Monitoring Changes of the Earth's Electric Resistivity for Earthquake and Crustal Activity Research

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Abstract

Stationary magnetotellurics (MT) monitoring systems were installed at the Mizusawa Geodetic Observatory and Esashi Observatory of the Geographical Survey Institute (GSI). The MT system monitors the electric resistivity of the Earth continuously in order to detect resistivity changes related to earthquake occurrence and crustal activity. Though day-to-day changes of the resistivity show large errors because of noise, careful analysis has produced good results. Eliminating noise and apparent changes, we found 30% changes of the apparent resistivity at Esashi, suggesting changes in electric current flow in a rather wide region.

1. Introduction

The most reliable way to know the underground structure of the Earth and its activity is to dig up the Earth and examine it directly. But it is expensive and the deepest hole has not reached the bottom of the crust. Thus, for practicality, we use seismic waves, gravimetric and electromagnetic signals as tools to investigate the Earth. So electromagnetic survey is one of the limited ways of research of earthquake and crustal activity..

The GSI has been conducting geomagnetic surveys in Japan since 1948. The purpose of the surveys is to clarify the geographical distribution of the geomagnetic field and its secular variation. The Kanozan and Mizusawa Geodetic Observatories are operated to get continuous reference geomagnetic fields for the geomagnetic surveys. The geomagnetic field is related to the underground structure of the Earth, particularly electric resistivity.

To monitor the electric resistivity of the Earth, stationary Magnetotellurics monitoring systems were installed at the Mizusawa Geodetic Observatory and Esashi Observatory in 1996. The MT system has several advantages over ordinary geomagnetic observations because it directly measures the physical character (resistivity) of the Earth. The geomagnetic changes are the result of some physical processes in the Earth but they can not explain all the processes occurring in the Earth. However, the MT system directly gives us electric resistivity values of the Earth. Therefore, we can monitor the state of the Earth's interior more effectively using the MT system. So monitoring the resistivity of the Earth helps interpretation of the geomagnetic changes obtained in the geomagnetic survey and is a valuable tool for crustal research.

2. What is Magnetotellurics (MT)?

The Magnetotellurics method is a way of determining the electrical resistivity structure of the subsurface from measurements of natural (or artificial controlled source) transient electric and magnetic fields on the surface (e.g. Vozoff, 1972; Kaufman, 1981).

2.1. Natural geomagnetic field of the Earth (signal)

In the MT method, naturally existing electromagnetic fields are used. These natural electromagnetic fields of the Earth contain appreciable energy over a very wide spectrum of frequencies and arise from a variety of causes. The electromagnetic fields at frequencies below one Hz originate from complex interactions between the Earth's permanent main magnetic filed and the flow of plasma (ionized particulate material) from the Sun. At frequencies above a few Hz, the ambient electromagnetic field has contributions from meteorological activity, in particular, lightning associated with thundershowers and storms, and from man-made noises (power lines, electric railways, etc.).

The time-varying magnetic field always presents noise in the geomagnetic fields. When it is very large, it interferes with magnetic surveys. In the conducting Earth, the changing magnetic field induces telluric eddy currents and voltages; they are the electric signals for the MT.

2.2. Basic concepts of the MT method

When the magnetic variations reach the surface of the Earth, reflection and refraction occur but the signals can be treated as plane electromagnetic waves. A portion of the signal is transmitted into the Earth and travels vertically downward. To the conducting (low resistivity) rocks or sediments, this signal energy appears as a magnetic field which changes with time, and electric fields are induced so that currents, called telluric currents, can flow. The telluric currents (*E*) are perpendicular to the associated magnetic fields (*H*). Figure 1 shows an example of variations of the telluric currents and the magnetic fields observed at Esashi. *Hx* and *Hy* correspond to *Ey* and *Ex*, respectively.

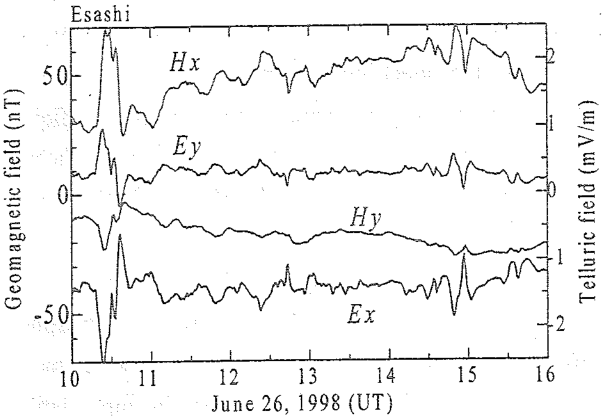

Figure 1 Example of geomagnetic and telluric variations observed at Esashi

Energy in the down-going disturbance is quickly dissipated as heat. So the depth of penetration of the fields into the Earth is related to the resistivity. In a uniform structure, the electromagnetic fields weaken exponentially with depth. The depth at which the fields have fallen off to 1/*e* of their value at the surface is called the skin depth *d* (km);

