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THE PRECURSORY SIGNATURE EFFECT OF THE KOBE EARTHQUAKE ON VLF SUBIONOSPHERIC SIGNALS

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ABSTRACT

The subionospheric VLF Omega signal transmitted from Tsushima, Japan (geographic coordinates: 34°37'N, 129°27'E) is continuously received at Inubo (35°42'N, 140°52'E), and the propagation characteristics (especially phase) of this signal have exhibited abnormal behavior (especially around the sunrise and sunset local times) a few days before the main shock of the 1995 Hyogo-ken Nanbu earthquake. A statistical study based on long-term (four months before and four months after the earthquake) observational data has strongly suggested that this anomaly was not coincidental, but it is highly likely to be related to the earthquake. We have found from a computer simulation of VLF signal propagation that this observed effect can be explained by a decrease of about 1.5 km in the VLF reflection height. Plausible mechanisms for this decrease are discussed.

Keywords: Kobe earthquake, VLF subionospheric propagation, Omega transmitter

1. Introduction

Short-time earthquake prediction is an urgent yet elusive goal, but recently electromagnetic phenomena have been recognized as a promising basis for future earthquake prediction [e.g., Hayakawa and Fujinawa(1)]. Several electromagnetic approaches have been proposed for earthquake prediction [Hayakawa(2)], including the measurement of DC and AC seismogenic electromagnetic fields. Among these, there is recently proposed a new means of the possible use of subionospheric propagation of VLF transmitter signals in the earthquake prediction [Gokhberg et al.(3)]. Additional studies on this subject have been performed by Gufeld et al.(4), Hayakawa and Sato(5) and Morgounov et al.(6). Before any precursory phenomena can be applied for earthquake prediction, though, two essential requirements must be met:(1) there must be a sufficient body of evidence that supports the validity of the method, and (2) a model must be created that can generate such propagation anomalies. We try to satisfy these two requirements in this paper.

A large active fault earthquake occurred near Kobe, Japan on January 17, 1995 (5:46 am, L.T.), with its epicenter at the geographic coordinates (34.6°N, 135.0°E). Its magnitude was 7.2 and its focus was shallow (about 20 km deep). The high level of destruction led to the usual question being

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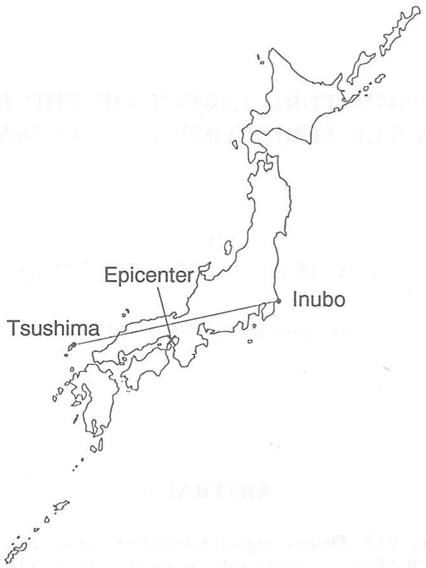

Fig. 1 The location of the transmitter (Omega, Japan) at Tsushima and the receiving station at Inubo is shown, together with the great-circle path connecting these two stations and the epicenter of the Kobe earthquake (indicated by a cross).

raised: is it possible to find a precursory signature of earthquakes like the Kobe earthquake? Unfortunately, conventional geophysical methods have been unsuccessful in predicting this and previous earthquakes, so we have examined the possibility of using radiophysical measurements as early indicated(1). First, we considered a VLF signal method, in which we observe the phase and amplitude of VLF navigational transmitter signals propagated inside the Earth-ionosphere waveguide. If the frequency and reception distance are fixed, then the observed VLF signal parameters are mainly determined by the ionospheric reflection height h, which depends on the D-layer electron density profile. This is why the VLF signal method is often used to record short-term electron density variations in the lower ionosphere that are associated with solar radiation, cosmic rays (the Forbusch effect), energetic particle precipitation [e.g. Wait(7), Alpert and Fligel(8)] and lightning-induced heating [Armstrong (9), Inan et al.(10)]. Recently, the use of this method to search for earthquake precursory activity has been studied. Gokhberg et al.(3) were the first to report an precursory influence of earthquakes on subionospheric VLF propagation, which was suggested as a possible method of earthquake prediction. Later, Russian(4) and Japanese(5) researchers have accumulated additional evidence on anomalies in subionospheric propagation associated with earthquakes. They have analyzed deviations in the signal phase (or amplitude) from the monthly averaged level during the night hours and found that deviations increased during a period from about one month to a few days before an earthquake. This paper describes the observed subionospheric propagation of VLF Omega signals from Tsushima, as observed at Inubo, Chiba. The observed results show significant precursory effects as a signature of the Kobe earthquake. Also, we propose an interpretation of the observed main effects and discuss their possible causes.

