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ULF geomagnetic field measurements in Japan and some recent results associated with Iwateken Nairiku Hokubu earthquake in 1998

K. Hattori [a,*], I. Takahashi [b], C. Yoshino [a], N. Isezaki [c], H. Iwasaki [d], M. Harada [b], K. Kawabata [d], E. Kopytenko [e], Y. Kopytenko [e], P. Maltsev [f], V. Korepanov [f], O. Molchanov [g], M. Hayakawa [h], Y. Noda [d], T. Nagao [d], S. Uyeda [d]

[a] *Marine Biosystems Research Center, Chiba University, 1-33, Yayoi, Inage, Chiba 263-8522, Japan*
[b] *Graduate School of Science and technology, Chiba University, Japan*
[c] *Department of Earth Sciences, Faculty of Science, Chiba University, Japan*
[d] *Tokai University, Shimizuorido, Shizuoka 424-8610, Japan*
[e] *IZMIRAN St. Petersburg Filial, St. Petersburg 188, Russia*
[f] *Lviv Center of Institute Space Research, 290601 Lviv, Ukraine*
[g] *Institute of Physics of the Earth, Moscow, Russia*
[h] *The University of Electro-Communications, Chofugaoka, Chofu 182-8585, Japan*

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Abstract

Previous studies on Spitak, Loma Prieta, and Guam earthquakes indicate that large earthquakes were accompanied by preceding magnetic anomalies. In order to confirm these facts and to investigate ULF phenomena in details, a network of ULF magnetometers has been installed in Japan. Network observations including small arrays have been carried out. Also, the geomagnetic data observed at Matsukawa station associated with Iwateken Nairiku Hokubu earthquake (M6.1, September 3, 1998, depth 10 km) are presented. 4.5 years data have been analyzed and the obtained result is discussed. The variation of spectral density ratio between the horizontal and vertical components (polarization) exhibits an anomalous behavior two weeks before the earthquake. This is a unique change discovered from the rather long-term analysis, which suggests that this anomalous change might be a possible signal associated with the earthquake preparation phase.

Keywords: ULF magnetometers; Network observation; Iwateken Nairiku Hokubu earthquake; Polarization

1. Introduction

Electromagnetic phenomena are recently considered as a promising candidate for the short-term prediction of large earthquakes (e.g., Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002) and there have been accumulated observational reports in a very wide frequency range. Measurements of electromagnetic phenomena can be classified into three types; the passive ground-based observation for lithospheric emissions (Fraser-Smith et al., 1990; Bernardi et al., 1991; Molchanov et al., 1992; Kopytenko et al., 1993, 1994; Lighthill, 1996; Hayakawa et al., 1996a; Kawate et al., 1998), the ground-based observation with the use of transmitter signals for the study of seismo-atmospheric and -ionospheric perturbations (Gokhberg et al., 1982; Gufeld et al., 1994; Hayakawa et al., 1996b; Molchanov and Hayakawa, 1998), and the satellite observation (Galperin and Hayakawa, 1996; Parrot, 1999). One of the most promising methods among them is a method of detecting seismogenic ULF emissions because there have been reported convincing evidences of ULF magnetic signature (Fraser-Smith et al., 1990; Kopytenko et al., 1993; Molchanov et al., 1992, 1995; Hayakawa et al., 1996a; Kawate et al., 1998; Hayakawa et al., 2000; Uyeda et al., 2002; Gotoh et al., 2002;

* Corresponding author. Tel.: +81-43-290-2801; fax: +81-43-290-2859.
E-mail address: hattori@earth.s.chiba-u.ac.jp (K. Hattori).

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Hattori et al., 2002). In order to verify electromagnetic phenomena preceding large earthquakes and to clarify the relationship between electromagnetic phenomena and possible physics, we intended to install sensitive geomagnetic sensors in Japan.

In this paper, we will present our observation system and an example of our results of ULF emissions observed at Matsukawa station associated with 1998 Iwateken Nairiku-Hokubu earthquake (M6.1).

2. Observation system

2.1. ULF magnetometer network

Fig. 1 shows the summary on the occurrence of the earthquake-related ULF activity in the form of earthquake magnitude versus epicentral distance from an ULF magnetic station. White and black circles show an earthquake with and without ULF anomalies, respectively. The dashed line indicates the empirical threshold for appearance of the anomalous ULF signals preceding large earthquakes. This figure demonstrates that ULF emissions could be observed about 60 km from the source region for an earthquake with $M \geqslant 6$, and the detectable distance of ULF magnetic anomalies would be extended to about 100 km in the case of an earthquake with $M \geqslant 7$.

It is important to predict earthquakes with $M \geqslant 6$ in a highly populated region to mitigate disasters. Therefore, we decided to install a network of ULF magnetometers with high sampling rate to cover the Kanto (Tokyo)—Tokai area with inter-sensor distances of about 100 km. Two types of magnetometers are adopted; torsion and induction types. Taking account of the existence of Kakioka Geomagnetic Observatory, Japan Meteorological Agency (JMA) (36.2°N, 144.2°E), we planned to set up stations to cover the area, as shown in Fig. 2.

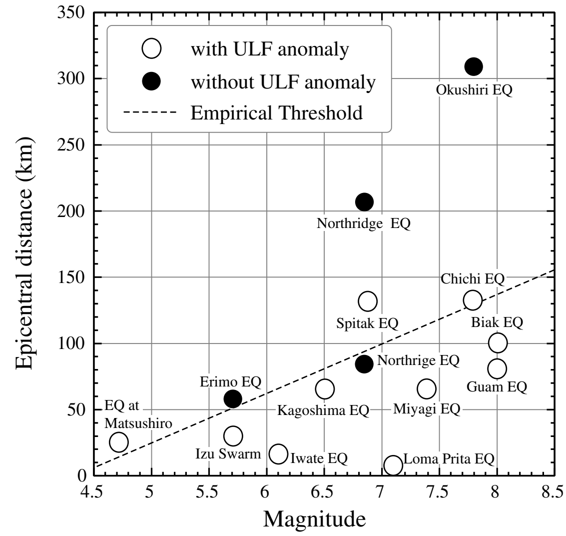

Fig. 1. The diagram indicating the ULF signature of earthquakes in the form of earthquake magnitude versus epicentral distance.

