

ULF Electromagnetic Environment at Southern Boso Peninsula : DOA and waveform investigation of signals

Ichiro Takahashi¹, Katsumi Hattori^{2*}, Makoto Harada³, Nobuhiro Isezaki⁴ and Toshiyasu Nagao³

¹Graduate School of Science and Technology, Chiba University 1-33, Yayoicho, Inage-ku, Chiba 263-8522 Japan

²Marine Biosystems Research Center, Chiba University 1-33, Yayoicho, Inage-ku, Chiba 263-8522 Japan

³Earthquake Prediction Research Center, Tokai University 3-20-1, Shimizu-Orido, Shizuoka 424-8610 Japan

⁴Department of Earth Sciences, Faculty of Science, Chiba University 1-33, Yayoicho, Inage-ku, Chiba 263-8522 Japan

Geoelectrical and geomagnetic fluctuations are the end product of several geophysical phenomena. In particular these signals measured in seismically active areas can be attributed to stress and strain changes associated with earthquakes. The complexity of this problem has suggested the development of advanced statistical methods to investigate the heterogeneous nature of these fluctuations. In this paper, we analyzed the time dynamics of short-term variability of geoelectrical potential and geomagnetic fields measured at Kiyosumi, Uchiura, and Fudago stations, located in the southern part of Boso Peninsula, one of the most seismically active areas in Japan. The directions of signal arrival have been investigated in order to understand background and anomalous behaviors based on geoelectrical potential data. External intense signal reduction with use of the interstation transfer function method have been also examined. These analyses have shown the capability to discriminate the signal sources. Especially, direction finding analysis of time series data has shown the effective source separation. To identify waveform and to estimate direction of arrival is an important role for monitoring the ULF electromagnetic environment in seismic areas and for understanding the preparation process of crustal activity.

1. Introduction

Electromagnetic phenomena are recently considered as a promising candidate for the short-term prediction of large earthquakes⁽¹⁾⁻⁽³⁾ and there have been accumulated convincing reports in a wide frequency range from DC to VHF. Measurements of electromagnetic phenomena can be classified into three types which are the passive ground-based observation, the ground-based observation with the use of transmitter signals, and the satellite observation. Among these observational methods, one of the most promising methods is a method of analyzing seismogenic ULF emissions because of deep skin depth⁽⁴⁾⁻⁽¹⁴⁾. The precursory geoelectric potential changes, called "Seismic Electric Signals (SES)", have been also reported in Greece by the VAN group. In order to verify earthquake-related ULF electromagnetic phenomena and clarify the possible physical mechanisms, a network observation has been installed in Japan.

Fig.1 shows a configuration map of our ULF geoelectromagnetic stations. There is a geomagnetic sensor array with intersensor distance of about 5 km in the Boso Peninsula. This region is located in one of the most active seismic zones in Japan. Torsion-type

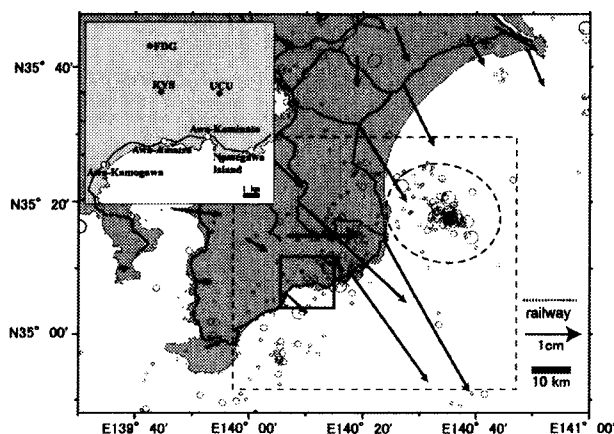


Fig. 1. The configuration map of geoelectric and geomagnetic stations in Southern Boso Peninsula, Japan. KYS, UCU, and FDG indicate the stations. The railway lines are also shown. The rectangular region corresponds to the source region of the 2002 Boso Slip event. Vectors indicate the data of GPS deformation and small circles are epicenters.

