Data Processing Procedures for Minami-Kayabe Magnetotelluric Soundings

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MT and AMT surveys were conducted in the Minami-Kayabe area, southern Hokkaido, over a period of about two months in the fall of 1988. In this survey, 161 sites were arranged in a square lattice shape. FFT techniques were used in the initial data processing in 1988. Here we describe improved data processing using the cascade decimation technique. Data were processed efficiently by constructing a system using coherency and remote-reference. More than 10 sets of threshold values for the coherencies of (E_x, H_y) and (E_y, H_x) were then determined. Power spectra were sorted by these threshold values and then stacked. Satisfactory results were obtained for the frequency range from 3.4 Hz to 250 Hz. At frequencies below 3.4 Hz, however, the result of cascade decimation was not satisfactory because a sufficient number of stacks could not be obtained due to high local noise and limited measurement time.

1. Introduction

The New Energy and Industrial Technology Development Organization (NEDO) has been conducting a "Geothermal Development Promotion Survey" in the Minami-Kayabe area located in southern Hokkaido, Japan. Since the exploitation of near-surface geothermal resources is expected in this area, surface surveys such as geological and electrical surveys have been carried out, and seven wells approximately 1,000 m deep have been drilled.

In 1988, MT and AMT sounding was conducted in the Minami-Kayabe area, using the high accuracy MT system described by Takasugi *et al.* (1992a). As the performance of computers has improved, large-volume and fast data processing has recently become possible as compared to the time when the field survey was conducted. In those days, the FFT processing was employed for data processing, the results of which have already been presented (Takasugi *et al.*, 1992b).

However, the processed data was not always of good quality. To improve the data quality, the cascade decimation algorithm (Wight and Bostick, 1980) was employed to reprocess the same time series data as used previously. This is a fast calculation algorithm, and the various MT parameters from the same time series can be obtained for a variety of coherency check criteria. It should be noted that the time series data for 209 measurement sites must be processed.

In this paper, we describe the procedures for reprocessing the time-series data of the Minami-Kayabe MT sounding and for estimating MT parameters such as apparent resistivity.

2. Survey Design

Figure 1 shows the locations of the MT measurement sites. In this survey, 161 sites were arranged in a square lattice shape. The electric dipoles were continuous in the lattice area. These lattice points were surrounded by 48 other measurement sites located outside the lattice area.

In the name designations for the measurement sites, the first two letters, "KB", indicate Kayabe, the name of the survey area, the third letter indicates the name of the measurement line in the lattice area, and the fourth and fifth numbers indicate the measurement site numbers. For measurement sites outside the lattice area, the third space letter is replaced with a 0 and the measuring site numbers are shown as the fourth and fifth numbers. Two remote sites, LD-1 and LD-2, were located in the northeast of the survey

Fig. 1. MT measurement sites in the Minami-Kayabe area. The solid circles show the "local" MT measurement sites and the open circles indicate the remote-reference sites at LD-1 and LD-2. The double circles show the positions of the wells.

area for remote-reference processing.

Since the topography of the survey area is very rugged, a complete lattice arrangement of MT sites was not possible. There were 13 measurement sites for most of the lines, but there were only 12, 9, and 10 measurement sites, respectively, on lines K, L, and M. On line J, site KBJ09 was moved about 20 m southeast from the lattice-point location, and on line K, site KBK10 was moved about 50 m southwest and the measurement setup at this site was rotated clockwise by 90 degrees from the normal dipole configuration used for the other sites. Although the standard dipole length was 100 m, the E_y dipole length at site KBL08 was reduced to 50 m, and the E_x and E_y dipole length at site KBM09 to 56 m and 30 m, respectively.

3. Data Acquisition

For these MT soundings, the "high accuracy" MT system developed by NEDO between 1984 and

1988 was used (Takasugi *et al.*, 1992a). This system allows simultaneous measurements at four stations; each site is connected to the data acquisition and processing truck with fiber optic cables. A similar measurement system was used at the remote-reference sites, and these data were synchronized using quartz clocks. The MT-1 system manufactured by ElectroMagnetic Instruments, Inc. (California, U.S.A.) was used for the AMT soundings. This compact and portable MT measurement system is operated with batteries.