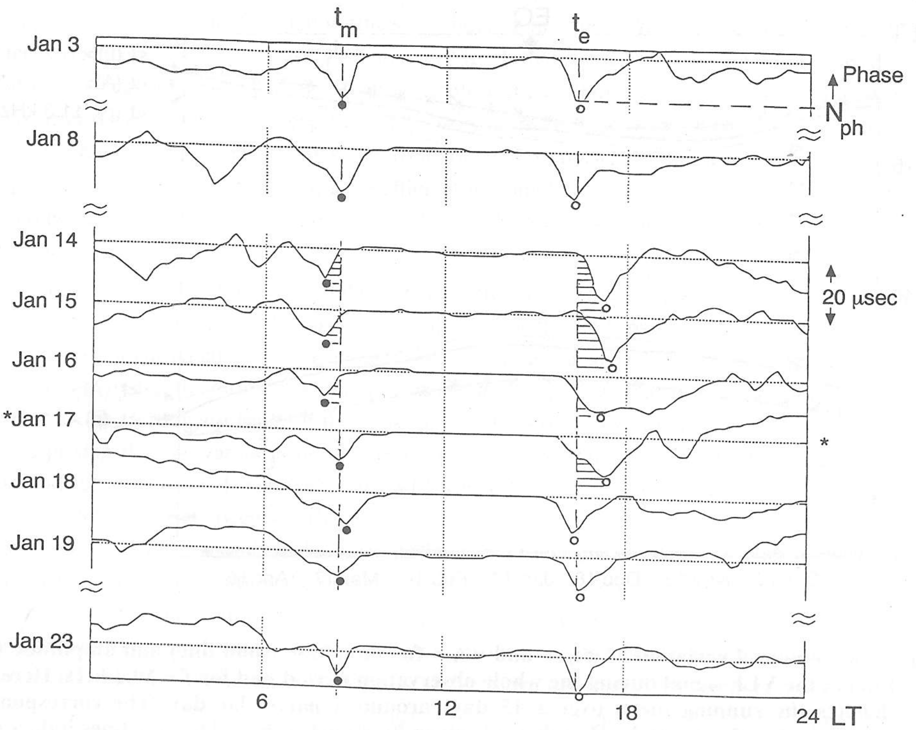

Fig. 2 Sequential plots of the diurnal variation of VLF signal (f = 10.2 *kHz*) phases observed at Inubo. Here, t_m and t_e denote the times where the phase reaches a minimum around sunrise and sunset; the value of the phase at the phase minimum is defined as N_{ph}. The phase of each day is shown in the same relative units.

2. Method of Data Analysis and Main Effects

We have examined data on VLF signals received at Inubo (near Tokyo) (geographic coordinates: 35°42′N 140°52′E) that were transmitted from "Omega," Japan (Tsushima, 34°37′N, 129°27°E). The relative location of the transmitter and receiving station is given in Fig. 1, together with the great circle path between them. The epicenter of the Kobe earthquake is indicated by a cross and it is about 70 km from the VLF signal path. We have used the data on the phase and amplitude of the signal at a frequency of 10.2 kHz and phase of 11.3 kHz during the time period from about four months before the earthquake and four months after. We consider this eight-month period sufficient for statistical purpose because the usual time scale of electromagnetic precursors of earthquakes is a few days or weeks [Rikitake(11)].

