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Global diagnostics of the ionospheric perturbations related to the seismic activity using the VLF radio signals collected on the DEMETER satellite

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Abstract. The analysis of the VLF signals radiated by ground transmitters and received on board of the French DEMETER satellite, reveals a drop of the signals (scattering spot) connected with the occurrence of large earthquakes. The extension of the "scattering spots" zone is large enough (1000–5000 km) and, probably, it increases with the magnitude of the "relative" earthquake. A possible model to explain the phenomenology, based on the acoustic gravity waves and the ionosphere turbulence, is proposed. The method of diagnostics applied to this study has the advantage to be a global one due to the world wide location of the powerful VLF transmitters and of the satellite reception. However, a specific disadvantage exists because the method requires rather a long time period of analysis due to the large longitudinal displacements among the successive satellite orbits. At the moment, at least, one month seems to be necessary.

1 Introduction

During the last 10–20 years, the disturbances of the ionosphere related to the seismic activity attracted noticeable attention keeping in mind possibilities to use them both for the earthquake forecast and for studying the lithosphere-ionosphere coupling. There are two directions of the researches in this field as it will be explained in the following.

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The first one is the observation in situ, i.e. on board satellites, of the disturbances. Several papers have been published on such topic (Parrot et al., 1993; Hayakawa, 1997; Molchanov et al., 2002). However, the satellite observations are not so easy to be accepted. The previous papers were useful for triggering the attention on the phenomenon, but they are controversial because generally no way exists to reject the hypotheses of pure coincidences taking into account the possibility of many internal ionosphere instabilities. The statistical studies seem to be obviously more reliable, but the results are partial ones and difficult to compare because of some difference in the sensors used (electric or/and magnetic sensors), in the sensor sensitivities, in the data selection, in the parameters to extract, in the way to estimate them and the validity tests. The actual controversies on the interpretation of the statistical studies performed by several low altitude satellites, are related to the quoted problems. Nevertheless, recent papers have shown that weak but reliable changes in the ionospheric plasma turbulence appear around (±7 days) the occurrence of large earthquake. Its intensity decreases for spatial scales of tenths-hundreds kilometers and it increases for scales of hundred meters (Molchanov et al., 2004; Hobara et al., 2005).

The second research direction is the far distant remote sounding of the ionospheric perturbations related to the seismic activity by means of electromagnetic signals. Many results have been published on sounding in UHF frequency range (F∼ GHz) by GPS signals (Liu, 2001), on HF sounding (F∼0.5–20 MHZ) from the ground-based or satellite-based ionospheric sondes (Liperovsky et al., 2000; Pulinets, 1998), on LF sounding (F∼200 kHz) from the

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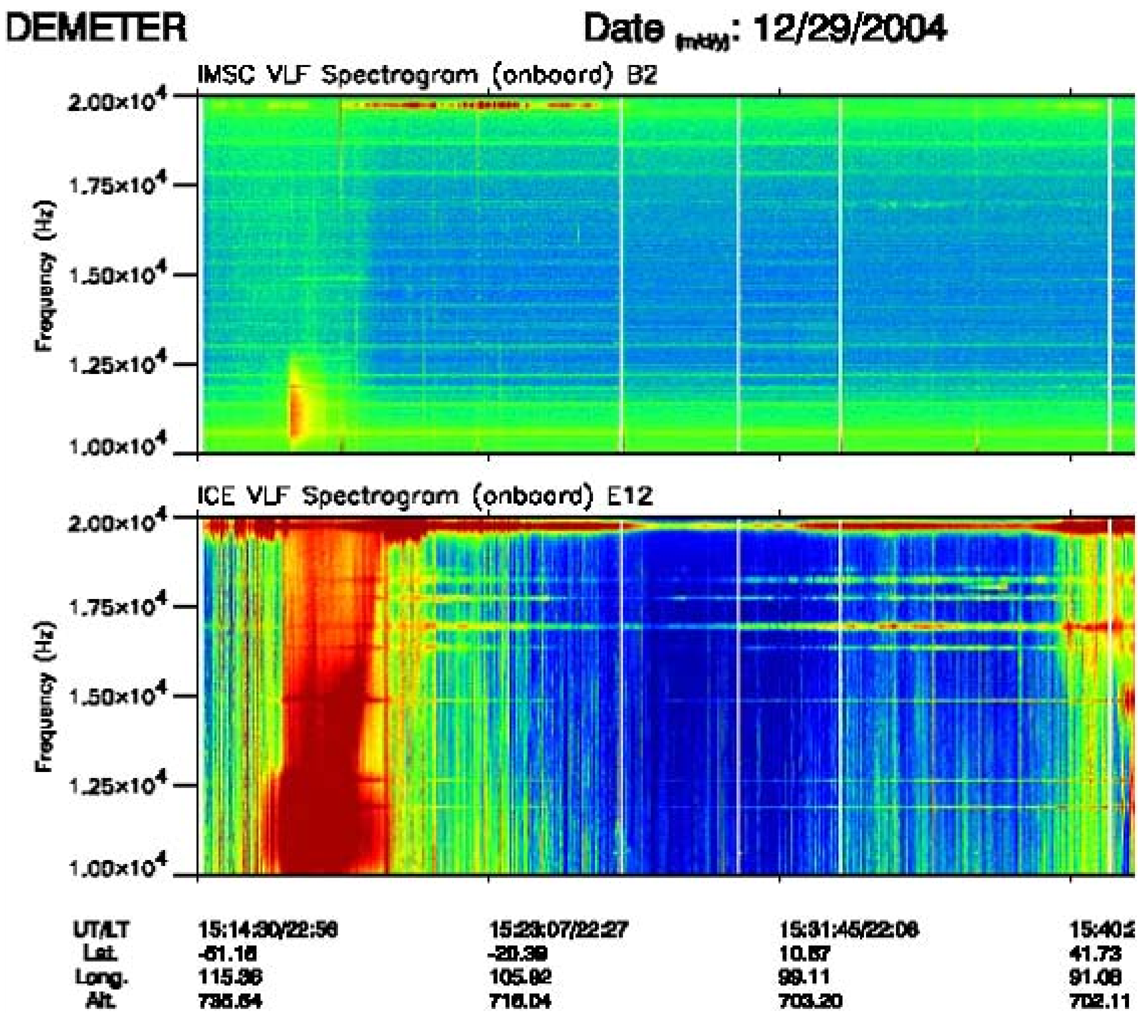

