK, as illustrated in Fig. 1. We searched for the minimum AIC in the ranges of $0 \leq K \leq 20$ and $0 \leq L \leq 10$

since hourly data from April 1 to May 10, 1986 (40 days) were used in the analysis and the number of data was 960.

We first describe the result when the multiple regression method was applied to geoelectric variations of KSM-MTO in the Mito group. The direction of the observation line of KSM-MTO is close to the predominant direction of the geoelectric field in the Mito area (Takayama and Mori, 1987), so the ratio of induced variation to noise is the greatest of all observation lines in the Mito group. Therefore, it is logical to compare the result for the very noisy data of the Numazu group with that for KSM-MTO to examine the effect of noise on the multiple regression analysis. The AIC takes the minimum value when $(K, L) = (18, 3)$, which indicates that the induced geoelectric field at a certain time point would be best calculated by using data during the period from the past eighteen hours to the future three hours of the geomagnetic X and Y components. The coefficients of the impulse response for the geomagnetic field, $a(m)$ and $b(m)$, are provided at the top of Fig. 2. This figure

Fig. 1 Map of observation stations (solid circles, geoelectric observations; solid squares, other observations), nearby electric railways (solid lines, supplied with direct-current power; broken lines, supplied with alternating-current power) and locations of crustal events listed in Table 1 (open circles, epicenters of major earthquakes; shaded area, earthquake swarms).

indicates that the impulse response near the initial time point for the X component is more than twice as large as that for the Y component, and the geoelectric variation $E(t)$ at a certain time t is greatly affected by the values of the geomagnetic fields from one hour before to six hours after the initial time point for the X component and from three hours before to two hours after for the Y component. The middle and bottom charts in Fig. 2 depict the gain and phase obtained by Fourier transform of impulse responses $a(m)$ and $b(m)$. The gains are nearly proportional to $1/\sqrt{T}$ for periods shorter than 100 hours for the X component and from 3 to 30 hours for the Y component. The gain for the Y component was nearly constant for period ranges shorter than 3 hours and longer than 100 hours. The geoelectric variations were affected not only by the X (N-S) component but also by the Y (E-W) component of the geomagnetic variations, even though the direction of KSM-MTO is nearly east-west (93 degrees clockwise from north).

The upper three curves in Fig. 3 represent the observed values of the geomagnetic and geoelectric

variations (OBS), the fourth signifies the induced geoelectric field (EST) calculated from the convolution of observed geomagnetic variations and the estimated impulse responses, and the bottom curve represents the residual geoelectric variation (RES) that remains after subtracting EST from OBS. This figure verifies that daily variations and telluric storms that accompanied the magnetic storms have been satisfactorily eliminated from the observed values. Variations with periods shorter than a few hours still remain, which may represent the limit of the present method.

The above-mentioned estimation can be more clearly expressed by the results of an analysis in the frequency domain. Figure 4 reveals the coherencies of the observed and residual geoelectric fields with the geomagnetic field and power spectral densities of the observed and residual geoelectric fields. The coherencies and power spectral densities are calculated by fitting the autoregressive model introduced by Akaike (1969). Multiple coherencies of the observed geoelectric field with the geomagnetic fields (X and Y) are high for

Fig. 2 Impulse responses and their gains and phases for KSM-MTO. (a) ~ (c) are for the X component, and (d) ~ (f) are for the Y component. From the top to the bottom, impulse responses in mV/km/nT, common logarithms of amplitude characteristics in mV/km/nT, and phase characteristics in degrees.

Fig. 3 Result obtained by convolution of the impulse responses and observed geomagnetic variations for KSM-MTO. The upper three curves represent the observed values of the geomagnetic and geoelectric field variations. The fourth represents the estimated values of the induced geoelectric field variations. The bottom curve indicates the residuals that remained after subtracting the estimated values from the observed values.

periods shorter than a few days. The partial coherency for the X component decreases gradually after about 24 hours, but that for the Y component decreases sharply. In contrast, multiple and partial coherencies of the residual geoelectric field with the geomagnetic fields are both small over the entire range. This indicates that the geoelectric fields induced by geomagnetic variations are almost all eliminated from the observed geoelectric field. The power spectral density of the observed geoelectric field has sharp predominant peaks for S_1 , S_2 , S_3 , and S_4 constituents, but that of the residual geoelectric field has only broad peaks near S_1 and S_2 and less dominant peaks near S_n ($n=4, \dots, 8$). Furthermore, the power spectral density of the residual geoelectric field is fairly small relative to that of the observed geoelectric field for periods shorter than a few days.

Next we will examine the result when the multiple regression method is applied to the data of the geoelectric field at SUZ-ITO. The direction of SUZ-ITO is nearly E-W (95 degrees clockwise from north), as is that of KSM-MTO, and the data is comparably less noisy among the Numazu group. However, the noise level during the day is much greater than at night, suggesting that a larger part of the daily variations can be attributed to artificial noise (Takayama and Mori, 1990). In this

case, the AIC takes the minimum value when $(K,L) = (20,10)$. The determined impulse responses are provided at the top of Fig. 5, where the ordinates are half as sensitive as those in Fig. 2. Gains and phases are shown in the middle and bottom panels. The impulse responses for the X component are similar and large only near the initial time point when compared with the result for KSM-MTO, but those for the Y component are small over the entire range of time and the magnitudes do not vary as much. The gains for the X component are similar as well, except for the magnitude, and there is a small depression near 3.39 hours, while those for the Y component do not increase as the period decreases in a range shorter than about 20 hours. They become very small at several periods, i.e., 14.1, 3.04, 2.74, and 2.47 hours, where phase changes considerably. It is not surprising that the geoelectric variations are affected by only the X (N-S) component of geomagnetic variations, given that the direction of SUZ-ITO is nearly E-W.

Figure 6 compares the observed, estimated, and residual variations in the time domain. This figure indicates that a fair amount of daily variations and telluric storms are eliminated from the observed values, and the apparent variations of the residual geoelectric field are considerably reduced. However, temporal

INPUT = (KAK (X)),(KAK (Y)) OUTPUT = (KSM-MTO)
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 28 (original) cohsp1
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 28 (residual) cohsp1

Fig. 4 Characteristics in the frequency domain of the time series in Fig. 3. (a), (c), (e), and (g) are for the observed values, and (b), (d), (f), and (h) are for the residuals. The upper three curves signify the multiple and partial coherencies, and the bottom curve represents the power spectral density in common logarithms in $(\text{mV/km})^2 \cdot \text{hour}$.