The previous works mentioned above(3)–(6) have dealt with subionospheric VLF propagation paths over distances of several thousand kilometers, but the distance between Tsushima and Inubo is only about 1000 km, which can be considered a rather short-distance propagation. Furthermore, in the case of earthquake influences, we expected to find long-term VLF signal variations (with a period exceeding one day), unlike the usual short-time variation with a scale of hours or minutes. Figure 2

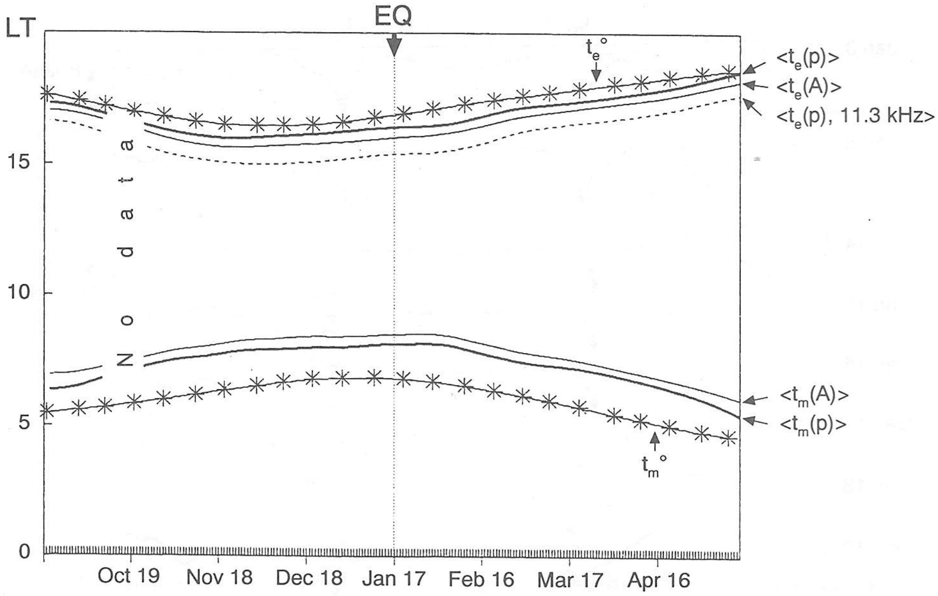

Fig. 3 The temporal variation of $< t_m >$ and $< t_e >$ for the phase (solid line) and amplitude (thin line) of the VLF signal during the whole observation period and for $f = 10.2$ kHz. Here, $< >$ denotes the running mean over ± 15 days around a particular day. The corresponding value of $< t_e >$ for $f = 11.3$ kHz (phase) is given by a dashed line. The star lines indicate the times of sunrise and sunset observed at Tokyo. The vertical line marks the time of the Kobe earthquake and we have no data for the period from Oct. 5 to Oct. 23 (as in the other figures).

shows a sequential plot of the diurnal variation of the VLF(f = 10.2 kHz) signal phase observed at Inubo between two weeks before and one week after the earthquake. The scale of the phase (the vertical axis) is given in the figure, and is the same for all days. Some days were omitted from the figure, because the diurnal phase variations on those days were very similar to those two weeks before and one week after the earthquake. We performed a conventional analysis[(4)(5)] by examining the fluctuations in phase, especially during nighttime, for the VLF data collected during the entire period described above. We found that the fluctuation in the nighttime phase seemed to increase considerably before the earthquake (though not shown here), but this effect was not particularly convincing. Hence, we can conclude that the analysis method which was successful for long-distance propagation paths (several thousand kilometers long), does not seem to be appropriate for a path as short as the one considered in this paper.

As an alternative (or complement) to the conventional analysis, we propose a new method of using "terminator times," which is more suitable for short-distance propagation paths and which is much more useful than the conventional analysis. Consider the diurnal phase variation on January 3, shown in Fig. 2, when there seems to be no effect of the earthquake. The terminator times, when the phase (and amplitude) reaches a characteristic minimum, can be easily defined twice a day as t_m and t_e for the morning and evening, respectively. The formation of minima in the phase at the terminator times, t_m and t_e, is known to be the consequence of the wave interference of several modes [Wait[(7)]], and so the terminator times are a physical quantity that provides us with useful information. The accuracy in estimating the terminator times is about 6 minutes. We can see, from the specially selected sequence of the daily phase variations in Fig. 2, that the terminator time t_m decreased and t_e shifted to a later time in the evening a few days before the earthquake. This effect was found to last one day after the earthquake. Judging from the observations in Fig. 2, it is likely that the extension of the daytime hours felt in terms of the subionospheric VLF radio waves, might be associated with the earthquake. However, the data length is insufficient to completely convince us that this phenomenon is not coincidental, but is actually earthquake-related. Therefore, we attempted to prove this by means of statistical studies.