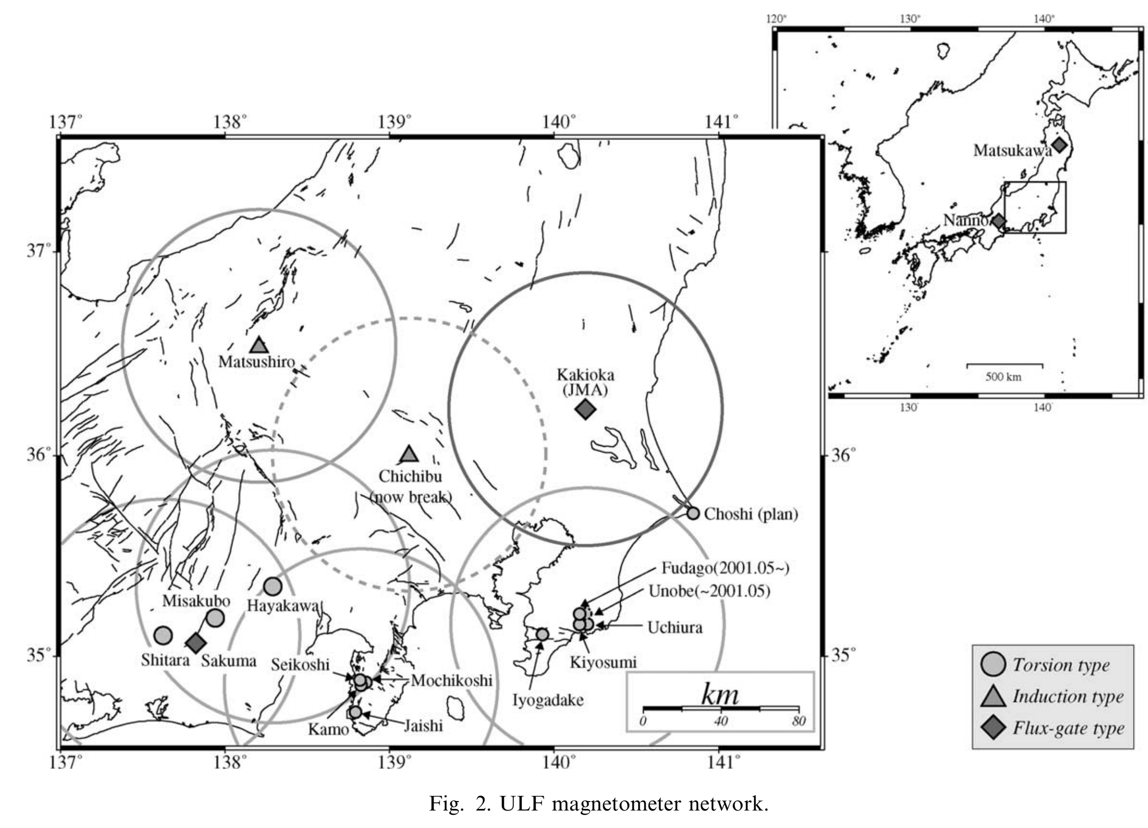

Fig. 2. ULF magnetometer network.

Circles in the figure indicate the 60 km distance from the station (the circle from Kakioka observatory is also displayed). The clock system at each station is controlled by GPS. The information on all of our stations is summarized in Table 1.

One of the sensors (induction magnetometer) has been installed in JMA's Matsushiro Seismological Observatory (36.5 °N, 138.2 °E), in which strain meters, tilt meters, and short-period seismometers are already in operation by JMA. Comparison between the seismic and electromagnetic data will be useful in understanding the fundamental physics of the earthquake preparation process. The location of sensors there is shown in Fig. 3. We also installed the induction magnetometer at Chichibu station. Induction magnetometers installed at these two stations are search coil type with 85 Hz sampling rate, named LEMI-30 produced by Lviv Center of Institute of Space Research, National Academy of Science of Ukraine. Fig. 4(a) shows the photo and Fig. 4(b) is the block diagram of the observation. Sensors are intended for the study of frequency band from 0.01 to 30 Hz and their frequency response is shown in Fig. 5. Their dynamic range is more than 120 dB and output voltage is ±10 V. 16 bit AD converters (National Instruments, AT-MIO16XE-50) are used for data collection and the obtained data are stored at the data acquisition computer (a 12 bit AD converter (Advantech, PCL-812) was used till January 2000). Detailed specification of them is summarized in Table 2. Also the acoustic emission sensor was installed at Matsushiro station (see Fig. 3). The acoustic sensor records the emissions at four frequency bands of 30, 160, 500, and 1000 Hz. The lowest band corresponds to the uppermost frequency of LEMI-30.

A small L-shaped array has been composed with three torsion magnetometers, of which the distance is about 5 km at the western part of Izu peninsula and the southern part of Boso peninsula. With these arrays, we expect to develop a method to find out the arrival direction of ULF waves. Both Izu and Boso Peninsulas are seismic active regions, so that we consider it good for precise observation for direction finding of ULF

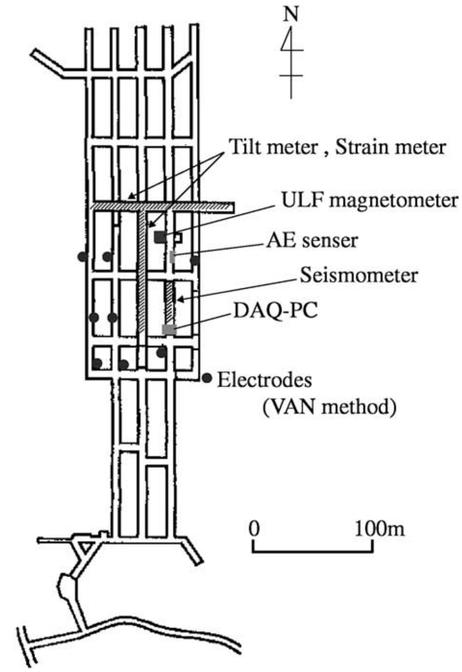

Fig. 3. The configuration of the tunnels at Matsushiro Seismological Observatory, Japan Meteorological Agency. The depth of the tunnel is about 50 m. A three component induction magnetometer, an acoustic emission sensor, and electrodes for geoelectric potential difference measurements have been installed in the tunnel. Besides inside the cave, some electrodes have been installed outside for vertical electric potential difference measurements.

Table 1
List of ULF Stations (May 1, 2003)

Station name	Code	Geographic coordinates	Type of magnetometer	Sampling rate	
Seikoshi	SKS	34.90 °N, 138.82 °E	Torsion	50 Hz	Western Izu
Mochikoshi	MCK	34.88 °N, 138.86 °E	Torsion	50 Hz	Western Izu
Kamo	KMO	34.86 °N, 138.83 °E	Torsion	50 Hz	Western Izu
Jaishi	JIS	34.70 °N, 138.79 °E	Torsion	50 Hz	Western Izu
Unobe	UNB	35.21 °N, 140.20 °E	Torsion	50 Hz	Southern Boso till May, 2001
Fudago	FDG	35.19 °N, 140.14 °E	Torsion	50 Hz	Southern Boso from May, 2001
Uchiura	UCU	35.16 °N, 140.10 °E	Torsion	50 Hz	Southern Boso
Kiyosumi	KYS	35.16 °N, 140.15 °E	Torsion	50 Hz	Southern Boso
Iyogatake	IYG	35.10 °N, 139.92 °E	Torsion	50 Hz	Southern Boso
Matsushiro	MTS	36.54 °N, 138.21 °E	Induction	85 Hz	Seismological Observatory
Chichibu	CCB	36.00 °N, 139.12 °E	Induction	85 Hz	Now stopped
Shitara	STR	35.10 °N, 137.62 °E	Torsion	50 Hz	
Misakubo	MSK	35.19 °N, 137.94 °E	Torsion	50 Hz	
Hayakawa	HYK	35.35 °N, 138.29 °E	Torsion	50 Hz	
Matsukawa	MTK	39.88 °N, 140.94 °E	Fluxgate	1 Hz	
Sakuma	SKM	34.98 °N, 137.71 °E	Fluxgate	1 Hz	
Nanno	NNO	35.20 °N, 136.59 °E	Fluxgate	1 Hz	

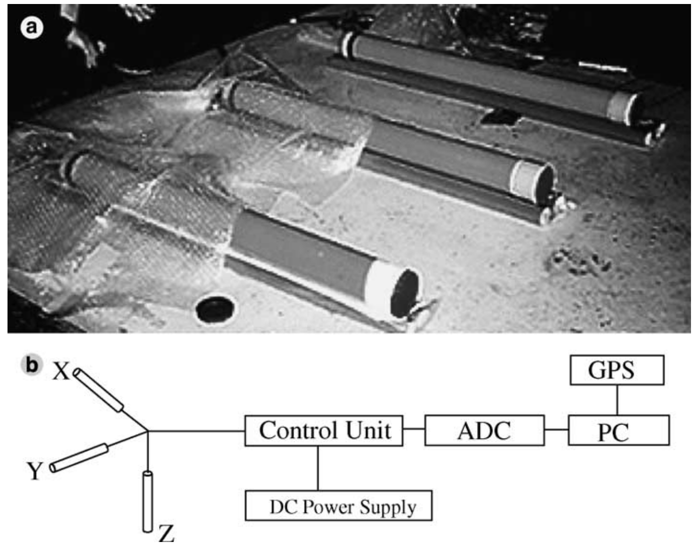

Fig. 4. Induction magnetometer, LEMI-30. (a) Photograph and (b) block diagram.