Fig. 5 Impulse responses and their gains and phases for SUZ-ITO. (a) ~ (c) are for the X component, and (d) ~ (f) are for the Y component. From the top to the bottom, impulse responses in mV/km/nT, common logarithms of amplitude characteristics in mV/km/nT, and phase characteristics in degrees.

variations with periods shorter than a few hours are still conspicuous. An impulsive change on April 22 notable in the residual variation is recognized in the original variation. The residual variation on May 3 and 6, when magnetic storms occurred, is slightly larger than average. Figure 7 depicts the coherencies and power spectral densities. The multiple coherency and the partial coherency for the X component of the observed variation are slightly lower compared to those for KSM-MTO. It is notable that the partial coherency for the Y component is very low, except at periods of 24 hours and its harmonics, so the gain and phase for the Y component are unstable, as shown in Fig. 5. The low partial coherency over the entire period range indicates that the geoelectric variations and the Y component of the geomagnetic variations are less correlated. In contrast, the highness at periods of 24 hours and its harmonics may be apparent, because daily variations are predominant in both variations and the temporal variations in amplitude are not large. The multiple coherency for the residual geoelectric field is

considerably low compared with that for the observed geoelectric field, except in a period range from five to seven hours. The power spectral density of the observed variation has sharp predominant peaks for S_n ($n=1, \dots, 12$) constituents, with particularly higher peaks at S_1 and S_3 constituents than at other peaks compared with KSM-MTO. In contrast, the power spectral density of the residual variation has broad peaks for near S_n ($n=1, \dots, 5$) constituents and sharp peaks for near S_n ($n=6, \dots, 12$) constituents.

Parameters K , L , $a(m)$, and $b(m)$ in equation (2) are calculated next using the data for NMZ-ATM, whose direction, 92 degrees clockwise from north, is close to the directions of KSM-MTO and SUZ-ITO. Geoelectric variations of the observation lines including NMZ are very noisy, since the NTT repeater station at NMZ is close to Numazu railway station on the Tokaido line, an electric railway supplied with direct-current power, and the Numazu station is located near the middle between two power suppliers. Thus, departures of electric trains cause significant current leakage, which contaminates

Fig. 6 Result obtained by convolution of the impulse responses and observed geomagnetic variations for SUZ-ITO. The upper three curves represent the observed values of the geomagnetic and geoelectric field variations. The fourth represents the estimated values of the induced geoelectric field variations. The bottom curve indicates the residuals that remained after subtracting the estimated values from the observed values.

the geoelectric potential at NMZ (Takayama, 1989).

The AIC takes the minimum value for NMZ-ATM when $(K, L) = (2, 10)$. The impulse response for the X component is significant near the initial time point, but it is large for the Y component at points of small m , as indicated at the top of Fig. 8. The gain for the X component is noticeably low at 3.45 hours and does not decrease with an increase of period in a range longer than 100 hours, while that for the Y component is nearly flat except for depressions near 2.87, 4.87, and 8.57 hours. The phase characteristics fluctuate considerably in a period range shorter than 3.5 hours for both X and Y components. Figure 9 presents the observed, estimated, and residual variations of the geoelectric field as well as geomagnetic variations. The greater part of the variations of period ranges shorter than a few hours and longer than a day remains in the residual. The multiple coherency is lower than 0.5 in these period ranges, as illustrated in Fig. 10. The partial coherency for the Y component is low except at periods of 24 hours and its harmonics similar to SUZ-ITO. In comparison with the cases in the Mito group and SUZ-ITO, partial coherency for the X component is low and multiple coherency of the residual geoelectric variation with geomagnetic variations is high and exceeded 0.5 at S_1 and S_7

constituents and near 18.1 hours. The power spectral density of the original variation has sharp peaks at periods of 24 hours and its harmonics and that of the residual variation has broad peaks at S_n ($n=1, \dots, 5$) constituents, but sharp peaks at S_n ($n=6, \dots, 12$) constituents, which does not differ from the original.

We applied the multiple regression method to geoelectric variations in the Numazu group to demonstrate that daily variations and telluric storms can be effectively eliminated and that the detectability of anomalous changes is improved. Judging from gain and phase characteristics, the response to the X component of geomagnetic variations is considered to be electromagnetic induction. However, the response to the Y component is apparent daily variations due to artificial noise, not electromagnetic induction. In summary, the multiple regression method is successfully applied to geoelectric variations in the Numazu group, but the frequency response, particularly that for the Y component, exhibit some unusual behavior. This is attributed to the presence of artificial noise in geoelectric variations in the Numazu group.

INPUT = (KAK (X)),(KAK (Y)) OUTPUT = (SUZ-ITO)
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 26 (original) cohsp1
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 28 (residual) cohsp1

Fig. 7 Characteristics in the frequency domain of the time series in Fig. 6. (a), (c), (e), and (g) are for the observed values, and (b), (d), (f), and (h) are for the residuals. The upper three curves signify the multiple and partial coherencies, and the bottom curve represents the power spectral density in common logarithms in $(\text{mV/km})^2 \cdot \text{hour}$.

(<MODEL> 86 4 1D OH OM (JST) DT = 60 MIN MDATA = 960 MFPEC = 26 K = 2 L = 10 NMZ-ATM)

Fig. 8 Impulse responses and their gains and phases for NMZ-ATM. (a) ~ (c) are for the X component, and (d) ~ (f) are for the Y component. From the top to the bottom, impulse responses in mV/km/nT, common logarithms of amplitude characteristics in mV/km/nT, and phase characteristics in degrees.

2.2 Analysis Using BAYTAP-G

2.2.1 Method

A time series (y_i) can be separated into four components through use of the BAYTAP-G program (Ishiguro, 1981; Ishiguro et al., 1984; Tamura et al., 1991), as shown below.

$$y_i = \sum_{m=1}^M \alpha_m \cos(\omega_m^* i + \phi_m^* + \phi_m) + \sum_{k=0}^K b_k x_{i-k} + d_i + \varepsilon_i \quad (5)$$

($i=1, 2, \dots, n$).