In both the MT and AMT soundings, data were acquired for the two components of the electric field (E_x and E_y) and the three components of the magnetic field (H_x , H_y , H_z). The measurement frequencies for the MT soundings ranged from 0.01 Hz to 130 Hz. Data were acquired separately in the HF band (sampling frequency 1,024 Hz), the MF band (sampling frequency 32 Hz) and the LF band (sampling frequency 4 Hz) to enable broad-band frequency analyses. AMT data were acquired over a range of 130 Hz to 20,000 Hz, using the SD (synchronous detection) mode (Takasugi *et al.*, 1992b).

Time series were recorded only for MT. Details of the on-site processing are discussed in Takasugi *et al.* (1992c). In this paper we discuss on data reprocessing using cascade decimation.

4. Data Processing

In MT soundings, the intensities of natural electromagnetic fields are very low and the signals are easily contaminated by noise. In order to obtain results of high quality, it is necessary to acquire and stack a large amount of data.

Local noise is generally removed by conducting simultaneous measurements at some measurement sites and then making remote-reference processing (Gamble *et al.*, 1979a). Taking these points into consideration, the time series data of the Minami-Kayabe MT soundings were reprocessed, following the procedures described below.

At the time of the survey, the time series data were processed by the Fast Fourier Transform method (FFT), whereas the cascade decimation method was employed for data re-processing.

In conventional FFT processing, the time series data are divided into segments consisting of a number of data points (the number being a power of 2, usually 512 or 1024). The time series data are edited by removing data in segments where saturation has occurred. When the coherency for a segment is smaller than a preset threshold value, this segment is not used in the estimation of the power spectra. Consequently, the number of stacks is usually reduced. This often causes greater variances of the estimated values. To obtain accurate spectra over a wide frequency band, large-volume data processing is necessary. For this, the FFT method is time-consuming.

Therefore, we employed the cascade decimation method, which is suitable for fast calculations over a wide frequency band. The cascade decimation method consists of several Fourier calculations, aliasing filters, and decimator parts. Figure 2 shows the block diagram of the cascade decimation algorithm. The sampling frequency is varied continuously for each level, and the Fourier coefficients are calculated in each case. The sampling frequency is reduced by half whenever the level is raised by one stage, so that the same number of data points are sampled. Since the Nyquist frequency is changed due to reduction of the sampling frequency, data are passed through an aliasing filter (low-pass). Normally, the number of data is set to be 32, and only the sixth and eighth harmonics are calculated using the discrete Fourier transform method. For example, the sixth harmonic component is expressed as follows:

$$C_6^{\text{real}} = \sum S_n H_n \cos(6\pi n / 16),$$

$$C_6^{\text{imag}} = \sum S_n H_n \sin(6\pi n / 16)$$

where S_n is a time series data set, and H_n is a Hanning window. Using this cascade decimation algorithm, we constructed a system for processing of huge and out of data.

Fig. 2. Block diagram of the cascade decimation (after Wight and Bostick, 1980). The Hanning window and sine, cosine transforms are applied at each level. Calculations of the 6th and 8th harmonics at each level give seven estimates per decade.

After the time series data were processed using the cascade decimation method and the Fourier coefficients were obtained, power spectra were calculated. The data were sorted by the multiple coherency between appropriate horizontal field components. The multiple coherency of a dual input and single output linear system is represented by the following equation.

$$O_i = G_{ix}I_x + G_{iy}I_y \quad (i = x \text{ or } y).$$

This is given in terms of auto and cross spectra of the inputs and output (I_x , I_y , O_i) as

$$C_{1-\alpha}^2 = \frac{\left| \langle I_y O_i^* \rangle \right|^2 \langle I_x I_x^* \rangle + \left| \langle I_x O_i^* \rangle \right|^2 \langle I_y I_y^* \rangle - 2 \operatorname{Re} \left\{ \langle I_x O_i^* \rangle \langle I_y O_i^* \rangle \langle I_x I_y^* \rangle \right\}}{\langle O_i O_i^* \rangle \left\{ \langle I_x I_x^* \rangle \langle I_y I_y^* \rangle - \left| \langle I_x I_y^* \rangle \right|^2 \right\}} \quad (i = x \text{ or } y).$$