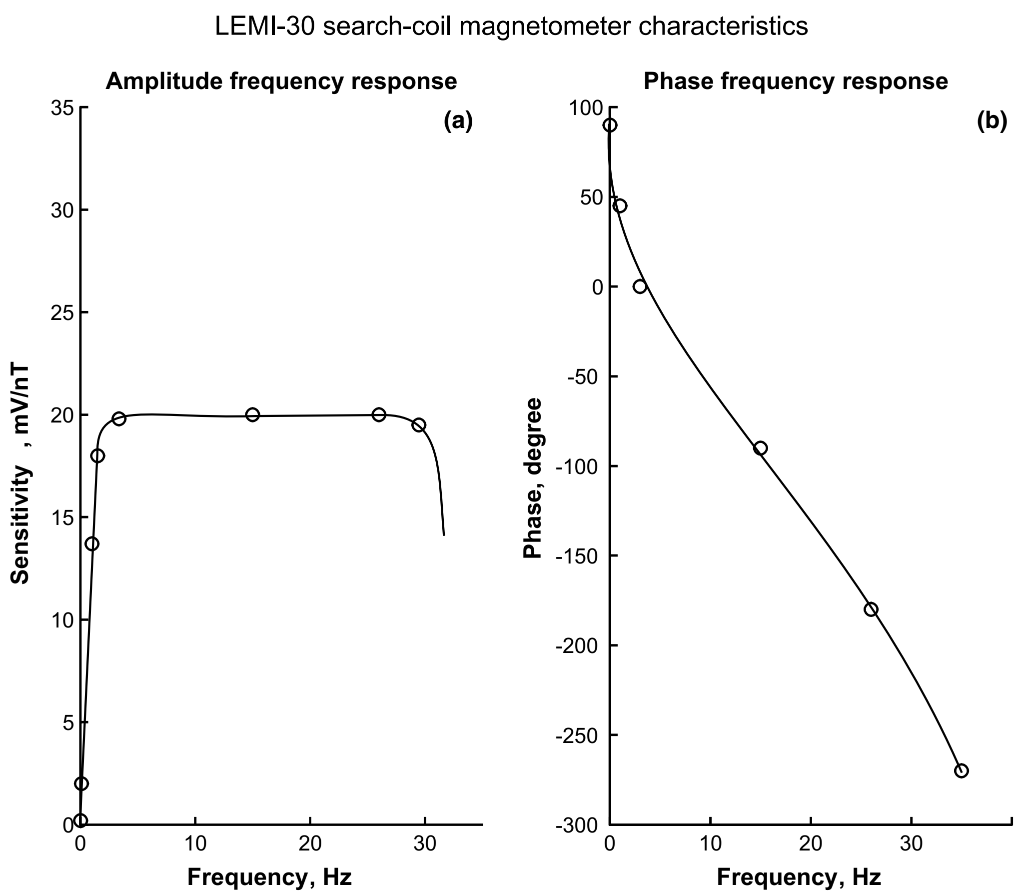

Fig. 5. Frequency response of LEMI-30. (a) Amplitude response and (b) phase response.

anomalous signals by means of the arrays. We also installed torsion magnetometers at Jaishi, Iyogatake, Hayakawa, Misakubo, and Shitara. These torsion magnetometers, MVC-2DS, were produced by Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Saint Petersburg Filial (SPbF IZMIRAN), Russian Academy of Sciences. Fig. 6(a) is the photo of the MVC-2DS which consists of the sensor unit, ADC unit and GPS unit, and Fig. 6(b) is the block diagram of the whole system. The principle of a torsion magne-

Table 2
Technical parameters of LEMI-30

Frequency band	From 0.01 to 30 Hz
Shape of transfer function	Linear from 0.01 to 1 Hz Flat from 1 to 30 Hz
Transformation coefficient value on two symmetrical outputs	
On the flat part	20 mV/nT; 200 mV/nT
On the linear part	20 $*$ f mV/nT, 200 $*$ f mV/nT (where f is the frequency of received signal)
Transformation coefficient error	$\leqslant$ 3dB
Magnetic noise level	$\leqslant$ 20 pT/Hz$^{1/2}$ at 0.01 Hz $\leqslant$ 2 pT/Hz$^{1/2}$ at 0.1 Hz $\leqslant$ 0.2 pT/Hz$^{1/2}$ at 1 Hz $\leqslant$ 0.04 pT/Hz$^{1/2}$ at 10 Hz and higher
Noise rejection on 50 ± 0.2 and 60 ± 0.2 Hz	$\geqslant$ 60 dB
Power supply voltage	12 ± 0.2 V
Temperature range of operation	−10 to 50 °C
Outer dimension	$l = 900$ mm, $d = 95$ mm
Mass (without connecting cable)	$\leqslant$ 6.5 kg
Maximum length of cable	200 m
Waterproof housing	

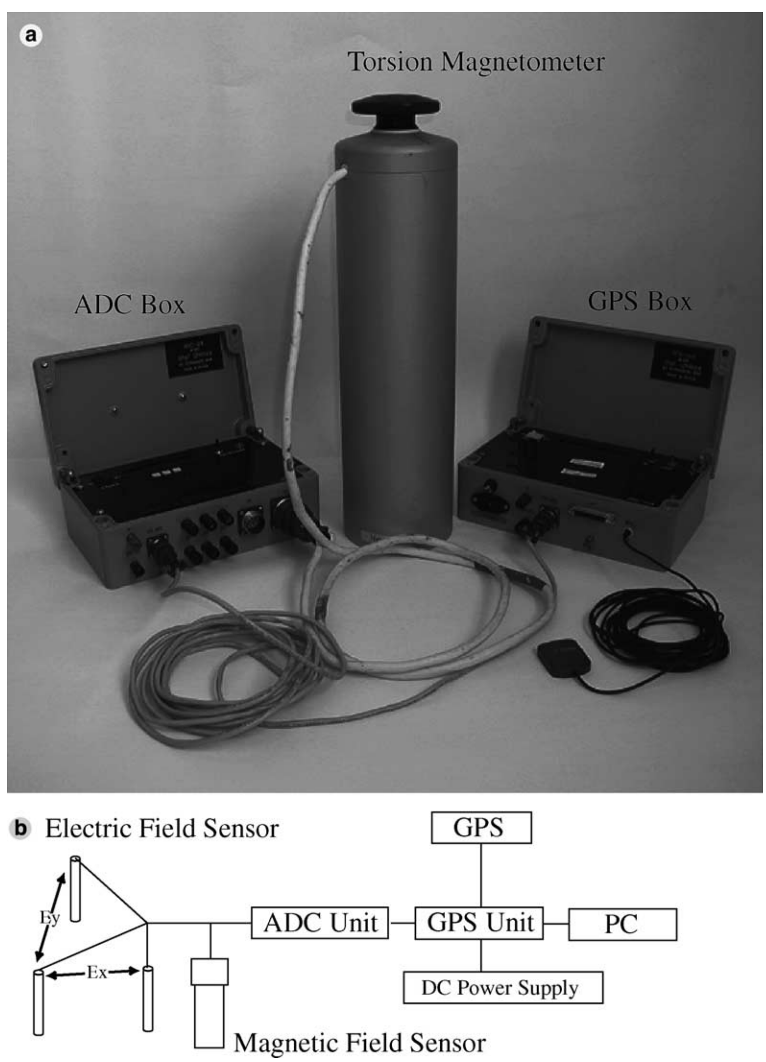

Fig. 6. Torsion magnetometer, MVC-2DS. (a) Photograph and (b) block diagram.

