A Statistical Study on the Dependence of Characteristics of VLF/LF Terminator Times on the Propagation Direction

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Keywords: subionospheric VLF/LF propagation, terminator times, day-night asymmetry, TT method, ionospheric perturbations, seismic effect

Radio waves from VLF/LF transmitters are known to propagate inside 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. Minima occur in the receiving amplitude and phase (so-called Terminator times) during sunset and sunrise. The generation mechanism for such sunrise/sunset minima is generally accepted to involve significant mode conversion at the transition region between the day and night portions of the subionospheric waveguide. Phase and amplitude anomalies associated with earthquakes have been reported recently. Subionospheric VLF/LF radio wave monitoring is widely used in recent years for analyzing this earthquake preparatory process. Hayakawa et al. paid a particular attention to the short-term deviations of terminator times and 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.

When any seismo-TT anomaly is considered, we need the detailed overall statistical study of VLF propagation characteristics (TT features) with respect to the propagation direction. We have installed seven VLF observing stations and we have been observing several VLF/LF transmitters. This installation of a VLF/LF network in Japan was carried out within the framework of NASDA's Earthquake Remote Sensing Frontier Project, and we have accumulated a lot of data since the year of 1996. In this paper we examine the statistical behavior on the dependence of VLF/LF TT characteristics on the propagation direction by means of our data during about three years. We pay a particular attention to the TT characteristics for the East-West and North-South propagation paths. We also focus on the short-term TT characteristics in order to reinforce the previous study which is based on the TT method.

A typical example of amplitude data is shown in Fig. 1. Vertical bars indicate the sunset and sunrise times at the transmitter NPM and the receiving point CHO. Minima occur in the received amplitude during sunset (so-called TT evening) and sunrise (so-called TT morning).

From the data and analysis a few basic conclusions can be drawn: First, regular annual deviations of TT for the East-West path were confirmed to follow well the time series of sunrise/sunset time at the receiving point. However, TT

Fig. 1. A typical example of amplitude data on May 4-8, 2001

behavior for the North-South path is more complicated than that for the East-West path. Then, we focused on the short-term TT characteristics in order to reinforce our previous study which is based on TT method. We can confirm the spectral peaks with periods of 5, 7 and 13 days. These frequency ranges are of atmospheric oscillations, so the periodic components of atmospheric oscillations might have appeared in TT deviations. We studied the distribution of short-term deviations of TT and we confirmed the σ (standard deviation) of TT evening is larger than that of TT morning. The difference between TT evening and TT morning is caused by the ionospheric conditions as results of the difference between the sunset and sunrise transition.

We found that the deviation of TT is very enhanced in winter season for North-South short path. TT behavior in winter season is also seen to vary a lot for North-South long path. However, we cannot find this effect for East-West path. So, we can conclude that winter effect in TT is a phenomenon peculiar to North-South path. TT behavior is regularly influenced by the lower-ionospheric condition which depend on sunrise/sunset transition and season. Therefore, we can conclude that the lower-ionosphere condition can be monitored by VLF/LF terminator times. The short-term variations in the dependence on the propagation direction that is associated with earthquakes (so-called TT method) will be the focus of our future study.

A Statistical Study on the Dependence of Characteristics of VLF/LF Terminator Times on the Propagation Direction

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We present a detailed statistical study over two years on the times of amplitude minima (so-called terminator times) observed for the VLF/LF transmitters NPM/NWC/JJY as received at three sites. We analyzed three paths: East-West long propagation path, North-South long propagation path and North-South short propagation path. In this paper we examine the statistical behavior on the dependence of VLF/LF terminator time characteristics on the propagation direction and also we focus on the short-term terminator time (TT) characteristics. We found from the data analysis that TT behavior is regularly influenced by the lower-ionospheric condition which depends on the sunrise/sunset transition and season.