The asterisk (*) indicates the complex conjugate. The multiple coherency is unity, if I_x , I_y and O_i are noise free, and it decreases to zero with increasing noise in any components. For the present data processing we calculate four multiple coherencies.

$$C_{H-E_x}^2, C_{H-E_y}^2, C_{E-H_x}^2, \text{ and } C_{E-H_y}^2.$$

The multiple coherency is a measure for linear relationship between the input I_x and I_y , and the output, O_i ($i = x$ or y) of a dual input and single output system. In the notation used here, the first two multiple coherencies are for linear systems with E_x and E_y inputs, and H_x or H_y as the output. Note that the $H-E_x$ and $E-H_y$ multiple coherencies after rotation to the principal direction are sensitive to the XY -mode, while the $H-E_y$ and $E-H_x$ multiple coherencies are sensitive to the YX -mode. This is because the off-diagonal elements of the impedance tensor are usually larger than the diagonal elements.

In our reprocessing scheme, the coherency sorting algorithm was added to the original cascade decimation. First, incoming data are passed through operator-specified minimum amplitude screening criteria, based on the magnetic field amplitude of 6th and 8th Fourier coefficients from the cascade decimation. The auto power spectra and cross power spectra are calculated from the Fourier coefficients and sorted in the temporary storage at each level of decimation. When the number specified for averaging is reached at a given level of decimation, four multiple coherencies are calculated for each harmonic. The average of spectra is then sorted and accumulated into a storage file based on the value of the geometric mean of the $H-E_x$ and $E-H_y$ coherencies, and of the $H-E_y$ and $E-H_x$ coherencies. The storage file into which the temporary spectral averages are sorted is divided into ten bins, each containing complete data sets from which MT parameters can be calculated, with different data quality based on the multiple coherency.

Whenever the time series data are saturated by the noise, usually in the form of a spike, the decimation processing is reset, and processing is restarted from the level 0. Table 1 shows an example of data processing results in the HF band (sampling frequency 1,024 Hz) at site 2 on the J-line when the coherency sorting function is added. In this table, bins 1–10 represent groups according to the coherency thresholds. The number of spectral values that meet each threshold can be seen for each frequency. In this example, four thresholds (bin1–bin4) are specified from the coherency of (E_x, H_y) , four (bin5–bin8) from the coherency of (E_y, H_x) , and two (bin9–bin10) from both.

Figure 3 shows the apparent resistivities calculated from each sorted spectrum. Differences in the smoothness of apparent resistivity curves and the size of error-bars can be observed depending on the coherency threshold values. When the quality was considered insufficient, the coherency threshold values were varied, and the data were reprocessed.

It should be noted that a higher coherency value does not necessarily assure better quality. This is because the number of stacks is often reduced when the coherency value is increased. This is also because coherent noise mixing in the components of both electric and magnetic fields cannot be removed by simply raising the coherency value. Besides, the remote reference site in this survey is close to survey sites, and so the remote reference processing does not reduce this kind of noise efficiently. In the present system, the data were arbitrarily selected due to sorting by the coherency threshold value. Therefore, if coherent noise becomes dominant, it is difficult to discard noisy data giving a high coherency value.

The data can be processed efficiently by constructing a data processing system using the coherency parameters and the reference partner. When remote reference processing was conducted using ten preset coherency values, the execution time was about one minute for each band (on a HP-9000/755 computer, SPECfp92: 170). Thus rapid processing could be realized for most of the combinations and high-quality data could be selected.

In parallel with the cascade decimation processing, remote reference processing was also conducted. The remote reference processing method, which was proposed by Gamble *et al.* (1979a, b), has proved to be quite effective, and is now widely used. In Japan, where the level of cultural noise is quite high, however, employment of this method is often insufficient to reduce noise to a satisfactory level. Therefore the triple reference processing method, in which two reference sites are used, was also applied (Takasugi and Muramatsu, 1991).