Fig. 1. An example of registration in the 10–20 kHz range during one orbit of the satellite on 29 December 2004. Dynamic spectra of magnetic component (above) and electric component (below) together with orbital data on universal/local time (UT/LT), latitude, longitude and altitude (km) along the orbit. The horizontal lines are the signals from the VLF transmitters. The lines at F=11.90 kHz, F=12.64 kHz and F=14.88 kHz are the signals of the Russian system RSND (A_1, A_2 and A_3 in Table 1), but the strongest signals at F=19.8 kHz come from the Australian NWC transmitter.

Table 1. Characteristics of some VLF transmitters.

Frequency (kHz)	Code	Place of transmitter	Longitude	Latitude
11.9; 12.64; 14.88	A1	Krasnodar, Russia	38.39	45.02
11.9; 12.64; 14.88	A2	Novosibirsk, Russia	82.58	55.04
11.9; 12.64; 14.88	A3	Komsomolsk Na Amure, Russia	136.58	50.34
16.56	DFY	Germany	13.0	52.5
17.8	JP	Southern Japan	∼130	∼32
18.3	FTU	Le Blanc, France	1.05	46.37
19.8	NWC	North-West Australia	114.08	−21.47

broadcasting transmitters (Biagi et al., 2001, 2004), on VLF sounding (F∼10–40 kHz) from the navigational transmitters (Gufeld et al., 1992; Hayakawa et al., 1996) and on ULF sounding (F<1 Hz) by magnetospheric magnetic pulsations (Molchanov et al., 2003). Except rather questionable results by satellite topside sounding, all the other ones were obtained

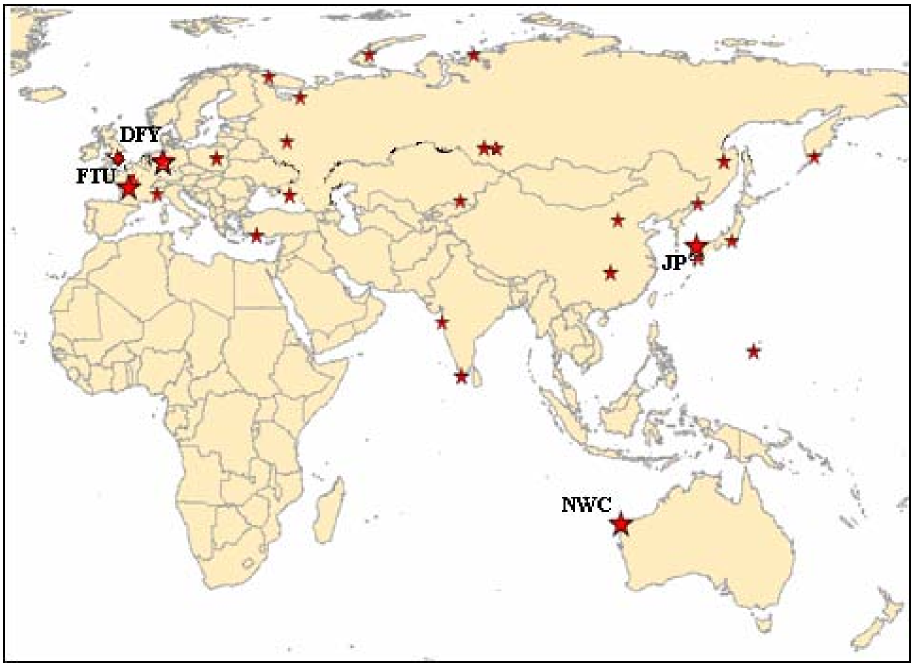

Fig. 2. The stars indicate the location of the powerful VLF transmitters in the eastern hemisphere. The transmitters used in this paper are shown by the larger stars with the indication of their code.