Figure 3 shows the temporal evolution of the terminator times $< t_m >$ and $< t_e >$, together with the local times of sunrise $t^o{}_m$ and sunset $t^o{}_e$ near the end of the VLF path (at Tokyo). The values $< t_m >$ and $< t_e >$ on a particular day are estimated as the running mean values of $< t_m >$ and $< t_e >$ for ± 15 days. In the figure, the terminator time for the phase, t_e (p), as well as that for the amplitude t_e (A) are included. The terminator time for the phase at $f = 11.3$ kHz is also plotted ($< t_e(p)$, $11.3\ kHz >$). It is not surprising that the variation in the terminator times correlates very well with the astronomical sunrise and sunset times and "sunrise" in the VLF signal behavior occurs a little later, $\Delta t_m = \langle t_m \rangle - t^o{}_m > 0$, but the VLF "sunset" occurs earlier, $\Delta t_e = \langle t_e \rangle - t^o{}_e < 0$. Note that $|\Delta t_e| < \Delta\ t_m$ for both the phase and amplitude variations and it is very difficult to find any earthquake signatures in those characteristics. However, earthquake signatures are more easily found in the deviations (or fluctuations) of the phase and amplitude $dt_e = t_e - \langle t_e \rangle$, which are presented in Fig. 4, where t_e is the terminator time on a particular day (a running mean over ± 1 day period is used in the figure). To determine the statistical importance of these deviations, we calculated the temporal variation of the dispersion of data $\sigma = \langle (t_e - \langle\ t_e \rangle)^2 \rangle^{1/2}$, averaged over a ± 1.5 month period around a particular day, and plotted the level of 2σ. The upper panel in Fig. 4 refers to the phase, while the lower panel, the amplitude. The earthquake date is indicated by an downward arrow in both panels. In both panels of Fig. 4, there is only one unsually high peak that exceeds the significant 2σ level which occurred a few days before the earthquake. This fact, based on the whole period, suggests that the relation of the deviation spikes in Figs. 4(a) and 4(b) with the earthquake is not coincidental. Results for the morning deviations are less evident, but these deviations were found to be in anti-phase with the evening ones, as shown in Fig. 5. Figure 5(a) is the overall view of the temporal evolution of the evening and morning phase terminator times, and Fig. 5(b) is a detailed view for only January. An anti-phase between $<t_e>$ and $< t_m >$ is clearly recognized in Fig. 5(b), indicating the extension of daytime hours felt by the VLF signal.

Next, we analyzed the phase value itself at the terminator time N_{ph} in the evening (Fig. 2). The same analysis procedures were followed as for the terminator times. The results on the phase deviation are shown in Fig. 6 at frequencies of (a) 10.2 kHz, and (b) 11.3 kHz. These parameters also seem to be related to the seismic activity, but this relationship is not as clear as for the deviations in Fig. 4.

To gather additional proof that the precursory effect in the terminator times in Fig. 4 is not coincidental, we also investigated the temporal evolution of several phenomena which might have an influence on the VLF anomaly. These were: (1) magnetic indices, which could lead to particle precipitation into the lower ionosphere, (2) solar radiation, and (3) a rainfall index, which is related to lightning electric field perturbations, etc. We found that none of these could have caused the abnormal VLF signal perturbations shown in Fig. 4.

