The observation of ULF emissions at Nakatsugawa in possible association with the 2004 Mid Niigata Prefecture earthquake

Kenji Ohta[1], Nobuo Watanabe[1], and Masashi Hayakawa[2]

[1]*Department of Electronics Engineering, Chubu University, 1200 Matsumoto-cho, Kasugai, Aichi 487-8501, Japan*
[2]*Department of Electronic Engineering, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan*

(Received February 8, 2005; Revised July 11, 2005; Accepted August 28, 2005)

The observation of ULF/ELF electromagnetic emissions at Nakatsugawa, Gifu, has indicated that ULF emissions in the frequency below 0.1 Hz take place about two-three weeks before the 2004 Mid Niigata Prefecture earthquakes. The most important support to this is based on the goniometric direction finding for those ULF emissions in the period of October 2–6, which indicates their azimuth being very close to the epicenters of the earthquake. So, these ULF emissions on October 2–6 are likely to be associated with the 2004 Mid Niigata Prefecture earthquake.
Key words: Seismogenic ULF emissions, 2004 Mid Niigata Prefecture earthquake, goniometric direction finding.

1. Introduction

There have been recently reported that electromagnetic emissions are observed in a wide frequency range from DC, ULF to VHF in possible association with earthquakes (Hayakawa, 1999; Hayakawa and Molchanov, 2002). However, the lower frequency range like ULF (ultra-low-frequency, frequency less than 10 Hz or so) is the most attractive because there have been convincing evidences on the precursory occurrence of ULF emissions before large earthquakes including Spitak, Loma Prieta, Guam etc. (e.g. Hayakawa and Hattori, 2004 as a review on seismogenic ULF electromagnetic emissions). Our recent studies (Hayakawa and Hattori, 2004) have suggested that ULF emissions can be observable within the epicentral distance of ∼100 km for an earthquake with magnitude 7, while ∼70–80 km for an earthquake with magnitude 6. However, Ohta *et al*. (2001) have successfully detected in Japan the ULF/ELF emissions which are associated with the Chi-chi earthquake in Taiwan. Once they are exited into the atmosphere, they seem to be able to propagate over great distances as in the case of Ohta *et al*. (2001).

This short letter reports on the detection of seismogenic DC/ULF electromagnetic emissions which are likely to be associated with the 204 Mid Niigata Prefecture earthquake.

2. Observation of ULF/ELF Waves at Nakatsugawa

Figure 1 illustrates the block diagram of our ULF/ELF observing system at Nakatsugawa in Gifu Prefecture. We have three orthogonal induction coils (1.2 m permalloy) as magnetic sensors and we observe three magnetic field components (B_x, B_y and B_z; x, y are the horizontal axes, and z, the vertical axis). The signals from magnetic field components are amplified by means of pre-amplifiers (gain = 66 dB) with the low pass filter (with cutoff of 30 Hz). Then the signals are converted by means of an A/D converter with sampling frequency of 100 Hz, and they are stored on a hard disc every six hours. The file is consisted of four files; file 0: 00 h to 6 h L.T., file 1: 06 h to 12 h, file 2: 12 h to 18 h, and file 3: 18 h to 24 h. The details of our ULF/ELF observation system have already been described in Ohta *et al*. (2001).

Signal analysis is based on the FFT with the data length of 1024, so that the temporal resolution is about 10 seconds and the corresponding frequency resolution is about 0.1 Hz. We can measure the amplitude ratio and phase difference among the three components in the frequency range from 0 Hz to 50 Hz.

3. Observation of Seismogenic ULF/ELF Emissions at Nakatsugawa

Figure 2(a) shows the temporal evolution of the magnetic field intensity (horizontal B_y component: sensitive to the waves propagating in the NS meridian plane) at a particular frequency of 0.1 Hz (to be exact, this frequency means the frequency below 0.1 Hz). The intensity is averaged over one file with duration of six hours, and the period is from the middle of September to the end of October, because the 2004 Mid-Niigata Prefecture earthquake occurred on October 23. While, Figs. 2(b), 2(c) and 2(d) refer to the corresponding variations at higher frequencies of 1.0 Hz, 3.0 Hz and 5.0 Hz, respectively. The intensity expected by dB at different frequencies is given by the same unit.

Figures 3(a) and 3(b) show the dynamic spectra (sonograms) on October 5 (file 3; 18 h–24 h L.T.) and October 30 (file 3: 18 h–24 h), respectively. The vertical axis is the frequency from 0 Hz to 50 Hz, and the intensity is plotted in color.