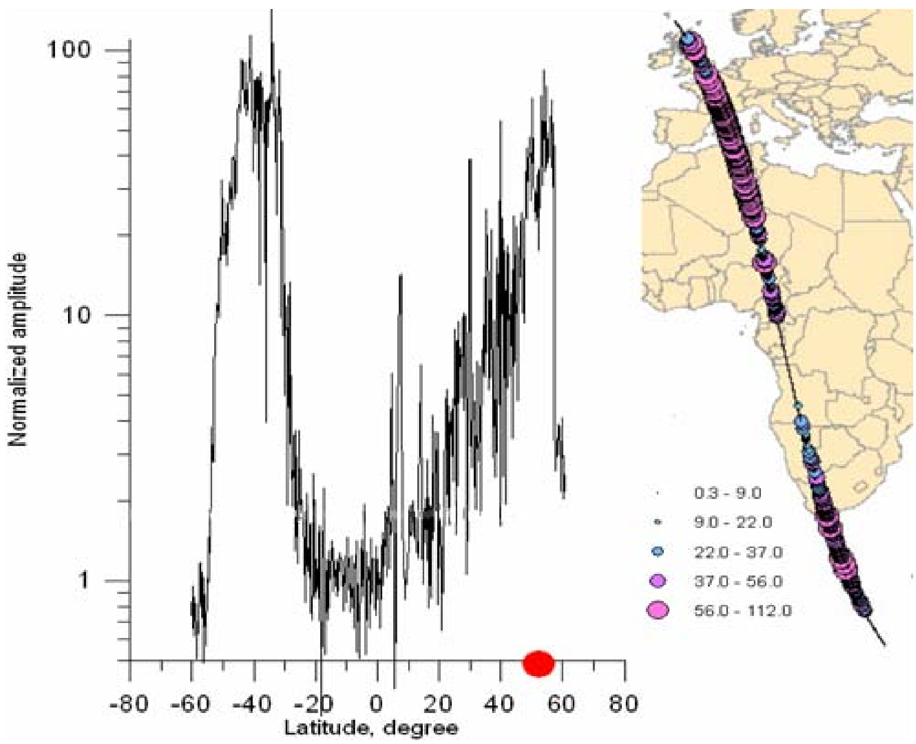

Fig. 3. Evolution of the signal to noise ratio (SNR) values along the orbit on 12 February 2005 at evening (LT∼22.00). The red circle indicates the latitude for which the projection on the ground is at the minimal distance from the VLF transmitter (DFY, 16.56 kHz, in this case). The orbit projection and the color legend is on the right. The reception zones above the transmitter and at the conjugate region in the southern hemisphere are evident.

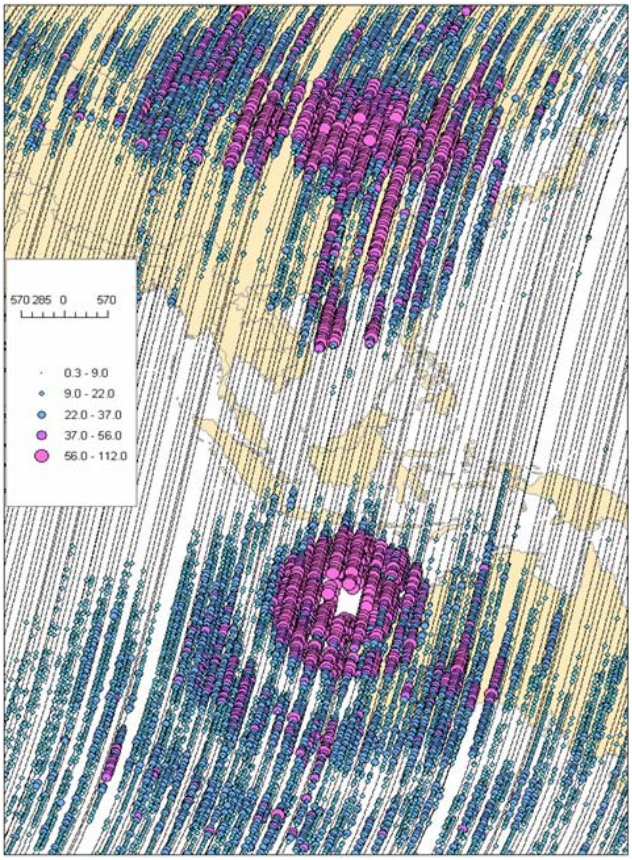

Fig. 4. The averaged SNR distribution during two months of observation for the NWC transmitter (F=19.8 kHz). The orbits are at day-time (LT∼10 h). In such a case the signal amplitudes and the reception zones are smaller than at night time. Interference parts appear in the region above the transmitter but they are absent in the conjugate area.

Fig. 5. The stars indicate the location of the earthquakes occurred in Europe during November–December 2004. The relative time occurrence and magnitude are indicated. The area involved by the seismic activity is approximately indicated with a rectangle.

by observations on the ground and consequently they were related to more or less local conditions. For example, the registration of VLF radio signals has provided valuable information on the perturbations in the upper atmosphere-lower ionosphere boundary in an interval of plus/minus several days around the time occurrence of large earthquakes; but the spatial area of the analysis was limited to a narrow zone along the path between the transmitter and the receiver (Molchanov and Hayakawa, 1998; Rozhnoi et al., 2004).