$$d = 0.5\sqrt{R/f} \tag{1}$$

where *R* is apparent resistivity (ohm-m), and *f* is frequency (Hz).

The magnitude of *R* is

$$R_{xy} = \frac{1}{5f}\left(\frac{|Ex|}{|Hy|}\right)^2 \tag{2}$$

$$R_{yx} = \frac{1}{5f}\left(\frac{|Ey|}{|Hx|}\right)^2 \tag{3}$$

Ex and *Ey* are measured in mV/km, and *Hx* and *Hy* are measured in nT (nano-tesla). In the example of Figure 1, if *Ex/Hy* is larger than *Ey/Hx,* then *Rxy* is larger than *Ryx* (see Figure 6a for real resistivity values). The phases of two components are also measured.

$$PH_{xy}=PH(Ex)-PH(Hy) \tag{4}$$

$$PH_{yx}=PH(Ey)-PH(Hx) \tag{5}$$

3. MT system at Mizusawa and Esashi

The MT systems were installed at the Mizusawa Geodetic Observatory and Esashi Observatory. Mizusawa and Esashi are located in Iwate Prefecture in northeastern Japan (Figure 2), about 20 km away from each other. This distance is enough for remote-reference analyses because the remote-reference analysis needs the signals to be the same at the two stations but the noises to be different.

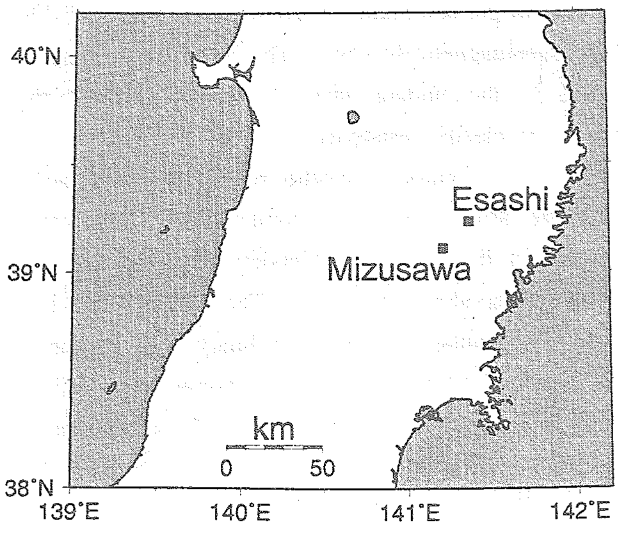

Figure 2 Location of Mizusawa and Esashi

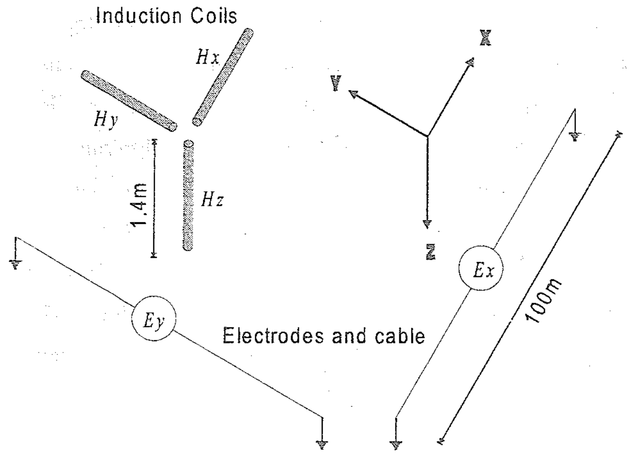

Figure 3 Arrangement of sensors

Two telluric measurement dipoles (*Ex* and *Ey*) with electrodes are permanently installed with dipole cable buried in the ground. Two horizontal (*Hx* and *Hy*) and one vertical (*Hz*) magnetic sensors (induction coils) are permanently installed in concrete bunkers.