tometer is shown in Fig. 7. A magneto-sensitive element of the torsion sensor is a permanent magnet (1; number 1 in Fig. 7) suspended with quartz or metallic fibers (2) which serve as the rotation axis of the magneto-sensitive element. The reflecting surface (3) which transforms angular displacement of the magneto-sensitive element (MSE) into electric signal by means of photoelectric converter (4: a photo emitter (EMT), 5: a photo receiver (PHR)) is mounted rigidly to the magnetic-sensitive element. When the element is turned by the force of the external magnetic field, the light beam deviates from the zero position, leading to an increase of one diode illumination and a decrease of the other. As a result, there appears a signal proportional to the disturbed magnetic field value for the sensor output. The element is suspended inside the fluid-filled capsule on the thin metallic fibers and a low-powered monochromatic infra-red emitting diode is used for the photo emitter. The feedback circuit which produces a magnetic field opposite to the external field are adopted. Also the coil for current compensation of constant magnetic field to set up the magnetic-sensitive element at the zero position and the coil for calibration are installed as shown in Fig. 7(b). The main technical parameters of MVC-2DS are described in Table 3. The MVC-2DS has capacity to measure three electric (telluric) components and three seismic components (reserved). Its frequency range and measurement range are ∼15 Hz and ±5000 nT, respectively. The sampling frequency is 50 Hz. Output voltage of the sensor is ±10 V and 24 bit AD converters (Analog Devices, AD7712AN) are used. Fig. 8 gives itsfrequency dependence.

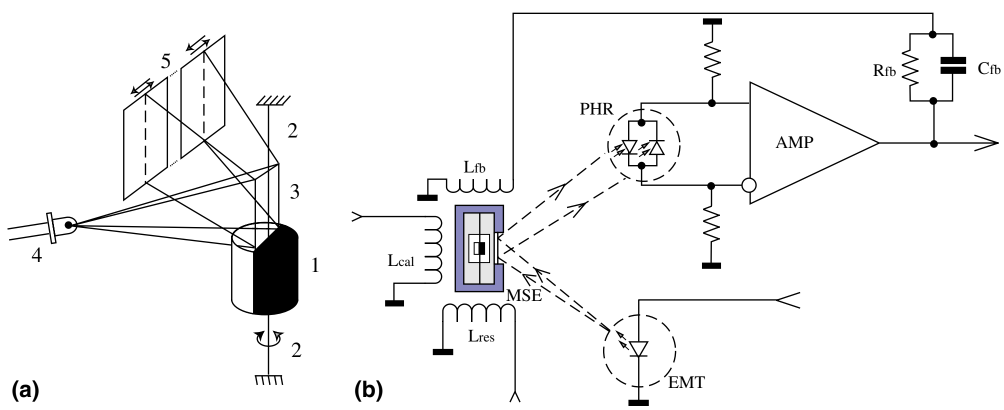

Fig. 7. Principle of a torsion magnetometer. (a) Magnetic field measurement and (b) electric circuit for a sensor device.

Table 3
The technical parameter of torsion magnetometers MVC-2DS

Values to be measured	
MVC-2DS	Three mutually orthogonal components of magnetic field, H, D, and Z
	Three components of electric field (E_x, E_y, E_z)
	Three components of seismometer (reserved)
Frequency range (MVC-2DS)	From 0 to 50 Hz (analog signal)
	From 0 to 10 Hz (digital signal)
Dynamic range	±5000 nT for magnetic components
	±2.5 V for electric (telluric) components
Output voltage for magnetic port	±10 V
Output voltage for electric port	±2.5 V
Noise level	3 pT/Hz$^{1/2}$ at 1 Hz
Integral noise level for magnetic components (peak to peak)	∼0.01 nT (analog signal) from 0.01 to 15 Hz
Integral noise level for magnetic components (peak to peak)	∼10 μV (analog signal) from 0.1 to 10 Hz
Supply voltage	12 V (from 10.5 to 18 V)
A/D converter resolution	24 bit
Sampling rate	50 Hz
Consumed power (including A/D converter)	⩽ 7.5 W
Drift of zero point with temperature	⩽ 1 nT/°C
Operating temperature range	−20–50 °C
Value of internal calibration coils constant (for H, D, Z sensors)	170 ± 10 nT/mA
Dimensions	500 mm height, 125 mm diameter
Weight	12.5 kg
GPS unit voltage	AC 100 V or DC 12 V

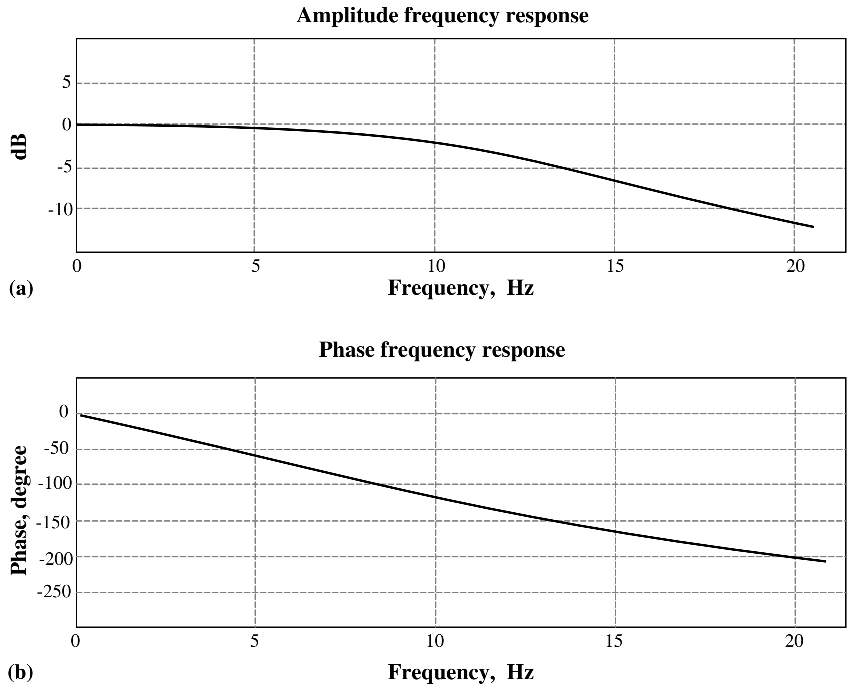

Fig. 8. Frequency response of MVC-2DS. (a) Amplitude response and (b) phase response.

Some fluxgate 3 components magnetometers have been installed in addition to the above-mentioned ULF network, which are JCS-107F (Chiba Electronics Inc.: frequency range ~1 Hz; dynamic range: ±400 nT; output voltage: ±10 V). The output data are registered at SES93/SES96 loggers (Ad Systems Co. Ltd.). Fig. 2 shows the distribution map of fluxgate magnetometers. Table 1 also gives information about the location of fluxgate magnetometers. The sampling rate for them is 1 Hz. Data are recorded after passing through the 2 s low pass filter with the use of a 20 bit AD converter. Stored data are transferred to Chiba University through Tokai University at Shimizu once a day by the internet. Matsukawa, Nanno, and Sakuma satations are in operation now. In this paper, we present the Matsukawa station data only.