Here, the reception on board the DEMETER satellite of the VLF signals radiated by ground transmitters is analyzed. In the past, the reception of such signals was undertaken on many satellites for the investigation of the VLF wave propagation and of the interaction with the ionospheric plasma (Aubrey, 1968; Inan and Helliwell, 1982; Molchanov, 1985). The present analysis can be considered as a new method of ionospheric sounding in association with the seismic activity. It was suggested among the perspectives of the DEMETER satellite, whose major scientific objectives are the study of the ionospheric disturbances in relation to the seismic activity and the definition of the pre and post seismic effects (Parrot, 2002). The satellite has been launched on 29 June 2004 and its functioning is rather successful.

2 Data analysis

Figure 1 shows an example of satellite VLF electromagnetic registration by both the magnetic field receiver (IMSC) and the electric field receiver (ICE) (Parrot, 2002). In this paper, we will investigate only the electric field data. Frequency resolution of the spectra is ΔF=19.53 Hz and the time averaging is about 2 s. The signals from several powerful VLF ground transmitters are recorded on any orbit. The location in the eastern hemisphere of these VLF transmitters is shown in the Fig. 2. Some characteristics of the transmitters mentioned in this study are listed in Table 1.

The signal to noise ratio (SNR) was computed as follows:

$$\mathrm{SNR} = 2\mathrm{A}(\mathrm{F}_0)/[\mathrm{A}(\mathrm{F}_+) + \mathrm{A}(\mathrm{F}_-)]$$

where $A(F_0)$ is the amplitude spectrum density in the frequency band including the transmitter frequency F_0 and $A(F_\pm)$ are the values outside of the signal band. The choice of these last values is complicated by the signal spectral broadening in the band $F_0 \pm \delta F$ and by the presence of neighboring VLF signals. The spectral broadening is attributed to the VLF signal interaction with the natural ionospheric turbulence and it mainly depends on the transmitter power and on the position of the reception point (Bell et al., 1983; Titova et al., 1984; Tanaka et al., 1987). δF usually does not exceed 100 Hz but for powerful transmitters as NWC (19.8 kHz) it

