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Anomalies of LF signal during seismic activity in November–December 2004

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Abstract. A signal transmitted by Japan Time Standard LF station (40 kHz, Fukushima prefecture) and recorded in Petropavlovsk-Kamchatski (Russia) is analyzed during a time interval from 1 July 2004 till 24 January 2005. This interval is characterized by quiet seismic conditions up to the beginning of November, but rather strong seismic activity occurs in November and December not far from Hokkaido (Japan) and in the region of northern Kuril Islands. There were three series of earthquakes with M=5.6–7.1 in a zone of sensitivity of our wave path during two months. Nighttime "bay-like" phase and amplitude anomalies of the LF signal are observed several days before and during every series of earthquakes. During the whole period of seismic activity a significant shift in terminator times is also evident. The spectrum of LF seismo-induced anomalies shows a clear increase for the period of about 25 min.

1 Introduction

Subionospheric VLF/LF signal monitoring is widely used in the last 15 years for the search of possible short-time precursors of earthquakes. The observed VLF/LF signal parameters are mainly dependent on the reflection height (typically 80–85 km), which depends on the value and gradient of the electron density near the atmosphere-ionosphere boundary. Perturbations in these parameters of the boundary layer lead to correspondent disturbances in subionospheric VLF/LF signals.

Analyzing the famous Kobe earthquake (M=7.2), Hayakawa et al. (1996) have proposed a terminator time (TT) method. The TT is determinated by a position of a characteristic minimum of the phase and/or amplitude of the signal during sunset and sunrise. This method was applied for processing the VLF signal received at Inubo observatory and transmitted by the Omega station in Tsushima (Japan). The authors found that the evening TT deviated significantly from the monthly averaged value 3 days before the main shock. Using TT method for 11 events with M>6 Molchanov and Hayakawa (1998) had found that an anomalous shift in TT fluctuations appears in a 3 to 10-days period before a crust earthquake and continues a few days after it. Terminator time shift was lately found a few days before two earthquakes in Japan with M>6 in 2004 (Yamauchi et al., 2005).

Another method to study VLF/LF phenomena associated with seismic activity is based on the analysis of nighttime phase and amplitude fluctuations. Anomalies in phase and amplitude of VLF/LF signals before earthquakes with M>5.5 have been reported recently (Rozhnoi et al., 2004; Shvets et al., 2004).

Observations in Petropavlovsk-Kamchatski have been carrying out since June 2000. The wave path location was determined by strong seismicity of the Kurile-Kamchatka region and Japan. The area of wave path sensitivity covers almost the whole high activity Idzu-Bonin and Kurile-Kamchatka arcs. During 4.5 years of monitoring in the third Fresnel zone of our wave path 73 earthquakes with M>5.5 and 5 earthquakes with M≥7.0 have been registered (according USGS catalog).

Several cases of nighttime anomalies of the LF signal during a few days before enough strong isolated earthquakes have been revealed. We consider anomalies of the LF signal connected with seismic events if they do not continue less than 3 days at quiet heliogeomagnetic condition and if there are not any deviations of the LF signal in other wave paths at the same time.

2 Description of measurements

The OMNIPAL receiver is used for the registration of VLF/LF signals. It is located in Petropavlovsk-Kamchatski (53.15° N, 158.92° E) in Russia and registers signals from several transmitters: Australia (19.8 kHz), China (22.2 kHz),

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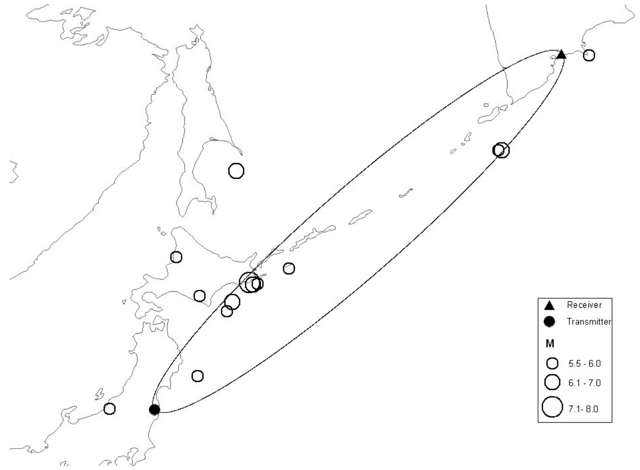

Fig. 1. A map of earthquakes epicenters in November-December with M>5.5 and LF wave path.

