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VLF/LF signal studies of the ionospheric response to strong seismic activity in the Far Eastern region combining the DEMETER and ground-based observations

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A B S T R A C T

The paper presents the results of a joint analysis of ground-based and satellite observations of very low-frequency and low-frequency (VLF/LF) signals during periods of strong seismic activity in the region of Kuril Islands and Japan in 2004–2010. Ground and satellite data was processed using a method based on the difference between the real signal in nighttime and that of a model. The results of the analysis show a good correlation between ground-based and satellite data for several cases of strong ($M \geqslant 6.8$) earthquakes.

1. Introduction

French micro-satellite DEMETER had a low-altitude (~710 km) and a nearly polar orbit (Cussac et al., 2006). The launch by CNES (French National Space Agency) was in June 2004, and the satellite's science mission had come to an end in December 2010.

Due to the specific orbits, DEMETER was always located either shortly before the local noon (10:30 LT) or local midnight (22:30 LT) above the same point. The satellite performed 14 orbits per day and measured continuously between −65° and +65° of invariant latitude every 2 s in survey mode.

The major scientific objectives of the satellite were to study the ionospheric disturbances in relation to seismic activity and to examine the pre- and post-seismic effects (Parrot, 2002). The first paper, showing examples of unusual ionospheric observations made by the DEMETER satellite over seismically active regions, was published by Parrot et al. (2006a). Later, statistical investigations confirmed the existence of small but statistically significant decreases of wave intensity at a frequency around 1.7 kHz a few hours before an earthquake (Nemec et al., 2009; Píša et al., 2013).

DEMETER observations also provide a new possibility to analyze ground based transmitter signals that may be detected onboard the satellite above seismic regions. Such observations have been undertaken on many satellites for the investigation of VLF wave propagation and VLF wave interaction with ionospheric plasma (e.g. Aubrey, 1968; Inan and Helliwell, 1982). However, in the application of VLF signals to long-time seismic effects special data processing is necessary. Therefore, it can be considered as a new method of ionospheric sounding in association with seismicity. The first results of such analysis have been reported by Molchanov et al. (2006) for several strong earthquakes that occurred in 2004. The method estimated changes in the reception zone of the transmitters signal using the signal to noise ratio. An evident effect that occurred before and during the great Sumatran earthquakes with long-time duration of the order of one month has been confirmed later by Solovieva et al. (2009). After the first publication, similar effects were observed in the transmitter signals received onboard DEMETER during periods of strong seismic activity (e.g. Muto et al., 2008; Boudjada et al., 2008; Slominska et al., 2009; YuFei et al., 2009).

However, the method of reception zone changes does not allow for separating pre-seismic and post-seismic effects. Therefore a new method of satellite data processing has been developed

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(residual method) which is similar to the data processing used at ground stations. In this work we summarize the results of a joint analysis of the satellite and ground-based measurements in connection with strong earthquakes which occurred during the DEMETER mission in the Far Eastern region.

2. Used data

2.1. Satellite data

The high-quality DEMETER database has been built during the mission. It includes data from several instruments which provided a nearly continuous survey of the plasma, waves and energetic particles. All details concerning the onboard experiments can be found in Berthelier et al. (2006a,b), Lebreton et al. (2006), Parrot et al. (2006b) and Sauvaud et al. (2006).

For our analysis we chose data recorded by the electric field receiver (ICE) for night orbits. Signals of the powerful VLF transmitters were clearly seen in the electric field data (Fig. 1). Frequency resolution of the spectra was $\Delta F = 19.5313$ Hz in the range of $F \leqslant 20$ kHz and it was worse ($\Delta F = 3.255$ kHz) at higher frequency range 3 kHz $\leqslant F \leqslant$ 3 MHz, so that we mainly used the signals with $F \leqslant 20$ kHz for our analysis. In this frequency range the NWC transmitter signal (19.8 kHz) is the most powerful. The reception zone of this signal covers entirely all Eastern hemisphere (Rozhnoi et al., 2007b), and therefore we could analyze the signal in a large area including Japan and Kuril Islands.

The first step in satellite data processing was to obtain the intensity of the VLF transmitter signal. At this point it was necessary to correct the collected data for parasitic effects such as the instrument background noise and the natural emissions that can superimpose themselves on the signal. It was necessary, however, to take into account the influence of the scattering which was the major effect for some parts of the DEMETER orbit. Therefore as the main characteristic of a VLF/LF signals, we computed the signal to noise ratio (SNR) as follows:

$$\mathrm{SNR} = 2A(F_0)/[A(F_+) + A(F_-)] \quad (1)$$

where $A(F_0)$ is the amplitude of spectrum density for the frequency band that includes the transmitter frequency F_0. The amplitude A (F_0) was estimated based on how well the transmitter frequency coincided with discrete frequency of the spectrum. This may be done using either the amplitude of the signal in the frequency band closest to F_0 or the average of the amplitudes of the two frequency channels that bracket F_0. $A(F_\pm)$ are the minimum amplitude values inside of the signal band (δF).