When the field survey was actually conducted, the data for each measurement site were processed using two fixed reference sites (triple reference processing). However, reference sites close to the measurement sites were used, the quality of the data at the reference sites was not always satisfactory. During reprocessing, besides single processing, both usual remote-reference processing and triple remote-reference processing were conducted taking all the combinations of sites which were simulta-

Table 1. Data processing results by coherency sorting. The number of spectrum values that meet each threshold for each frequency is shown.

[illegible]

Fig. 3. Apparent resistivity curves given by coherency sorting. The sorted impedance is shown in each bin. For example, "XY > 0.7" means that the spectra for Z_{xy} with the coherency higher than 0.7, is used. "ALL" indicates all spectra are used for calculating MT parameters. "DOF = 30" represents that the impedance derived from 30 highest coherencies for Z_{xy} and Z_{yx} are used.

KB024

Cascade Decimation

FFT

(a)

KBG05

Cascade Decimation

FFT

(b)

Fig. 4. Comparison between FFT and cascade decimation processing. The apparent resistivity curves for sites (a) KB024, (b) KBB05, (c) KBB08, (d) KBA00, and (e) KBJ01 are shown. The AMT data covering the frequencies from 500 Hz to 5,000 Hz are eliminated, because poor data quality. The cascade decimation processing yields smooth apparent resistivity curves. However, DC noise contamination cannot be avoided, because the remote reference site is close to the survey area.

KBB08

FFT

Cascade Decimation

(c)

KBA00 **Cascade Decimation****FFT**

(d)

Fig. 4. (continued).

KB J 01

Cascade Decimation

FFT

(c)

Fig. 4. (continued).

neously processed. Since six MT measurement sites, including the two reference sites were normally processed at the same time, processing was done in sixteen ways for each band. Both in the single and multiple reference processing, ten set values for the coherency thresholds were used. This means that the data were processed in 160 ways for each band for each measurement site. Selection of the final results was done based on the smoothness of the apparent resistivity distribution and the values of the error-bar and the phase. When the DC noise is dominant, the value of phase approaches to zero, regardless of the smoothness of the apparent resistivity curve. Finally, the best data were selected by the operator. Even when the error-bar was somewhat large, the results of the remote reference processing were accepted.

5. Data Editing

The quality of some data was too low to be improved by the cascade decimation technique (see Fig. 4(a), for example). These data were removed prior to interpretation.

In general, the quality of data was poor in the following frequency ranges: (1) the AMT range of several hundreds of Hertz to 10,000 Hz, (2) the range of 0.1 Hz to 1.0 Hz, and (3) the range lower than 0.01 Hz.

The reason for poor data quality in the AMT band is that the intensity of natural MT signals is usually weak in this frequency range, and the quality could not be improved simply by increasing the number of stacking during measurements at these sites.

In the range of 0.1 Hz to 1.0 Hz, the error-bars were small, the apparent resistivity curve increases very steeply. This can arise from the DC effect due to local artificial noise or large frequency noise. This feature did not disappear even when remote-reference processing was conducted. In this sense, the reference sites should have been selected in more remote areas.

One of the causes for poor data quality in the range lower than 0.01 Hz could be the insufficient number of stacking. These data were not improved by reprocessing.

6. Results of Data Processing

The Minami-Kayabe MT survey was conducted as a part of the confirmation study for development of the high accuracy MT sounding system by NEDO. The main purpose of the sounding was to demonstrate how well the hardware works. The instrument truck for measurement sites and that for the reference sites were located at the same place to continuously monitor the synchronization of measurements at the measurement sites and the reference sites. For this reason, the reference sites were not located very far from the measurement area. There was also a limitation in the measurement time because measurements at 209 sites was to be completed in a month. The overall quality of the time series data turned out to be rather poor after all. For many measurement sites, however, the data quality could be improved through cascade decimation re-processing. The final power spectra were rewritten in the MT/EMAP standard format (SEG-EDI format) determined by the Society of Exploration Geophysicists (Wight, 1988).