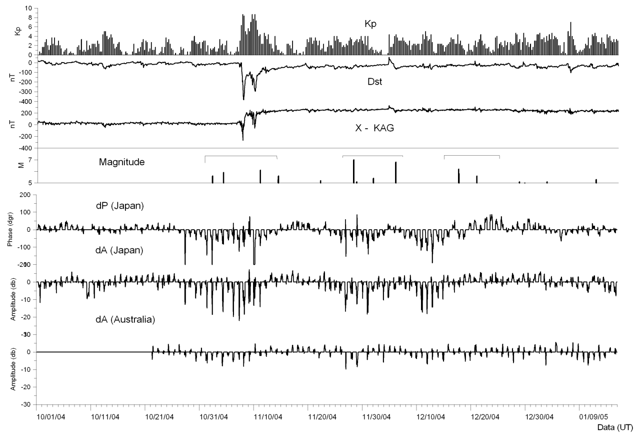

Fig. 2. Residual signal of phase dP and amplitude dA of nighttime for Japanese propagation path and dA for Australian path, magnitudes of earthquakes, magnetogram of observatory Kagashima, K_p and D_{st} indexes during the period from 1 October 2004 till 15 January 2005.

Hawaii (21.4 kHz) and JG2AS (JJY) (40 kHz) in Fukushima prefecture, Japan (37.37° N, 140.85° E). In this work we only analyze the signal from the Japan transmitter. The signals from the other transmitters are regarded as a control. We use for our analysis the 20-s digital data of amplitude and phase of the LF signal. Several strong earthquakes with M∼6–7 occurred in November and December 2004 not far from Hokkaido (Japan) and in the region of northern Kuril Islands. In this paper we report some results of LF signal monitoring on the wave path Japan-Kamchatka during this period.

3 Results of the LF signal processing

The interval from 1 July 2004 till 24 January 2005 is included in the examination. This interval is characterized by quiet seismic conditions up to the beginning of November and rather strong seismic activity in November and December close to Hokkaido (Japan) and in the region of northern Kuril Islands. The seismic activity in the zone of sensitivity of our wave path is determined by three series of earthquakes with M=5.6–7.1. Within almost 3 months there were not any strong earthquakes with M>5.0 in this region until the first earthquake (M=5.6) in November took place. Figure 1 shows the third Fresnel zone for our wave path and positions of the epicenters of the earthquakes with M>5.5 for November-December. Figure 2 presents the running average (within one hour) of the residual signal of phase dP and amplitude dA (defined as the difference between the hourly-mean signal and the average signal for the quiet days of the month) for the period from 1 October 2004 till 15 January 2005. Only night-time measurements are taken into account.

Anomalies in amplitude and phase of LF signal begin 1-2 days before the first set of earthquakes, continue 13–14 days and finish on the day of the last earthquakes of this set (M=6.2, 11.11.04). Afterward, a quiet period in seismicity and in LF signal is observed during about fortnight. Then 2–3 days before two earthquakes (M=7.1, 28 November 2004 and M=6.8, 6 December 2004) the next anomalies in phase and amplitude appear and they continue 8 days. The next anomalies after the small quiet period (4 days) are observed before two earthquakes in December (M=5.8, M =5.6) and last 17 days. Most strongly and obviously anomalies are shown in the amplitude of LF signal. After 21 December a seismic activity decay may be observed.

It is necessary to note that in accordance with the registration of the magnetic observatory Kagashima located in the nearest magnetic meridian to our wave path in the period under consideration a strong magnetic storm took place in 8–10 November with D_{st}∼400 nT. The examinations of the influence of magnetic storms and substorms on the behavior of the LF signal carried out previously in the network of VLF/LF receiving stations have shown that anomalies in the signal are observed during the main phase of storms or substorms only if the sudden commencement (SC) happens to the night time. It was found that during the maximum of the bursts of Pi3 geomagnetic pulsations at nighttime there are observed (sometimes with the delay of a few tens of minutes) "bay-like" LF phase and amplitude anomalies. In this case the magnetic storm had two stages. The sudden commencement of the first stage took place in the daytime and it had no effect on the LF signal. The second maximum of the storm happened in the nighttime and caused a strong anomaly in amplitude and phase of the signal in that day.