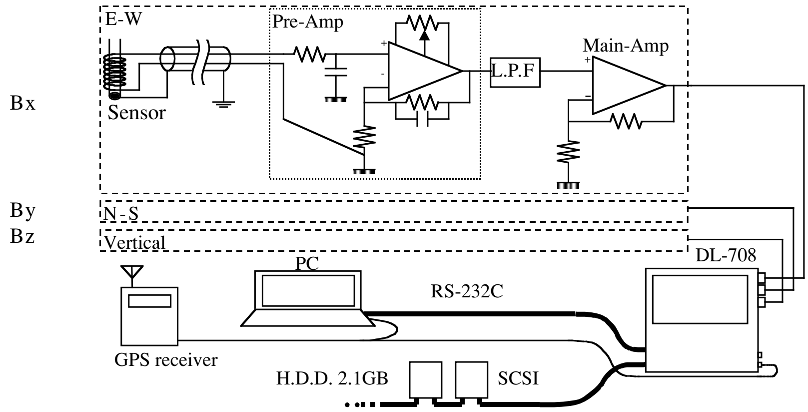

Fig. 1. The block diagram of our observation system of electromagnetic waves in the ULF/ELF range.

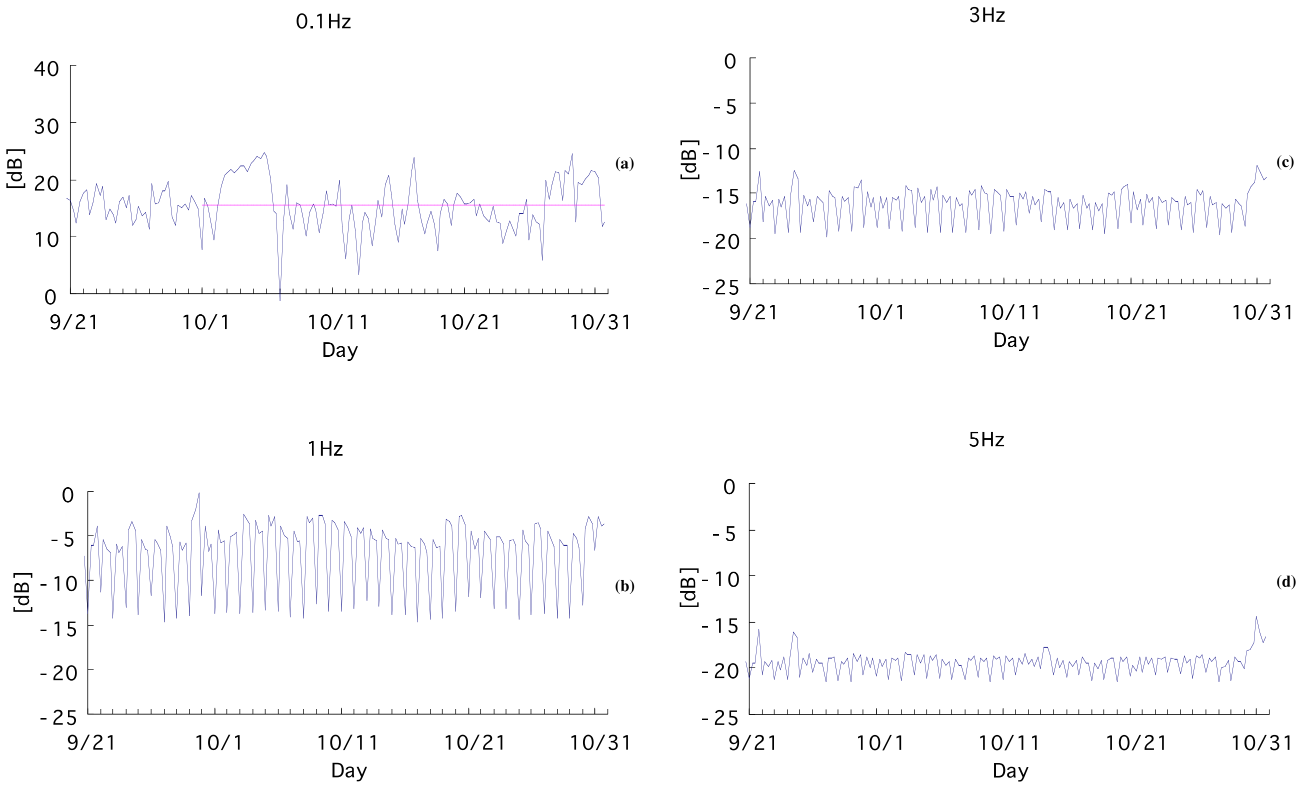

Fig. 2. Temporal evolutions of the magnetic field component (B_y component) at different frequencies; (a) 0.1 Hz, (b) 1.0 Hz, (c) 3.0 Hz and (d) 5.0 Hz. The period is from September 21 to October 31, 2004.

