Paper

Electromagnetic phenomena associated with earthquakes: Review

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NASDA (National Space Development Agency of Japan) has just finished the Earthquake Remote Sensing Frontier Project (for which the author was the principal scientist) conducted since 1996 within the framework of the Earthquake Frontier Projects by the former S.T.A. (Science and Technology Agency). Main emphasis of NASDA's Frontier Project was the complete understanding of lithosphere-atmosphere-ionosphere (LAI) coupling by making full use of different kinds of observational items and finally we would like to contribute to the short-term earthquake prediction. The most exciting finding from our Frontier project was the discovery of convincing evidence of the presence of seismo-ionospheric perturbations, which has been extensively investigated by using the subionospheric VLF/LF propagation, and several important findings have been presented, including the initial result for the Kobe earthquake and a few case studies from many data. Then, our latest result on seismo-atmospheric perturbation is presented on the basis of the reception of over-horizon FM transmitter signal. Finally, the initial and boundary condition of the LAI system (i.e., lithosphere) has been investigated by means of the measurements of ULF (ultra-low-frequency) emissions and acoustic emissions, whose latest results are summarized as well.

Keywords: lithosphere-atmosphere-ionosphere (LAI) coupling, earthquake prediction

1. Introduction

Electromagnetic phenomena are recently considered to be a very promising candidate for the short-term earthquake prediction [1,2] because there have been accumulated a lot of convincing evidence on seismo-electromagnetic phenomena in a wide frequency rane from ULF (ultra-low-frequency) to HF and also the observational means for such seismo electromagnetic phenomena has extended very much from the subsurface measurement to the in-situ satellite observation [1,2].

NASDA and our university (UEC) have been engaged in the overall study of electromagnetic phenomena associated with earthquakes, which take place in the atmosphere and ionosphere, and we would like to establish a new science field; electromagnetic phenomena in the coupled system of lithosphere, atmosphere and ionosphere (LAI system). In the beginning of this Frontier project, we did not know much what was happening in different areas in association with earthquakes, so that we decided to adopt different kinds of observations; (1) radio sounding; monitoring of the ionospheric perturbations associated with earthquakes by means of VLF/LF subionospheric propagation, (2) satellite observation of plasma perturbations and wave emissions inside the ionosphere, (3) ionospheric density mapping by means of GPS receivers, (4) seismo-atmospheric perturbations by means of radio sounding, (5) subsurface measurement of seismogenic emissions (at ULF/ELF, and VLF) and acoustic emissions and (6) remote sensing of Earth's surface temperature. We will report on the latest results from each item in the followings.

2. The use of subionospheric VLF/LF propagation in detecting seismo-ionospheric perturbations

We have to mention briefly about the history of this research. Some time ago, Russian colleagues suggested the use of VLF subionospheric signal for studying seismo-ionospheric perturbations for some large earthquakes, but we have to describe the first convincing result on the ionospheric perturbations associated with the Kobe earthquake (on January 17, 1995) by means of subionospheric VLF propagation [3,4]. By using the same analysis procedure (amplitude and phase fluctuations) as the Russian colleagues, we find some increase in such fluctuations in amplitude and phase before the Kobe earthquake (though not shown), but they were not convincing as a precursor to the earthquake. So, we proposed the method of terminator time. We have discovered a significant shift in terminator times as shown in Fig. 1, which illustrates the day-to-day sequence of diurnal variation of the phase (10.2kHz) measurement at Inubo of the VLF Omega signal transmitted from Tsushima. The terminator time is defined as the time when the diurnal phase (or amplitude) variation exhibits a minimum around sunrise and sunset (we call those morning (*tm*) and evening (*te*) terminator times). Fig. 1 shows a surprising result on the significant change in terminator times before the quake. The point exhibiting a minimum around sunrise is indicated by a black dot, and the time with the black dot is called tm. While, the time with a white dot is called *te*. The vertical lines indicate the *tm* and *te* on the normal (unperturbed) conditions, so that the hatched area means the deviation or shift in the terminator time from the corresponding unperturbed situation. Hence, it is clear that *tm* shifts to early hours and the evening one (*te*) to later hours. This effect is also confirmed by the analysis for a much longer data length (±4 months; as the total eight months) in Fig. 2. The black line indicates the terminator time (*te*, phase) over ±1 day on each day and 0 means the mean value (in *te*). This figure shows the deviation in *te* from the mean value (0) and also the $\pm 2\sigma$ (σ: standard deviation) lines are drawn. This figure indicates that only a significant peak is seen just before the quake. Also, after studying the correlation of this anomalous propagation with other possibly related phenomena (magnetic activity, solar activity, rainfall etc.), we have not found any remarkable correlation with any of those, so that we could conclude that this propagation anomaly is highly likely to be associated with the quake.