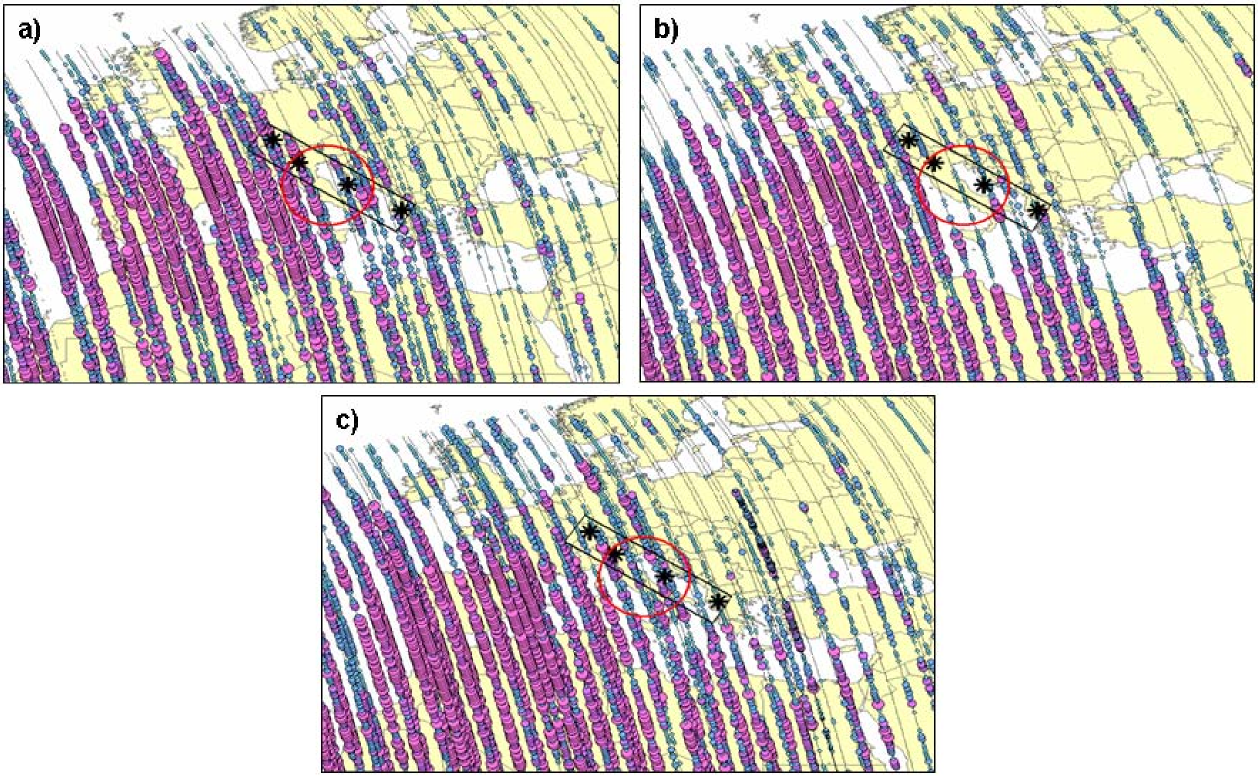

Fig. 6. **(a)** For the transmitter FTU (18.3 kHz), the SNR distribution averaged during about a month (from 25 October to 22 November 2004) before the earthquakes series. **(b)** The same as in panel (a), but during/after the earthquakes series (from 23 November to 12 December 2004). **(c)** The same as in panel (a), but during the period from 26 December 2004 to 31 January 2005, that is after the earthquakes series. The color legend is given in Fig. 4. The red circled area defines roughly the possible "scattering spot" zone.

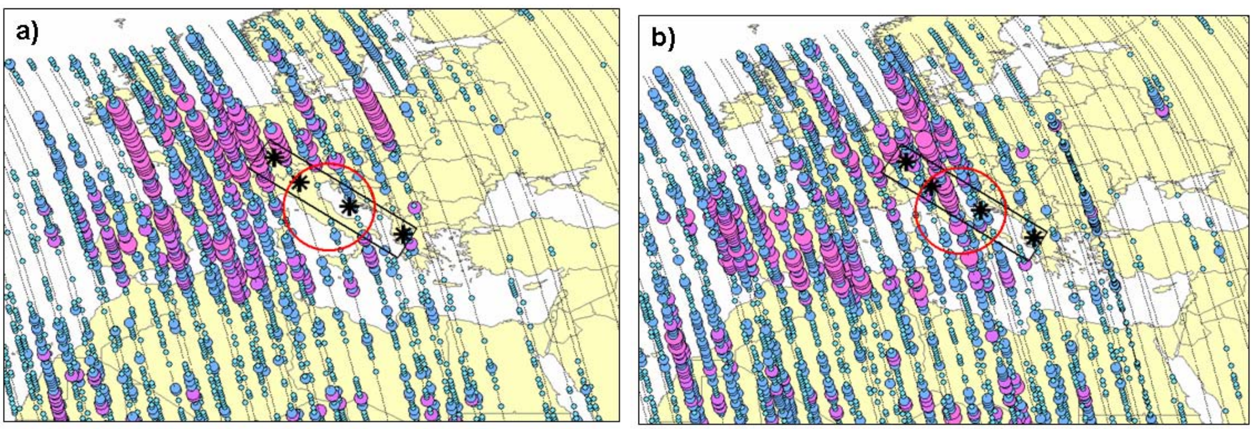

Fig. 7. Averaged SNR distributions for the DFY transmitter (16.56 kHz): **(a)** the same as in Fig. 6b, i.e. during/after the earthquakes series, **(b)** the same as in Fig. 6c, i.e. after the earthquakes series. The color legend is given in Fig. 4. The meaning of the red circled area is the same as in Fig. 6.

can reach the value of 500 Hz. A computation of $F_{\pm}$ for each VLF signal and each selected orbit was made by a special procedure. It is based on the analysis of the averaged background level as function of the difference $|F_{\pm}-F_0|$. An example of SNR trend is shown in Fig. 3. The following basic features of the reception zones must be noted: a) the first

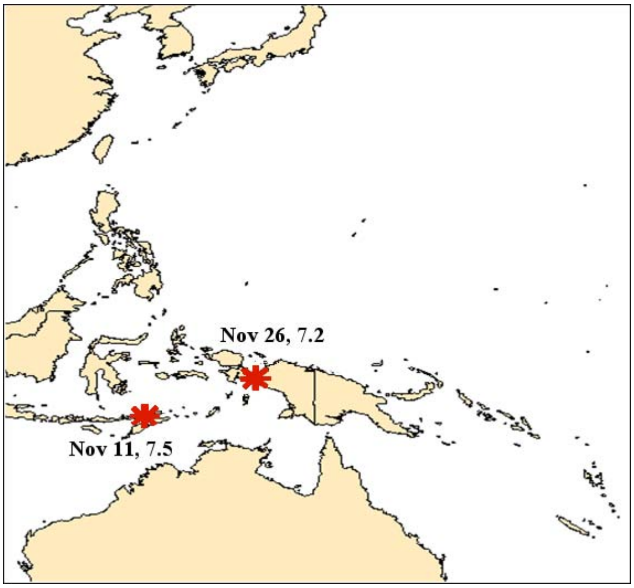

Fig. 8. Map showing the location, magnitude and time occurrence of the two strong earthquakes happened in Indonesia during November 2004.

reception zone is above the position of the transmitter; b) the second reception zone is in the conjugate area, due to the magnetospheric VLF propagation; c) the near equatorial region is characterized by a disappearance of the signal. Also expected and obvious fast variations of the signal exist and are due to the ionospheric irregularities. In the present study we need to average the signal over the fast variations and try to seek for slow changes in the reception zones during seismically active periods.