When we look at the temporal evolutions at different frequencies in Fig. 2, we notice a noticeable and significant difference between the two (one for 0.1 Hz and others for higher frequencies). For higher frequencies such 1.0 Hz, 3.0 Hz and 5.0 Hz, the temporal evolution is found to exhibit a very regular diurnal pattern such that the noise for the file 0 (00 h to 06 h L.T.) is extremely at low level, it increases to the maximum due to the human (or industrial) activity for the file 1 (06 h to 12 h), it shows a slight decrease due to the lunch-time effect for the file 2 (12 h to 18 h), and it increases again for the file 3 (18 h to 24 h). Figure 2(a) indicates that there are only very limited time intervals in which the noise level keeps the high level (approximately above 20 dB); that is, the period from October 2, file 1 to October 6, file 0 and another is October 30 and 31. Figure 3 indicates that the intensity is rapidly depressed above the frequency of 25 Hz, which is due to the effect of the LPF inserted in the pre-amplifier in order to discriminate the power line radiation at 50/60 Hz. The line emissions at 14 Hz and 20 Hz are the well-known Schumann resonances (Nickolaenko and Hayakawa, 2002). A glance at Fig. 3(b) for the file 3 (18 h to 24 h) on October 31, suggests the numerous occurrence of pulsive atmospherics. On these two days at higher frequencies we can notice the more enhanced effect of atmospherics over the lower frequency background noise. So, the enhanced level on October 30 and 31 in Fig. 2(a) is apparently due to the effect of atmospheric noise. Then, we make some more detailed analysis for the enhancement of noise level during the elongated period of October 2 to 6.