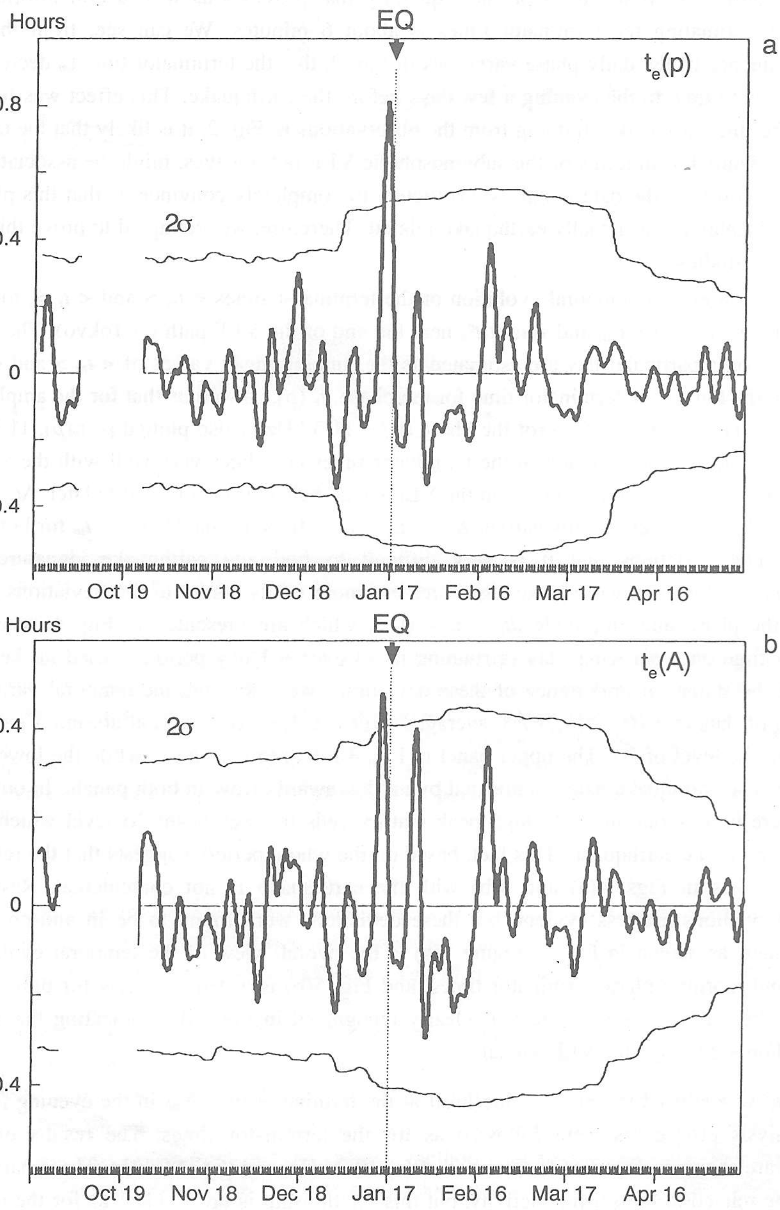

Fig. 4 Temporal evolution in the deviation in t_e (in hours) from monthly average values for the phase (panel *a* solid line) and amplitude (panel *b*, solid line). A running mean for the period of ± 1 day around each day is used. The ± 2σ level (two times the standard deviation) is also plotted for comparison (thin lines). The earthquake date is indicated by the arrow at the top of each panel.