The first term represents the tidal component (m : group number), where α_m , ω_m , and ϕ_m are the theoretically given values (M : the number of tide groups, which is specified by taking data length into account), and the second term represents the response to the associated data x_i (K : lag number). The third and fourth terms, d_i and ε_i , are the trend representing a slow variation and the residue representing irregular noise. The parameters, α_m , ϕ_m , b_k , d_i , and ε_i are determined for a given lag number, K , so that the sum of the squares of the residue ($\sum |\varepsilon_i|^2$) is minimized with other imposed conditions, and the $ABIC$ is calculated. Details of the $ABIC$ are

given in Ishiguro et al. (1984). The lower the $ABIC$ value, the better the model. In this study, y_i are the observed geoelectric field data and we designated the geomagnetic field as the associated data x_i to which the response is taken. Therefore, the response indicates the induced earth potential due to changes in the geomagnetic field in the above case. Consequently, the observed earth potential is separated into the i) tidal component, ii) induced earth potential, iii) trend, and iv) irregular component.

2.2.2 Results

The results when BAYTAP-G is applied to geoelectric variations in the Mito group are reported in detail by Ozima et al. (1989). We offer the result for KSM-MTO in Fig. 11 as an example, where three (X, Y, and Z) components of the geomagnetic field were taken as associated data. The first trace represents the observed original data, and the fourth to seventh traces represent the four components separated by BAYTAP-G. The bottom three traces indicate the geomagnetic

Fig. 9 Result obtained by convolution of the impulse responses and observed geomagnetic variations for NMZ-ATM. The upper three curves represent the observed values of the geomagnetic and geoelectric field variations. The fourth represents the estimated values of the induced geoelectric field variations. The bottom curve indicates the residuals that remained after subtracting the estimated values from the observed values.

fields used as associated data. The second and third traces indicate the estimated and residual variations obtained by applying the multiple regression method. It is important to note that, without any further treatment (such as separation or subtraction of the induced component from the original data), the crustal signals could be detected only when their amplitudes exceeded that of the induced component.

The induced component (response component) seems to be separated out by this analysis to a large extent, except for the duration of magnetic storms. Figure 11 indicates that the amplitudes of the irregular component during the disturbed and quiet days is about 6 ~ 8 and 2 ~ 4 mV/km, respectively. Therefore, we should be able to detect quick variations of the amplitude above the values for periods shorter than a few tens of hours that appear associated with crustal activities.

The trend can be regarded as representing a slow variation of crustal self-potential. Anomalous changes possibly due to crustal activities could be easily detected if they are slow (periods longer than a few tens of hours) and if their amplitudes exceed that of the usually existing slow variation.

The residual variation (third trace) obtained by the multiple regression method seems to correspond to the

sum of the trend, tidal, and irregular components in BAYTAP-G when compared with the four components separated by BAYTAP-G (fourth to seventh traces in Fig. 11). Hence, an analysis using BAYTAP-G is more effective for improving the detectability of anomalous changes than the multiple regression method for geoelectric data with little noise, as in the Mito group. This conjecture is confirmed by the fact that the amplitude of each component separated by BAYTAP-G is smaller than that of the residual variation obtained by the multiple regression method.

2.3 Application to the Geoelectric Field in the Numazu Group that Exhibited Anomalous Changes

The daily means of geoelectric and geomagnetic variations and daily precipitation from 1985 to 1988 are shown in Fig. 12. Almost all remarkable changes of geoelectric daily mean variations in the Numazu group are not proportional to lengths of observation lines, but show specific values dependent on each observation site for each change. Therefore, the unit of geoelectric variations for both the Numazu and Mito groups is mV with the same scale. Those of the geoelectric and geomagnetic variations at KAK are mV/km and nT, and

INPUT = (KAK (X)),(KAK (Y)) OUTPUT = (NMZ-ATM)
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 28 (original) cohsp1
 START TIME = 86 4 1 0 0 , N = 960 , DT = 60 MIN , H = 480 , IFPEC = 27 (residual) cohsp1

Fig. 10 Characteristics in the frequency domain of the time series in Fig. 9. (a), (c), (e), and (g) are for the observed values, and (b), (d), (f), and (h) are for the residuals. The upper three curves signify the multiple and partial coherencies, and the bottom curve represents the power spectral density in common logarithms in $(\text{mV/km})^2 \cdot \text{hour}$.

Fig. 11 Separation of the geoelectric variations by multiple regression method and by BAYTAP-G. (after Ozima et al., 1989)

KSM-MTO	Original data at KSM-MTO	} by multiple regression method
ESTIM	Estimated variation of the induced component	
RESID	Residual component	
IRREG	Irregular component	
TREND	Trend	} by BAYTAP-G
TIDAL	Tidal component	
RESP	Response to associated data	
KAK X, Y, Z	Associated data (magnetic variations at KAK)	

precipitation is in mm/day. The variations in the Numazu group are quite large, while those in the Mito group are small, even compared with those at KAK. The bars and arrows with Arabic numerals in Fig. 12 indicate the times when major earthquakes or a volcanic eruption took place near the observation networks. The events are listed in Table 1. Locations of seismic activities are designated by shaded areas and open circles in Fig. 1 with the same numerals as used in Fig. 12. We provide the results obtained by applying the two methods, the multiple regression method and BAYTAP-G, to geoelectric variations in the Numazu group at the periods when anomalous changes were discerned, but they were significantly contaminated by artificial noise.

2.3.1 Multiple regression method

We applied the multiple regression method to the geoelectric field in the Numazu group to see how it improves the detectability of anomalous changes, analyzing the hourly mean values of geoelectric variations of all ten observation lines in the Numazu group during the periods from September through November in both 1985 and 1986. The minimum *AIC* was sought in ranges of $0 \leq K \leq 30$ and $0 \leq L \leq 20$ since the number of data is larger than 2000.

The residual variations for September 1 through November 30, 1986 are shown in Fig. 13. The original variations for the same period are shown in Fig. 14. These figures indicate that the variances of residual geoelectric variations are considerably reduced. Daily

Fig. 12 Daily values of the geoelectric and geomagnetic variations and precipitation from 1985 to 1988. Bars and arrows with Arabic numerals indicate the times when the earthquakes and volcanic eruptions listed in Table 1 occurred.

variations, particularly those in the first half-period, and telluric storms are almost eliminated. However, daily variations are seen to remain in residual geoelectric potentials at NMZ and ODW in the later half-period after October 21. This is clear in the data of geoelectric variations of SUZ-NMZ and SUZ-ODW. The difference between the daily variations in the former and latter periods is not noticeable in the original observed variations. In addition, the residual variations are not very different from the original ones, including daily

variations, after November 6, when the geoelectric potential of ODW could change.