3.1. Measuring hardware

The MT system is based on Phoenix V5-16 MT units, which are commercial MT units used widely in the world for geophysical exploration such as finding oil, and gas fields and metal deposits.

The system measures two telluric components (*Ex* and *Ey*) and three magnetic components (*Hx*, *Hy* and *Hz*). The magnetic sensors are composed of three induction coils which are two horizontal components, (north-south (*x*) and east-west (*y*) components) and one vertical component. All the coils are installed in separate permanent concrete bunkers (Figures 3 and 4). One telluric component is measured with deferential voltage of two Pb-$PbCl_2$ electrodes (dipole) buried in the ground 100m apart from each other. The cables, telluric lines and pre-processor unit (pre amp) are buried in the ground to protect them from rain, snow, temperature change and animal attack (animals often chew on cables). Measurements at two sites are synchronized by clocks using GPS signals and subsequently reprocessed with the remote-reference technique.

All operations are performed automatically, including data editing, display of day-to-day variation of resistivity, and restart in case of power failure lasting more than 24 hours. All instruments are powered by a UPS power supply which can last more than 24 hours during a power failure.

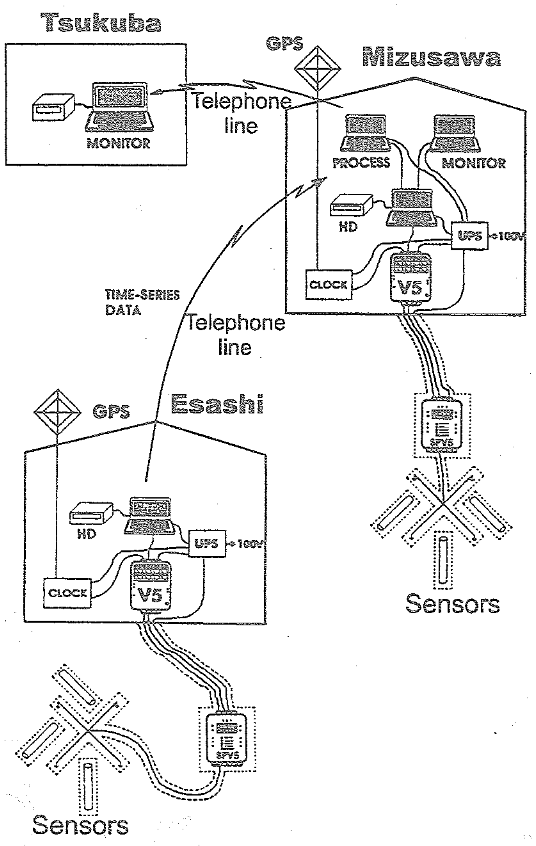

Figure 4 Diagram of MT system installed at Mizusawa and Esashi

SPV5 is a sensor pre-processor unit and installed in a concrete bunker. Day-to-day results can be monitored at the GSI main office in Tsukuba.

3.2. Processing

Measurements are taken, 24 hours per day and measured time-series data are continuously stored in hard disks automatically. The data at Esashi are transferred through a public (NTT) telephone lines every hour. Time-series data from both stations are reprocessed every day at Mizusawa and processed data are then sent to the Tsukuba monitoring system every day through an NTT line.

3.3. Special features for GSI system data acquisition

The following are differences between the GSI and conventional V5-16 MT systems:

(1) With conventional MT the data acquisition is 10 to 16 hours per day, but the data in the GSI system are acquired continuously 24 hours a day.

(2) The data acquisition is performed simultaneously in all frequency ranges (high and low bands) with the GSI system.

(3) DC telluric components are also measured and recorded in the GSI system while the conventional MT system only measures AC telluric components. DC telluric components are used for long-term MT and earthquake prediction using earth current anomalies.

4. Observations and Preliminary Results

Although equipment was damaged slightly by severe lightning once in July 1996, the system hardware has functioned rather well.

4.1 Data quality and noise

At Mizusawa, strong artificial noise has been observed. One of the noise sources may be the JR Shinkansen bullet trains running through a tunnel close to the site (approximately 700 m). However, as data quality at Mizusawa is poor even when the Shinkansen is not running, other unknown noise sources likely exist.

Figures 5a and 5b show standard apparent resistivity and phase curve vs. frequency, and there are unusual phase curves both in *PHxy* and *PHyx*. This indicates strongly-polarized responses and Mizusawa may be located directly on the boundary of very different resistivity structures between East and West.

At Esashi, the data are much better than those at Mizusawa, but strong local noise is still observed. Figures 6a and 6b show standard apparent resistivity and phase at Esashi.