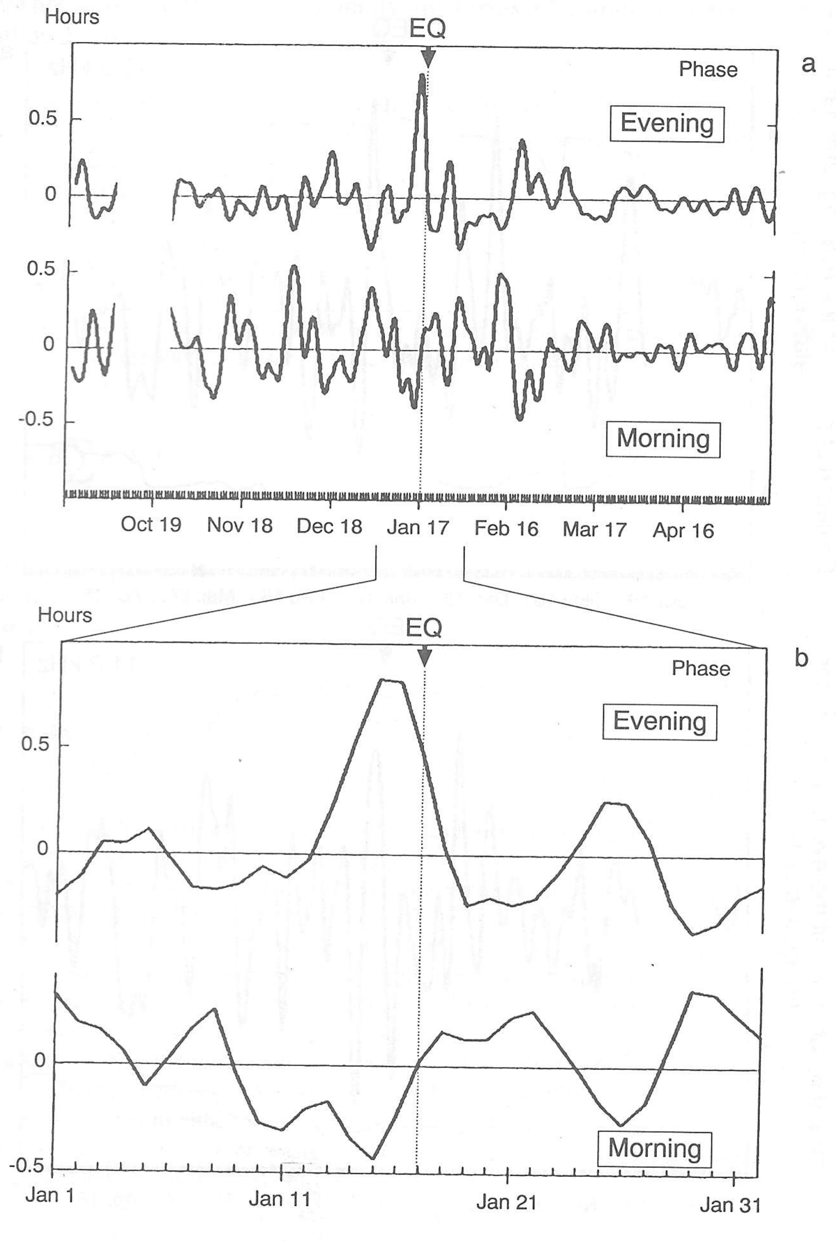

Fig. 5 (a) Comparative variation of phase terminator times in the evening and morning. The running mean over ± 1 day around each day was used. (b) The detailed change in phase terminator times (evening and morning) for only January, 1995. An enhanced deviation in t_e is observed a few days before the earthquake, while the change in t_m is found to be in opposite phase compared to in t_e.

