VARIATIONS OF VLF SIGNALS RECEIVED ON DEMETER SATELLITE IN ASSOCIATION WITH SEISMICITY

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Abstract. We present two methods of the global ionosphere diagnostics using VLF signals received on board the DEMETER satellite in association with two cases of strong seismic activation. The method of reception zone changes reveals an evident effect before and during the great Sumatra earthquake with long-time duration of the order of one month. The result leads to the conclusion on the size of perturbation area of the order of several thousands kilometers. Disadvantage of this method is in its difficulty to separate preseismic and postseismic effects. In contrast, the difference method allows us to overcome this difficulty and it shows the appearance of preseismic effect for several days for seismic activation near Japan. However, we need such an analysis for reliability in regular satellite data to be checked by ground reception of subionospheric VLF signals. It is not so obvious that both of these satellite and ground effects are excited by the same generation mechanism on the ground. So, these look as complementary.

1. Introduction
During the last 10-20 years there have been attracted noticeable attention in the effects of ionospheric plasma related to seismicity, with keeping in mind both possibilities to use them for earthquake forecast and to study the fundamental problem of lithosphere-ionosphere coupling. There are two directions of this research. The first is in-situ observation of those effects, i.e. satellite observation. Numerous papers have already been published on such observations (see the reviews by Parrot et al., 1993; Molchanov et al., 2002). The second direction is far-distant remote sounding of the ionospheric perturbations in connection with seismic events by means of electromagnetic signals. Results of VLF sounding in different frequency bands have been published in many papers (Gufeld, et al., 1992; Hayakawa, et al., 1996; Molchanov and Hayakawa, 1998; Rozhnoi et al., 2004; Horie et al., 2007).

We are going to discuss here the reception of VLF transmitter signals on board the DEMETER satellite. Such a reception was undertaken on many satellites for the investigation of VLF wave propagation and VLF wave interaction with ionospheric plasma (e.g. Inan and Helliwell, 1982; Molchanov, 1985). However, in the application of VLF signals to long-time seismic effects we need a special data processing both on board the satellite and on the ground in addition to the reception itself. Therefore it can be considered as a new method of ionospheric sounding in association with seismicity.

2. Satellite VLF Data
Here we will discuss only the data of electric field from a powerful Australian NWC (19.8 kHz) transmitter. As the main characteristic of a VLF signal, we compute the signal to noise ratio (SNR) as follows: \( SNR = \frac{<A_0>}{A_{min}} \), where \( <A_0> \) is an average amplitude spectrum density in the frequency band including the
transmitter frequency $F_0$ and $A_{\text{min}}$ is the minimum value outside of the signal band. Due to large longitudinal distances between adjacent orbits (about 2500 km at the middle latitudes) we need the averaging period of, at least, 3-4 weeks in order to obtain statistically significant results and longitudinal spatial resolution of 100-200 km. It dictates a selection of rather long periods of seismic activity related to very strong earthquakes or to a series of large earthquakes. We need to average the signal over fast variations and try to seek for slow changes in the reception zones during seismically active periods. We discuss two methods for revelation of the seismic influence: analysis of changes in reception zones for finding the large-scale space variation and analysis of SNR differences for finding of temporal variation during seismic activation.

3. Change in reception zone

As an example we analyse the reception zone of the NWC transmitter in relation to a strong earthquake activity near Sumatra which started with a great seismic shock on December 26, 2004 (magnitude $M = 9$). There were several strong shocks with following weaker ones until January 3, 2005 and the aftershock series continued until the summer of 2005 with new explosions of activity on March 28, 2005 ($M=8.7$, so-called Sumatra-2 earthquake) and on July 24, 2005 ($M= 7.5$). Fig. 1 shows the area of Sumatra activity and two reference zones with rather weak seismic activity during this period.