The choice of $F_\pm$ depended mainly on the transmitter power and position of the reception point. Usually δF was 150–300 Hz, but for the powerful transmitters such as NWC (19.8 kHz) it could reach a value of 500 Hz when the satellite was in vicinity of the transmitter. As a result we produced a computation of $F_\pm$ for each VLF/LF signal and each selected orbit by a special procedure.

2.2. Ground-based data

Mainly data measured in VLF receiving station in Petropavlovsk–Kamchatsky (Russia) were used for the analysis. OmniPAL receiver was installed in Petropavlovsk–Kamchatsky (geographic coordinates; 53.090N, 158.550E) in June 2000 within the framework of Japanese-Russian ISTC project. The receiver in Kamchatka is a part of the Far East (or Pacific) network which has been formed after the installation of seven Japanese stations. All the stations receive simultaneously both the amplitude and phase of MSK (Minimum Shift Key) modulated signals from the same four transmitters: JJY (40 kHz, Fukushima) and JJI (22.2 kHz, Miyazaki) in Japan, NWC (19.8 kHz, Australia) and NPM (21.4 kHz, Hawaii). MSK signals have fixed frequencies in narrow band 50–100 Hz around the main frequency and adequate phase stability. The receivers can record signals with time resolutions ranging from 50 ms to 60 s. For our purpose we use sampling frequency of 20 s. The relative locations of the transmitters and two of our observing stations are plotted in Fig. 2. Among them the signals from JJY and JJI transmitters are most interesting for our analysis owing to the fortunate position of Petropavlovsk–Kamchatsky (PTK) station relative to the transmitters. The path NWC-PTK is somewhat outside the area of the main earthquakes in Japan and Kuril Islands, it is very long (about 10,000 km) and also crosses the equator where typhoon activity is very strong. Besides, the path passes through Indonesia, the region with strong seismic activity. So, this path is rather difficult for the ground analysis because the effects are cumulative.

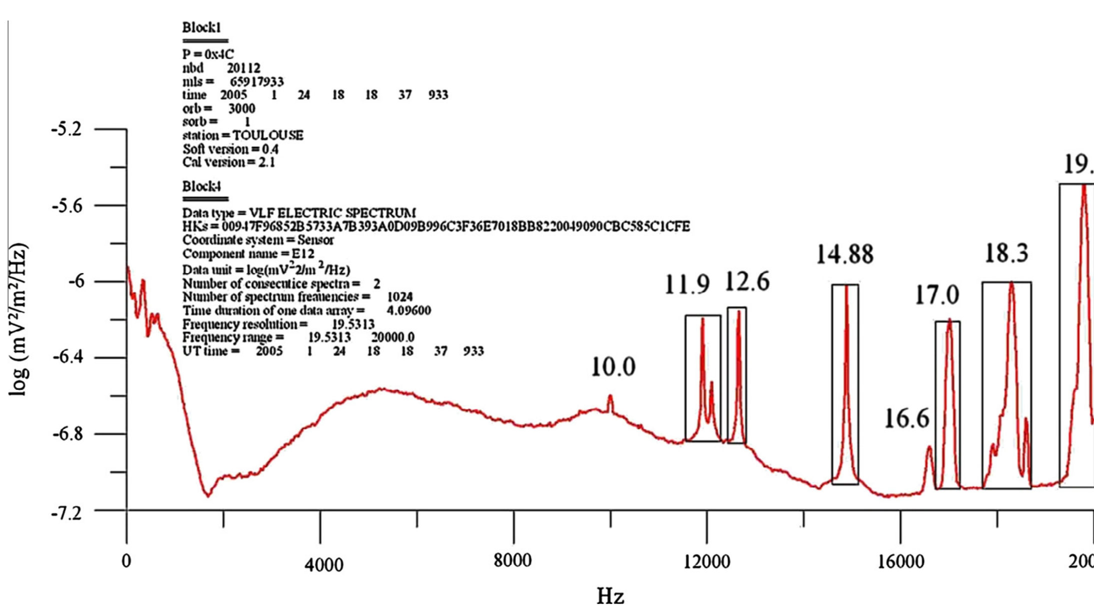

Fig. 1. An example of the summary spectrum for one night orbit recorded by ICE on board of the DEMETER (in frequency range 19.53 Hz-20 kHz). Signals of the several powerful VLF transmitters are easily noticed as vertical peaks in the dynamic spectra.