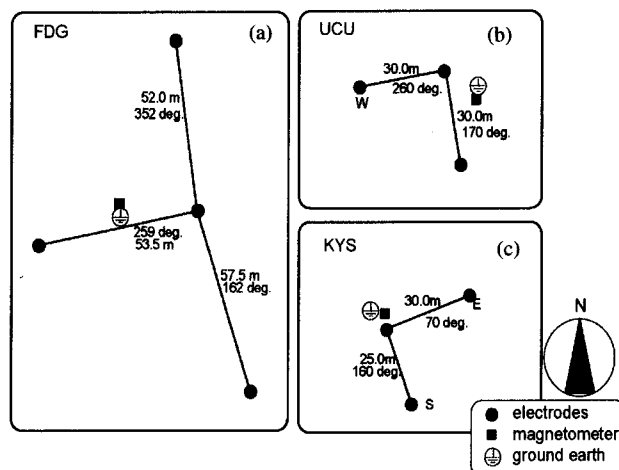


Fig. 2. The configuration of ULF electromagnetic station. A 3 component magnetic sensor and electrodes for two horizontal geoelectrical potential measurements have been installed. (a) FDG, (b) UCU, and (c) KYS station.

magnetometers with three components are in operation and two horizontal geoelectric fields are measured by pairs of electrodes, whose distance is about 30-50 m⁽¹⁸⁾.

The observed ULF geomagnetic and geoelectric potential data are a superposition of signals. They are (1) signals originated from the external source field associated with the solar-terrestrial interactions such as geomagnetic pulsations and geomagnetic storms, and their inductive field, which appears simultaneously in the global (hundreds of km) scale, (2) the regional (a few tens of km) signals such as artificial noises associated with the leakage current from DC-driven trains, and earthquake-related signals, and (3) local (less than a few kms) signals around the sensors. The signals associated with the crustal activity are very weak in general, and therefore the signal separation is of critical importance. As for the ULF geomagnetic and geoelectrical potential data, we have already developed an effective method for eliminating the external global source fields and their induction, which is based on the interstation transfer function (ISTF) method with wavelet transform in the periods smaller than 1000 seconds.

In this paper, we investigated the direction of signal arrival with the use of geoelectrical potential data observed at local midnight in order to evaluate the ordinal ULF electromagnetic environment at the stations. That is, we have studied signal discrimination between background noises, intense transient artificial noises such as the leak current of DC driven trains, and the other signals using the potential gradient and we have analyzed signal characteristics at stations. We also apply our proposed ISTF method to the observed ULF geomagnetic and geoelectrical potential data, which include an apparent crustal activity. We use geomagnetic data observed at Kakioka Magnetic Observatory (26.23°N, 140.19°E), Japan Meteorological Agency, as the remote reference data. We found strange variations in ULF geomagnetic and geoelectrical potential data in midnight.

2. ULF Electromagnetic Observation and Crustal Activity

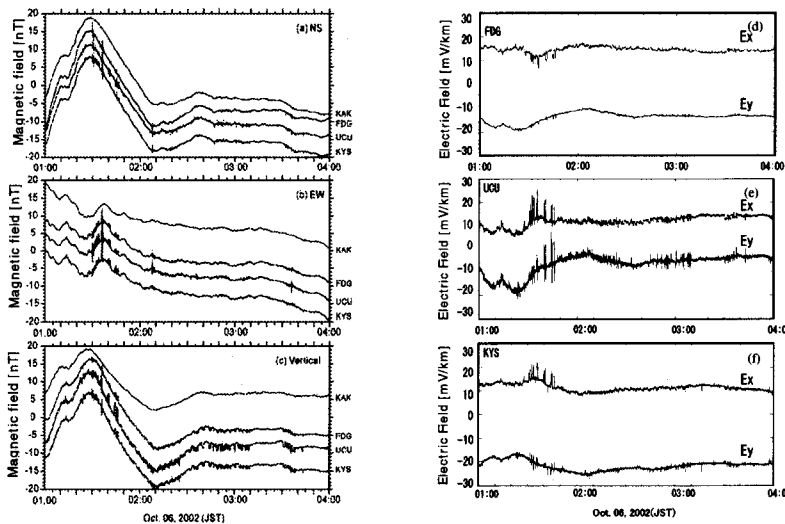


Fig. 3 The observed data at interbal of 01:00- 04:00 on October 6, 2002 (JST). For magnetic field, remote reference data at KAK are also displayed for comparison and for the geoelectrical data, the data are normalized by baseline length

Fig.1 shows the map of stations at southern Boso Peninsula. There is an array network with interstation distance of about 5 km. These stations are Uchiura (UCU), Kiyosumi (KYS), and Fudago (FDG). Fig. 2 indicates the configuration at three stations. At each site, three components of geomagnetic field and two horizontal geoelectrical potential difference components are recorded with 50 Hz sampling⁽¹⁸⁾. The clock is synchronized by GPS. At the reference site, three geomagnetic fields are measured with 1 Hz sampling rate. Therefore, the data down sampled to 1 Hz have been used in this paper.

