

Some results of subionospheric LF radio monitoring on the ionospheric perturbations for the 2004 Off Kii-Peninsula earthquakes

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1 Introduction

Radio waves from VLF/LF transmitters are known to propagate within the Earth-ionosphere waveguide. This waveguide is formed by the lower ionosphere (D layer) and the Earth's surface, so that any changes in the lower ionosphere lead to significant variations in VLF/LF amplitude and phase. It is well known that these variations were caused by different mechanisms including solar flares, lightning-induced electron precipitation, direct lightning heating, etc.

Anomalies in phase and amplitude associated with earthquakes have been reported recently. Subionospheric VLF/LF radio wave monitoring is widely used in recent years for analyzing the ionospheric perturbations as the earthquake preparatory process. We have proposed the terminology, 'lithosphere-atmosphere-ionosphere' coupling or 'electromagnetic phenomena in the coupled lithosphere-atmosphere-ionosphere system', which is currently used in the society of seismo-electromagnetics.

There are two possible approaches for the analysis of subionospheric VLF/LF radio wave propagation. The first approach is the so-called VLF/LF terminator time (TT) method. Hayakawa et al. [1] [2] paid a particular attention to the short-term deviations of TTs which are defined as the time where a minimum occurs in the receiving amplitude and/or phase during sunset and sunrise. This approach to examine subionospheric anomalies for seismic effects was applied to the Hyogo-ken Nanbu earthquake (January 17, 1995, $M=7.2$) for the first time [1]. These authors used the VLF signal transmitted by an Omega station in Tsushima (36.4°N , 129.5°E) and received at the Inubo station (geographic coordinates: 35.7°N , 140.9°E) which is located at a distance of about 1000 km in the East-West direction. The earthquake epicenter was located about 70 km from the great circle path. They found that the evening TT deviated significantly from the monthly averaged value a few days before the earthquake. This TT anomalous shift exceeded the 2σ (σ : standard deviation) level over 8 months of TT data and the observed evening TT at the peak deviation was nearly 50 min later than the monthly average. Using this TT method for other 10 large seismic events with $M \geq 6$, Molchanov and Hayakawa [3] have found that anomalous shift in TT fluctuations appeared from 5 to 10 days before large earthquakes and disappeared a few days after them. These authors used the same VLF signal transmitted by the Omega station in Tsushima and received at the Inubo sta-

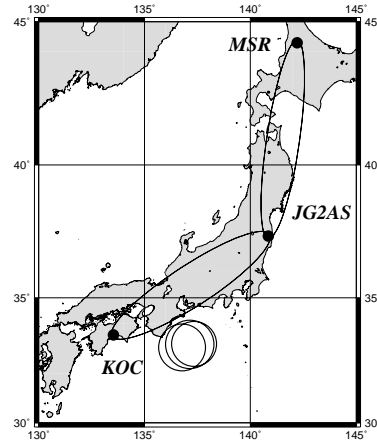


Figure 1: A map of Kii-Peninsula earthquakes and of LF propagation paths employed for monitoring. The LF observatories, Moshiri in Hokkaido and Kochi, and JG2AS transmitter are marked in the figure with the bold letters MSR, KOC and JG2AS respectively.

tion. Five of these shocks associated with evening TT anomalies was reported and this deviation ranged from ~ 15 to ~ 32 min. Molchanov and Hayakawa concluded that this TT anomaly was caused by the earthquakes which were reasonably shallow (≤ 80 km) and occurred within 70 km of the great circle path.

The second approach is based on the analysis of nighttime fluctuation of VLF/LF signals [4] [5] [6]. Our latest result by Shvets et al. [7] shows that nighttime fluctuation has exhibited a clear anomaly associated with the Tokachi-oki earthquake ($M \sim 8$, Hokkaido, September 25 (UT), 2003).

The 2004 Off Kii-Peninsula earthquakes occurred on 5 September 2004, and in this paper we report some results on ionospheric perturbations by means of subionospheric LF monitoring performed simultaneously at two widely spaced receiving stations during the Kii-Peninsula earthquakes.