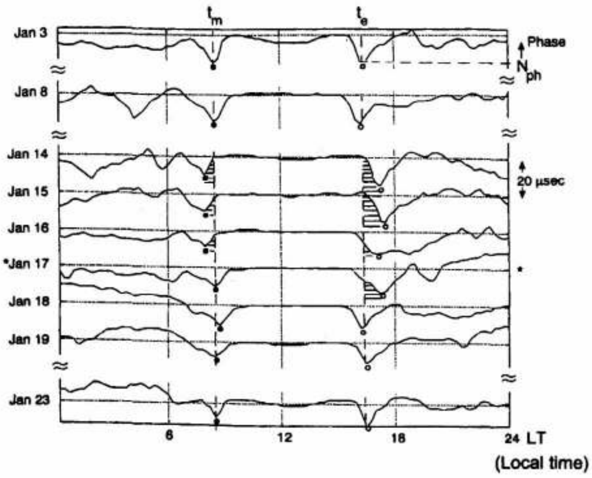

Fig. 1. Sequential plot of diurnal variation of phase measurement at Inubo of Tsushima Omega transmission (f=10.2kHz) just around the Kobe earthquake (happened at 5:46h JST(LT) on Jan. 17, 1995, indicated by an asterisk in the figure). The morning terminator time (*tm*) is indicated by a black dot, while *te* is given by a white dot. The normal (unperturbed) values of *tm* and *te* are indicated by the vertical broken line, and a significant change is noticed in the terminator times (*tm* and *te*) just around the quake, with their shifts from the corresponding unperturbed values being hatched.

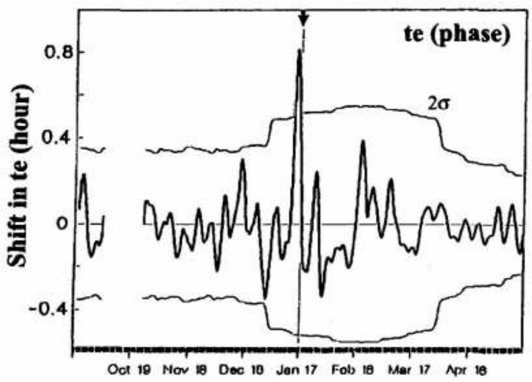

Fig. 2. Change in terminator time (here *te*, phase) for a longer period (±4 months around the quake). The thick line is the average shift from the mean over ±1 day at each day. A significant change (exceeding 2σ line) is seen only before the quake.

Hayakawa et al. [3] and Molchanov et al. [4] have suggested the change in the lower ionosphere by means of the theory on subionospheric VLF propagation over a short distance (~1,000km) for which there exist several modes of propagation (i.e., terminator time is the consequence of wave interference of those modes) and have concluded, on the basis of the comparison of theoretical estimations with the experimental data, that the lower ionosphere might have been lowered by a few kilometers. Some more sophisticated modeling, though essentially the same, has been performed by Rodger et al. [6], who have suggested more lowering of the lower ionosphere.

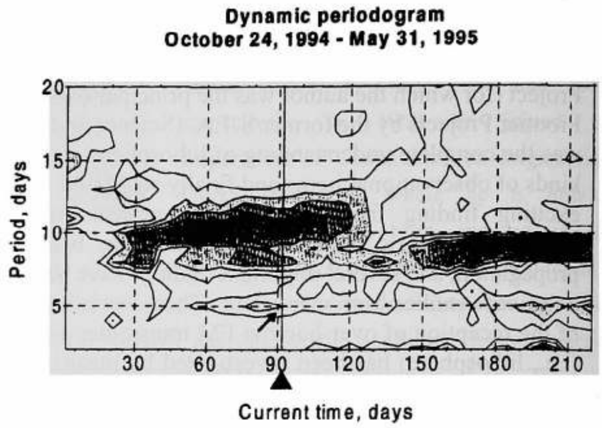

Fig. 3. An example of enhancement of the atmospheric oscillations with periods of 5 days and 9-11 days for the same Kobe quake indicated by a black triangle. The enhancement of such oscillations with periods of 5 days and ~10 days can be seen as the appearance of wavelets before the quake.