The horizontal line in Fig. 2 (a) indicates the average

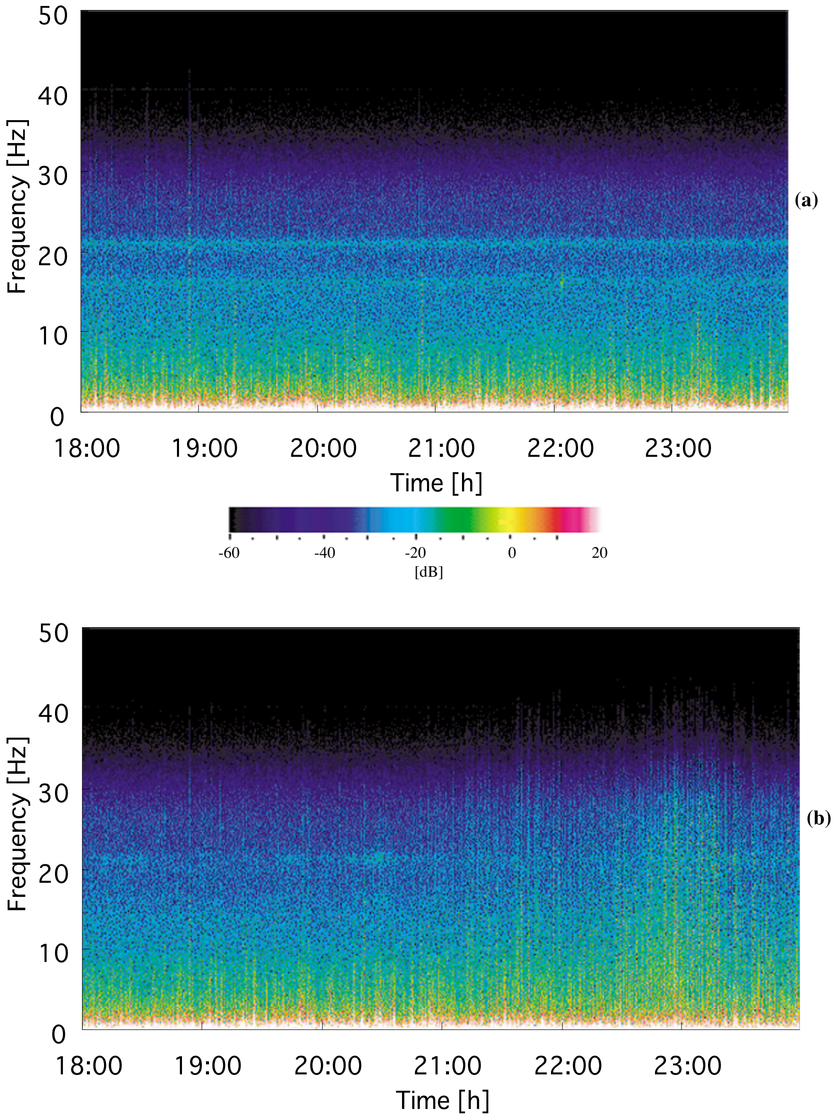

Fig. 3. (a) Dynamic spectrum for the file 3 (18:00 to 24:00 L.T.) on October 5, 2004. The magnetic field is B_y. (b) The corresponding dynamic spectrum for the file 3 (18:00 to 24:00 L.T.) on October 30, 2004.

level during one month of October for the By component, and the broken line indicates the +3 dB above the average. We perform the direction finding for the noises during the period when the noise intensity exceeds +3 dB above the average. The direction finding is the conventional goniometer by using only the two horizontal magnetic components (Hayakawa, 1995; Ohta *et al.*, 2001). Of course, the system of direction finding at lower frequencies of our concern is not well established. When we observed seismogenic ELF emissions at Nakatsugawa, which are possibly associated with the Chi-chi earthquake in Taiwan, the polarization was nearly linearly polarized so that we could expect that the waves are quasi-TEM mode (Ohta *et al.*, 2001), which enabled us to perform the successful use of a goniometer. This is the reason why we use the goniometer here.

The measuring accuracy of the goniometric direction finding depends on the antenna length and antenna alignment accuracy. The length of one induction magnetometer is only 1.2 m, so that the overall estimate of the measuring accuracy is on the order of ±5°. Table 1 is the summary of the direction finding results (the average value for each file (or for six hours)), together with the average intensity. The azimuth is indicated northward from the geographic East direction (as estimated from $\tan^{-1}(B_y/B_x)$). The average azimuth is about 55° northward from the east, which means the noises during the period of October 2 to 6 are arriving from 55° north of the east. These noise enhancements are found to exhibit no diurnal patterns as in Figs. 2(b)–(d) for higher frequencies, which may be indicating that these noises are not artificial (due to human activity). Figure 4 shows the average azimuth in Table 1. As the conclusion, this azimuth is very close to the epicenters of the 2004 Mid Niigata Prefecture earthquakes, so that the noises on October 2–6 are highly likely to be associated with the Niigata earthquakes. In order to support this conclusion we show the corresponding direction finding results for some periods (October 27–30) with intensity exceeding +3 dB above the average in Fig. 2(a). The direction finding results for these few days have indicated that the azimuth estimated is peaked at 60–65° with extremely wide distribution. This

Table 1. Summary of the intensity and azimuthal angle estimated at the frequency of 0.1 Hz. The average intensity and average azimuthal angle are indicated for each file.

Day	File number	Intensity [dB]	Azimuth angle [°]
Oct. 2	2	18.9	52
Oct. 2	3	20.6	51
Oct. 3	0	21.2	50
Oct. 3	1	21.7	52
Oct. 3	2	21.2	51
Oct. 3	3	21.7	53
Oct. 4	0	22.4	61
Oct. 4	1	22.4	59
Oct. 4	2	21.3	51
Oct. 4	3	22.9	55
Oct. 5	0	23.3	54
Oct. 5	1	24.1	55
Oct. 5	2	23.7	52
Oct. 5	3	24.8	53
Oct. 6	0	24.0	59
Oct. 6	1	20.3	66

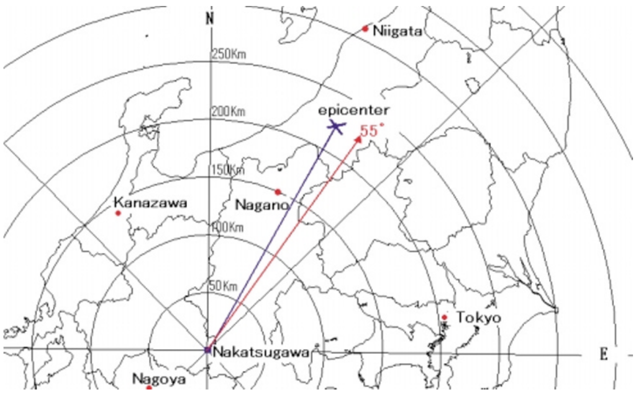

Fig. 4. Relative location of our observing station at Nakatsugawa (Gifu prefecture) and the epicenter of the main shock of the 2004 Mid Niigata Prefecture earthquake. The goniometric direction finding result from Nakatsugawa is given by an arrow (55°).