2 Description of VLF/LF measurements

A signal transmitted by Japan Time Standard LF station (JG2AS, 40 kHz; Fukushima Prefecture, 37.37°N , 140.85°E) has been monitored at two different locations; these are Moshiri station (MSR) in Hokkaido and the station at Kochi (KOC) [8]. The

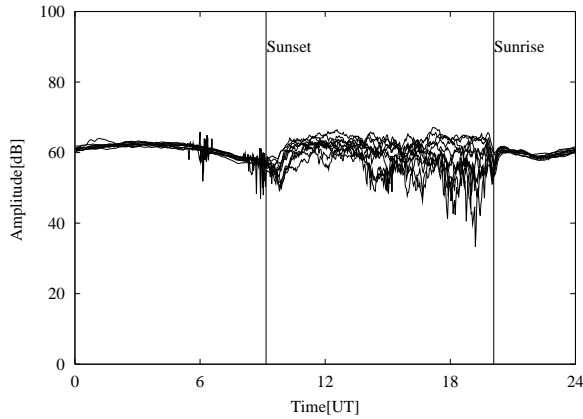


Figure 2: A typical example on the LF amplitude for the path of JG2AS-KOC on August 20-30 2004.

fifth Fresnel zone is plotted in Fig. 1 for each signal propagation path. The length of wave path of JG2AS-KOC is 780km and that of wave path of JG2AS-MSR is also 780km. The positions of the events corresponding to the Kii-Peninsula earthquakes are marked with large empty circles in the map in Fig. 1 (with their centers being epicenters).

For receiving and round-the-clock logging of the VLF/LF signals, the JAPAL system receiver has been used at all the stations [8]. The vertical electric field is received with a rod antenna installed on the roof of the laboratory building at each location. Fig. 2 shows a typical example on the LF amplitude for the path of JG2AS-KOC for about 10 days of August 20-30 2004. Vertical bars indicate the sunset and sunrise times at the transmitter JG2AS. Fig. 2 shows that the propagation condition exhibits high variability during nighttime. While the propagation condition during the day is relatively stable as compared with nighttime one. During the transition between nighttime and daytime propagation conditions, it is easy for us to notice the minima in amplitude (i.e. so-called terminator time).

3 Some results of the LF data processing on the ionospheric perturbations

3.1 Terminator time shift associated with the 2004 Off Kii-Peninsula earthquakes

In a case study of different strong earthquakes Molchanov and Hayakawa have shown effectiveness of the terminator time shift for revealing precursory ionospheric phenomena in VL/LF signals [3]. Terminator times are determined by the positions of characteristic minima occurring in diurnal dependencies of amplitude of VLF/LF signals when the terminator crosses a propagation path during the evening and

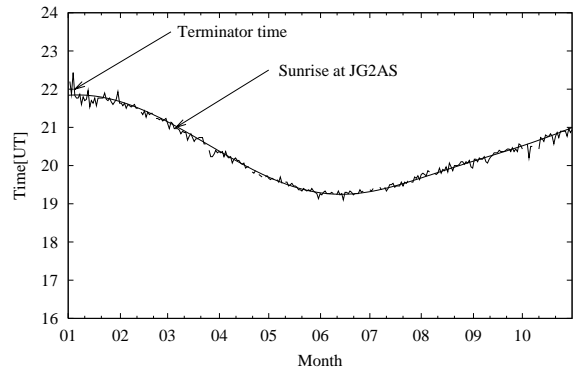


Figure 3: Regular annual variations of TT during the period from January to October 2004. Polygonal line shows the TT. In addition to the TT, we plot the sunrise time at JG2AS.

morning periods of the time. Terminator minima occur due to the influence between different waveguide modes and their positions are sensitive to ionospheric irregularities along the propagation path as was shown by Hawakawa et al. [2] for the case of relatively short (≤ 1000 km) propagation path which is very perpendicular to the terminator line.

Fig. 3 illustrates regular annual variations of TT (morning) during the period from January to October 2004. In the addition to the plot of TT, we have also shown the sunrise time at transmitter JG2AS. The time of modal minima observed at the receiver is known as being associated with regular sunrise/sunrise variation [9]. It has been suggested that an anomaly shift of the TT in the regular annual variations is a result of the influence of effects from seismic activity, the study of which has become known as the TT method [3]. We calculate the short-term deviations of the TT during the period from January to October using a high-pass filter and we show in Fig. 4 the occurrence probability of short-term deviations of the TT. The distribution of short-term deviations was well approximated by a Gaussian distribution using the least squares fit.