Keywords: subionospheric VLF/LF propagation, terminator times, day-night asymmetry, TT method, ionospheric perturbations, seismic effect

1. Introduction

Radio waves from VLF/LF transmitters are known to propagate inside 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 factors including solar flares, geomagnetic storms, lightning-induced electron precipitation, etc. We also know that mode conversion effects are a prominent phenomenon particularly during the sunrise/sunset transition in VLF radio wave propagation. Minima occur in the receiving amplitude and/or phase during sunset and sunrise. The generation mechanism for such sunrise/sunset minima is generally accepted to involve significant mode conversion at the transition region between the day and night portions of the subionospheric waveguide. Regular annual variations of the time of amplitude minima caused by changing illumination conditions on an East-West propagation path were noticed by Ries⁽¹⁾. Lynn⁽²⁾ discussed the TT characteristics for the North-South propagation path. Studies of the VLF radio propagation were actively performed in the 1960s–1970s in association with the OMEGA navigation system. In a recent study, Clilverd et al. have reported that the interpretation of the timing of minima is consistent with modal conversion taking place as the sunrise terminator crosses the propagation path at specific, consistent locations⁽³⁾.

Phase and amplitude anomalies associated with earthquakes have been recently reported. Subionospheric VLF/LF radio wave monitoring is widely used in recent years for analyzing this earthquake preparatory

process⁽⁴⁾. There are two possible approaches for such a study. The first approach is the so-called VLF/LF terminator time (TT) method⁽⁵⁾. The second approach is based on the analysis of nighttime fluctuation of VLF/LF signals^{(6)–(8)}. Hayakawa et al. 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 Hyogoken Nanbu earthquake (January 17, 1995, $M = 7.2$) for the first time⁽⁵⁾. 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 (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 and the observed evening TT at the peak deviation was nearly 50 min later than the monthly average. Hayakawa et al. reported that the evening TT effect was much larger than that for the morning in this case.

On the other hand, Clilverd et al.⁽⁹⁾ reported that the time of the sunrise modal minimum does not change significantly during the TT anomalous cases associated with earthquakes. These authors considered the 12 Mm path from the VLF transmitter with code name NAA (24.0 kHz, 1 MW) to Faraday, Antarctica (65°S , 64°W) during 1990–1995. Note this propagation path is parallel to the sunrise/sunset transition (i.e. North-South path). These authors considered that the largest changes in minimum time are associated with the next terminator mode-conversion region. Their conclusion is that the oc-

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currence rate of successful earthquake predictions using the TT method cannot be distinguished from that of chance for their analysis.

In response to Clilverd et al.'s conclusion, Soloviev et al.⁽¹⁰⁾ have performed the full-wave computation, and have shown that a perturbation in the lower ionosphere during the day/night transmission would exhibit a significant change in the TT, in support to the TT method.

When any seismo-TT anomaly is considered, we need a detailed overall statistical study of VLF propagation characteristics (TT features) with respect to the propagation direction (propagation angle relative to the terminator line; EW or NS direction), but there have been no reports on this^{(1) (2) (11)}. In this paper we examine the statistical behavior on the dependence of VLF/LF TT characteristics on the propagation direction by means of our data during about three years. We pay a particular attention to the TT characteristics for the East-West and North-South propagation paths. We also focus on the short-term TT characteristics in order to reinforce the previous study which is based on the TT method⁽⁵⁾.

2. Description of VLF/LF Measurements

We have established a VLF/LF network (JAPAL network) consisting of seven stations in Japan within the framework of the NASDA's Earthquake Remote Sensing Frontier Project⁽¹²⁾. Amplitude and phase of the VLF/LF signals from a radio transmitter is monitored at each station using the advanced digital VLF/LF receiver⁽¹³⁾. At each station we receive the signals which are transmitted from JJY (40 kHz), NPM (21.4 kHz), NWC (19.8 kHz) and NLK (24.8 kHz). We analyze the results of our observations during a long period of 1999-2003 with time resolution of 20 s. In this work we shall confine ourselves to the analysis using 2 min average

data. We consider three VLF paths with different properties (i.e. East-West long propagation path, North-South long propagation path and North-South short propagation path). Figure 1 shows a map of the great circle paths from the NPM transmitter to Chofu station (CHO), the NWC transmitter to Chofu (CHO) and JJY transmitter to Moshiri (HOK). Table 1 is the summary of the three VLF transmitters used in this paper. The length of wave path of NPM-CHO is 6184 km, that of wave path of NWC-CHO is 6921 km and that of wave path of JJY-HOK is 777 km.