The rectangular area with broken lines in Fig.1 indicates a source region of the 2002 Boso Slow Slip Event. Slow slip event means a crustal activity without any mechanical vibrations like creep phenomena. This event was recorded by a GPS deformation network. The arrows in Fig.1 show the direction and magnitude of displacement. The results of GPS deformation measurement and there is a few cm

displacement in early October. It is reported that the estimated displacement at the source region under the ground could be about 10 cm and the converted magnitude could be $M_w 6.6$ ⁽¹⁹⁾. This crustal activity is very unique because it is large and it occurred just below our small array network station.

Furthermore, there starts a small swarm activity at the edge of the slow slip region on October 6, as shown Fig. 1. The strange variations in geomagnetic and geoelectrical potential difference data are found at midnight. Figs. 3 (a) – (f) show geomagnetic and geoelectrical variations in the midnight during 00h – 04h L.T. For geomagnetic data (Figs. 3(a)-(c)), the reference data are also plotted and it is smooth, on the other hand lower three curves simultaneously have transient variations in each component. Figs. 3 (d) – (f) show geoelectrical potential differences at FDG, UCU, and KYS station, respectively. The strange transient changes in geomagnetic and geoelectrical

potential difference data detected simultaneously. Around the station, intense artificial noises are originated from DC-driven train as shown in Fig.1, no DC-driven trains were passing through around the stations at this moment. These strange signals seldom observed at three stations simultaneously in midnight (after 01:00 – 03:00 JST). There are only two times by eyes for analyzed four years data from 2000 to 2003.

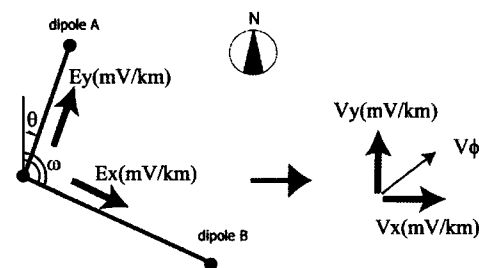


Fig. 4 The projection procedure of geoelectrical potential difference data.

3. Direction Finding Based on Geoelectrical Potential Data

Baselines for potential measurements are not oriented to the real north-south and east-west direction as shown in Fig.2 Therefore using an adequate rotation, observed values are projected to the actual NS and EW directions and this computation gives the gradient of potential or preferred orientation of the geoelectric field. The concept of this projection is shown in Fig. 4. The procedure is formulated by following equations.

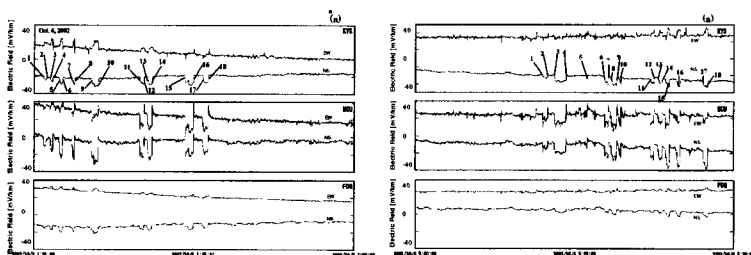


Fig. 5 The strange electromagnetic field variations obtained at KYS, UCU, and FDG October 6, 2002. 01:30-02:00 (T < 940 sec).