Generally, two types of ionospheric response to earthquakes forcing could be assumed. The first is the direct influence of the seismic pulses, which is a co-seismic effect with a duration ranging from several minutes to some hours. The second is a longer indirect response due to some processes related to earthquakes preparation and post-seismic relaxation, with a duration of days or weeks. By using one satellite a very small chance exists to observe a coseismic effect. A better possibility is the finding of the indirect influence. However, even on this way, the following intrinsic drawback of the satellite observations above a fixed point at the ground, exists: too large longitudinal distances between adjacent orbits (about 2500 km in a case of DEMETER orbits at the middle latitudes) and day time intervals between orbits above the point in the same local time. So, in order to obtain statistically significant results and a longitudinal spatial resolution of 100–200 km, an averaging period of 2–3 weeks, at least, is necessary. It dictates a selection of rather long periods of seismic activity, ad example a series of successive strong earthquakes. Another problem of the analysis is the incompleteness of the satellite data. However, since the end of October 2004, the data completeness becomes more than 70%; then, the data are missing from 16 December to 25 December 2004, while the completeness reaches a level of 80–90% since January 2005. The averaged (over a period of 2 months) background variation in the reception zones of the NWC transmitter is shown in the Fig. 4. In the reception zone where the transmitter is located, it can be noted the appearance of interference parts of the VLF modes. This effect does not appear in the conjugate reception zone.

At first, a series of large earthquakes occurred in Europe from 23 November to 5 December 2004 (23 November, M=5.5; 24 November, M=5.5; 25 November, M=5.4; 5 December, M=5.5) were selected. Their epicentres are shown in Fig. 5 and the extent of the area is approximately indicated with a rectangle. These earthquakes are rare ones for the large magnitude and the rather short time interval among them. The distribution of the SNR values in the selected area for the signals of the FTU transmitter (F=18.3 kHz) is shown in the Fig. 6 during a period before (from 25 October to 22 November 2004) the earthquakes series (Fig. 6a), during/after (from 23 November to 12 December 2004) the series (Fig. 6b) and after (26 December 2004 to 31 January 2005) it (Fig. 6c). The missing data period 16–25 December 2004 must be taken into consideration. With this account, the selected three periods of analysis are enough equal in length and adjacent in time. Here and after, only the data for evening orbits are used, because their space reception zone is larger than the day-time orbits ones (Figs. 3 and 4). For the same earthquakes series**,** the signals of the DFY transmitter (F=16.56 kHz) during/after and after the occurrence of the earthquakes were analysed. Figures 7a and b show the averaged distribution of the SNR values in the selected area from 23 November to 12 December 2004 and from 26 December 2004 to 31 January 2005, respectively.

Then, two large earthquakes occurred in Indonesia during November 2004 (11 November, M=7.5; 26 November, M=7.2) were selected. In Fig. 8, their location, magnitude and occurrence time are indicated. In Fig. 9, the averaged SNR distributions for the JP (17.8 kHz) transmitter during a period before/during (from 30 October to 28 November 2004) the occurrence of the quoted earthquakes (Fig. 9a) and a period after (from 6 January to 7 February 2005) their occurrence (Fig. 9b), are shown.

Finally, the Fig. 10 shows the location of the Sumatra big (M=9.0) earthquake on 26 December 2004. The averaged SNR distributions for the NWC (19.8 kHz) transmitter during a period before (from 1 November to 15 December 2004) the occurrence of the quoted earthquake (Fig. 11a) and a period after (from 6 January to 15 February 2005) its occurrence (Fig. 11b), are shown in Fig. 11.

3 Discussion

The data reported in Fig. 6 indicate: a) none definite indication of effects exists (Fig. 6a) before the Europe earthquakes