We have developed a software named *TT Morning And Evening Characterizing Helper And Reading Navigator (TT-MAECHARN)* to find out the TT quantitatively. We trace the positions of the amplitude local minima as relative to the sunrise/sunset time. And then, we detect TT in consideration of the regular relationship between TT and sunrise/sunset time using this software.

3. Observational Results

3.1 NPM-Chofu VLF Propagation Path (East-West Long Propagation Path) A typical example of amplitude data for the NPM (Hawaii)-CHO (Tokyo) VLF propagation path is shown in Figs. 2 and 3. Figure 2 shows the amplitude data for the path NPM-CHO in a particular month, May 2001. Regular daily variation are seen in Fig. 2 to occur in the received amplitude from day to day. Black gaps in Fig. 2 indicate no transmission.

Figure 3 shows a sequential plot of the diurnal variation of amplitude data from the NPM-CHO path for several days on May 4-8, 2001. Vertical bars show the sunset and sunrise times at the transmitter NPM and the receiving point CHO. Figure 3 indicates that the propagation condition shows high variability at night; the nighttime amplitude is seen to vary a lot. While the propagation condition during 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 minima in the amplitude. We can find, from Fig. 3, a minimum in amplitude during the transition from daytime to nighttime and two minima in amplitude during the transition from nighttime to daytime. That is, the situation of terminator time "morning" is found to be different greatly from that of terminator time "evening". The resultant minima can be seen at about 6 UT, 17 UT and 18 UT. We detect these three amplitude minima and log the time at which they occurred using the software. Figure 4 shows the regular annual deviations of TT during the period from January 2000 to May 2002. In this plot each dot represents detected minima (i.e. TT). In addition to the plot of TT, we have also shown the sunset and sunrise times at the receiving point CHO and transmitter NPM. Regular annual deviations of TT seem to be approximated by the components of a sinusoidal function (as expressed by a solid line in Fig. 4). We have found that TT can be expressed by a combination of annual and semi-annual components using the least squares fit in this path (Eq. (1) indicates the case of TT evening)

Fig. 1. A map of the great circle paths from the NPM transmitter to Chofu station (CHO), the NWC transmitter to Chofu station (CHO) and JJY transmitter to Moshiri station (HOK)

Table 1. Transmitters

Call	Frequency [kHz]	Location	Power [kW]
NPM (Hawaii)	21.4	21°N, 158°W	600
NWC (Australia)	19.8	22°S, 114°E	1000
JJY (Fukushima, Japan)	40.0	36°N, 130°E	10

in the following way:

$$5.8 - 1.1 \sin \left(\frac{2\pi x}{365} + 1.8 \right) + 0.7 \sin \left(2 \frac{2\pi x}{365} + 0.03 \right), \quad \dots \dots \dots (1)$$

where x is current day number of the year. TT can be expressed easily with sinusoidal functions for this path. Annual and semi-annual variations are the main

Fig. 2. Amplitude data for the path of NPM-CHO in May 2001; Regular minima can be seen at 6, 17, 18 UT in the received amplitude from day to day

Fig. 3. Amplitude data for the path of NPM-CHO on May 4-8, 2001; Vertical bars indicate the sunset and sunrise times at the transmitter NPM and the receiving point CHO. Minima occur in the received amplitude during sunset and sunrise