In the control wave path Australia-Kamchatka (19.8 kHz) anomalies in the VLF signal during the whole period under review are not found. Taking into account that earthquakes in the region of northern Kuril Islands fall within the zones of sensitivity of both Japanese and Australian wave paths it is probable that anomalies in LF signal are resulting from the earthquakes of Hokkaido region.

Figure 3 illustrates the anomalies of the LF signal phase and amplitude and their wavelets for one of the disturbed

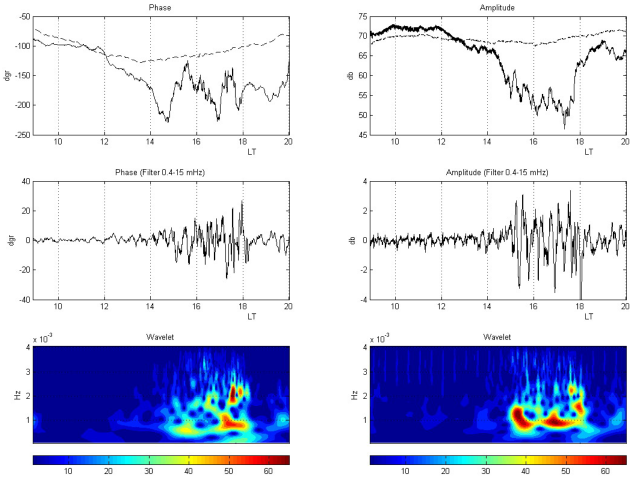

Fig. 3. Phase and amplitude anomalies (top two panels), filtered signals (middle panels) and their wavelets (bottom panels) for 4 November 2004.

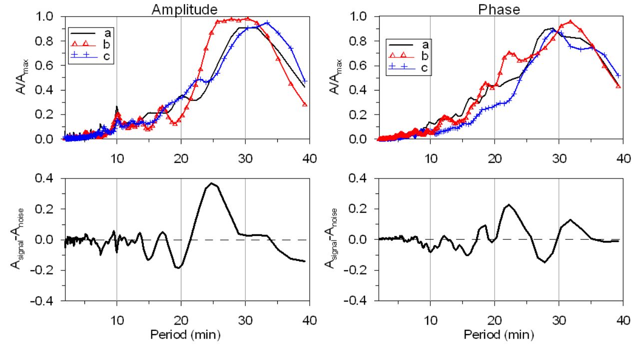

Fig. 4. Averaged normalized spectra of several days for phase and amplitude of the LF signal (top panels) and difference between normalized spectra of seismo-induced anomalies days and quiet days (bottom panels). **(a)** quiet days; **(b)** days with seismo-induced anomalies; **(c)** days with magnetic-induced anomalies.

days (4 November 2004). Only nighttime of the signal filtered in a frequency band of 0.4–15 mHz (as shown in the middle panels) is used for wavelet analysis. The signal maximum with the period of about 0.7–0.8 mHz (20–25 min) is clearly observed in the bottom panels. The second maximum has a period of 1.5–2.0 mHz (8–10 min). The shorter periods (smaller than 4 min) are not revealed. The frequency range of the signal corresponds to the gravity wave frequency (Miyaki et al., 2002). The summary spectra of several anomaly days and several quiet days for November-December are presented in Fig. 4 together with the spectrum of several anomaly days during magnetic storms and substorms for 2001–2004 (top panels). The bottom panels show the difference between normalized spectra of days with seismo-induced anomalies and quiet days. It is easy to see that the spectrum maximum of seismo-induced anomaly days is broader in comparison with background spectra and has a frequency shift towards smaller periods (20–25 min).