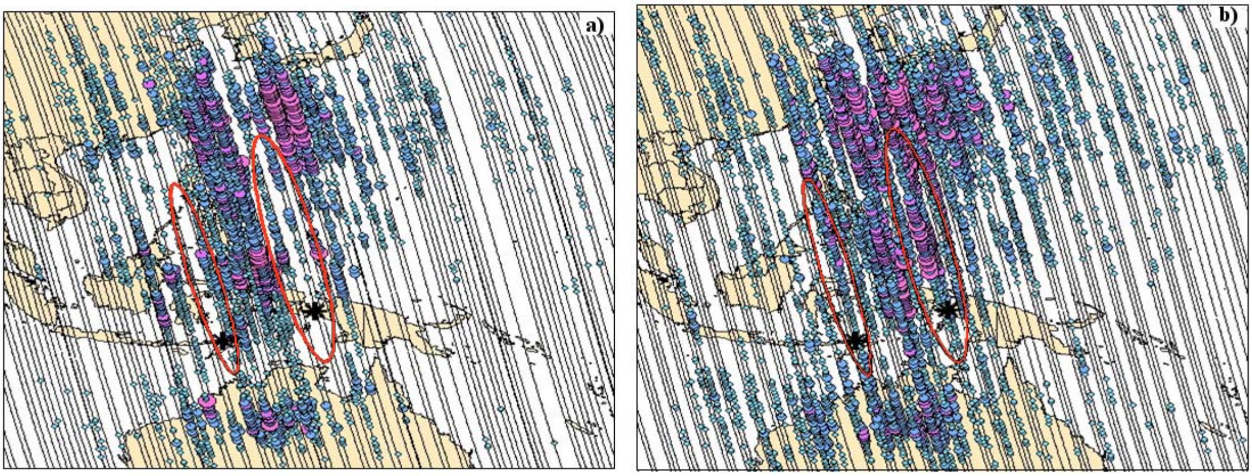

Fig. 9. (a) Averaged SNR distribution for the JP (17.8 kHz) transmitter during the period from 30 October to 28 November 2004, i.e. before and during the time occurrence of the strong earthquakes in Indonesia. **(b)** The same as in panel (a) but during the period from 6 January to 7 February 2005, i.e. after the occurrence of the earthquakes. The color legend is given in Fig. 4. The red circled areas define roughly the possible "scattering spot" zones.

series on November–December 2004; b) a "scattering spot" seems to appear in the time period which includes the interval of the earthquakes series (Fig. 6b); c) the effect disappears in the period after it (Fig. 6c). For the same earthquakes, the data reported in Fig. 7 confirm the appearance of a "scattering spot" in a period including their time occurrence. The data presented in Fig. 9 seem to confirm the results indicated in the previous b) and c) items for the Indonesia earthquakes on November 2004. For the big Sumatra earthquake on December 2004 the data presented in Fig. 11 seem to indicate the appearance of a "scattering spot" before the earthquake occurrence (Fig. 11a). Anyway, since the data period 16–25 December 2004 is missed, this last result is doubtful.

The "scattering spots" have a size of about 1000 km in the case of the earthquakes series in Europe with magnitude M$\sim$5.5. They are about 2000–3000 km large for the Indonesia earthquakes with M$\sim$7–7.5 and, perhaps, a huge extension of the order of 5000 km, can be considered for the Sumatra earthquake with M=9.0. The previous values are only indicative ones and represent the (greater) extension of the red circled areas reported in the Figs. 6/7, 9 and 11.

The previous results seem to indicate that "scattering spots" in VLF radio signals exist in connection with large earthquakes and their spatial extension increase with the magnitude of the relative earthquake.

The previous long in time and large in extension regions of perturbation in the ionosphere cannot be produced by the seismic shocks itself (duration of minutes/hours). So, it is necessary to suppose some long lasting agent which influences the ionosphere around the time occurrence of a strong earthquake. According to our opinion, the initial agent is an upward energy flux of atmospheric gravity waves (AGW)

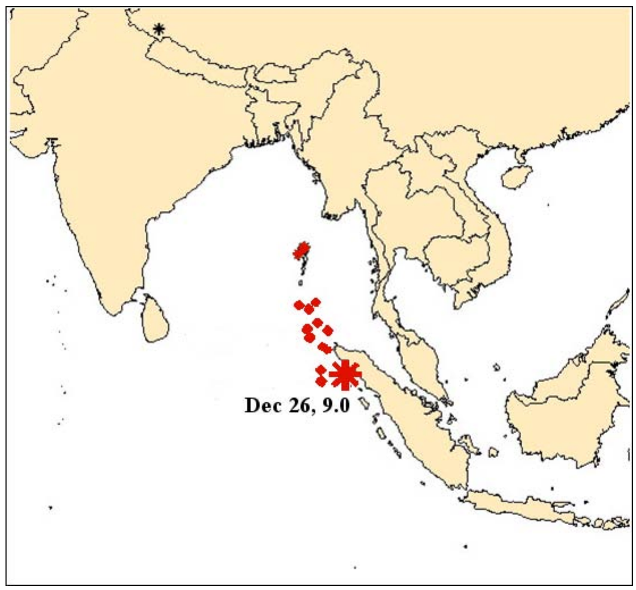

Fig. 10. Map showing the location, time occurrence and magnitude of the big Sumatra earthquake on December 2004. The location of other main shocks is also indicated.

which are induced by the gas-water release from the earthquake preparatory zone (Liperovsky et al., 2000; Molchanov, 2004). The penetration of AGW waves into the ionosphere leads to modification of the natural (background) ionospheric turbulence, especially for space scales $\sim$1–3 km and wave numbers $k_T \sim 10^{-4}$–10^{-3} m^{-1}. Previously, this weak but reliable effect was revealed from direct satellite observations (Molchanov et al., 2004; Hobara et al., 2005). Resonant