2.2. Typical ULF magnetic station

Fig. 9 shows the typical configuration of a ULF magnetic station with MVC-2DS. Magnetic sensor unit is installed under the ground of about 1 m depth in a plastic waterproof box. Besides the sensor unit, AD converter unit is set up also in the plastic box. Pb–$PbCl_2$ electrodes are buried at 1–2 m depth for telluric measurements. At least, an orthogonal couple of short dipoles with some tens meters has been deployed. The ADC is connected with GPS unit for timing and obtained data are digitized at the ADC unit. Then, digitized data are recorded in a hard disk drive at the data acquisition PC (DAQ PC). The stored data after resampled down to 1 Hz are sent to Chiba University once a day or on demand through internet or ISDN public phone line. At the university the database is created automatically. The raw data sampled with 50 Hz are stored only at the remote DAQ PC and sent to Chiba University with the use of off-line transfer. As for other devices, the data transfer procedure is quite similar except the re-sampling process, which is not used.

3. Observed data

In this section, we will present an example of the observed data related to Iwateken Nairiku Hokubu earthquake occurred in the vicinity of Mt. Iwate, the northern part of Honshu island ($M = 6.1$, depth ~10 km, September 3, 1998). The epicentral distance from Matsukawa station was about 15 km. The ULF magnetic phenomena associated with this earthquake were observed, as well as anomalous pre-seismic electric potential change (Uyeda et al., 2000) and co-seismic electric potential and magnetic field changes (Nagao et al., 2000).

3.1. ULF magnetic anomaly preceding 1998 Iwateken Nairiku Hokubu earthquake

The volcanic activity of Mt. Iwate has increased since 1998. In order to investigate the electromagnetic phenomena associated with this volcanic activity, a three-component fluxgate type magnetometer has been

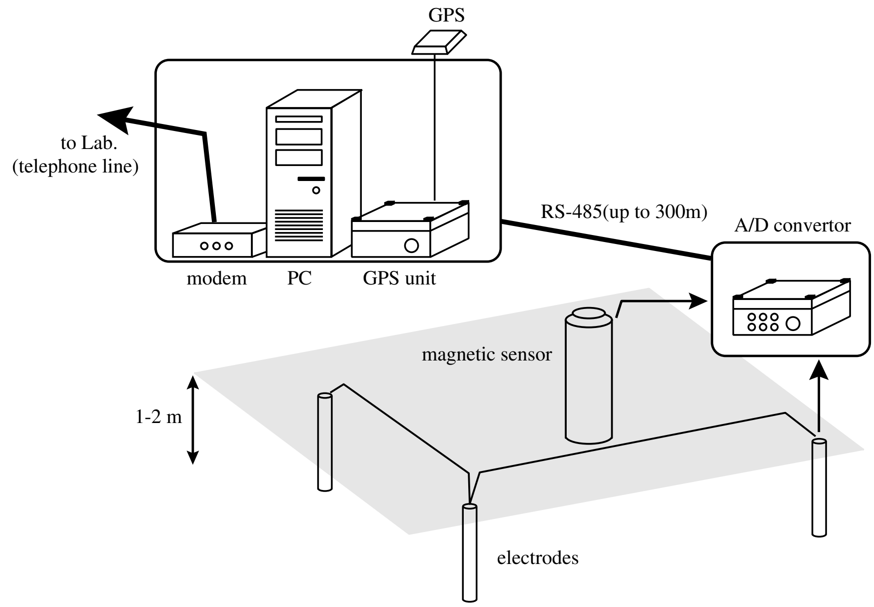

Fig. 9. The typical feature of a ULF magnetic station (a station with MVC-2DS is drawn here).

installed near Mt. Iwate (40.0 °N, 140.9 °E) with 1 Hz sampling rate since May 24, 1998. First, we summarize the volcanic activity of Mt. Iwate.

Mt. Iwate is an active volcano in the northern part of Japan, but its activity was quite low till 1998. Volcanic tremors and low-frequency earthquakes were observed nearby the top of Mt. Iwate from September 1995. The occurrence rate of those phenomena is a few per month. The volcanic earthquakes with shallow focal depth began to occur in the western part of Mt. Iwate in January 1998. The activity gradually increased after the middle of February 1998, and there were more than 200 volcanic earthquakes around 15:00 L.T. on April 29. The number of them often exceeded 100 in the period of June and July 1998. Furthermore, the number of felt earthquakes was also increased and volcanic tremors and low-frequency earthquakes were observed during this period. After a tremor with a large amplitude on July 10, the activity was decreasing gradually. However, still 139 volcanic earthquakes occurred in a short period on August 30 and two tremors were also observed. After the end of July, volcanic earthquakes occurred under the summit even though the number and scale were small. Then, Iwateken Nairiku Hokubu earthquake with $M = 6.1$ occurred at 16:58 L.T. on September 3, 1998, focal epicenter was located at 39.8 °N and 140.9 °E, and whose depth was about 10 km. The earthquake was caused by the compression in east–west direction and produced a reverse slip fault. There were 555 earthquakes on September 3.

Fig. 10 shows the locations of earthquake epicenter and Matsukawa station where the magnetometer has been installed. The distance between the epicenter and the magnetometer was about 15 km. Matsukawa station has been in operation with 1 Hz sampling rate since June 24, 1998. The observed data were recorded by a logger Datamark LS-3300Ptv (Hakusan Co. Ltd., 20 bit) from June 24 to September 17. After middle September 1998, data have been stored in SES96 (Adsystem Co. Ltd., 20 bit) and transferred to the central office by telephone line every day.

It is important to extract the underground effects at the background of the geomagnetic activity to verify and to clarify the relationship between the earthquakes and ULF magnetic activity. The observed data have been analyzed in a similar manner as reported in Hayakawa et al. (1996a).

(1) The data observed in the midnight (0:0 h–0:4 h local time) have been used because the artificial disturbances and effects of magnetic pulsations are considered to be much smaller than those in the daytime.
(2) Spectral analysis based on FFT method with 30 min interval has been applied to the waveforms of three magnetic field components, what gives 8 units files.
(3) Earthquake-related activated frequency range has been checked.
(4) In order to separate the underground effects from the geomagnetic variations more clearly, the ratio of vertical and horizontal components of spectral density S_Z/S_H has been investigated (Hayakawa et al., 1996a). This ratio is called polarization.
(5) The FFT files at a certain frequency band have been averaged and taken as a daily value. The data observed at a place far from the epicentral region have been analyzed as a remote reference in order to dis-