The multiple regression method was applied to the two periods of September 7 through 26 and November 7 through 26 for NMZ-ODW to clarify why daily variations in the latter period were not eliminated. The results for the two periods are shown in Figs. 15 and 16. The estimated variations for both X and Y components are also shown in the figures along with the estimated geoelectric variation, which is the sum of the two

Table 1 List of major earthquakes and volcanic eruptions that occurred near observation networks.

No.	Date	Location		Depth	Mag
1	1985 Oct. 13~Nov. 10	E off Izu Peninsula (earthquake swarm)			3.8*
2	1986 Oct. 10~Oct. 29	E off Izu Peninsula (earthquake swarm)			4.6*
3	1986 Nov. 15~Nov. 23	Eruptions of Izu-Oshima volcano			
4	1987 May 6~Jun. 4	E off Izu Peninsula (earthquake swarm)			5.0*
5	1988 Jul. 26~Aug. 25	E off Izu Peninsula (earthquake swarm)			5.2*
6	1985 Oct. 4	35°52.1' N	140°09.5' E	78km	6.1
7	1986 Feb. 12	36°25.0'	141°05.0'	44	6.1
8	1986 Jun. 24	34°49.4'	140°43.2'	73	6.5
9	1986 Nov. 29	36°23.5'	141°10.8'	42	5.8
10	1987 Feb. 6	36°57.7'	141°53.8'	35	6.7
11	1987 Apr. 7	37°18.0'	141°52.0'	44	6.6
12	1987 Sep. 24	36°37.6'	141°19.1'	41	5.8
13	1987 Dec. 17	35°22.3'	140°29.8'	58	6.7

Numerals with * in Mag indicate the maximum magnitude in each earthquake swarm.

estimated variations for both X and Y components obtained by a convolution of each component of geomagnetic variation and each impulse response. It is clear that the geoelectric daily variations for the two periods are quite different; there is one crest and one trough in September, while two sharp peaks are seen in one day in November. The amplitude of the Y component of the geomagnetic variation in September is much greater than that in November. Most of the daily variations and telluric storms in the former period can be estimated respectively by the Y and X components. In contrast, daily variations cannot be estimated by either the X or Y component in the latter period. Coherencies and power spectral densities are depicted in Figs. 17 and 18 for the same periods. The partial coherency for the X component of the observed variations is considerably lower in November than in September. The partial coherency for the Y component in November has peaks at the S_1 constituent and its harmonics similarly to that in September, but their magnitudes at S_1 , S_2 , and S_3 constituents are much lower. Coherencies of the residual variations are low for both September and November. The power spectral density of the observed variations in the September period has sharp peaks at the S_1 constituent and its harmonics, but no peaks at the S_1 , S_2 , and S_3 constituents are seen for the residual variation. The power spectral density of the observed variation

also has peaks at the S_1 constituent and its harmonics in the November period, but the widths at the S_1 and S_2 constituents are much broader than those in the September period. The power spectral density of the residual variation has peaks at the S_1 constituent and its harmonics, and their magnitudes do not differ much from those of the original.

The minute values are shown for the periods of September 11 to 15 and November 11 to 15 in Figs. 19 and 20 to detail the fine features of the geoelectric variations. It is clear from the records for ITO-ODW, ATM-ODW, and SUZ-ODW that the amplitudes of short-period artificial noise at ODW is greater in November and that daily variations are pretty different between the two periods. The reason for this difference is not presently clear.

As previously described, daily variations in the observed geoelectric variations after November 6, 1986, were not eliminated by applying the multiple regression method (Fig. 13). We presume that two facts are related to this, i.e., the pattern of daily variations differed due to substantial artificial noise, and the amplitude of the Y component of geomagnetic variation that was effective to eliminate daily variations was much smaller.

The residual variations for September 1 through November 30, 1985 are presented in Fig. 21. Telluric storms have been largely eliminated, and the daily

Fig. 13 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the residual geoelectric variations of the Numazu group, and the geomagnetic variations from September 1 to November 30, 1986. Horizontal bars indicate the periods when crustal events took place near the observation network.

variations are much smaller than the original variations in Fig. 22. These figures verify that the geoelectric potential at ATM, ITO, and SUZ decreased in the middle of October. The anomalous geoelectric changes in ITO-ODW and SUZ-NMZ are more clearly seen in the residual variations. The amplitudes of daily variations are substantial in the latter half-period because daily variations of the Y component of the geomagnetic field decreased.

The multiple regression method is useful for eliminating daily variations and telluric storms in geoelectric variations in the Numazu group. Application of this method considerably improves the detectability of anomalous changes in geoelectric variations.

2.3.2 BAYTAP-G

We applied BAYTAP-G to the geoelectric field in the Numazu group to examine how the program

Fig. 14 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the original geoelectric variations observed in the Numazu group, and the geomagnetic variations from September 1 to November 30, 1986. Horizontal bars indicate the periods when crustal events took place near the observation network.

improves the detectability of anomalous changes. Hourly mean values of geoelectric variations in the Numazu group during the periods from September through November in both 1985 and 1986 were analyzed. Parameters α_m , ϕ_m , and b_k in equation (5) were estimated for three periods of 31 days, from September 1 to October 1, October 1 to October 31, and October 31 to November 30, in both 1985 and 1986. The minimum ABIC was sought in the range of $0 \leq K \leq 5$ with the associated data of two (X and Y) and three (X, Y, and Z)

components of the geomagnetic field.

BAYTAP-G was applied to the observation lines data for September 1 through November 30, 1986, including NMZ and ODW, where the geoelectric potentials seemingly exhibited anomalous changes. The geoelectric data after November 29 in this period are missing because of a problem with the recording system.