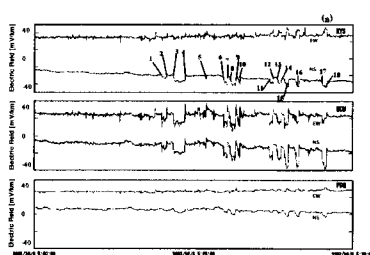


Fig. 6 The typical electromagnetic field variations for DC driven train obtained at KYS, UCU, and FDG

(b) show signals associated with the DC-driven train at 05:00 - 05:30 on October 6, 2002 (JST) in geoelectric fields and geomagnetic fields, respectively. In the similar manner as indicated in Figs. 5 and 6, the times of the signal change are registered. The waveform of the transient signals in Figs. 5 and 6 looks like very similar. Therefore, it is required to signal discrimination method to identify signal sources. The direction finding is one of the powerful tools for this aim.

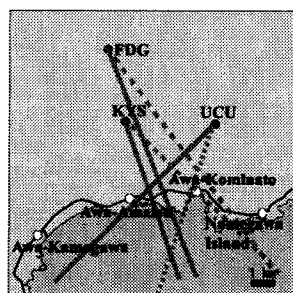


Fig. 7 (left) Estimated directions of arrival for the strange signals observed on October.6, 2002, using preferred orientation investigation in geoelectrical data.

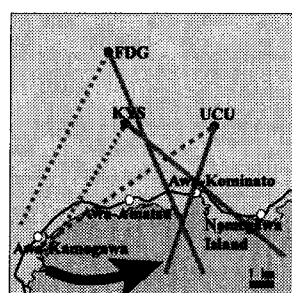


Fig. 8 (right) Estimated directions of arrival associated with DC driven train. The preferred orientation approach is adopted for geoelectrical data.

In order to make enhance the strange variation clearly, the interstation transfer function (ISTF) method with wavelet transform has been performed⁽¹⁵⁾⁻⁽¹⁷⁾. The ISTF method is based on the correlation between a site and a quiet remote reference station. ISTFs correspond to the correlation coefficients and have information on underground conductivity. We developed ISTF method to reduce variations due to global natural source in ULF geomagnetic data. That is, once ISTFs are estimated with high accuracy, which is considered to be invariant in time, it is possible to estimate the ideal geomagnetic variations originated from external solar-terrestrial interaction and their ideal inductive variations of the geoelectrical potential differences at the site using the reference data. Therefore, the residuals between the observed and estimated variations at the site provide only regional and local variations and earthquake-related phenomena are included. We use geomagnetic data observed at Kakioka Magnetic Observatory, Japan Meteorological Agency, as the remote reference data.

We applied the ISTF method to the data shown in Fig. 3. In computation, we use the ISTFs estimated in Harada et al 2003⁽¹⁵⁾ and 2004⁽¹⁶⁾ for geomagnetic components and those for electromagnetic component for Harada et al in press⁽¹⁷⁾.

$$V_x = (-E_x \cos \omega + E_y \cos \theta) / \sin(\theta - \omega)$$

$$V_y = (E_x \sin \omega - E_y \sin \theta) / \sin(\theta - \omega)$$

V_x and V_y correspond to the geoelectric fields of EW and NS component, respectively. E_x and E_y mean the observed electric fields (potential / base n general). The direction of the line of apsides indicates the apparent direction of signal arrival around the site at the time.

After the preferred direction of known signals such as a leak current of DC driven trains is determined, the observed data are projected to the orthogonal to the preferred direction. Then, the artificial noise is removed⁽²⁰⁾⁽²¹⁾.

In this paper, the preferred directions of geoelectrical signal arrival is investigated at first. Figs. 5 (a) and (b) represent the strange signals observed at 01:30 - 02:00 on October 6, 2002 (JST) in geoelectric fields and geomagnetic fields, respectively. The strange transient signals are picked up and the moment of transient change are noted by sequential number. The waveform of strange signals are looks like rather rectangular one. Figs. 6 (a) and

Figs. 7 and 8 show direction finding results of geoelectrical data for the strange signals and those associated with the train, respectively. The number corresponds to that in Figs. 7 and 8. From Fig. 7 it is found that the directions of geoelectric field are faced to the southward of stations and they are stable. On the other hand, the signals associated with the train seem to move with following the train location as shown in Fig. 8. These results suggest that the strange signals are not concerned with the train.

Furthermore, the characteristics of background noises at each station are also evaluated. Fig. 9 shows the result and the direction seems to be oriented to the nearby village, radio wave equipment antenna and/or along the geographical condition such as a local valley, a stream or a river.