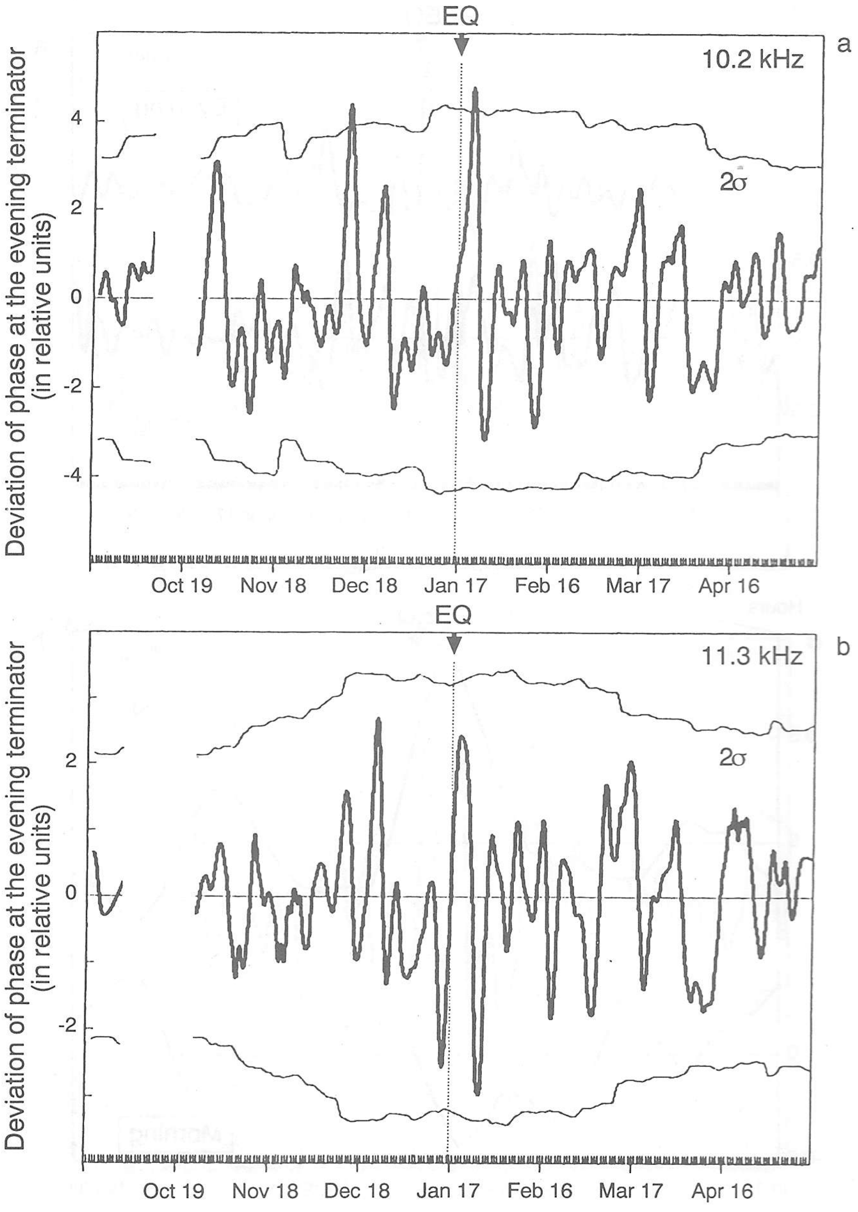

Fig. 6 Deviation of phase from the monthly averaged level (in relative units) for the evening terminator. The ± 2σ level is shown by thin lines.

3. Interpretation of the VLF Anomaly in Terms of Subionospheric VLF Propagation Theory

A perfect explanation of the observed effect is difficult to provide. We performed a simple computation of subionospheric VLF propagation by using the formulation by Wait[(7)]. The observed VLF electric field E_z is given as:

$$E_z = W E^0 \quad (1)$$

where E^0 the field in free space and W is an attenuation function associated with the medium properties that is described as a sum of the propagation modes:

$$W = B \sum_{n=0}^{\infty} \delta_n S_n^2 H_0^{(2)}(k S_n D) \quad (2)$$

where D is distance, k is the wave number in free space depending only on frequency f, B and excitation factor δ_n are constants for a fixed D and f, $H_0^{(2)}$ is the Hankel function of the second kind and S_n is given by,

$$S_n = a_n - i \frac{\varepsilon_n \tilde{\Delta}}{2kh} / a_n \quad (3)$$

where $\varepsilon_0 = 1$, $\varepsilon_n = 2(n \neq 0)$, $a_n = [1 - (\pi n/kh)^2]^{1/2}$ and h is the height of the reflection point. Here, $\tilde{\Delta}$ is a function related to the dissipation of VLF energy in the conductive ground and ionosphere and can be estimated from the observed attenuation of the dominant mode over a long distance. We made the following assumptions as in Wait[(7)]: (a) there are four modes of propagation, (b) attenuation of the first, dominant mode is 3.0 dB/1000 km, (c) the height of the VLF wave reflection is 85 km at night and 75 km during the day (see Fig. 7(c)) and (d) the characteristic time of the terminator change is 2 hours. Given these assumptions, we can reconcile our theoretical results with the observed regular diurnal variation in phase and amplitude, as shown in Fig. 7(a). To obtain the observed changes in the terminator times during the seismically perturbed period, we need only to assume a total decrease in the reflection height of $\Delta h \sim 1.5$ km as shown in Figs. 7(b) and 7(c). This decrease in reflection height might be related to either an increase in the reference atmosphere conductivity of about 30% or an increase in the density of charged particles assuming an unchanged scale height of an exponential altitude conductivity profile.

In the above discussion, we have shown from the standpoint of wave-propagation theory that a decrease in the VLF reflection height of about 1.5 km is sufficient to explain the change in the terminator times. Next, we must consider how and why such a conductivity or density perturbation might be produced by seismic precursory effects. At present, we speculate that the primary reason for these changes is associated with an intensified emission of radioactive radon from the earth before an earthquake, which increases the electric field in the upper atmosphere as suggested in a theoretical scheme developed by Pierce[(12)]. Indeed, there have been many papers on the increased appearance of radioactive gases before an earthquake (e.g. King[(13)], Yamauchi[(14)]) and there have been reports of radon emanation with ion density increased by about 10 times before the Kobe earthquake. Another