Fig. 4. Regular annual deviations of TT during the period from January 2000 to May 2002; Dots show the TT; In addition to the TT, we plot the sunset and sunrise times at CHO and NPM

components of the regular sunrise/sunset variation. The time of modal minima observed at the receiver is known more commonly as being associated with regular sunrise/sunset variation⁽¹⁾. Figure 5 indicates TT morning (y) plotted against the CHO sunrise time (x) during the period from January 2000 to May 2002. Local sunrise time in summer is found to range from about 19:30 to 20:00, while that in winter, 21:30 to 22:00 in Fig. 5. It was found from Fig. 5 that TT morning is well approximated by $y = 1.04x - 2.04$ and $y = 0.91x - 1.35$. Therefore, regular annual deviations of TT morning well following the time series of CHO sunrise time were confirmed. We also confirmed that TT evening follows good the time series of CHO sunset time.

It has been suggested that short-term deviations (shorter than 20 days) in the regular annual deviations are a result of the influence of effects from seismic activity, the study of which has become known as the TT method⁽⁵⁾. We calculate the short-term deviations of the TT using a high-pass filter and we show the results for April 2001 through December 2001 in Fig. 6.

We calculate the periodogram to find the modulation in the frequency range of atmospheric oscillations from short-term TT variation. It is well known that any fluctuation, say $f(t)$, can be characterized by its power

Fig. 5. TT morning (y) plotted against the CHO sunrise (x) during the period from January 2000 to May 2002; In addition to the TT, lines of regression are also shown

Fig. 6. Short-term variations of the TT Evening during the period from April 2001 to December 2001

spectrum $P_0(F)$, which is introduced in the following manner:

$$\langle f(t)^2 \rangle = \int_0^\infty P_0(F) dF, \dots\dots\dots (2)$$

where F is frequency of constitutive oscillation. In the same manner, the distribution of fluctuation energy with oscillation period $\tau = 1/F$ can be introduced:

$$\langle f(t)^2 \rangle = \int_0^\infty P(\tau) d\tau, \dots\dots\dots (3)$$

and the comparison between Eqs. (2) and (3) immediately leads to

$$P(\tau) = P_0(1/\tau)/\tau^2. \dots\dots\dots (4)$$

It means that normal spectrum distribution of stochastic fluctuation $P_0(F) \sim F^{-2} \sim \tau^2$ will be flat in the $P(\tau)$ representation. That is why any deviation of $P(\tau)$ from the flat behavior is a signature of non-stochastic processes. An example of above FFT analysis of short-term TT variation during the period from November 2001 to December 2001 is shown in Fig. 7.

We can confirm in Fig. 7 the spectral peaks with periods of 5, 7 and 13 days. Atmospheric planetary wave

is known to have wave periods falling into three well-defined intervals which are 1.9–2.2 days, 4 to 7 days and 10 to 20 days. These are often termed as the quasi 2-day, quasi 5-day and quasi 16-day oscillations, respectively⁽¹⁴⁾. As the conclusion, we do not obtain any direct evidence of the effect of atmospheric planetary waves in the observed atmospheric parameters, but it seems that the lower ionosphere is modulated by atmospheric oscillations. So the periodic components of atmospheric oscillations might have appeared in TT deviations.

Figure 8 shows the dynamic periodogram of short-term TT variation during the period from May 2001 to December 2001. We can find the spectral peaks with periods of quasi 2 days, quasi 4 days and 6–16 days, but, these periodic components are not so stable through a year. These spectral peaks might be associated with the seasonal variation of atmospheric oscillations, but these relations are not clear at present.

Molchanov et al.⁽¹⁵⁾ have reported the change of atmospheric oscillations from winter to summer regime through spring time (March) transition period. However, we cannot envisage such a change of atmospheric oscillations due to the lack of data. A correlation of TT anomaly associated with earthquakes with atmospheric oscillations was also reported by Molchanov et al. and Shvets et al.^{(15)–(17)}. Molchanov et al. suggested that the seismic influence on the TT is explained by the generation of long-period atmospheric oscillations during the earthquake process.