![Fig. 1. Seismic activity during the period from October 1, 2004 to December 31, 2005. A triangle indicates the place of NWC transmitter, positions of the strong earthquakes with $M > 6.6$ are shown by solid circles, and the area of Sumatra activity is outlined by an open circle. Reference zones with rather weak seismic activity are outlined by circles with the numbers 2 and 3.](image)

We use DEMETER data during the period of more than one year from October 24, 2004 to December 31, 2006. In order to find a possible EQ influence we divide the observation period into the intervals with duration of 30 working days, taking into account the missing days and keeping about the same volume of recording points. Then we compare the reception in the different time intervals both in the Sumatra area and in the reference zones. In such a way some seasonal variations can be expected. So we computed values $\langle \text{SNR} \rangle$ averaged over the central part of the NWC transmitter reception zone for each month from October 2004 to August 2006 and found a small seasonal variation of the order of 25% with an increase in the winter time. Therefore we analyse the normalized SNR values: $S_n = \text{SNR}/\langle \text{SNR} \rangle$ and calculate the ratio $p = N(S_n \geq 1)/N_0$, where $N_0$ is the total number of recording points and $N(S_n \geq 1)$ is the number of points with increased value $S_n \geq 1$ inside the Sumatra area or inside the reference zones. The result is presented in Fig. 2. We conclude an essential depression of VLF signal intensity during the period of November-December 2004 only above the Sumatra
area, which is probably connected with the preparation of seismic activity in this area.

4. Difference method

We use the method for correlated analysis of VLF subionospheric signals from transmitters located in Japan (JJY and JJI) and in Australia (NWC) that were measured at the ground stations and on board the DEMETER satellite. So we develop the satellite data processing which is similar to the processing of data at the ground station (Rozhnoi et al., 2004).

Fig.2. Ratio of reception points with strong signals ($S_n \geq 1$) to the total number of recording points inside the Sumatra area (second panel from above) and inside the reference zones (shown in Fig.1, first and third panels) together with magnitude difference ($M - 7$) of the great earthquakes inside the Sumatra area (forth panel) and seismic energy released (fifth panel).

For ground observation we use a residual signal of phase $dP$ or amplitude $dA$ defined as the difference between the observed signal and the average of quiet days of the current month. For satellite observation we calculate a “reference surface” (model) over the region of interest as a function of longitude and latitude. In this study, a simplified approach to compute this surface was used. The method consists in averaging all the data available in the considered region, regardless of the global disturbances, in particular, of the magnetic activity. The length of this period was selected equal to 2 months in order to be not affected by the seasonal variations. The method of the local polynomial interpolation was used to build the reference surface with a longitude and latitude resolution of 0.32°. Using the reference surface, at any time and for any longitude and latitude, it is possible to define the residual VLF signal as the difference between the measured amplitude $S(t, \text{longitude, latitude})$ and the reference value $S_m$ (longitude, latitude).

We present here a comparison of satellite and ground reception during July-September 2005. There were several large EQs ($M \geq 6.2$) at the area of Japan in this period, which occur inside or close to the sensitivity zone of our ground reception and inside of the satellite reception zone for NWC transmitter (19.8 kHz). Positions of these EQs are shown in Figure 3a for the ground reception and in Figure 3b for satellite reception (right rectangle). Additionally for the control of satellite reception we select another rectangle that is also inside of the reception zone but it is free from seismic activity (left rectangle in Fig. 3b).
A comparison of results of the satellite and ground observations is presented in Fig. 4. Here we show the differences averaged over night time for the ground reception and differences averaged along the orbit crossing the seismic or reference area depicted in Fig. 3. By paying attention to the hatched regions, we notice an evident decrease in VLF signal both on the ground and on the satellite in association with seismicity.