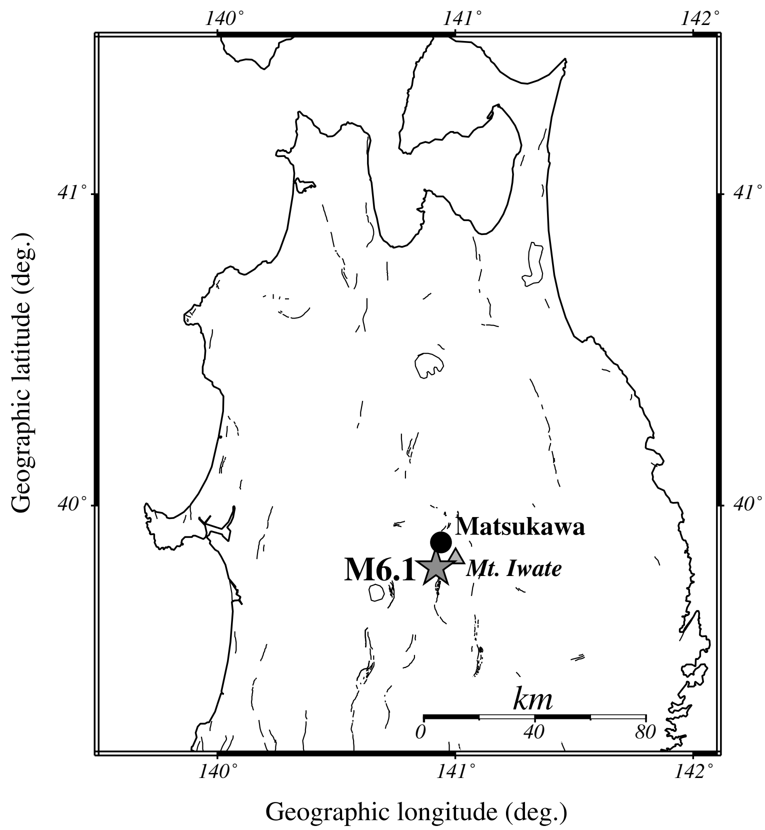

Fig. 10. The relative location between the epicenter and Matsukawa station.

tinguish between the local and global phenomena. In this paper, Memambetsu and Kanoya stations are taken as remote reference stations in order to investigate whether the obtained ULF magnetic phenomena are global or local. Memambetsu station (43.9 °N, 144.2 °E) belongs to JMA and is located at 500 km distance in north direction from the epicenter. Kanoya station (31.4 °N, 130.9 °E) also belongs

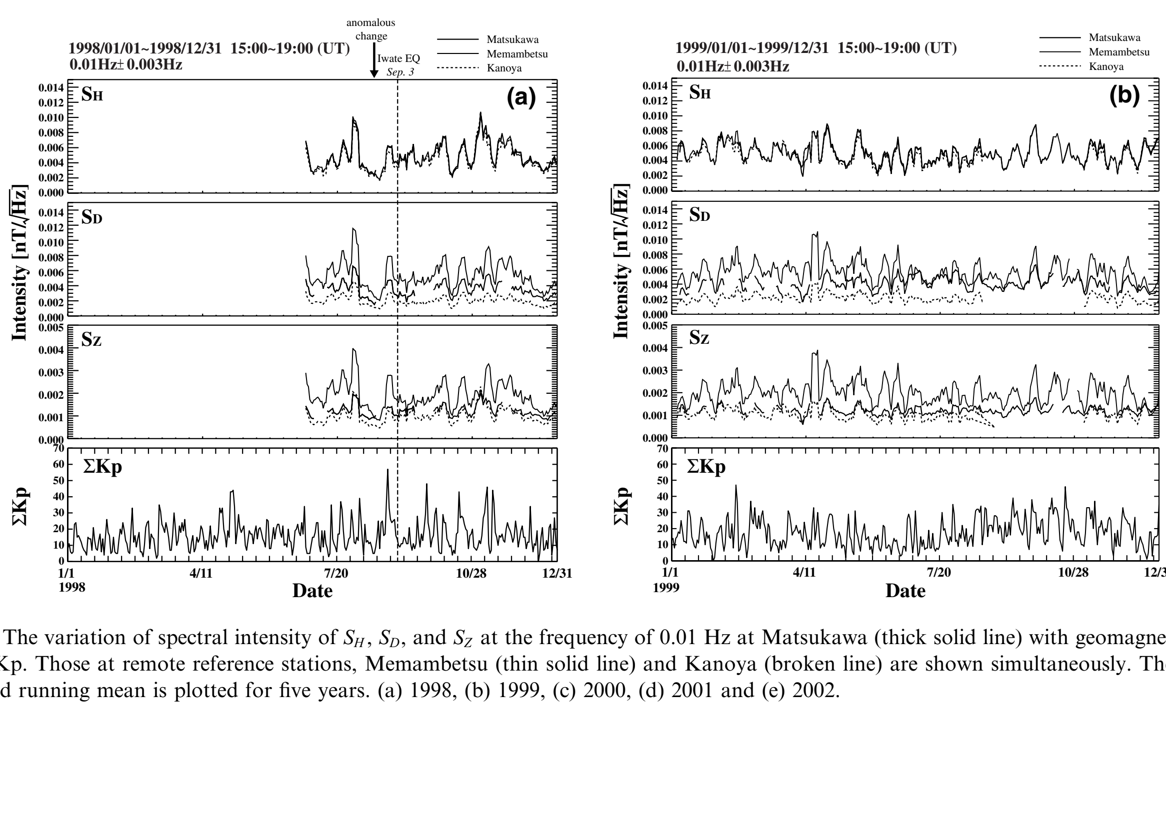

Fig. 11. The variation of spectral intensity of S_H, S_D, and S_Z at the frequency of 0.01 Hz at Matsukawa (thick solid line) with geomagnetic activity index ΣKp. Those at remote reference stations, Memambetsu (thin solid line) and Kanoya (broken line) are shown simultaneously. The five days backward running mean is plotted for five years. (a) 1998, (b) 1999, (c) 2000, (d) 2001 and (e) 2002.

to JMA, which is 1300 km south-west of the epicentral region. The different fluxgate magnetometers were in operation with 1 Hz sampling rate.

(6) The regional seismic activity around the station have been investigated in comparison with the ULF magnetic activity.

We analyzed midnight time data during about 4.5 years from June 24, 1998 to December 31, 2002. Unfortunately, there were data missing in the following periods; (1) July 4–8, 1998, (2) August 19–21, 1998, (3) September 17–27, 1998, (4) November 21–23, 1998, (5) January 1–3, 15–36, 28–30, 1999, (7) February 10–12, 15, 26–27, 1999, (8) March 12–15, 25–26, 1999. (9) April 8–9, 15–16, 1999, (10) August 13, 1999, (11) October 14–15, 1999, (12)November 25–26, 1999, (13) April 17–20, 29–30, 2000, (14) May 1, 2000, (15) October 18–19, 2000, (16) December 13–14, 27–28, 2000, (16) January 10–11, 19, 24–25, 2001, (17) March 7–8, 2001, (18) April 18–19, 2001, (19) August 4–5, 8–10, 22–23, 29–31, 2001, (20) September 1–6, 15–18, 21–24, 27–30, 2001, and (21) October 1–4, 12–16, 2001.

The seismic activity related frequency range has been found to be around 0.01–0.05 Hz and this frequency range agrees with previous reports (Fraser-Smith et al., 1990; Hayakawa et al., 1996a; Hattori et al., 2002). Fig. 11 shows the variation of intensities at the frequency of 0.01 Hz at Matsukawa, Memambetsu, and Kanoya stations with information of the day of the earthquake (M6.1, September 3, 1998). The alphabetic order cor-