central azimuth seems to be coincident with the nearby industrialized area of the city center of Nakatsugawa because our observatory is located about 15 km from this industrialized city area. The additional direction finding results for $f = 1$ Hz emissions on these days (which have already been suggested to be culture noise due to the definite diurnal change in Fig. 2(b)) have yielded the nearly same extremely wide distribution in azimuth as above, with the same central peak azimuth (60–65°). On the other hand, the azimuthal distribution for the seismogenic emissions during October 2–6 is extremely well peaked (of course, different azimuthal direction) as compared with this noise during October 27–30.

Here we have to check the geomagnetic activity and local lightning activity during the period of Fig. 2. First, this period is in the low geomagnetic activity. Figure 5 illustrates the temporal evolution of ΣKp (daily sum of Kp index) during the period. Because the maximum ΣKp is only 34 during the period of Fig. 2, suggesting that this period is generally geomagnetically quiet. Next, Fig. 6 illustrates the temporal evolution of occurrence number of total lightning discharges on a current day observed within 150 km around our observation station of Nakatsugawa. Figure 6 shows the local enhancement of lightning discharges on October 30 and 31 and September 24, but a comparison of this with Fig. 2(a) indicates that an enhancement on October 30 and 31 in Fig. 2(a) may be related with the local lightning, but no effect is seen in Fig. 2(a) on September 24. The period of the most enhanced wave activity on October 2–6 in Fig. 2(a) is found to be completely free from the local lightning activity in Fig. 5. So that, the enhancement on October 2–6 is likely to be a precursor to the earthquake.

4. Concluding Remarks

We paid our particular attention to the two time periods when the noise level below 0.1 Hz is enhanced; October

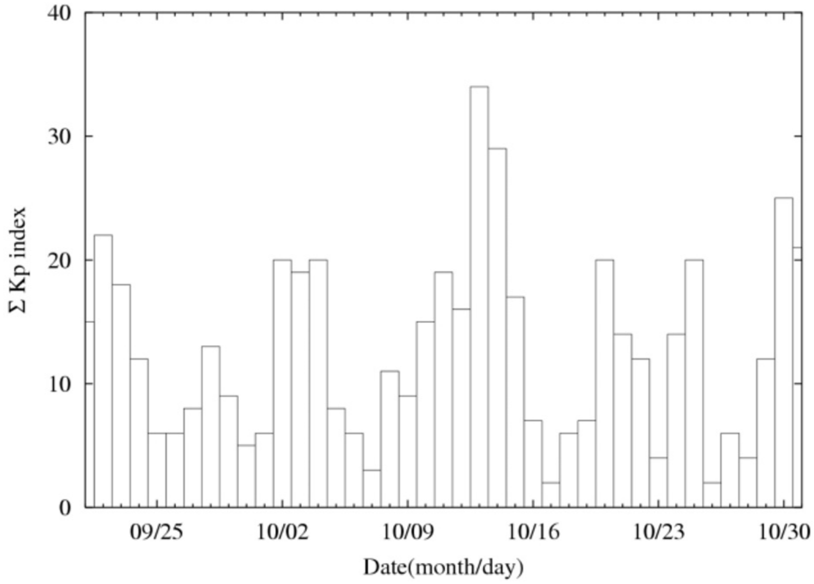

Fig. 5. Temporal evolution of ΣKp index during the relevant period.

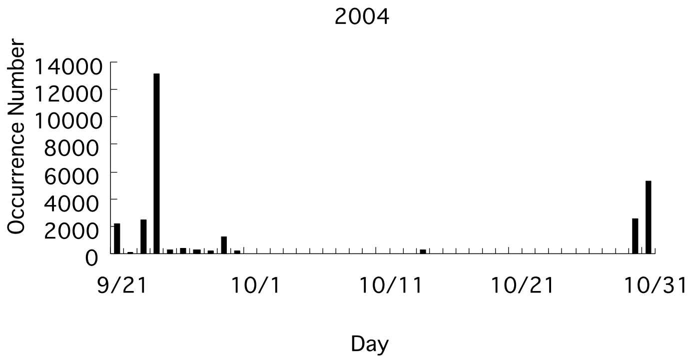

Fig. 6. Temporal evolution of the occurrence number of lightning discharges around our ELF station of Nakatsugawa.