The result for SUZ-NMZ is provided in Fig. 23. The ABIC takes the minimum value when $K=0$ with the associated data of two (X and Y) components. The

(<MODEL> 86 9 7D OH OM, N = 480, K = 16, L = 1, MFPEC = 36)
 (<DATA> 86 9 7D OH OM, N = 480, DT = 60 MIN)

Fig. 15 Time series for NMZ-ODW from September 7 to 26, 1986. The upper three curves signify the observed values of the geomagnetic and geoelectric field variations. The fourth represents the estimated values obtained by convolution of the impulse responses and the observed geomagnetic variations for the X component, the fifth represents those for the Y component, the sixth is the sum of those for the X and Y components, and the bottom curve represents the residual.

response to geomagnetic variations is small, but the tidal component is substantial. This may be apparent, because the amplitude for only a 24-hour period is extremely large and the amplitude of the tidal component is comparatively large relative to that in the Mito group, e.g., KSM-MTO, shown in Fig. 11. Although the daily variations of SUZ-NMZ that remain in the residual variations after applying the multiple regression method are relatively significant after October 21, as illustrated

in Fig. 13, the change is not clear in the result obtained using BAYTAP-G, but the amplitude of the tidal component in this period is seen to be slightly greater than that in the previous period. The amplitude of the irregular component does not vary much over the entire period.

BAYTAP-G was applied next to the data for NMZ-ODW, and the result is presented in Fig. 24. The *ABIC* takes the minimum value when $K=1$ with the associated

(<MODEL> 86 11 7D OH OM, N = 480, K = 17, L = 9, MFPEC = 54)
 (<DATA> 86 11 7D OH OM, N = 480, DT = 60 MIN)

Fig. 16 Time series for NMZ-ODW from November 7 to 26, 1986. The upper three curves signify the observed values of the geomagnetic and geoelectric field variations. The fourth represents the estimated values obtained by convolution of the impulse responses and the observed geomagnetic variations for the X component, the fifth represents those for the Y component, the sixth is the sum of those for the X and Y components, and the bottom curve represents the residual.

data of two (X and Y) components. The response to geomagnetic variations is greater than that for SUZ-NMZ. This may be because the direction of the observation line is close to the predominant direction of the geoelectric field in this area, i.e., E-W (Takayama, 1989). Anomalous changes are found in both the trend and irregular components. The trend began to increase gradually on November 4 and reached a peak of 700 mV on November 8. Another peak of 700 mV in the trend appeared on November 24. The commencement of the

change in the trend is more gradual than in the original variation, because the trend is assumed to vary slowly in BAYTAP-G. The irregular component also increased after November 6, when the geoelectric potential of ODW began to change, suggesting that anomalous changes occurred in both short- and long-period ranges. The result for ITO-ODW is shown in Fig. 25. The *ABIC* takes the minimum value when $K=0$ with the associated data of two (X and Y) components. The response to geomagnetic variations is smaller compared to that for

INPUT = (KAK (X)) , (KAK (Y)) OUTPUT = (NMZ-ODW)
 START TIME = 86 9 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 26 (original) cohsp1
 START TIME = 86 9 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 24 (estimate) cohsp1
 START TIME = 86 9 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 25 (residual) cohsp1

Fig. 17 Characteristics in the frequency domain of the time series for NMZ-ODW from September 7 to 26, 1986. (a), (c), (e), and (g) are for the observed values, and (b), (d), (f), and (h) are for the residuals. The upper three curves represent the multiple and partial coherencies, and the bottom curve represents the power spectral density in common logarithms in $(\text{mV})^2 \cdot \text{hour}$.

INPUT = (KAK (X)),(KAK (Y)) OUTPUT = (NMZ-ODW)
 START TIME = 86 11 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 27 (original) cohsp1
 START TIME = 86 11 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 43 (estimate) cohsp1
 START TIME = 86 11 7 0 0 , N = 480 , DT = 60 MIN , H = 480 , IFPEC = 27 (residual) cohsp1

Fig. 18 Characteristics in the frequency domain of the time series for NMZ-ODW from November 7 to 26, 1986. (a), (c), (e), and (g) are for the observed values, and (b), (d), (f), and (h) are for the residuals. The upper three curves represent the multiple and partial coherencies, and the bottom curve represents the power spectral density in common logarithms in $(\text{mV})^2 \cdot \text{hour}$.

NMZ-ODW. The anomalous changes observed in the trend and irregular components are similar to those for NMZ-ODW.

The trends for all ten observation lines in the Numazu group from September 1 through November 30, 1986 are depicted in Fig. 26. It is clear that the geoelectric potential at ODW decreased at the beginning of November (see also the daily mean variation in Fig.

12). However, the change appears to begin on November 4, earlier than that seen in the daily mean variation (November 6). This is attributed to the assumption of BAYTAP-G that the trend varies slowly.

BAYTAP-G was applied next to the data for the observation lines of SUZ-NMZ and ITO-ODW from September 1 through November 30, 1985, in which period anomalous changes were observed in the middle

Fig. 19 Minute values of geoelectric and geomagnetic variations from September 11 to 15, 1986, JST. The upper ten traces signify the geoelectric variations of the Numazu group, and the lower three traces represent the geomagnetic field at KAK.

of October when the multiple regression method was applied (Fig. 21).

The result for SUZ-NMZ is shown in Fig. 27. The *ABIC* takes the minimum value when $K=0$ with the associated data of two (X and Y) components. The response is small and the tidal component is large, especially that for a 24-hour period. A change in the geoelectric variation in the middle of October, which is

not clear in the original data, becomes apparent in the trend. There is no remarkable change in the irregular component.

The result for ITO-ODW is provided in Fig. 28. The *ABIC* takes the minimum value when $K=0$ with the associated data of two (X and Y) components. The response is very small and the tidal component for a 24-hour period is very large. The gradual change of

Fig. 20 Minute values of geoelectric and geomagnetic variations from November 11 to 15, 1986, JST. The upper ten traces signify the geoelectric variations of the Numazu group, and the lower three traces represent the geomagnetic field at KAK.

geoelectric variation in the middle of October is clearly seen in the trend. The daily variation in the original variation became small coincident with this appearance, which corresponds to the amplitude decrease of the tidal component. The irregular component decreased at the same time.

The trends for all ten observation lines in the Numazu group from September 1 through November 30, 1985 are depicted in Fig. 29. It is obvious that the

geoelectric potentials at ATM, ITO, and SUZ decreased in the middle of October. There was another kind of change in the geoelectric potential at ATM in November, which increased and decreased by 500 ~ 600mV in one day. The geoelectric potential at ODW showed a similar change at the same time.