The data is reprocessed by the remote-

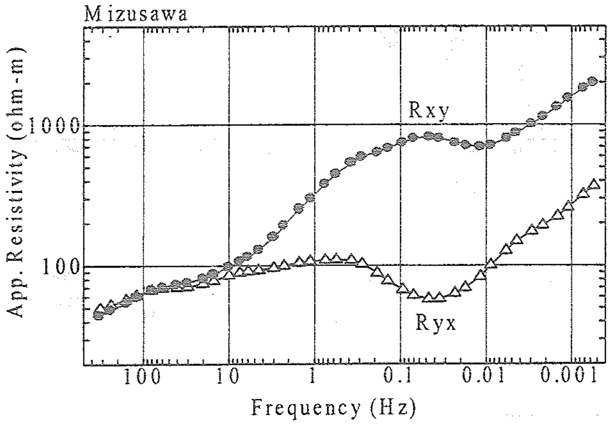

Figure 5a Standard apparent resisitivty at Mizusawa

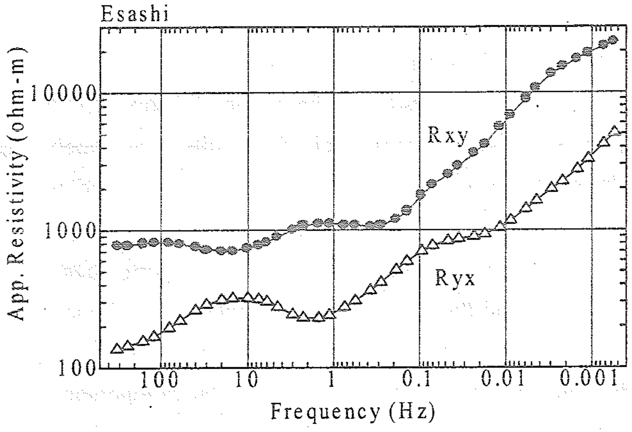

Figure 6a Standard apparent resisitivty at Esashi

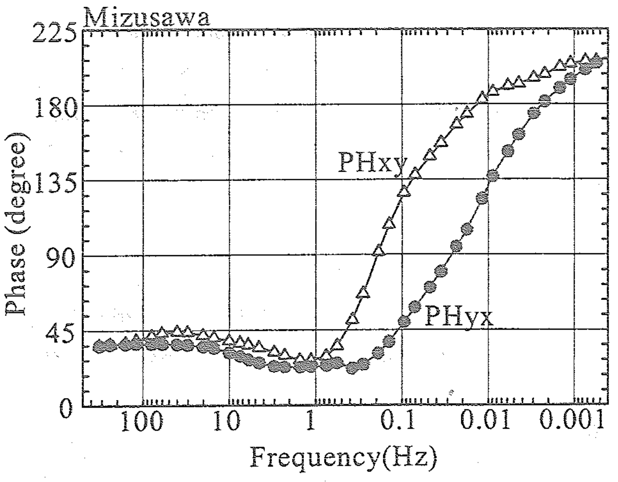

Figure 5b Standard phase at Mizusawa

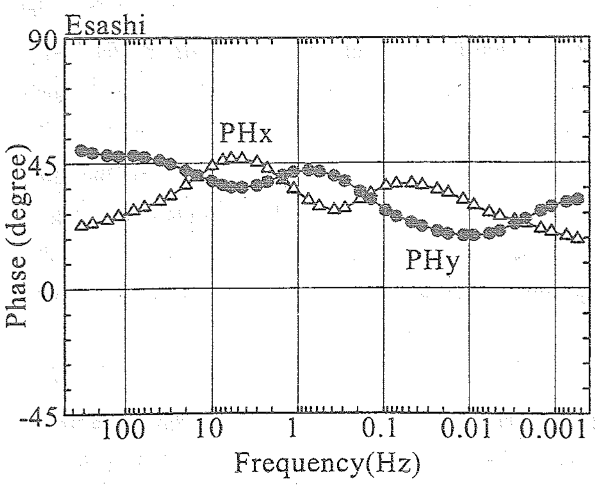

Figure 6b Standard phase at Esashi

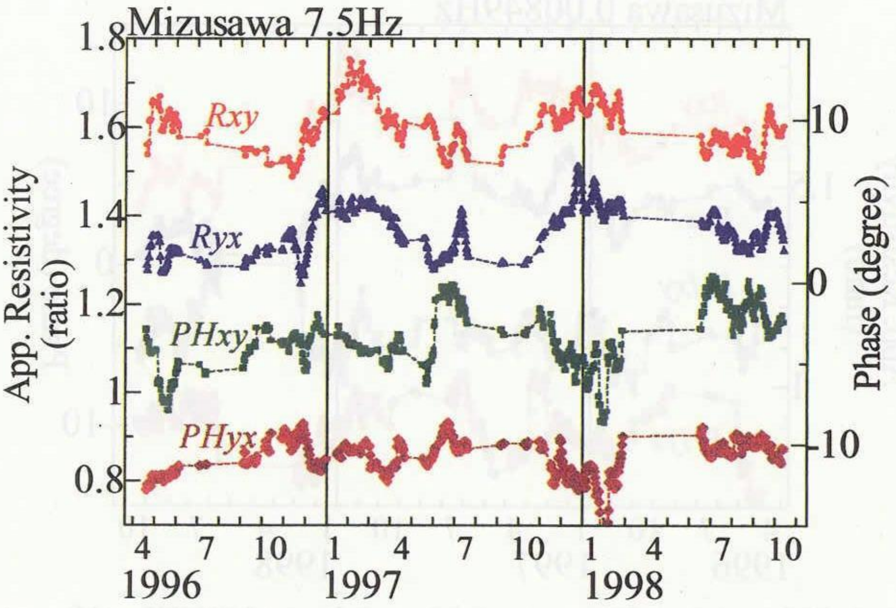

Figure 7a Daily variation of apparent resistivity and phase at 7.5 Hz at Mizusawa

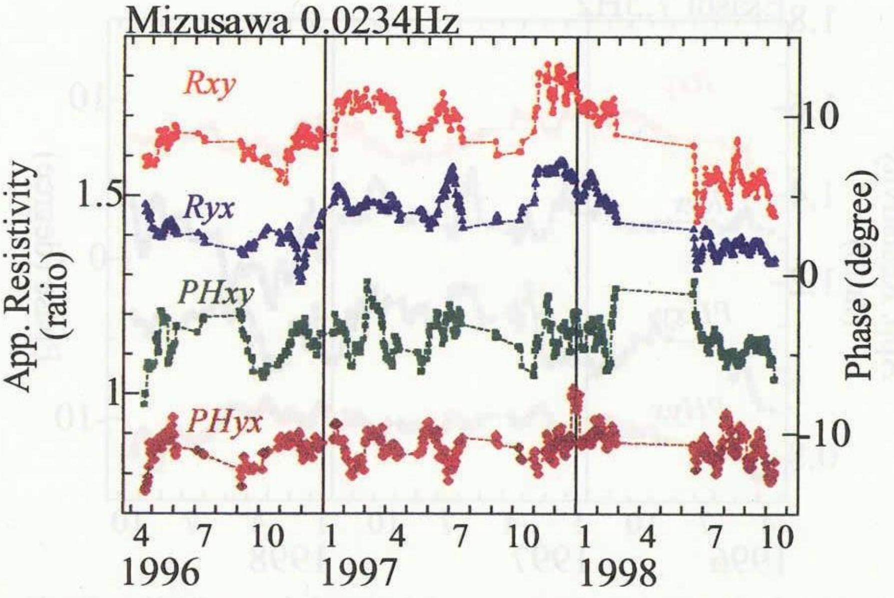

Figure 7b Daily variation of apparent resistivity and phase at 0.0234 Hz at Mizusawa

reference technique to minimize the effect of local noise. Both Mizusawa and Esashi data are reprocessed using the other site as the reference site. Though artificial noise is strong at both sites, the noise characteristics are different. Therefore, the remote-reference reprocessing is fairly effective in improving data quality.

4.2 Stability of apparent resistivity

Characteristic of MT measurements, time-to-time data quality depends on various noises and signal strengths which are not consistent. Because natural magnetic fields are used, the signals measured by MT and source direction continuously vary. Though true apparent resistivity and phase should be constant, measured values vary with noise.

As day-to-day variations of apparent resistivity usually have more than 100 % error, smoothing in the frequency domain and day-to-day plotting are carefully done. Figures 7 and 8 show daily variations of apparent resistivity and phase at several frequencies. In the range from 0.096 Hz to 0.009 Hz (in particular, 0.0234 Hz) and at 7.5 Hz, data are relatively stable and these frequencies are used for daily monitoring.