4. Removing Global External Variations with Interstation Transfer Function (ISTF)

Here we pay attention to polarities of the strange geomagnetic changes at three stations and assume these signals are generated under the ground due to the current flow based on the electrokinetic process. Then, the signals during the time shown in Fig. 5, the source region under the ground could be estimated inside the triangle area and the direction of the fluid flow could be indicated by an arrow. On the other hand, the records a few hours later present the change of pattern of polarities at three stations.

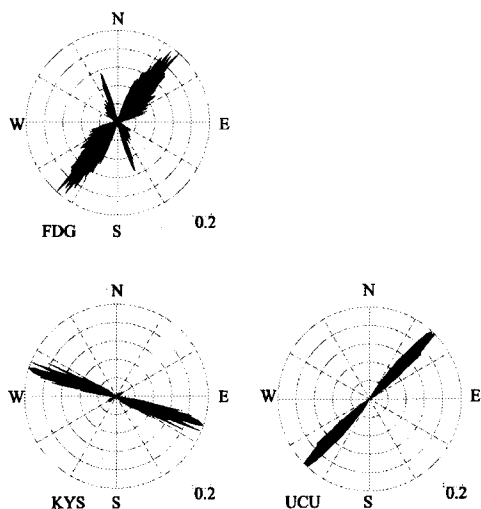


Fig.9. The estimated direction of the background noise. The amplitude shows correlations of E-W and N-S components.

5. Conclusion and discussion

Geoelectrical and geomagnetic fluctuations are the end product of several geophysical phenomena. In particular, these signals measured in seismically active areas can be attributed to the stress and strain changes associated with crustal activity. The complexity of this problem has suggested the development of sophisticated signal processing and advanced statistical methods to investigate the heterogeneous nature of these fluctuations. In this paper, the time series variation of geoelectrical potential and geomagnetic data measured at Kiyosumi (KYS), Uchiura (UCU), and Fudago (FDG), located at the southern part of Boso Peninsula, which is one of the most seismically active areas in Japan.

The directions of signal arrival have been investigated in order to understand background and anomalous behaviors. External intense signal reduction with use of the interstation transfer function method have been also examined. These analyses have shown the capability to discriminate the signal sources. Especially, direction finding analysis of time series data has shown the effective source separation. To identify waveform and/or to estimate direction of arrival are an important role in monitoring the ULF electromagnetic environment in seismic areas and for understanding the preparation process of crustal activity.

It is safe to say that the strange signals observed on October 6, 2002 are different from those originated from the train and other cultural noises according to the investigation on preferred directions of geoelectric field. Although the effective direction finding method does not exist for ULF geomagnetic field, the investigation on amplitude for quasi-static fields provides the consistent.

The electrokinetic assumption under the ground seems one of the possible solutions for the generation of strange signals. In order to evaluate this hypothesis, the electrical underground structure around the stations should be determined. The observed signals at three stations should be explained clearly from the point of waveforms (amplitude and phase) by means of model computations based on the structure and assumed source region.