Being encouraged by the result for Kobe earthquake, Molchanov and Hayakawa [1998] [5] have performed the same analysis (terminator times) for a lot of large earthquakes (with magnitude greater than 6.0) during 13 years by using the same Inubo data for Tsushima Omega transmission. We have found that when the earthquake is shallow (depth less than 50km) and is located very close to the great-circle-path, we can detect the propagation anomaly (in the sense of a significant shift in terminator times (i.e. ionospheric perturbations))for a large proportion (~80%) of the earthquakes. Another important finding is that when we have the propagation anomaly (ionospheric perturbations) the harmonic analysis on the data of terminator times have exhibited the enhanced modulation with the periods of 5 days or 9-11 days, which has implied that the atmospheric oscillations with those periods may play an important role in the coupling from the lithosphere to the ionosphere. Fig. 3 illustrates an example of the enhancement of such atmospheric oscillations before the same Kobe quake. The earthquake date is given by an upward arrow, and you can notice a strong wavelet with period of ~11 days and a small, less weak wavelet with period of 5 days just around the earthquake date. Recently we have proposed the gravity wave as the main career because of its stronger tendency of upward propagation in the lithosphere-ionosphere coupling, with the planetary wave as the modulating signal. Based on the study of fluctuation spectra of our observed data (on amplitude and phase), we have found an enhanced occurrence of fluctuation power in the frequency range (10 minutes to 2 hours) of gravity waves, probably associated with earthquakes. These findings would be a fundamental basis for the study of LAI coupling.

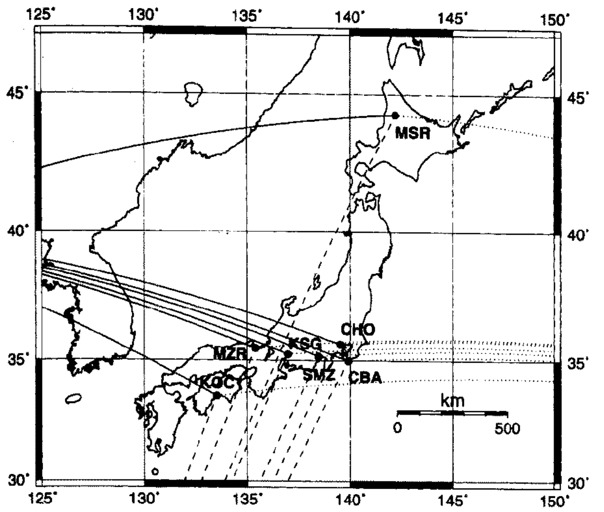

Fig. 4. A network of subionospheric VLF stations (CHO: Chofu; CBA: Chiba; KSG: Kasugai; SMZ; Shimizu; KOC: Kochi; MZ: Maizuru; MSR: Moshiri). The great-circle path is plotted at each observing station for different VLF transmitters.

Since the commencement of this Earthquake Remote Sensing Frontier Project in 1996, we started the installation of VLF receiving stations: initially we established two key stations in Chofu (UEC) and in Kasugai, Nagoya (Chubu University), where our new receivers are designed to receive simultaneously 4~5 VLF transmitters such as NWC (Australia), NPM (Hawaii), CHI (China) etc. Year by year we increased the number of receiving stations. Also, being stimulated by the closing down of the Omega VLF transmission on September 30, 1997, we started to pay more attention to the JG2AS (JJY)(40kHz) transmission (which was moved from the previous place to a new position in Fukushima Pref. on June 10, 1999 with an increase in radiation power up to 10kW). Fig. 4 illustrates only the VLF receiving network in Japan, and we also receive the 40kHz signal at those seven VLF stations. Fig. 5 illustrates one example of the reception of Tsushima Omega signal (10.2kHz) observed at Chofu, which is the result of our Frontier Project. This period of March 1997 (before the closing down) was the period of a seismic swarm at Izu peninsula, which was good to study a typical correlation between the VLF propagation anomaly (ionospheric perturbations) and seismic activity within the Fresnel zone. The change in terminator time (*te* in amplitude) is plotted around the running mean (indicated by a horizontal straight line), together with the 2σ line (indicated by an upward horizontal thick line). The occurrence of earthquakes on each day is indicated as a function of its occurrence time (U.T.), with the size being proportional to the quake magnitude. A seismic swarm is seen to take place during a period from March 3 to March 10, and probably in good correspondence with this swarm we have found a significant shift in terminator time (*te*, amplitude) during the period from March 4 to March 7. It is impossible for us to have a one-to-one correspondence between the quake and propagation anomaly. However, when we look at the propagation anomaly and seismic activity as a group, we can conclude a rather good correlation between the two and the propagation anomaly seems to precede the swarm. The ionospheric perturbation takes place as an integrated effect of a lot of earthquakes during the swarm.