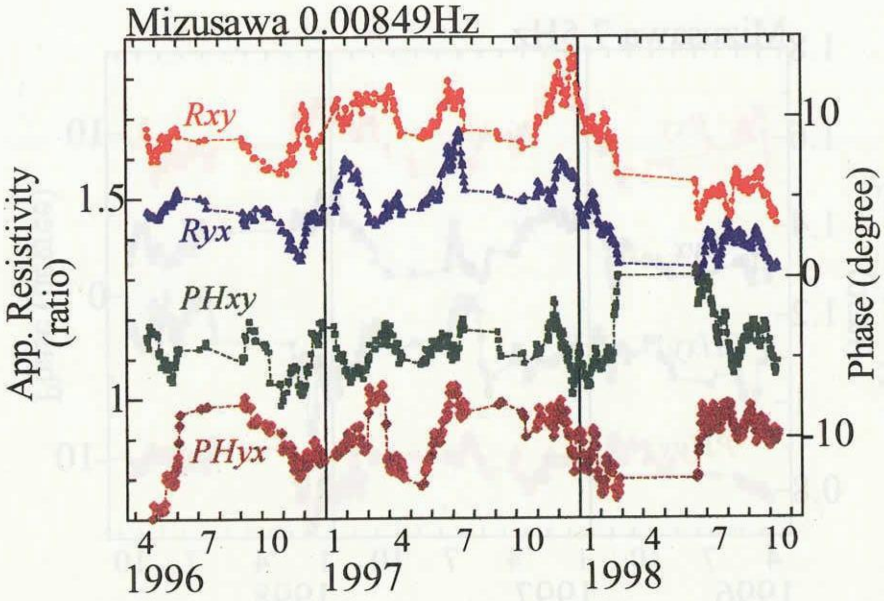

Figure 7c Daily variation of apparent resistivity and phase at 0.00849Hz at Mizusawa

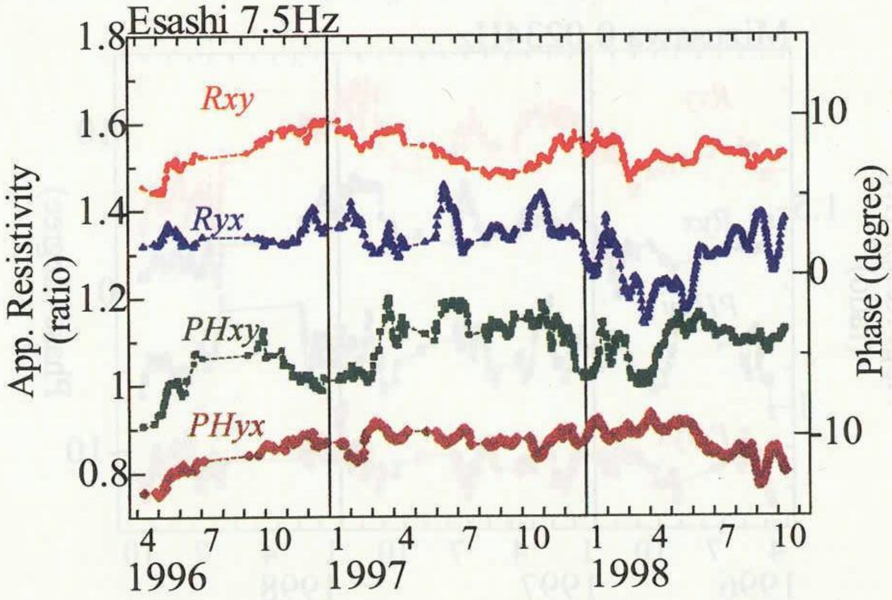

Figure 8a Daily variation of apparent resistivity and phase at 7.5 Hz at Esashi

4.3 Time variation of apparent resistivity

Mizusawa data are not good so we will mainly discuss Esashi data in this section. Figures 8 show that phase variation with time is very small. In Figures 8b and 8c, the apparent resistivity at Esashi at 0.0234Hz and 0.00849Hz shows a more than 30 % decrease in *Ryx* and 20 % decrease in *Rxy* in October 1996. It also shows 20 % decrease in *Ryx* in 1998 and similar variation is found in variation at 7.5 Hz. The following discussions examine possible causes of these variations.

(a) System response change

For stationary monitoring systems, the stability of system response is important. System calibrations including initial calibration, were performed four times and system response variation of all channels of V5 (receiver) and SPV5 (sensor pre-processor) was very small (less than 0.5 %). Coil response variation was also small (less than 1 %). Therefore, the system response has not affected the large variations.