We show in Fig. 5 the short-term deviation of TT for the relevant period of August 2004 through September 2004 and vertical bars indicate the occurrence days of the 2004 Off Kii-Peninsula earthquakes (5 Sep. and 7 Sep. 2004). We have found that the TT shift exceeds -1.5σ level on 1 September (4 days before the main shock of the earthquakes) and 10 September (5 days after the earthquake). This result is in agreement with the case of Hyogo-ken Nanbu earthquake [1]. Some electromagnetic modelings have been attempted in order to interpret such changes in VLF/LF TT associated with earthquakes. A theory is presented suggesting that the observed effect can be explained by decreasing the VLF reflection height (i.e. lower ionosphere) [2] and some more sophisticated modeling has been suggested by Soloviev et al. [10]

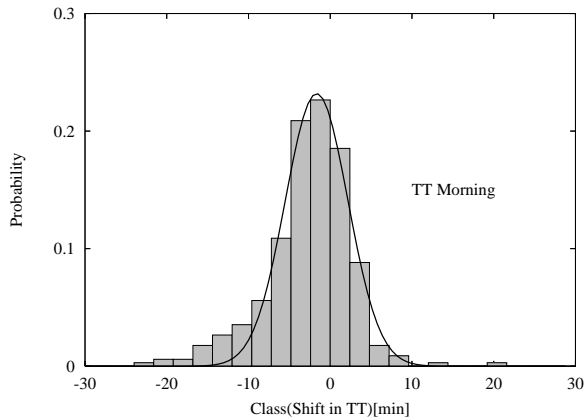


Figure 4: The distribution of short-term deviations of the TT. Bar chart shows the probability and a curve by means of the Gaussian approximation is also shown.

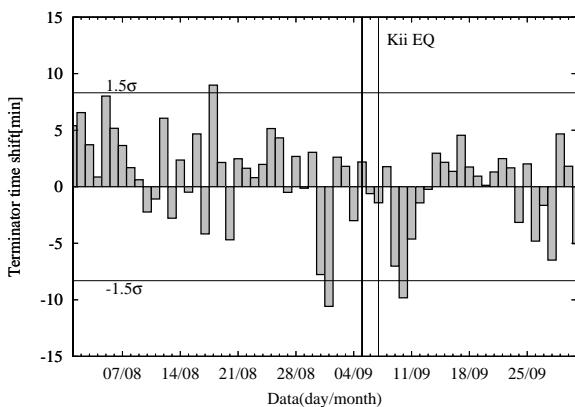


Figure 5: Short-term deviations of TT during the period from July to September. Vertical bars indicate the occurrence day of the 2004 Off Kii-Peninsula earthquakes.

by means of the full-wave method.

3.2 Anomaly in the nighttime fluctuation in amplitude associated with the 2004 Off Kii-Peninsula earthquakes

In this section we examine the anomaly in the the nighttime fluctuation in amplitude possibly associated with the 2004 Off Kii-Peninsula earthquakes. Shvets et al. [7] have reported that nighttime fluctuation increased 5-8 days before the Tokachi-oki earthquake ($M \sim 8$, Hokkaido, September 25 (UT), 2003) on the path from JG2AS to MSR and to Kamchatka.

Fig. 6 shows the original amplitude data and the corresponding fluctuation spectral intensity of LF signals during the period from 25 September to 10 August. The 2004 Off Kii-Peninsula earthquakes are marked by the two arrows. We have found clear and significant fluctuations in the nighttime amplitude on 27-31 August (4-8 days before the earthquake) and 7-

9 September (2-4 days after the earthquake) and the fluctuation spectral intensity increased in the period of 30[*min*]-3[*hour*]. This spectral intensity in the frequency range of atmospheric gravity wave [5] [4] [6] [11], is compared with the temporal evolution of earthquakes. Then, it is found that there seems to exist a definite correlation between the two, which gives us a further support to the important role of atmospheric oscillations in the lithosphere-ionosphere coupling.

We have also applied our data processing to above LF signals to estimate signal fluctuation quantitatively. To remove the regular seasonal variation, we have analysed the difference between current LF amplitude and monthly average as follows:

$$dA_k(t) = A_k(t) - \langle A_i(t) \rangle, \quad (1)$$

where k is a current day number, $A_k(t)$ is the amplitude diurnal dependence for the k_{th} day, and t is the time during a particular day. Signal fluctuation is defined in the following way:

$$Signal\ fluctuation(k) = \sum_{nighttime} dA_k(t)^2. \quad (2)$$

Time series of *signal fluctuation*(k) at the stations at KOC and MSR are summarized in Fig. 7. In addition to the signal fluctuation, we have plotted the planetary index of magnetic activity (ΣKp) for the sake of comparison.