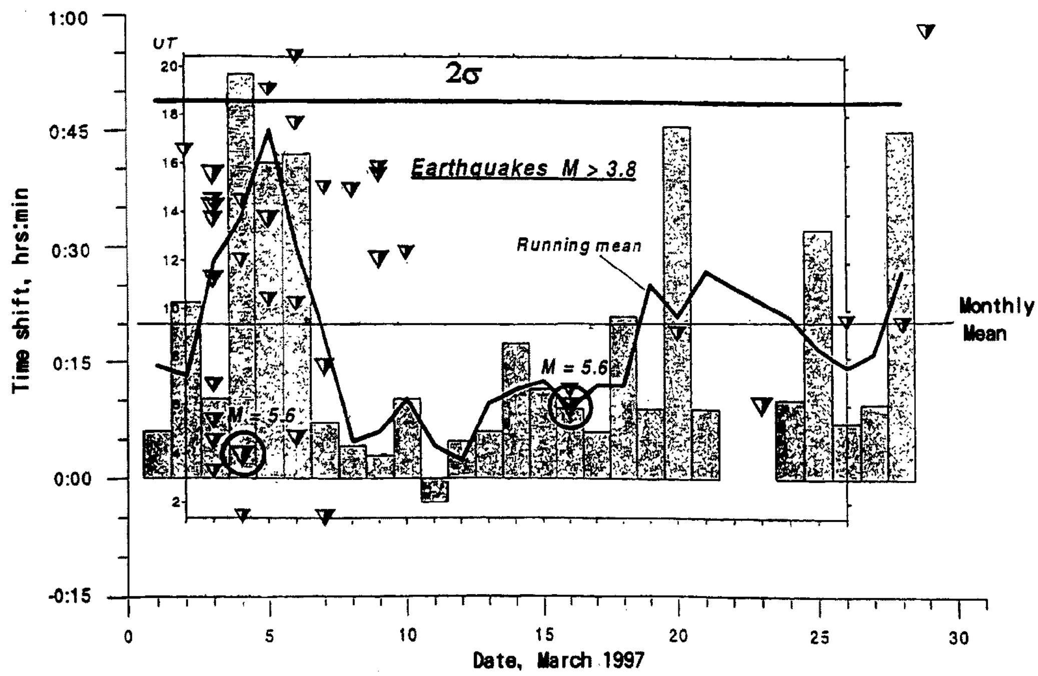

Fig. 5. The result of terminator time variation at Chofu for the Tsushima VLF Omega transmission. The period is March, 1997, when there was observed a seismic swarm in Izu area. The thin horizontal line indicates the mean value, and the thick line indicates the 2σ line. The earthquake is indicated by a triangle at the time of its occurrence, with its size being proportional to the quake magnitude.

We have already accumulated a few years' data on the basis of our Frontier VLF/LF network observation, and we are ready to perform the study on the statistical correlation between the ionospheric perturbations and quakes for different regions of interest; for example, NPM propagation anomaly observed at Chofu with the quakes in Ibaraki and Chofu area, the propagation anomaly observed at Kasugai for NWC (Australia) and the quakes in Nagoya area. Also, we are analyzing a few event studies for rather strong quakes; such as Tottori earthquake happened on October 6, 2000, Shizuoka quake on April 3, 2001, etc. Some of these results are summarized in Ref.(7).

