Ionospheric Perturbation Associated with Earthquakes, as Studied by Subionospheric VLF/LF Propagation

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Abstract: 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.

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 [3,5] 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 [3,5].

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 only from the ionospheric perturbation studies.

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 [8,11]. 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)

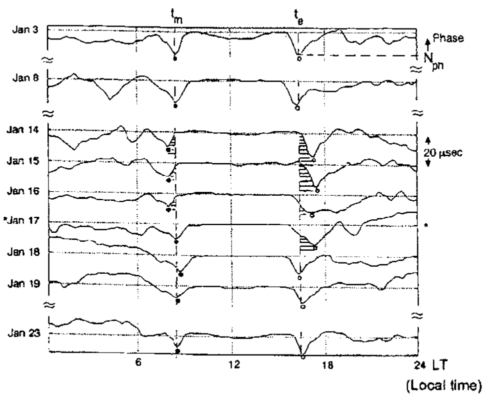

Fig. 1. Sequential plot of diurnal variation of phase measurement at Inubo of Tsushima Omega transmission (f=10.2kHz) just around the Kobe earthquake (happened at 5:46h JST(LT) on Jan. 17, 1995, indicated by an asterisk in the figure). The morning terminator time (tm) is indicated by a black dot, while 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.

and also the ±2σ (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.

Hayakawa *et al.* [8] and Molchanov *et al.* [11] 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.

Being encouraged by the result for Kobe earthquake, Molchanov and Hayakawa (1998) [10] 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

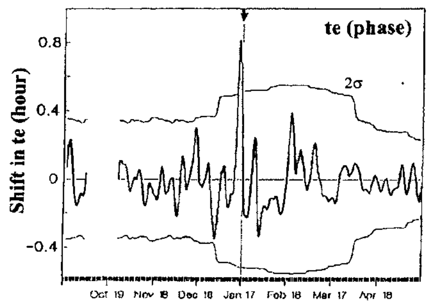

Fig. 2. . Change in terminator time (here *te*, phase) for a longer period (±4 months around the quake). The thick line is the average shift from the mean over ±1 day at each day. A significant change (exceeding 2σ line) is seen only before the quake.

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

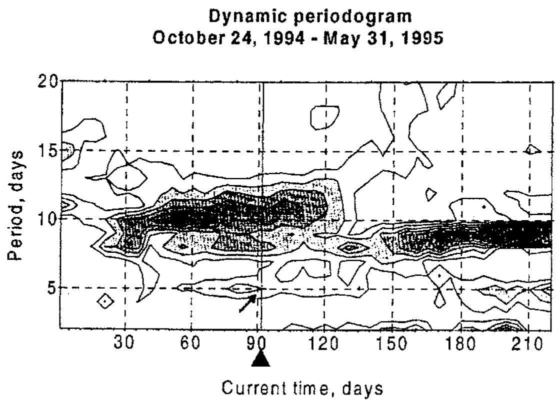

Fig. 3. . An example of enhancement of the atmospheric oscillations with periods of 5 days and 9-11 days for the same Kobe quake indicated by a black triangle. The enhancement of such oscillations with periods of 5 days and ~10 days can be seen as the appearance of wavelets before the quake.

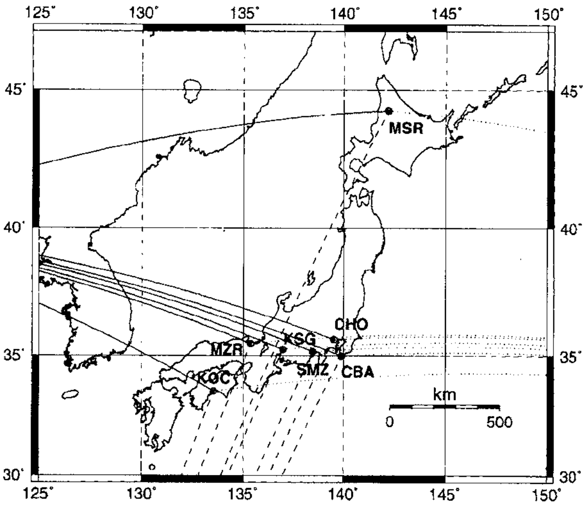

Fig. 4. A network of subionospheric VLF stations (CHO: Chofu; CBA: Chiba; KSG: Kasugai; SMZ; Shimizu; KOC: Kochi; MZ: Maizuru; MSR: Moshiri). The great-circle path is plotted at each observing station for different VLF transmitters.