![Fig. 3](image)

**Fig. 3** (a) Map of earthquakes with $M \geq 6.0$ during the period of July-September, 2005. Sensitivity zones for the ground reception of Japan transmitters are shown by red line, NWC and NPM transmitters - by dash lines; (b) Reception zone of the NWC transmitter during the period of July-September, 2005 (model) registered on the satellite DEMETER together with the positions of large EQ epicenters. Red circles – EQ in sensitivity zone of wavepath JJY-PTK. The selected area for the analysis of VLF signal reception above Japan is outlined by A) rectangle on the right, and the control rectangle B) that is free from earthquake activity is shown on the left.

5. Discussion

We have presented two methods of the global ionosphere diagnostics using VLF signal received on board a satellite in association with two cases of strong seismic activation. The method of changes in reception zone reveals an evident effect before and during great Sumatra earthquakes with long-time duration of the order of one month. The result leads to the conclusion on the size of perturbation area of the order of several thousands kilometers, which is found to be in good agreement with the suggestion by the ground-based subionospheric VLF propagation (NWC-Japan path) (Horie et al., 2006). The disadvantage of this method is in its difficulty to separate preseismic and postseismic effects. In contrast, the difference method allows us to overcome this difficulty and shows the appearance of significant preseismic effect for several days for seismic activation near Japan. However, we need such an analysis for reliability in regular satellite data and in the check by ground reception of subionospheric VLF signal. It is not obvious that both the effects are excited by the same generation mechanism at the ground, so that those methods are complementary to each other.

In general the methods of diagnostics discussed here have perspective to be global due to the world-wide
positioning of powerful VLF transmitters and satellite reception. However, they have specific disadvantage because they require a rather long time period of analysis due to large longitudinal distances between satellite orbits. Above a fixed area in the same local time the satellite appears only once a day. As the result, we need, at least, one month period of registration for the longitudinal spacing of about 1000km.

Fig.4. VLF signal differences in the ground observation for the wave paths: JJI-Kamchatka, JJY-Kamchatka, NWC-Kamchatka and NPM-Kamchatka and averaged satellite VLF signal differences observed on board the DEMETER from the reception of NWC transmitter: the solid line for the data above Japan, and dash-dot line for the data aside of Japan area (see Fig. 3b). Two panels below are Dst variations and EQ magnitude values.

As a mechanism of the observed effects, we suggest the following:
- Of course such a long-time and large-scale perturbation in the ionosphere cannot be produced by a seismic shock itself (duration of minutes) and we need to suppose some long-lasting agent, which influences the ionosphere around the date of an earthquake.
- We believe that this initial agent is an upward energy flux of atmospheric gravity waves (AGW) which are induced by gas-water release from earthquake preparatory zone (e.g. Liperovsky et al., 2000; Molchanov, 2004).
- Penetration of AGW waves into the ionosphere leads to the modification of natural (background) ionospheric turbulence, especially for space scales ~ 1-3 km and wave numbers $k\approx 10^{-4}-10^{-3}$ m$^{-1}$. This weak but reliable effect is revealed from direct satellite observations (Molchanov et al., 2004; Hobara et al., 2005).
- Resonant scattering of the VLF signals is possible on the following condition of the frequency- wave
number synchronism: \( \omega_0 = \omega_s + \omega_T \), \( \mathbf{k}_0 = \mathbf{k}_s + \mathbf{k}_T \), where \( \omega_0, \mathbf{k}_0 \) are for the incident VLF wave, \( \omega_T, \mathbf{k}_T \) are for the turbulence and \( \omega_s, \mathbf{k}_s \) are for the scattering waves. It can be found that the amplitude of incident wave \( A_0 \) decreases exponentially during the course of propagation through the perturbed medium: \( A_0 \sim \exp(-\alpha_0 A_T H) \), where \( \alpha_0 \) is the coefficient of nonlinear interaction, and \( H \) is the length of interaction region. In our case of VLF signals: \( \omega_T << \omega_0 - \omega_s \), and the interaction is especially efficient because \( k_0 \sim k_s \sim k_T \) (Molchanov, 1985). Therefore, even though the amplitude of the turbulence \( A_T \) is small, the scattering could be significant if the length \( H \) is large.

References


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