Figure 4 shows the comparison between the FFT processing made in 1988 and the present reprocessing. The impedance tensor is rotated so as to maximize the off-diagonal elements at each frequency. Figure 4(a) shows the comparison at measurement site 24, located outside the lattice area. The reprocessed data show some improvements in the apparent resistivities derived from Z_{xy} , particularly at frequencies lower than 1 Hz. Figure 4(b) shows the comparison at site 5 on the G-line. New reprocessing yields smoother apparent resistivity curves. Figure 4(c) shows the comparison at site 8 on the B-line. This reprocessing provides much smoother apparent resistivity curves, but the gradient of the curves are steep, nearly 45 degrees at frequencies lower than 1 Hz. This would be mainly due to the insufficient distance of the remote reference site. Site 1 on the A-line, indicated in Fig. 4(d), shows the same tendency. Figure 4(e) shows the comparison at a site on the J-line. The FFT calculation shows that gradient of the apparent resistivity curve at frequencies lower than 1 Hz is 45 degrees, but this reprocessing shows that the such

Fig. 5. The apparent resistivity and phase sections. The apparent resistivity sections give more rough images in the horizontal direction than the phase sections, suggesting the affects of static shift. (a) The impedance is derived from the *E* field parallel to the traverse, and (b) the impedance is calculated from the *E* field perpendicular to the traverse.

(b)

Fig. 5. (continued).

Fig. 6. The plane views of the apparent resistivities. Open circles represent measurement sites used here. The impedance is given for the E field parallel to the survey line at frequencies of (a) 100 Hz and (b) 1 Hz. The apparent resistivities calculated from the E field perpendicular to the traverse are also shown at frequencies of (c) 100 Hz and (d) 1 Hz.

a high gradient starts at 0.1 Hz. One large noise source was identified as the power line. In this cascade decimation processing, if saturation occurred due to large noise such as the processing was reset and made again from the zero level. This would be the reason why the frequency at which the apparent resistivity curve sharply rose moved from 1 Hz to about 0.1 Hz. However, since the time series data were split apart many times during calculations in the cascade decimation, unlike the case of FFT, the calculations were not made for frequencies lower than 0.01 Hz.

Figure 5 shows several of the reprocessed apparent resistivity sections for the lattice sites. The data are given as the E field perpendicular to the line (Fig. 5(a)) and the E field parallel to the line (Fig. 5(b)). This presentation turned out to be useful for 2- or 3-dimensional analysis. The apparent resistivity and phase sections in Fig. 5 show little evidence for large static shifts. Static shifts are usually characterized by abrupt apparent resistivity shifts and flat phase responses. The sections show low resistivity zones

(a)

Fig. 7. Comparison of the resistivity logging data and the results of Bostick 1D-inversion for sites KBF05 KBI08; the cascade decimation is applied. The mode (TE, TM) selection is determined as: if $|\text{tipper strike} - \text{impedance strike}| < \pi/4$, Z_{xy} is TE and Z_{yx} is TM, if $|\text{tipper strike} - \text{impedance strike}| > \pi/4$, Z_{xy} is TM and Z_{yx} is TE.

Fig. 7. (continued).

associated with a hydrothermal system and local abrupt features that suggest the presence of fracture or fault.

Figure 6 shows the plan views of apparent resistivities; the rotation angle of the impedance tensor is the same as for Fig. 5. Figures 6(a) and (b) show the apparent resistivities for the E field parallel to the line. No marked structure is recognized. Figures 6(c) and (d) show the plane views after apparent resistivities for the E field perpendicular to the line. A trend in the north-west to south-east may be direction recognized.

In this survey area there are seven wells, MK-1 to 7 (Fig. 1). Since the wells MK-2 and MK-6 are located in the central part of the survey area, resistivity logging data from these two wells were compared with the Bostick 1D inversions (the impedance being rotated toward the same direction as in Fig. 4) for nearby measurement sites. Unfortunately, only analog data records were available and so the resistivity values were read using a digitizer; this resulted in large error for low resistivity values (Fig. 7).

7. Conclusions

Time series data of the Minami-Kayabe MT survey were reprocessed by means of the cascade decimation method, and we could obtain improved results over FFT processing in the frequency range of 3.4 Hz to 250 Hz. However, we could not obtain good results for frequencies below 3.4 Hz because of insufficient number of stacking and also because of high local noise.

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