References

- (1) M. Hayakawa and Y. Fujinawa (eds.): "Electromagnetic Phenomena Related to Earthquake Prediction", Terra Scientific Pub. Comp., Tokyo, 677 pp. (1994)
- (2) M. Hayakawa (ed.): "Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes", TERRAPUB, Tokyo, 996 pp (1999)
- (3) M. Hayakawa and O.A. Molchanov (eds.): "Seismo Electromagnetics, Lithosphere-Atmosphere-Ionosphere Coupling", TERRAPUB, Tokyo, 477p (2002)
- (4) A. C. Fraser-Smith, A. Bernardi, P. R. McGill, M. E. Ladd, R. A. Helliwell, and O. G. Jr. Villard: "Low-frequency magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquakes", Geophys. Res. Lett., Vol. 17, pp. 1465-1468 (1990)
- (5) A. Bernardi, A. C. Fraser-Smith, P. R. McGill, and O. G. Villard: "ULF magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake", Phys. Earth Planet. Inter., Vol. 68, pp. 45-63 (1991)
- (6) O. A. Molchanov, Y. A. Kopytenko, P. M. Voronov, E. A. Kopytenko, T. G. Matishvili, A. C. Fraser-Smith, and A. Bernardi: "Results of ULF magnetic field measurements near the epicenters of the Spitak (Ms=6.9) and Loma Prieta (Ms=7.1) earthquakes: Comparative analysis", Geophys. Res. Lett., Vol. 19, pp. 1495-1498 (1992)
- (7) Y. A. Kopytenko, T. G. Matishvili, P. M. Voronov, E. A. Kopytenko, and O. A. Molchanov: "Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories", Phys. Earth Planet. Inter., Vol. 77, pp. 85-95 (1993)
- (8) J. Lighthill: *A critical review of VAN*, World Scientific, Singapore, 376 pp.(1996)
- (9) M. Hayakawa, R. Kawate, O. A. Molchanov, and K. Yumoto: "Result of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993", Geophys. Res. Lett., Vol.12, pp.241-244 (1996)
- (10) R. Kawate, 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., Vol. 105, pp. 229-238 (1998).
- (11) M. Hayakawa, T. Itoh, K. Hattori, and K. Yumoto: "ULF electromagnetic precursors for an earthquake at Biak, Indonesia on February 17, 1996", Geophys. Res. Lett., Vol. 27, pp. 1531-1534 (2000)
- (12) K. Hattori, Y. Akinaga, M. Hayakawa, K. Yumoto, T. Nagao, and S. Uyeda: "ULF magnetic anomaly preceding the 1997 Kagoshima earthquakes", in "Seismo Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling", edited by M. Hayakawa and O. A. Molchanov, TERRAPUB, Tokyo, pp.19-28 (2002)
- (13) S. Uyeda, M. Hayakawa, T. Nagao, O.A. Molchanov, K. Hattori, Y. Orihara, K. Gotoh, Y. Akinaga, and H. Tanaka: "Electric and magnetic phenomena observed before the volcano-seismic activity 2000 in the Izu islands region, Japan", Proc. US Nat. Acad. Sci., Vol.99, pp.7352-7355 (2002)
- (14) K. Gotoh, Y. Akinaga, M. Hayakawa, and K. Hattori: "Principal component analysis of ULF geomagnetic data for Izu islands earthquakes in July 2000", J. Atmos. Electr., Vol. 22, pp. 1-12. (2002)
- (15) M. Harada, K. Hattori, and N. Isezaki: "Global signal classification of ULF geomagnetic field variations using interstation transfer function", Inst. Electr. Eng. of Japan., FM, Vol. 123, pp. 1159-1165 (2003) (in Japanese)
- (16) M. Harada, K. Hattori, and N. Isezaki: "Transfer function approach to signal discrimination of ULF geomagnetic data", Phys. Chem. Earth, Vol. 29, pp. 409-417 (2004)
- (17) M. Harada, K. Hattori, and N. Isezaki: "Reduction of geomagnetic effects (periods $T < 940$ s) from geoelectric potential difference data", Inst. Electr. Eng. of Japan., FM, in press.
- (18) K. Hattori, I. Takahashi, C. Yoshino, N. Isezaki, H. Iwasaki, M. Harada, K. Kawabata, E. Kopytenko, Y. Kopytenko, P. Maltsev, V. Korepanov, O.A. Molchanov, M. Hayakawa, Y. Noda, T. Nagao, and S. Uyeda: "ULF geomagnetic field measurements in Japan and some recent results associated with Iwateken Nairiku Hokubu earthquake in 1998", Phys. Chem. Earth, Vol. 29, pp. 481-494 (2004)
- (19) S. Ozawa, S. Miyazaki, Y. Hatanaka, T. Imakiire, M. Kaizu, and M. Murakami: "Characteristic silent earthquakes in the eastern part of the Boso Peninsula, Central Japan", Geophys. Res. Lett., Vol. 30, 1283 (2003)
- (20) S. Uyeda, T. Nagao, Y. Orihara, T. Yamaguchi, and I. Takahashi: "Geoelectric potential changes: Possible precursor to earthquakes in Japan", PNAS, Vol. 97, pp. 4561-4566 (2000)
- (21) T. Nagao, Y. Orihara, T. Yamaguchi, I. Takahashi, K. Hattori, Y. Noda, K. Sayanagi, and S.Uyeda: "Co-seismic geoelectric potential changes observed in Japan", Geophys. Res. Lett., Vol. 27, pp. 1535-1538 (2000)