For this period of nighttime anomalies of the LF signal we found a significant shift in terminator times as shown in Fig. 5, illustrating the 3-D image day-to-day sequences of diurnal variations of the amplitude of the LF signal for the period from 1 October 2004 till 24 January 2005. In addition to strong perturbations in nighttime it is easy to see the significant evening TT deviation from its normal position. The shift runs up to 2 h. Similar TT behavior is observed in the phase of the signal too.

4 Discussion and conclusions

Strong nighttime anomalies in amplitude and phase of a LF signal and significant evening shift in terminator times are found during the period of strong seismic activity in November–December not far from Hokkaido. Such a considerable and long deviation in TT for our wave path is revealed firstly for the 4.5 years of monitoring.

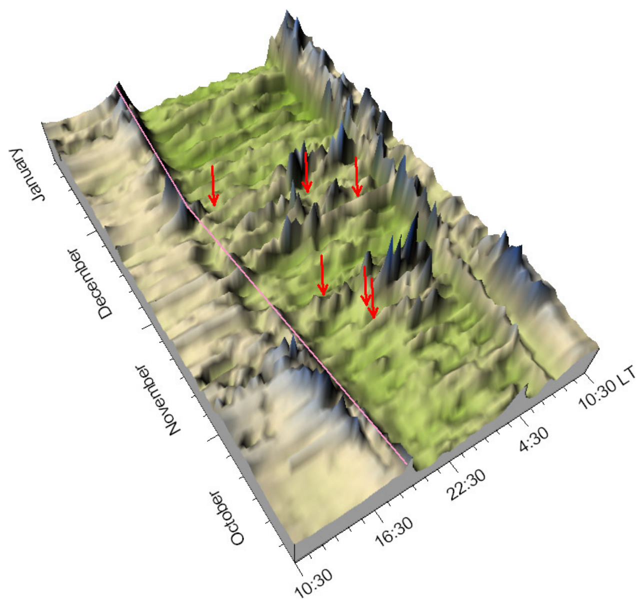

Fig. 5. 3-D image of day-to-day sequences of diurnal variations of the amplitude of the LF signal for the period from 1 October 2004 till 24 January 2005. Arrows indicate the moment of earthquakes; the line shows a normal position of the evening terminator.

The solar terminator is a part of the atmosphere between the space illuminated by the sun and the complete shadow space. The strongest variations of temperature, pressure and electron density altitude profile in the atmosphere occur at solar terminator passage (Soloviev et al., 2004). The ionospheric plasma is unstable during the period of terminator transition and more than usually sensitive to external actions.

In our case, a shift in TT is observed in the evening that can be explained by the peculiar passage of the solar terminator across this wave path in the period of analysis. The morning terminator comes up almost parallel to the wave path and the region from Kamchatka to Japan is illuminated in all parts practically at one time. At the same time the evening terminator is almost perpendicular to the wave path and night set in during two hours along the wave path. All this period the lower ionosphere and the upper atmosphere keep remain in an unstable state and an external action, which is induced by preseismic processes in the earth crust, can stimulate an increase of plasma density perturbations inside the ionosphere and atmosphere, that for their part affect the value and form of the registered LF signal due to multimode interaction.

The transformation of a plasma perturbation at the upper atmosphere and lower ionosphere into amplitude and phase variation of a subionospheric VLF signal was discussed in several papers (e.g. Molchanov et al., 1998) in supposition of some simplifications. A theory is presented suggesting that the observed effect can be explained by decreasing the effective height of the lower ionosphere. Recently Soloviev et al. (2004) have reported the relevant approach to the problem. Their paper presents a mathematical model, an asymptotic theory and an appropriate numerical 3-D algorithm to interpret the observational facts.

Another theoretical problem is the way of energy transfer from the seismic source to the ionosphere. Indeed it is a problem of lithosphere-atmosphere-ionosphere coupling due to seismicity. Different possibilities are discussed at present (see comprehensive monograph Hayakawa and Molchanov, 2002). The probable mechanism of the atmosphere-ionosphere coupling is connected with the generation of atmospheric gravity waves (AGW). This process was described in detail by Mareev et al. (2002) and Molchanov (2004). We demonstrate here the increase of the AGW intensity for the periods of 10–25 min that is in compliance with theory.

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