Higher LF (f=100~300kHz) subionospheric signals from three stations in Siberia, Russia have been measured at Kasugai and Chofu as a collaborative work with Italian colleagues. These LF frequencies are known to monitor the higher altitude of the lower ionosphere than at the former VLF/LF.

The network observation in Fig.4, will enable us to estimate roughly the region of seismo-ionospheric perturbations on the basis of the comparison of anomalies observed at several stations and for different propagation paths. An active probing of the seismo-ionospheric perturbation is being carried out on the basis of the simultaneous measurement of two horizontal magnetic fields and one vertical electric field, and this direction finding result will appear shortly.

3. Plasma density perturbations and wave emissions in the ionosphere

3.1. In-site satellite observation The most important finding of this Frontier Project is that there is likely to be present some kind of perturbations in the ionosphere in association with earthquakes. VLF/LF subionospheric signals are known to reflect from the lower D region of the ionosphere, but there may also be any seismo-influence onto the upper ionosphere. We have utilized the former satellite data for this study, and the Russian satellite, Intercosmos 24 was used to invesigate the density perturbations associated with earthquakes[8]. When we analyze the data for more than 7,000 hours all over the world during 1989-1990 on board Intercosmos 24, we have selected the basic parameters of our recording; geographic latitude, geographic longitude, local time (L.T.), altitude (H), magnetic index (Kp). By imposing the appropriate division to these parameters, we divide the whole volume of data into abundant elementary cells and we calculate the different values of density variations in each elementary cell. We have found a reliable correlation between the global distribution of seismic activity and ion density variations (see Fig. 6). The upper panel of Fig.6 illustrates the longitudinal distribution of the number of earthquakes with magnitude greater than 5 during 1989 and 1990, and the lower curve indicates relative standard deviation value (RNSD) which is defined as NSD/<NSD>, where NSD is the normalized standard deviation and < > means the average over all the cells with equal LT, H, and Kp parameter. The best parameters for good correlation with earthquakes are normalized standard deviation (NSD) and relative normalized standard deviation (RNSD) as given in Fig.6. Maximum values of ion density NSD correlated with seismic activity are 10-15% and a clear correlation is found only for daytime (10-16h LT) and altitude range from 500-700km. Further study has been continued, and we have found that the equatorial anomaly common at low latitude is strongly modified by the seismic activity, together with the study of plasma waves (ELF and VLF). See the details in Ref.(7)

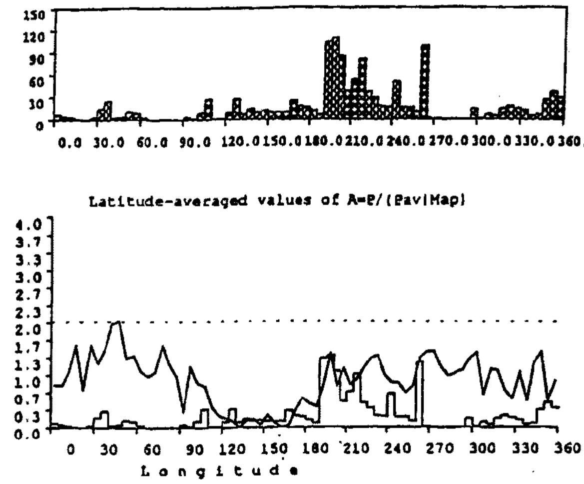

Fig. 6. Longitudinal dependence of occurrence number of earthquakes (M≥5) (upper panel) and the lower panel is the longitudinal variation of relative normalized standard deviation of electron density (h=500-1000km, Kp<3, LT=10-10h) (in order to have its comparison with the longitudinal distribution of earthquakes, the same plot in the upper panel is again given here).

3.2. GPS monitoring Another way of monitoring the ionospheric plasma perturbations associated with earthquakes is the use of GPS data. In Japan there have been established a lot of GPS receivers, which was done by Geological Survey of Japan. Their data will be utilized to monitor the ionospheric TEC (total electron contents) profile by the simultaneous use of the GPS data by means of inversion technique. We will continue this study in order to find the seismo-ionospheric effect by means of CT (Computer Tomography) method for the GPS data. These results will be compared with the results from Sections 2 and 3.