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.

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

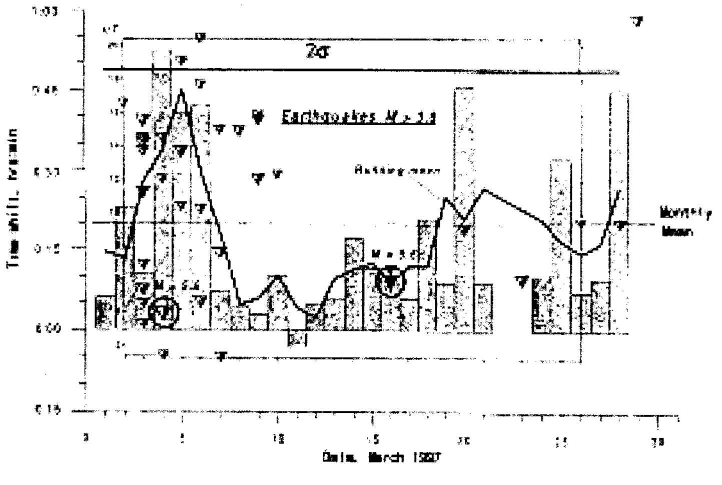

Fig. 5. The result of terminator time variation at Chofu for the Tsushima VLF Omega transmission. The period is March, 1997, when there was observed a seismic swarm in Izu area. The thin horizontal line indicates the mean value, and the thick line indicates the 2σ line. The earthquake is indicated by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

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.

Our latest results are concerned with the Tottori big earthquake on October 6 2002. The magnitude of this Tottori earthquake (7.3) is very comparable to that of the Kobe earthquake, so that is rather interesting to see what was happening on the ionosphere for this earthquake. Also, its epicenter depth is ~10km, so we could expect significant ionospheric perturbations. Fig.6 is the observational result on the temporal evolution of terminator time (te) for the VLF transmitter, China (CHI) as observed Chofu. The line zero, indicates the running mean, and the corresponding 2σ and 3σ lines are also indicated. The figure suggests that there exists a significant change in terminator time over 3σ line on October 1, 5 days before the Tottori earthquake. Like the case of the Kobe earthquake (as showen in Figs. 1 and 2), it is highly likely that this significant change in the evening terminator time is indicative of the precursory signature of the Tottori earthquake. However, the significance of the ionospheric perturbation for this earthquake is apparent to be much smaller than that for the Kobe earthquake.

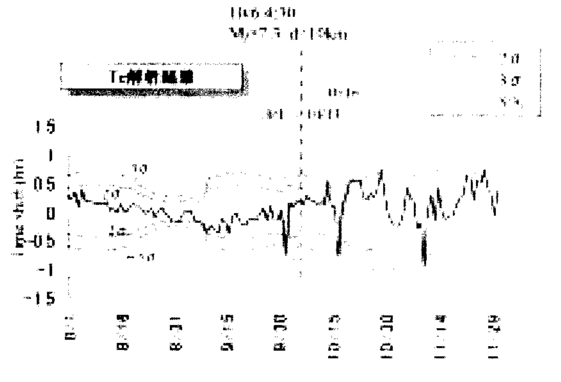

Fig.6 Temporal evolution of terminator time charge for the Tottori earthquake. Observation station is Chofo, and the VLF transmitter is located in Beijing (CHI).

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.

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