BAYTAP-G is useful for separating original variations into trend, response, tidal, and irregular components. The estimated tidal component may be

Fig. 21 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the residual geoelectric variations of the Numazu group, and the geomagnetic variations from September 1 to November 30, 1985. Horizontal bars indicate the periods when crustal events took place near the observation network.

attributed to apparent daily variations due to artificial noise, since the amplitude for only a 24-hour period is very large and the amplitude of that tidal component is particularly large compared with the other components, whose features differ from those observed for the data in the Mito group (e.g. KSM-MTO in Fig. 11). The predominant direction of the geoelectric field is nearly E-W in the Numazu area, and thus the response to geomagnetic variations is large for observation lines

between one of two stations in the western part (NMZ and SUZ) and one of three stations in the eastern part (ITO, ATM, and ODW) and is small for those between two stations located in the same western or eastern part. Slow anomalous changes are revealed clearly in the trend, although the commencement of slow events is apparently more gradual than the actual change, due to the assumption of the trend in the BAYTAP-G program. Some other anomalous changes with short periods can

Fig. 22 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the original geoelectric variations observed in the Numazu group, and the geomagnetic variations from September 1 to November 30, 1985. Horizontal bars indicate the periods when crustal events took place near the observation network.

be identified in the irregular component.

3. RELATIONSHIP OF GEOELECTRIC VARIATIONS WITH TIDAL CURRENTS AND TIDES

In this section, we investigate the relationship between ocean tide and geoelectric variations in the Mito group. We use the data in the Mito group, not Numazu, to examine the relationship because the former

is less contaminated by artificial noise. A part of the tidal component in the geoelectric variations may be related to ocean tides since the observation network in the Mito group is located within 10 ~ 30 km from the Pacific Ocean.

3.1 Relationship with Tidal Currents

Available data sets of tidal currents for an

Fig. 23 Separation of the geoelectric variations for SUZ-NMZ by BAYTAP-G for the time period from September 1 to November 30, 1986.

investigation of the relationship between electric currents and tidal currents are very limited. We could only use data of tidal currents at Kashima-nada that were obtained by the Hydrographic Department of the Maritime Safety Agency. The observations were carried out for short periods, from August 30 to September 13 and from September 13 to 27, 1984. The observation point, KAS, is depicted in Fig. 1. Figure 30 shows

hodographs that represent the velocities and directions of tidal currents for each constituent. It was not possible to separate S_2 from K_2 or K_1 from P_1 because the observation periods were only 15 days. Thus, S_2 represents the sum of S_2 and K_2 constituents and K_1 represents the sum of K_1 and P_1 . The amplitudes and directions of the maximum axes are very different between the two successive 15-day observation periods.

86 Sep.

Oct.

Nov.

Dec.

Fig. 24 Separation of the geoelectric variations for NMZ-ODW by BAYTAP-G for the time period from September 1 to November 30, 1986.

On the other hand, in order to obtain the amplitude and the direction of geoelectric variations, the plane, which is fitted to hourly geoelectric potentials at four sites (MTO, ISI, KSM, and HIO), was determined by the least squares method, and the north-south and east-west gradients were regarded as the geoelectric fields in the two directions. An example is given in Fig. 31 for August 30 to September 29, 1986. The upper two drawings

depict the estimated NS and EW components of the geoelectric field, and the nine drawings at the bottom depict the observed (OBS), estimated (EST), and residual (RES) geoelectric variations for ISI-MTO, KSM-MTO, and HIO-MTO.

Figure 32 shows ellipses that represent the amplitudes and directions of geoelectric variations for each constituent. These maps were drawn on the basis

Fig. 25 Separation of the geoelectric variations for ITO-ODW by BAYTAP-G for the time period from September 1 to November 30, 1986.

of amplitudes and phases of north-south and east-west tidal components estimated by applying BAYTAP-G to the data of August 30 to September 29 and from April 12 to May 12, 1986. The ellipses for the two periods differ greatly in amplitude. The directions of the major axes are also very different at some constituents, such as K_1 . The amplitudes of the tidal components of the geoelectric variations are nearly 1 ~ 2 mV/km. Most of the ellipses of the geoelectric variations are seen to be

constrained in a specific direction, NW-SE, which accords with the predominant direction of the observed geoelectric variations (Takayama and Mori, 1987). The major axes of the ellipses are not perpendicular to those of the hodographs of tidal currents.

The direction of geoelectric variations is likely affected by underground resistivity structures. Therefore, we investigated the correlation between the maximum amplitude of the tidal components in

Fig. 26 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the trends of the Numazu group separated by BAYTAP-G, and the geomagnetic variations from September 1 to November 30, 1986. Horizontal bars indicate the periods when crustal events took place near the observation network.

geoelectric variations and the velocity of tidal currents. The results are provided in Fig. 33. The analyzed period for the geoelectric field was August 30 to September 29, 1986, and that for the tidal currents was August 30 to September 13 (dots) and September 13 to 27 (crosses), 1984. Although the plotted points are largely dispersed for both periods, the cross marks indicate a somewhat linear relationship. The solid line represents the theoretical relationship, $e = z \cdot v \times 10^{-3}$, among the

geomagnetic vertical component, z in nT, horizontal velocity of conductor, v in m/s, and the electric field, e in mV/km, for the case of $z = 35000$ nT.

The amplitudes of the tidal components in both the geoelectric variations and tidal currents varied significantly from time to time. We could not clarify the relationship between the geoelectric variations and tidal currents since observation data from the same time periods were not available. However, we believe that the

Fig. 27 Separation of the geoelectric variations for SUZ-NMZ by BAYTAP-G for the time period from September 1 to November 30, 1985.

effect of tidal streams is included in the geoelectric variations.

3.2 Relationship with Tides

We investigated the relationship between the tidal components in the geoelectric variations and tides at Onahama (ONA), Ooarai (OAR), and Choshi (CHO). The locations of the tide observation sites are specified in

Fig. 1. We analyzed geoelectric data of KSM-MTO for comparison with geomagnetic variations at KAK and tidal data at ONA, OAR, and CHO, since the direction is nearly perpendicular to the coastline and nearly equal to the predominant direction of the geoelectric variations. Differences between tide data sets at ONA and CHO were used in the analysis, based on the assumption that the differences are related to tidal currents between the

Fig. 28 Separation of the geoelectric variations for ITO-ODW by BAYTAP-G for the time period from September 1 to November 30, 1985.

two observation sites. However, the relationship was not clear, so the tide difference data were used only as reference.