(b) Static shift due to shallow resistivity change

If ground resistivity near surface changes, it

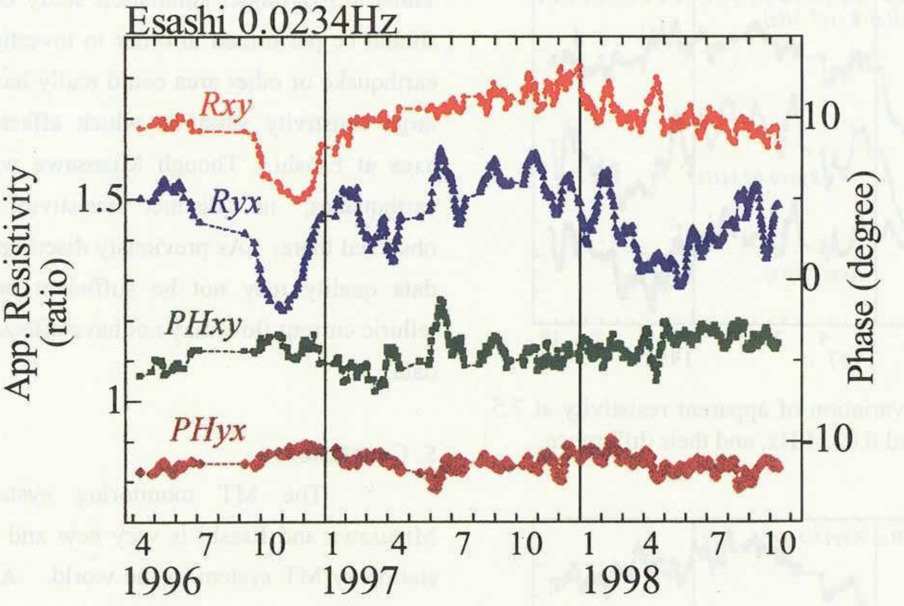

Figure 8b Daily variation of apparent resistivity and phase at 0.0234Hz at Esashi

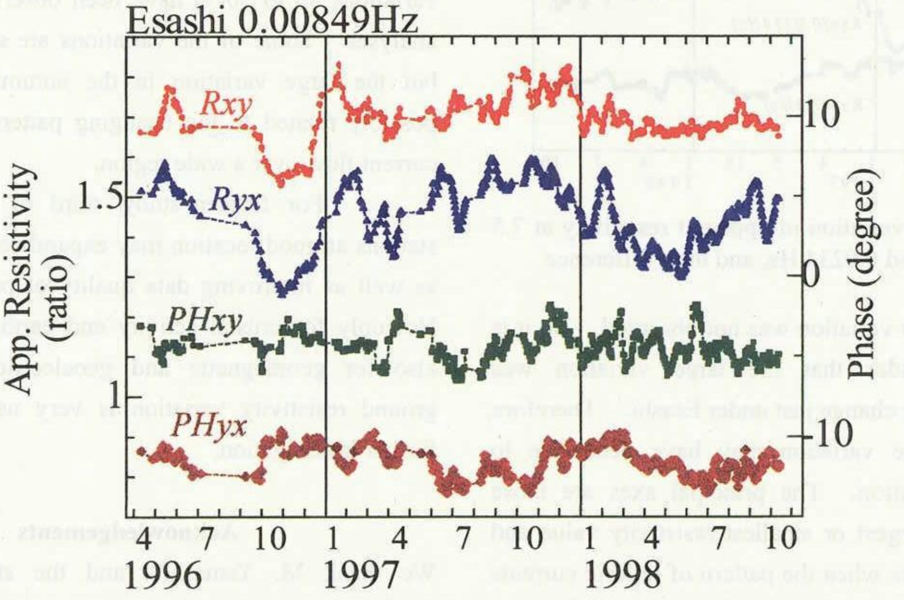

Figure 8c Daily variation of apparent resistivity and phase at 0.0849 Hz at Esashi

may cause 'static shift'. Static shift effect is generally a parallel vertical shift of apparent resistivity on a logarithmic scale over the entire frequency. Usually, phase is not affected by static shift. Figures 9a and 9b show a comparison of daily variation of apparent resistivity at 7.5 Hz and 0.0234 Hz at Esashi. Figure 9a shows that the variations of *Ryx* for the two frequencies have a close correlation. However, Figure 9b doesn't show a correlation between the variations of *Rxy*. Therefore, some variations of apparent resistivity are affected by the static shift effect and it is important to compare variations for different frequencies to distinguish them.