Figure 9 shows the occurrence probability of short-term deviations of the TT. We calculate the histogram

Fig. 7. An example of FFT analysis of short-term TT variation during the period from November 2001 to December 2001

Fig. 8. Dynamic periodogram of short-term TT variation during the period from April 2001 to December 2001

Fig. 9. The distribution of short-term deviations of the TT plotted against the class; Bar charts show TT morning and TT evening, and curves of Gaussian approximation are also shown (solid line)

Fig. 10. Amplitude and phase data from the path of JJY-HOK on July 1–10, 2004; The vertical bars indicate the sunset and sunrise times at the transmitter JJY and at receiving station HOK

using TT shift between -30 min to 30 min. The distribution of short-term deviations was approximated by a Gaussian distribution using the least squares fit. We consider that the distribution of short-term deviations of TT morning can be expressed by the following Gaussian function:

$$0.13 \exp \left\{ -\frac{(x + 0.39)^2}{9.7^2} \right\}, \dots \dots \dots (5)$$

and TT evening can also be expressed by the following Gaussian function:

$$0.10 \exp \left\{ -\frac{(x + 1.45)^2}{14.0^2} \right\}, \dots \dots \dots (6)$$

where x is class[min]. The units of mean (μ) and standard deviation (σ) are both in minutes. Hayakawa and Molchanov et al. reported that the evening TT effect was much larger than that for the morning⁽¹⁷⁾. We confirm the σ of TT evening is larger than that of TT morning in Fig. 9. The difference between TT evening and TT morning is caused by the ionospheric conditions as results of the difference between the sunset and the sunrise transition. We can conclude that TT evening is possibly sensitive to ionospheric disturbance as compared with TT morning.

3.2 JJY-Moshiri LF Propagation Path (North-South Short Propagation Path) The TT situation of North-South propagation path is likely to differ greatly from that of East-West propagation path because the sunrise/sunset transition is approximately parallel to the path. Figure 10 shows a sequential plot of the diurnal variation in amplitude data from the path of JJY-HOK on several days, July 1–10, 2004. Vertical bars indicate the sunset and sunrise times of the transmitter JJY and the receiving station, HOK. Unlike the East-West path in the previous section, TT in this case is exactly occurring at sunset and sunrise time (Please compare this with Fig. 3). We can find two minima near the times of sunrise and sunset. When we look at the variation during one year for this path, TT evening is seen to be unstable, although TT morning is stable. So, we can detect only TT morning and log the time at which they occurred using the software.

Figure 11 shows regular annual variations of TT for the JJY-HOK path during the period from August 1999

Fig. 11. Regular annual deviations of TT at the receiving station HOK during the period from August 1999 to December 2001; TT morning in summer season is occurring at sunrise time at the station HOK, but it is occurring at sunrise time at the station JJY in winter season

Fig. 12. The short-term deviations of the TT morning during the period from August 1999 to March 2004

to December 2001. In addition to the TT morning, sunset and sunrise times at the transmitter JJY and receiving station HOK are also shown. We define the summer season as the period from April to August, while the winter season as the period from September to March. In summer season, TT morning is found to occur at the sunrise time at the HOK receiving station. While, TT morning in winter season seems to be coincident with the sunrise time at the transmitter JJY station. We note the change from winter to summer (summer to winter) regime through the spring (autumn) transition period.