We have found the good correspondence of the peak in signal fluctuations in the end of August at KOC and the occurrence of the Kii-Peninsula earthquakes. However, we cannot find any peak in the signal fluctuations at MSR station. The Kii-Peninsula earthquakes occurred near the path of transmitter JG2AS to receiver KOC and are far from the path of JG2AS-MSR as shown in Fig. 1. Therefore, it seems highly likely that the signal fluctuation observed at the KOC station is influenced by the Kii-Peninsula earthquakes. Signal fluctuation is seen to have increased in the end of July for both signals at MSR and at KOC. During this period ΣKp index exceeded 40 as in Fig. 7. Rozhnoi et al. [6] have reported that VLF/LF amplitude is sometimes influenced by high magnetic activity (when ΣKp index exceeds about 40), and so we may conclude that an increased signal fluctuation in the end of July might be an influence by high magnetic activity.

4 Summary

The 2004 Off Kii-Peninsula earthquake occurred on 5 September 2004 and its aftershock two days later. This paper reports on some results of subionospheric LF monitoring performed simultaneously at two widely spaced receiving stations during the Kii-Peninsula earthquakes. We have analyzed nighttime fluctuation in LF signals and also terminator times which are defined as the time where a minimum occurs in the receiving amplitude during sunset and sunrise. From

the data analysis presented here a few basic conclusions can be drawn:

First of all, we have applied TT method [1] [2] to LF signals, and we have found TT shift exceeds -1.5σ level 4 days before and 5 days after the earthquakes. Some electromagnetic modelings have been attempted in order to interpret such changes in VLF/LF TT associated with earthquakes.

Then, we examined the nighttime fluctuation anomaly in amplitude. We have found the good correspondence of the peak in signal fluctuations in the end of August at the station KOC and Kii-Peninsula earthquakes. But, we cannot find the any peak in signal fluctuations at MSR staion which is far from the epicenter.

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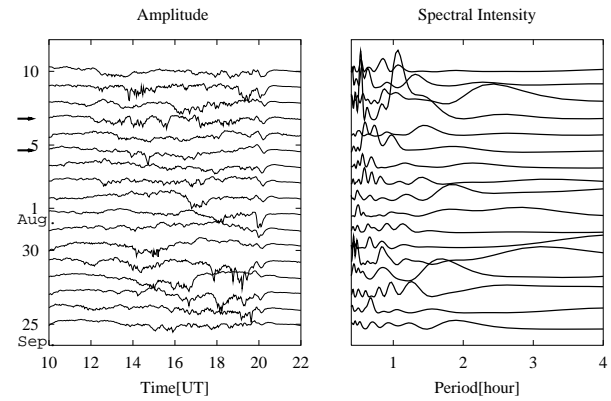


Figure 6: Original data on the amplitude(left) and corresponding fluctuation spectral intensity of LF signals(right) during the period from 25 September to 10 August. The 2004 Off Kii-Peninsula earthquakes are marked by the arrows.

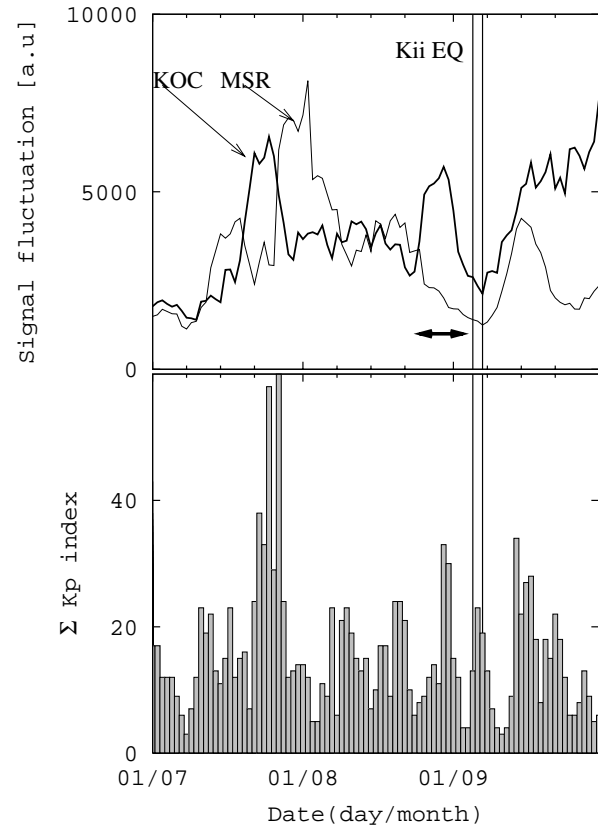


Figure 7: Temporal evolution of the nighttime fluctuation of LF signal at KOC and MSR during the period from July to September. In addition to the nighttime fluctuation, we plot the planetary index of magnetic activity ΣKp (Σ : daily sum for one day).