2–6 and October 30 and 31. The noises on the two days of October 30 and 31 are found to be the enhanced occurrence of atmospherics. While, the former, elongated period of October 2–6 is found to be completely different from the event on October 30 and 31. The most important finding is that the noises at 0.1 Hz are linearly polarized and they are coming to the observatory from 55° north of the east direction. This azimuth is very close to the area of epicentres of the 2004 Mid Niigata Prefecture earthquakes. We may conclude that these noises are highly likely to be related to the earthquakes or a precursor to the earthquakes. The lead time is of the order of 17 to 21 days (or two to three weeks), which seems to be consistent with the previous works (Hayakawa and Hattori, 2004).

A few things should be commented here. This is just the preliminary analysis result, but the most serious point is that the seismogenic ULF emissions have propagated from the epicentres over about 230 km. The former experimental facts for ULF emissions have indicated that the ULF emission is observable with the epicentral distance of about 100 km for the magnitude 7 (Hayakawa and Hattori, 2004). This discrepancy might be related with the generation mechanism of seismogenic ULF emissions. There have been proposed a few mechanisms including the microfracturing mechanism by Molchanov and Hayakawa (1995), and Kawate *et al.* (1998) used the Biot-Savart's law and full-wave computations to estimate the magnetic field intensity expected on the ground by assuming the current source in the hypocenter. When the seismogenic emissions are generated in the Earth's crust, the empirical law by Hayakawa and Hattori (2004) will be applied on the detection criterion between the magnitude and epicentral distance (i.e. about 100 km for $M = 7.0$). However, when the depth of an earthquake is very small (i.e. less than 10 km or so), the seismogenic ULF emissions might be generated near the Earth's surface or in the atmosphere. In this case they seem to be able to propagate in the Earth-ionosphere waveguide over great distances as the quasi-TEM mode of propagation. A typical example of this case is the Chi-chi case by Ohta *et al.* (2001). The present case will be the second case.

We have to suggest the future works to do. In this paper the important frequency of seismogenic emission is at ULF, below the frequency of 0.1 Hz. But, we have to enhance the frequency resolution in order to find at which frequency the DC/ULF emission is dominating. The next problem is the use of any other ULF/ELF station. We have a few stations;

e.g., Izu peninsula station and Moshiri (Hokkaido) station. We will perform the similar analysis at one of those stations, and will perform the direction finding there to locate the source.

Acknowledgments. This work is partly supported by Japan Society of Promotion of Science (#15403012), The Mitsubishi Foundation and R and D promotion scheme funding international joint research by NiCT, to which we are grateful. Finally, we would like to thank Chubu Electric Power Co., Ltd. for providing us with the lightning data.

References

Hayakawa, M., Whistlers, Chapt. 7 in *Handbook of Atmospheric Electrodynamics*, edited by H. Volland, CRC Press, Boca Raton, 1995.

Hayakawa, M. (ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes, Terra Sci. Pub. Co., Tokyo, 996 pp., 1999.

Hayakawa, M. and K. Hattori, Ultra-low-frequency electromagnetic emissions associated with earthquakes, Special Issue on Recent Progress in Electromagnetic Theory and its Application, Inst. Electr. Engrs. Japan, Trans. Fundamentals and Materials, **124**, 1101–1108, 2004.

Hayakawa, M. and O. A. Molchanov (ed.), Seismo Electromagnetics: Lithosphere—Atmosphere—Ionosphere Coupling, TERRAPUB, Tokyo, 477 pp., 2002.

Kawate, R., O. A. Molchanov, and M. Hayakawa, Ultra-low-frequency magnetic fields during the Guam earthquake of 8 August 1993 and their interpretation, *Phys. Earth Planet. Inter.*, **105**, 239–248, 1998.

Molchanov, O. A. and M. Hayakawa, Generation of ULF electromagnetic emissions by microfracturing, *Geophys. Res. Lett.*, **22**, 3091–3094, 1995.

Nickolaenko, A. P. and M. Hayakawa, *Resonances the Earth-Ionosphere Cavity*, Kluwer Acad. Pub., Dordrecht, 2002.

Ohta, K., K. Umeda, N. Watanabe, and M. Hayakawa, ULF/ELF emissions observed in Japan, possibly associated with the Chi-Chi earthquake in Taiwan, *Natural Hazards Earth System Sci.*, **1**, 37–42, 2001.

K. Ohta, N. Watanabe, and M. Hayakawa (e-mail: hayakawa@whistler.ee.uec.ac.jp)