Temporal variations of the hourly data of the geoelectric field of KSM-MTO in mV/km, the tide at OAR, the tide difference between ONA and CHO in cm, and three components of the geomagnetic field at KAK in nT are shown in Fig. 34 from the top to the bottom. The period is one year, from April 1, 1988 to March 31, 1989. The amplitude spectra of these time series data

were calculated, and the diurnal and semidiurnal parts are depicted in Figs. 35(a) and (b). The abscissa indicates the frequency in cycles per hour, and the arrows indicate the frequencies of the primary constituents of tides. The following features are revealed in these figures.

- (1) The amplitude spectrum of KSM-MTO has the highest peak at S_1 and peaks at O_1 , J_1 , and M_2 as well as at S_2 and K_2 .
- (2) The tide at OAR is dominated by peaks of the Q_1 , O_1 , M_1 , P_1 , K_1 , J_1 , OO_1 , N_2 , M_2 , S_2 , and K_2 constituents.

Fig. 29 From the top to the bottom, hourly precipitation at MSM, hourly mean values of the volumetric strain measured at HIZ, the trends of the Numazu group separated by BAYTAP-G, and the geomagnetic variations from September 1 to November 30, 1985. Horizontal bars indicate the periods when crustal events took place near the observation network.

- (3) The spectrum of the difference in tides between ONA and CHO is similar to that of tides at OAR in the semidiurnal range and has peaks at Q_1 , O_1 , P_1 , and K_1 in the diurnal range.
- (4) The amplitude spectrum of the X component of the geomagnetic variations has a slightly higher peak at K_1 than at S_1 , high peaks at S_2 and K_2 , and a broad peak at M_2 .
- (5) The spectra of the Y and Z components of the geomagnetic variations exhibit predominant peaks at S_1 , S_2 , K_2 , and M_2 .
- The multiple and partial coherencies were calculated for the system; the output was the geoelectric variations of KSM-MTO, and the five inputs were the tide at OAR, the difference in tides between ONA and CHO, and three components of the geomagnetic

(a) 1984.8.30 - 9.13 (tidal current)

— 0.025 m/sec

(b) 1984.9.13 - 9.27 (tidal current)

— 0.025 m/sec

Fig. 30 Hodographs representing velocities and directions of each constituent of tidal currents for the observation periods (a) from August 30 to September 13, and (b) from September 13 to 27, 1984.

Fig. 31 Example of the estimated northward and eastward geoelectric field obtained by fitting hourly geoelectric potentials at four sites to a plane during the observation period from August 30 to September 29, 1986.

variations. The diurnal and semidiurnal parts are indicated in Figs. 36(a) and (b). These figures clarify the following features.

(1) The multiple coherencies to the five inputs are greater than 0.9 in both the diurnal and semidiurnal parts.

(2) In the diurnal part, the partial coherencies to the X component of the geomagnetic variations are about 0.75. Geoelectric variations of KSM-MTO also correlate with the Y component of geomagnetic variations at the frequency of S_1 and with the tide at OAR at the frequency of O_1 . They do not, however,

Fig. 32 Ellipses representing amplitudes and directions of geoelectric variations at each constituent derived from amplitudes and phases of tidal components of the N-S and E-W components for the observation periods (a) from August 30 to September 29, and (b) from April 12 to May 12, 1986.

Fig. 33 Relationship between amplitudes of geoelectric variations and velocities of tidal currents.

Fig. 34 Temporal variations of hourly data. The upper three traces represent the geoelectric field of KSM-MTO in mV/km, the tide at OAR, and tide difference between ONA and CHO in cm, and the lower three traces represent three components of the geomagnetic field at KAK in nT.

exhibit a clear correlation with the difference in tides between ONA and CHO and the Z component of the geomagnetic variations.

- (3) In the semidiurnal part, coherencies with the tide at OAR are much lower than in the diurnal part, and

those with the X and Y components of geomagnetic variations are high. Coherencies with the difference in tides between ONA and CHO and with the Z component of the geomagnetic variations are low, as in the diurnal part.

Fig. 35 Fourier amplitude spectra of the time series for the (a) diurnal and (b) semidiurnal parts.

According to the definition of partial coherency (the coherency between the output and one of the inputs after subtracting the portions linearly related with other input variables), the partial coherency does not indicate an accurate contribution ratio, when any two of the

inputs are correlated. The tide at OAR and the tide difference between ONA and CHO are probably correlated in our case. Therefore, we recalculated the coherencies for a system with four inputs, excluding the tide difference between ONA and CHO. The results are

Fig. 36 Multiple and partial coherencies of the five-input system for the (a) diurnal and (b) semidiurnal parts.

provided in Figs. 37(a) and (b) for the diurnal and semidiurnal parts. The partial coherencies with the tide at OAR are very high at O_1 , K_1 (including S_1 and P_1), and M_2 .

Since the geoelectric variations of KSM-MTO and

the tide at OAR demonstrated high partial coherency, we compared the temporal variations of the amplitudes of KSM-MTO and the tide at OAR for O_1 and M_2 constituents. The amplitudes were obtained by applying BAYTAP-G with three components of geomagnetic

(a)

(b)

Fig. 37 Multiple and partial coherencies of the four-input system for the (a) diurnal and (b) semidiurnal parts.

Fig. 38 Result obtained by applying BAYTAP-G to every 31-day data set with a 30-day shift for geoelectric variations of KSM-MTO. From the top to the bottom: irregular, trend, responses to associated data, tidal component, and observed data. The period is 361 days from April 1, 1985 to March 27, 1986.