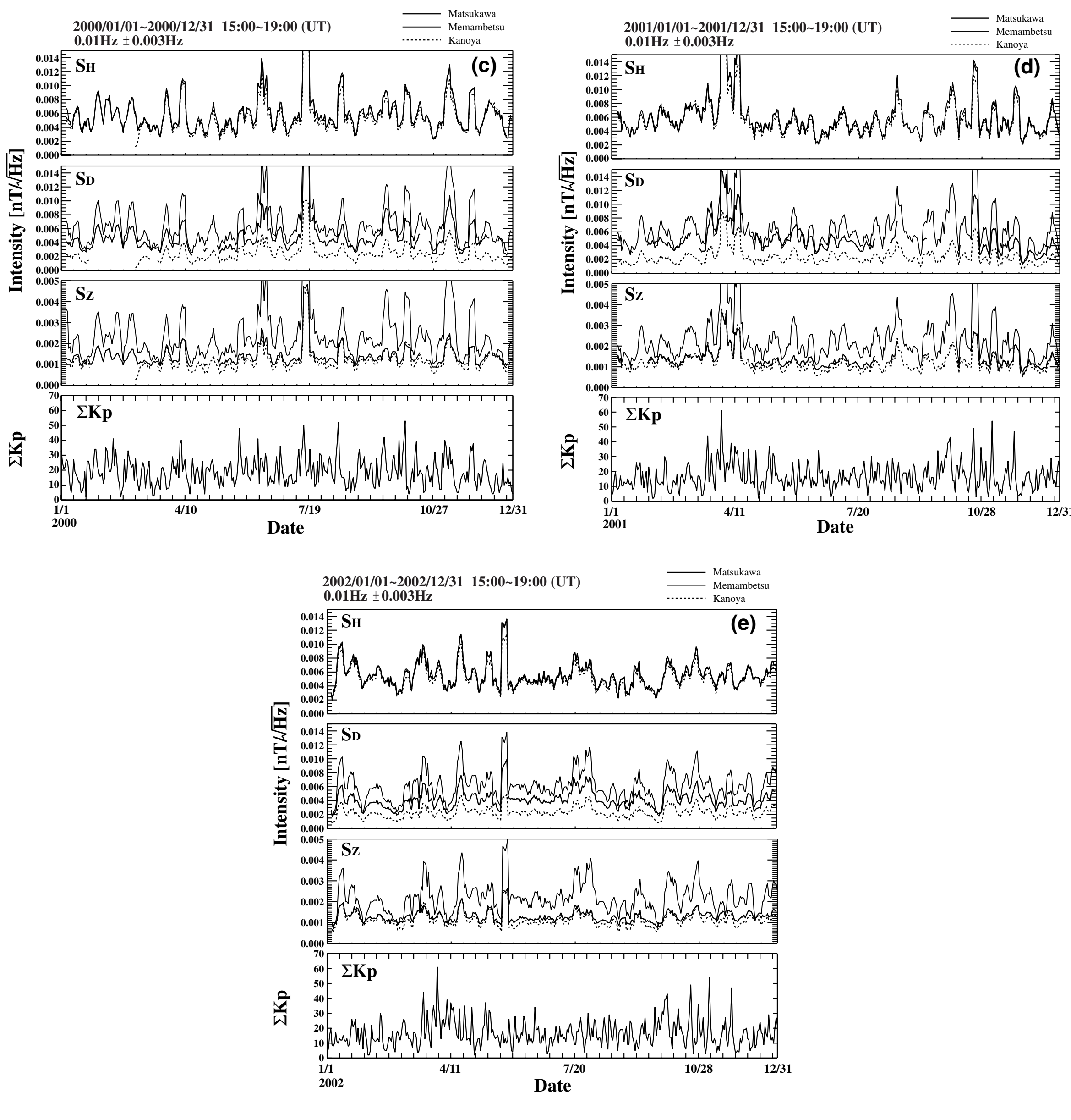

Fig. 11 (*continued*)

responds to the annual order from 1998 to 2002. 5 days backward running means of S_H, S_D and S_Z are plotted, where S_H, S_D and S_Z are corresponding to the spectral density of NS, EW and vertical component, respectively. Variations of horizontal two components are quite similar, and the variations in the vertical component are also generally similar to those of horizontal components. However, the variation around August 15, 1998 seems to be different; that is, values at Memambetsu and Kanoya are decreasing, while those at Matsukawa have a tendency of increase.

Fig. 12 demonstrates the results of polarization analysis. The alphabetic order is the same as in Fig. 11. The top panel illustrates the variation of polarization, S_Z/S_D at the frequency band of 0.01 Hz. The thick, thin and dashed lines indicate the 5 days backward running mean of computed diurnal S_Z/S_D at Matsukawa, Memambetus and Kanoya station, respectively. Generally, the variations of polarization seem to be very stable for Memambetsu and Matsukawa stations and that of Kanoya station is found to be most scattered among these three stations. But the pattern of variation is found to be very similar to other two stations. The information on the day of the earthquake is also marked by a vertical line. The most important fact is an enhancement in the polarization of S_Z/S_D at Matsukawa station around 16 days before the earthquake on September 3, 1998. The time when anomalous change is observed, is marked by a vertical line in this figure and Fig. 11. The peak of intensification of polarization reached about 1.5 in S_Z/S_D, which is about twice of the ordinary level. Similar tendency was also obtained in the polarization of S_Z/S_G, where S_G means the total horizontal spectral density. But the intensification on S_Z/S_D is more apparent than that of S_Z/S_G. This kind of anomalous change is not recognized at least on the variations on S_Z/S_D at Memambetsu and Kanoya stations. Unfortunately, we missed the data during August 20–22, 1998. However, this kind of anomalous change has not been detected for the analyzed 4.5 years interval, and it is an important experimental fact. Similar variations were obtained at other frequency bands of 0.02 and 0.03 Hz at Matsukawa. No such variations can be seen at higher frequency. The second panel plots the 5 days backward running mean and daily value of S_Z/S_D. A thick line and a thin line mean the running mean and the daily value, respectively. The anomalous peak of S_Z/S_D is not the resultant of only one high daily value only.

The lower two panels show the seismic activity around Matsukawa station in order to investigate the relationship between the seismic activity and above ULF S_Z/S_D at 0.01 Hz frequency band. The third panel shows the daily sum of earthquakes occurred within 100 km hypocenter distance from Matsukawa station. JMA earthquake catalog is used for this investigation. The anomalous change of S_Z/S_D before the earthquake (M6.1) on September 3 and the peak of seismic activity seemed to be somehow correlated with each other.