4. Seismo-atmospheric perturbations as revealed by the observation of over-horizon FM transmitter signal

Next we show one example of the perturbation of the atmosphere probably associated with earthquakes by means of the observation of over-horizon FM transmitter signal (which belongs to the same radio sounding category in Section 2). The observing station is our university, and the target VHF transmitter signal is FM Sendai (located at the city of Sendai, frequency=77.1MHz, horizontal polarization, power=5kW). The fundamental questions are, (1) can we really observe an over-horizon FM signal before (and after) the earthquake? and (2) what is the mechanism of reception of such an over-horizon FM signal (if there exists)? In order to answer these questions, we have adopted a rather sophisticated antenna array system (which enable us to make the direction finding (bearing and elevation angles) of the received signal). Each antenna is 5-element Yagi, and for the elevation angle 0° (this means horizontal) there are 3 antennas with different bearing (azimuth) angles (0° +30°, and -30°; 0° means the azimuth to FM Sendai from UEC, and +(-) indicate the east (west) of the path). Additionally, we have installed three antenna systems with different elevation angles (0°(horizontal), 45°, and 90°(vertical upwards)) for the fixed bearing of 0° (toward the transmitter). These are all for the same horizontal polarization. The last antenna system is for vertical polarization (bearing=0° and elevation=0°). The same frequency of 77.1MHz is used in Tokyo as the University of Air, so that the observation is limited only to the local time 0~6h in the midnight. Usually on normal conditions, the observed signal levels for all antenna channels are at the background level, while we can observe significant signal level increases (whose levels are depending on the direction of arrival) and one example is given in Fig. 7. We have confirmed by recording the audio signal that the observed signal is of the FM Sendai. Comparing the outputs from different bearings (for elevation=0°), the output from bearing =30° is found to be much larger than that for bearing = -30°, which means that the wave is coming from the east of the path. Of course, we can determine the bearing as +20° from the direction finding (comparison of outputs from +30° and -30° bearings). Further, the incident angle (or elevation angle) can be estimated from the comparison of the outputs from the antennas with elevation angles (0°, 45° and 90°), which yields the elevation angle of less than 10°. Based on the statistical study for many events during the period of February 1st to June 30, 2000 including one event in Fig.7, it is found that over-horizon FM signals can be observed on abnormal conditions probably being associated with earthquakes. The cross-correlation of signal reception with the earthquakes has yielded that the abnormal reception of over-horizon FM signals is observed about 7 days before an earthquake, and the direction finding has indicated that the

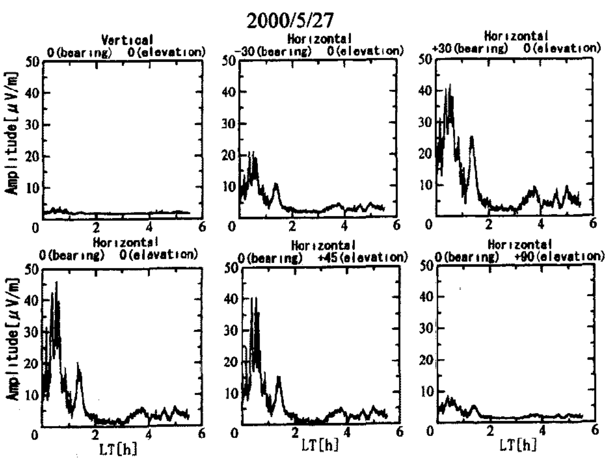

Fig. 7. An example of the reception of over-horizon FM transmitter signal at UEC on May 27, 2000. The outputs from different antenna systems are indicated.

signal is due to the favorable condition of the atmosphere (troposphere or stratosphere) caused by the pre-seismic activity.

5. Ground-based ULF and AE emissions

The initial and boundary condition for the LAI coupling and interaction, can be investigated by means of ULF and AE (acoustic emission) observation. These emissions are considered to be the manifestation of the microfracturing taking place at the focal zone. For example, Molchanov and Hayakawa [9] have proposed the mechanism of seismogenic ULF emissions in terms of the microfracturing. In addition to the famous two ULF events (for Spitak and Loma Prieta), there has been reported a ULF signature for the Guam earthquake [10], which was furthermore supported by a sophisticated signal analysis [11], named fractal analysis. An additional convincing evidence on the appearance of ULF emissions before a large earthquake at Biak, Indonesia in February, 1966, has been obtained by Hayakawa et al. [12].