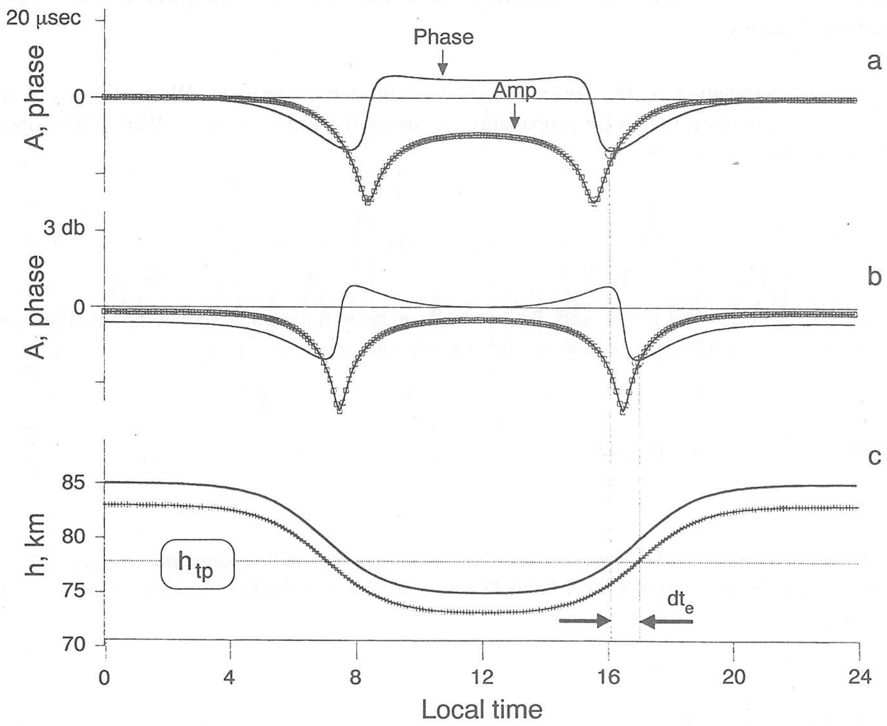

Fig. 7 Computed results for the expected diurnal variations in phase (thick line) and amplitude (thin line with small squares). The open circles correspond to t_e in Fig. 2 and dt_e is the change in t_e due to upper atmosphere perturbation. (a) Diurnal variation of phase and amplitude for regular behavior of the ionospheric height *h(t)*. (b) Diurnal variation of phase and amplitude for perturted behavior of the ionospheric height *h(t)*. (c) Assumed *h(t)* (solid line) and *h(t)* (thin line with crosses); h_{tp} is the value of *h* near the terminator point.

possible reason for the changes could be an intensification of planetary atmospheric waves with a period of about 10 days as can be seen from Fig. 5(b). We would expect less ionization due to solar radiation (EUV, or soft X-ray) at sunrise and sunset than during the day, and this is why we expect noticeable effects due to the possible radon effect at sunrise and sunset. A more detailed and quantitative discussion will be published elsewhere by Molchanov and Hayakawa[15] on the basis of either the intensification of the tropospheric electric field above the epicenter, or the excitation of planetary waves with a period of 9-10 days. However, further study is still needed.

4. Remarks

The primary purpose of this paper has been to describe the seismic influence on the subionospheric propagation of VLF Omega signals before and after the Kobe earthquake. Though the propagation distance between the transmitter and receiving station in this study was about 1,000 km, we initially applied the conventional analysis method, normally used for a long-distance (several thousand kilometers) propagation path, to study the fluctuation in the phase (and amplitude), especially at night. Our analysis showed that the fluctuation in phase at night seemed to increase slightly before the earthquake, but it was not convincing. Therefore, we developed a new method of using terminator times where there are observed minima in the phase (and amplitude) around sunrise and sunset. A detailed statistical study of the long-term data (4 months before and after the earthquake), has indicated that abnormal precursory behavior in the phase (and amplitude) terminator times is closely related to the earthquake. However, the phase value itself at the terminator times, was found to be not so useful in identifying any precursory effects.

The changes in the terminator times before the earthquake were interpreted in terms of the subionospheric VLF propagation theory by assuming that the VLF reflection height decreased by about 1.5 km. We speculate that this decrease may have been caused by either an increased emission of radioactive radon before the earthquake, or by an intensification of planetary atmospheric waves with a period of about 10 days. To determine the actual mechanism with certainty will require more work.

In conclusion, we believe the subionospheric VLF propagation is a very promising candidate for short-term earthquake prediction.

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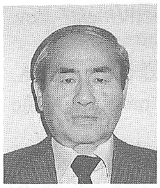

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