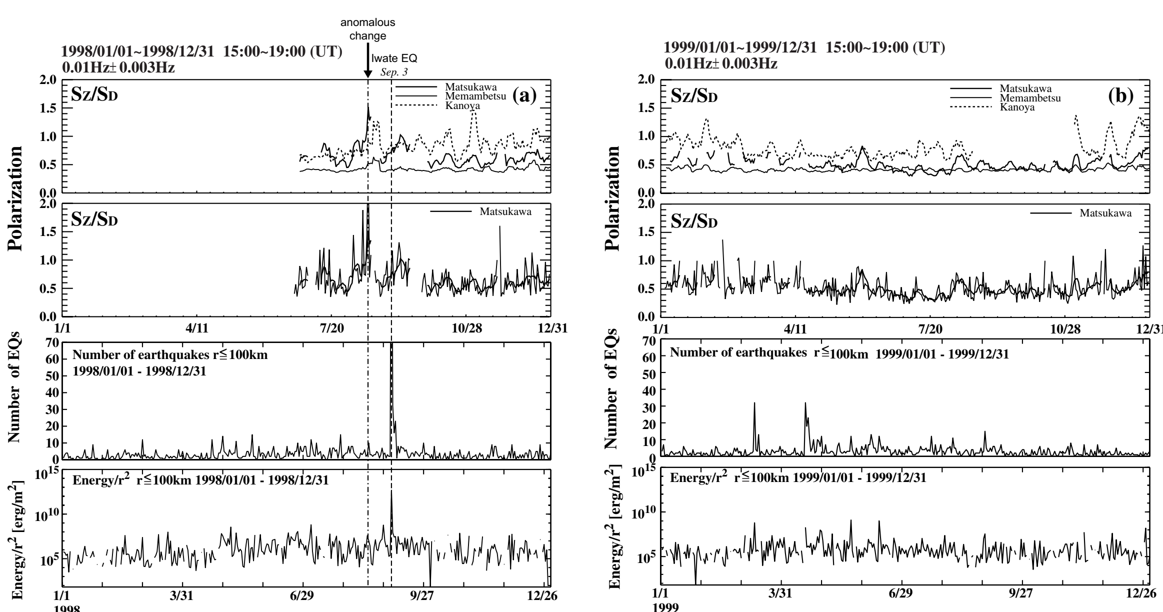

Fig. 12. The variation of polarizations S_Z/S_D at the frequency band of 0.01 Hz for five years: (a) 1998, (b) 1999, (c) 2000, (d) 2001 and (e) 2002. The top panel shows the variation of polarizations S_Z/S_D at the frequency band of 0.01 Hz. 5 days backward running mean values at Matsukawa station (thick solid line) and at two remote reference stations, Memambetsu (thin solid line) and Kanoya (broken line) are simultaneously plotted. The second panel displays the detailed variation of polarization S_Z/S_D at Matsukawa station. 5 days backward running mean (thick solid line) and daily values (thin solid line) are plotted. The third panel shows the number of earthquake near Matsukawa station ($r < 100$ km). The bottom panel indicates the variation of daily regional seismicity E/r^2, with taking account of hypocentral distance r.

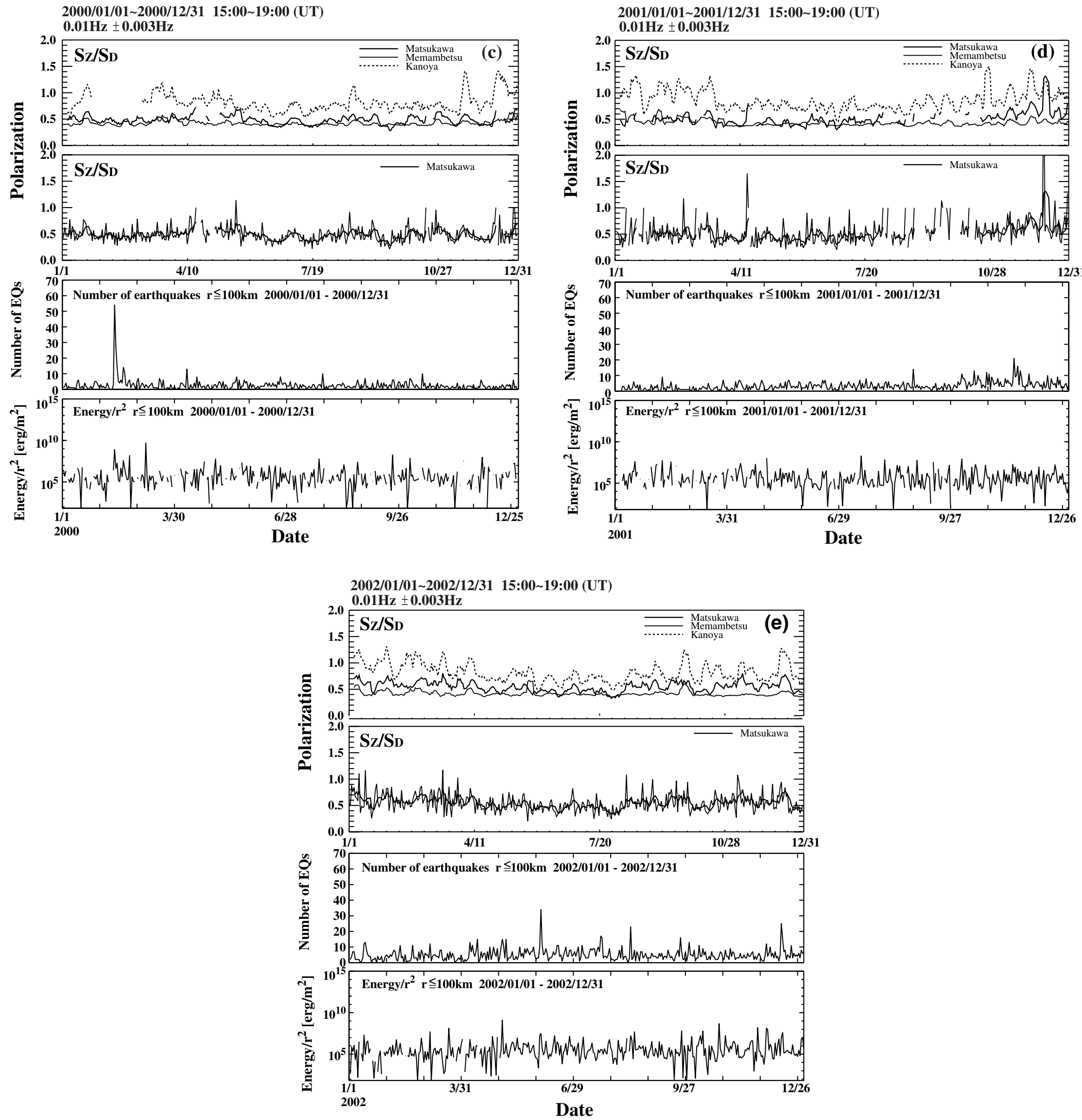

Fig. 12 (*continued*)

Therefore, the daily sum of the regional seismicity with taking account of hypocentral distances is displayed in the bottom. For this computation, the formula log $E = 11.8 + 1.5M$, has been accepted, where E and M are the energy and magnitude of an earthquake, respectively. Earthquakes with hypocentral distance of r less than 100 km have been collected from JMA catalog and the regional seismicity of E/r^2 has been calculated. Then, the daily sum of E/r^2 was plotted in the figure. Based on the analyzed period of 4.5 years, the apparent active seismic period around Matsukawa station is only the period of Iwateken Nairiku Hokubu Earthquake (M6.1) and $E/r^2 > 10^{10}$ erg at that moment. Correspondingly, the variation of polarization S_Z/S_D is found to show an anomalous increase and the peak in S_Z/S_D preceded the main shock by about 16 days. This long-term investigation highly suggests that there may be a certain correlation between the ULF activity and regional seismic activity. That is, the results suggest that the enhancement in polarization around September 3, 1998 is a local phenomenon around Matsukawa station, and there is a possibility to be associated with the Iwateken Nairiku Hokubu Earthquake.

4. Concluding remarks

The present paper gives still one evidence of the reality of ULF magnetic phenomena preceding a large earthquake and the possibility of short-term earthquake prediction using them. Our final goal is to formulate a convincing scenario. For this aim, a practical basis for the regular ground ULF monitoring system has been established in Japan. It consists of Kanto-Tokai network composed by sensitive sensors with high sampling rate and stations with a fluxgate type magnetometer. The network installed over the Kanto-Tokai region has base lines of 5–100 km. Among them, Matsushiro station of Kanto-Tokai network is a special station to make a bridge between electromagnetic and seismic phenomena.

In order to investigate ULF magnetic phenomena associated with Iwateken Nairiku Hokubu earthquake, data observed at Matsukawa station during the long interval from June 1998 to December 2002 have been analyzed. An anomalous change of polarization (as the ratio of vertical and horizontal components) has been confirmed. This anomalous enhancement was found about two weeks preceding the main shock and it was a local phenomenon around Matsukawa station with comparison to the remote reference data. Furthermore, the regional seismic activity around Matsukawa station was also investigated, which was highly suggestive of a certain relation between ULF and seismic activities of Iwateken Nairiku Hokubu Earthquake.

Correlations among ULF magnetic signatures, electric potential differences, acoustic emission activity, and seismic signals should be investigated in detail to clear up the origin of ULF phenomena in future. The use of direction finding techniques for ULF magnetic signals should be carried out to investigate the source and transmission mechanism.

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