Fig. 39 Result obtained by applying BAYTAP-G to every 31-day data set with a 30-day shift for the tide at OAR. The period is the same as in Fig. 38.

variations as associated data to every 31-day data set with a 30-day shift. The results for geoelectric variations of KSM-MTO for a period of about one year, from April 1, 1985 to March 27, 1986, are provided in Fig. 38, where the irregular, trend, responses to associated data, tidal component, and observed data are depicted from the top to the bottom. Results for the tide data at OAR, analyzed with no associated data, are presented in Fig. 39. The period is the same as for KSM-MTO. Figures 40(a) and (b) illustrate the temporal variations of the amplitudes for O_1 and M_2 constituents. The period is 1441 days from April 1, 1985 to March 11, 1989. Apparently no clear

correlation is seen between the temporal variations of the amplitudes for either the O_1 or the M_2 constituents. One possible explanation for this result is that variations correlated with the tide were removed and/or variations induced by geomagnetic variations were not completely removed with application of BAYTAP-G, since the tidal component of geoelectric variations includes variations correlated with both the tide and geomagnetic variations. Another possibility is that the sizeable coherency at the O_1 and M_2 constituents has no significant meaning, since the temporal variations in amplitude for these constituents are not substantial.

Fig. 40 Temporal variations of the amplitude of KSM-MTO and tide at OAR for (a) O_1 and (b) M_2 constituents. The period is 1441 days from April 1, 1985 to March 11, 1989.

This problem and the relationships with earth tide will be investigated further in the future.

4. CONCLUSIONS

Two new methods to eliminate induced geoelectric variations were developed to detect minor self-potential variations. The methods used are the multiple regression method and BAYTAP-G. We applied these methods to two digital data sets, one contaminated very little by artificial noise and the other significantly contaminated.

We assumed in our application of the multiple regression method that the induced geoelectric field is expressed as a linear combination of the past, present, and future values of the X and Y components of geomagnetic variations. The parameters for the model were determined so as to minimize the *AIC*. The method was applied to hourly mean values of the geoelectric variations of a few observation lines in the Numazu group, which were contaminated by extensive artificial noise. The result was compared with the case of KSM-MTO in the Mito group, whose data were little contaminated by artificial noise.

For the observation lines in the Numazu group, daily variations and telluric storms were apparently well eliminated, and the detectability of anomalous geoelectric changes was improved. However, the gain and phase characteristics, which are obtained by Fourier transformation of the estimated coefficients of the linear combination that correspond to impulse responses, do not yield information on underground resistivity structures. The presence of extensive artificial noise prevented the estimated impulse responses from correctly reflecting the relationships between the inducing geomagnetic field and the induced geoelectric field.

For the case of KSM-MTO in the Mito group, whose data were little contaminated by artificial noise, the coherency between the observed geoelectric variations and the geomagnetic X component and that between the geoelectric variations and the Y component exhibit very high values for periods shorter than a few days and shorter than about one day, respectively. In contrast, the coherency for the X component is also high for SUZ-ITO, with not much artificial noise, but is considerably low for NMZ-ATM, with a large amount of artificial noise. The coherency for the Y component is very low in the entire period range, except at periods of the S_1 constituent and its harmonics for both SUZ-ITO and NMZ-ATM. This low coherency for the Y component indicates lower correlation between the geoelectric variations in the Numazu group and the Y component of the geomagnetic variation. The high coherency at periods of the S_1 constituent and its

harmonics is attributed to the fact that both the geoelectric and the Y component of the geomagnetic variations have daily variations and their amplitudes do not vary much with time. The coherency for the residuals became very low for the Numazu group as well as for the Mito group.

BAYTAP-G separates the original data into four components, i.e., the trend, the tidal, the response to the associated data, and the irregular components. The method using BAYTAP-G is superior to that using a multiple regression model for more accurate estimation of each constituent amplitude since BAYTAP-G can separate out the tidal and the induced components from the observed data.

The two methods, the multiple regression method and BAYTAP-G, were applied to geoelectric data of the Numazu group for periods when anomalous changes were seemingly observed. The detectability was improved by successful elimination of the greater part of daily variations and the anomalous changes could be seen more distinctly. The multiple regression method clearly revealed an increase in the amplitude of daily variations for SUZ-NMZ after October 21, 1986, while BAYTAP-G separated the change as a gradual increase of the tidal component. BAYTAP-G verified a gradual change of geoelectric potential in the trend and an increase of the amplitude in the irregular component at ODW after the beginning of November 1986. These changes correspond to quick and slow variations. It was demonstrated that anomalous changes in the geoelectric field contaminated by substantial noise, as in the Numazu group, could be detected in the residual variations using the multiple regression method and/or in one or more of the components separated by BAYTAP-G, depending on the characteristics of the anomalous changes in amplitude and period.

We investigated the relationship between the tidal components of geoelectric variations and tidal currents or tides. The correlation between the tidal components of geoelectric variations and tidal currents was not clarified since simultaneous data of geoelectric variations and tidal currents were not available. Temporal variations in the amplitudes of geoelectric variations of KSM-MTO and the tide at OAR for O_1 and M_2 constituents were not correlated despite their high coherencies. The basis for this result and the relationships with earth tides will be investigated in the future.

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異常変化検出のための長基線地電位への統計モデルの適用

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地電位の異常変化の迅速な検出を目指して、地磁気変化による誘導成分を除去する2つの方法を試した。1つは多次元回帰モデルを用いる方法で、もう1つはBAYTAP-Gを用いる方法である。前者は地電位変化を過去、現在、未来の地磁気変化の線形結合として表し、誘導電位変化は地磁気変化とモデルパラメータのコンボリューションとして推定される。後者は地電位観測値を潮汐、電磁誘導、トレンド、不規則の4成分に分離する。これらの方法を、人工雑音が多いが異常な変化が見られた沼津グループの地電位変化に適用した。多次元回帰法は日変化と地電流嵐を見かけ上除去し、観測値では明瞭でなかった異常変化を明確にした。しかし、推定されたパラメータから得られる利得と位相は地下の比抵抗構造に関する情報をもたらさない。BAYTAP-Gは人工雑音による日変化を潮汐成分と誘導成分として分離し、異常変化はトレンドと不規則成分の中に明瞭に検出された。

BAYTAP-Gによって推定された地電位の潮汐成分と潮流および潮位との関係を調べた。地電位と潮流の同時期のデータが得られなかったため、その関係を明確にすることはできなかった。KSM-MTO（笠間-水戸）の地電位とOAR（大洗）の潮位の O_1 と M_2 成分の振幅の時間変化はコヒーレンシーが高いにもかかわらず相関は良くない。