Within the framework of NASDA's Frontier Project, we have established a network of ULF measurement in Kanto area; (1) Izu, (2) Chiba, (3) Kakioka, (4) Chichibu, and (5) Matsushiro. Especially, in Izu and Chiba area, we are establishing a differential array by using 3-4 closely spaced (spacing, 5-10km) ULF stations, which would be useful to increase the S/N ratio for seismogenic emissions and also for their direction finding. One example of ULF emissions associated with the seismic swarm in March-May, 1998 has been obtained by means of our developed polarization measurement and also some results on the precursory signature for the Izu islands earthquakes in July, 2000 are obtained by using a sophisticated signal processing (such as principal component analysis) for the simultaneous ULF data observed at three stations in Izu peninsula (see Ref.(7)). However, we think that we are in a position to wait for a rather large earthquake close to any one of our stations.

The measurement of AE was started two years ago at Matsushiro, where there are many sophisticated, highly sensitive sensors for crustal movement. So that, we have proposed the collaboration of our electromagnetic (ULF, AE) measurement with their measurement in order to have a bridge between seismologists and radiophysicists. Attempts to find AE associated with earthquakes have been undertaken for some years, and an anomaly in AE behavior in the range 800-1200Hz was recorded about 16 hours before the M=7.0 Spitak earthquake, Armenia, 1988, at the distance 80km from the epicenter. However, their conclusions were not completely convincing due to extremely weak signals, with their amplitude spectrum sharply declining with frequency. We have reported the facts of possibly extreme importance that clear AE intensification associated with EQs was recorded in the tunnel at the depth of about 100 meters at Matsushiro[13]. We used special receivers with magneto-elastic detectors of which sensitivity increases as cube of frequency. The AE intensification has been verified at four frequencies. The AE intensification has been verified at four frequency bands, namely 30, 160, 500 and 1000 Hz for several earthquakes in the surrounding area; earthquakes with M~3-5, distance ~20-150km. It was also found that the increase in AE activity started about 12 hours before quakes and decreased after the quakes in the manner as shown in Fig.8. The observation is continued at Matsushiro, and also we have installed two additional AE sites just around Matsushiro in order to form a differential array to estimate the direction of arrival.

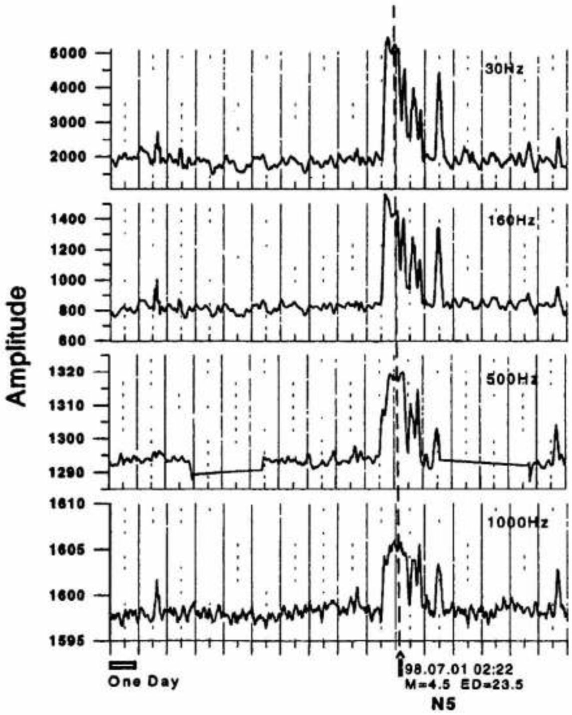

Fig. 8. Recording of AE at Matsushiro for an earthquake (M=4.5, distance=23.5km) on July 1, 1998. Amplitude is given as a relative value.

6. Conclusion

The most important contribution of this NASDA's Frontier Project is the accumulated evidence of ionospheric perturbations associated with earthquakes and some finding on seismo-atmospheric effect, as compared with the already-existing many results on lithospheric phenomena as revealed from the subsurface measurements. This is leading to the generation of a new science field such as "Lithosphere-atmosphere-ionosphere coupling", or "Electromagnetic phenomena in the coupled lithosphere-atmosphere-ionosphere system", and a lot of efforts are being devoted to the full understanding on the mechanisms of the coupling. We believe that the better understanding of this coupling mechanism will lead to the possible short-term earthquake prediction.

Acknowledgement

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