(c) Resistivity structure change

The apparent resistivity at 0.0234 Hz started to decrease around September 1996, dropped to a minimum around October, then went back to the average level. Because no distinct variation was observed at 7.5 Hz during this period, this variation was not static shift effect.

If ground resistivity structure just under the site had changed, the apparent resistivity would also have changed. In addition, the phase should also have

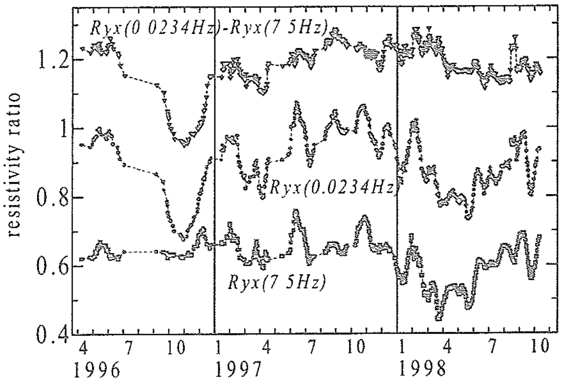

Figure 9a Daily variation of apparent resistivity at 7.5 Hz and 0.0234 Hz, and their difference

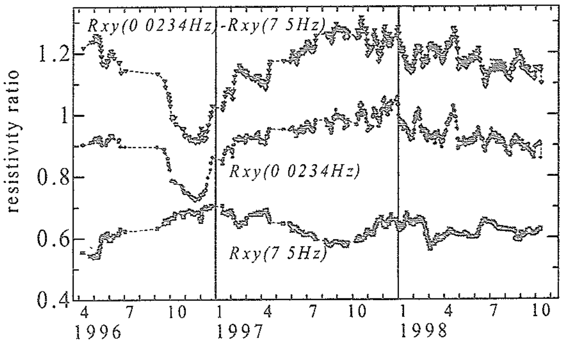

Figure 9b Daily variation of apparent resistivity at 7.5 Hz and 0.0234 Hz, and their difference

changed, but phase variation was not observed. So it is difficult to consider that the large variation was resistivity structure change just under Esashi. Therefore, the indicated large variation may have been due to principal axis rotation. The principal axes are those which have the largest or smallest resistivity value and their rotation occurs when the pattern of telluric currents flowing in a wide region changes. Namely, changes of resistivity in some areas (they are not just under the MT site) will cause changes in the pattern of the telluric current flow in a rather wide region, and they show up as a change of principal axes in the MT measurements. This change of the principal axes will change the apparent resistivity but not the phase.

Incidentally, a series of earthquakes of peak magnitude M5.9 occurred on August 11, 1996. Large resistivity variation started just after the earthquakes. Neither other remarkable earthquakes nor crustal activities were observed in that period. So far, there is no evidence of the large resistivity structure variation. Thus, a 3-D model simulation study covering the area should be performed in order to investigate whether the earthquake or other area could really have caused such a large resistivity variation which affected the principal axes at Esashi. Though Mizusawa was closer to the earthquakes, no distinct resistivity variation was observed there. As previously discussed, the Mizusawa data quality may not be sufficient or the pattern of telluric current flow may not have affected the Mizusawa data.

5. Conclusions

The MT monitoring system installed at Mizusawa and Esashi is very new and may be the first stationary MT system in the world. Although the data quality is not sufficient, large apparent resistivity variations up to 30 % have been observed after careful analyses. Some of the variations are static shift effect but the large variation in the autumn of 1996 was possibly related to the changing pattern of the telluric current flow over a wide region.

For further study, third or more new MT stations at good location may expand search area in 3-D as well as improving data quality of present two sites. Not only for crustal activity and earthquake study but also for geomagnetic and geoelectric study, getting ground resistivity variation is very useful and merits further investigation.

Acknowledgements

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References

Kaufman, A. A. (1981): The magnetotelluric sounding method. *Elsvier Scientific Pub.*, New York, 595pp.

Phoenix Geophysics (1997): Stationary MT monitoring system for earthquake research installed for the Geographical Survey Institute, *Phoenix Tech. Rep.*, Phoenix Geophysics, Tronto, *1*, 1-4.

Vozoff, K. (1972): The magnetotelluric method in the exploration of sedimentary basins. *Geophysics*, *37*, 98-141.