The short-term deviations of the TT during the period from August 1999 to March 2004 for this North-South propagation path is shown in Fig. 12. Figure 12 shows repeatedly the TT data over about five years. Unlike the East-West path, the deviations in summer season is found to be different from those in winter season. The deviation of TT is found to be very enhanced in winter season (Please compare this with Fig. 6). Figure 13 illustrates the distributions in the winter and summer seasons. The distribution of such short-term deviations is found to be approximated by a Gaussian distribution. The distribution in the summer season can be expressed by the following Gaussian function:

Fig. 13. The distribution of short-term deviations of the TT plotted against the class; Bar charts show TT of summer season and TT of winter season, and curves of Gaussian approximation are also shown (solid line)

$$0.28 \exp \left\{ -\frac{(x + 0.33)^2}{1.85^2} \right\}, \dots \quad (7)$$

The distribution in the winter season can be expressed by the following Gaussian function:

$$0.12 \exp \left\{ -\frac{(x - 0.37)^2}{4.13^2} \right\}, \dots \quad (8)$$

where x is class[μ]. The unit of mean (μ) and standard deviation (σ) are in minutes, and the σ in the winter season is larger than that in the summer. It is known that ionospheric condition is changing annually as a result of changing solar activity. Therefore, we consider that the short-term TT difference between the summer and winter season is caused by the ionospheric conditions.

3.3 NWC-Chofu VLF Propagation Path (North-South Long Propagation Path) The propagation path from the VLF transmitter, NWC (Australia) to the receiving station, CHO is a long-distance, as compared with the short-distance LF propagation in section 3.2. Figure 14 is the regular annual variations of TT for this NWC-CHO path during the period from January 2000 to June 2002. We can find, in Fig. 14, a complicated change of TT morning in winter season during the period from November to February. This phenomenon is caused by the sunrise/sunset transition which is approximately parallel to the path in winter season. We can find the gap of regular variation of TT Morning for November and February. In this period, TT Morning is not stable, so that we cannot detect the TT accurately. TT evening in winter season is also seen to vary a lot. The short-term deviations of the TT during the period

Fig. 14. Regular annual deviations of TT on NWC-CHO path during the period from January 2000 to June 2002; TT is generated intricately in winter season

Fig. 15. The short-term deviations of the TT Morning during the period in January 2000 to June 2002

from January 2000 to June 2002 for NWC-CHO path is shown in Fig. 15 and they increase during the period from November to March. We also confirm this winter anomaly in North-South short-distance path (please see section 3.2). However, we cannot find that in East-West path (please see section 3.1). So, we can conclude that winter effect in TT is a phenomenon peculiar to North-South path.

4. Conclusion

This paper reports on the observations over two years of the VLF/LF transmitters NPM/NWC/JJY as received in three paths, which were East-West long propagation path, North-South long propagation path and North-South short propagation path. We have shown the statistical behavior on the dependence of VLF/LF TT on the propagation direction. From the data and analysis presented here a few basic conclusions can be drawn:

First, regular annual deviations of TT for the East-West path were confirmed to follow well the time series of sunrise/sunset time at the receiving point. However, TT behavior for the North-South path is more complicated than that for the East-West path. Then, we focused on the short-term TT characteristics in order to reinforce our previous study which is based on TT method. We can confirm in Fig. 7 the spectral peaks

with periods of 5, 7 and 13 days. These frequency ranges are of atmospheric oscillations⁽¹⁴⁾, so the periodic components of atmospheric oscillations might have appeared in TT deviations. We studied the distribution of short-term deviations of TT and we confirmed the σ of TT evening is larger than that of TT morning in Fig. 9. The difference between TT evening and TT morning is caused by the ionospheric conditions as results of the difference between the sunset and sunrise transition.

We found in Fig. 13 that the deviation of TT is very enhanced in winter season for North-South short path. TT behavior in winter season is also seen to vary a lot for North-South long path. However, we cannot find this effect for East-West path. So, we can conclude that winter effect in TT is a phenomenon peculiar to North-South path. TT behavior is regularly influenced by the lower-ionospheric condition which depend on sunrise/sunset transitoin and season. Therefore, we can conclude that the lower-ionosphere condition can be monitored by VLF/LF terminator times. The short-term variations in the dependence on the propagation direction that is associated with earthquakes (so-called TT method) will be the focus of our future study.

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