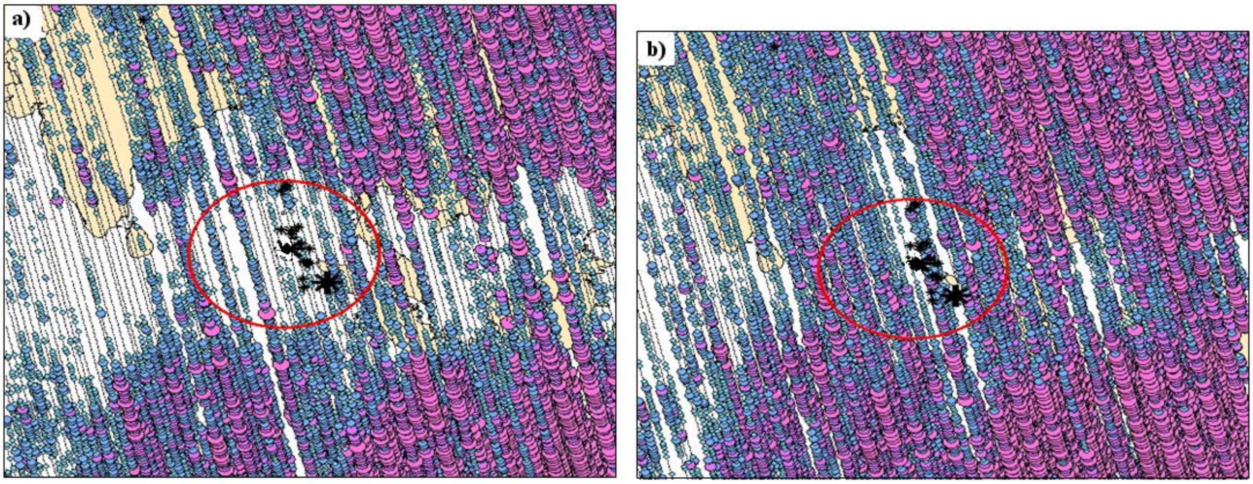

Fig. 11. (a) Averaged SNR distribution for the NWC (19.8 kHz) transmitter during the period from 1 November to 15 December 2004, i.e. before the occurrence of the Sumatra big earthquake. **(b)** The same as in panel (a), but during the period from 6 January to 15 February 2005, i.e. after the occurrence of the Sumatra earthquake. The color legend is given in Fig. 4. The red circled area defines roughly the possible "scattering spot" zone.

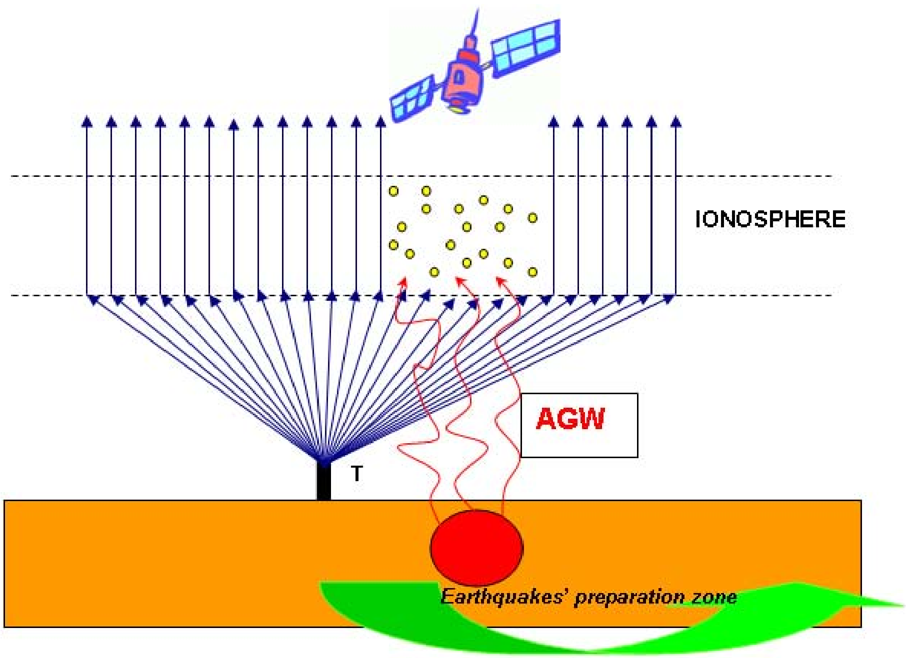

Fig. 12. Schematic model of the VLF signals scattering assumed to explain the observed effect. AGW indicates the Atmospheric Gravity Waves above the earthquake preparatory zone. The yellow circles represent the modification of the ionospheric turbulence.

scattering of the VLF signals is possible in condition of the frequency- wave number synchronism :

$$\omega_0 = \omega_s + \omega_T k_0 = k_s + k_T$$

where ω_0, k_0 are for the incident VLF wave; ω_T, k_T are for the turbulence and ω_s, k_s are for the scattering waves. It can be found that the amplitude A_0 of an incident wave decreases exponentially during its propagation through the perturbed medium according to the relation:

$$A_0 \cong e^{-\alpha_n A_t H}$$

where α_n is the coefficient of nonlinear interaction, H is the length of the interaction region and A_t is the amplitude of the turbulence. For the VLF signals it is $\omega_T \ll \omega_0 \sim \omega_s$, and the interaction is especially efficient because $k_0 \sim k_s \sim k_T$ (Molchanov, 1985; Trakhtengertz and Hayakawa, 1993). Therefore, even with a small amplitude A_T of the turbulence, the scattering of the wave could be significant if the length H is large. The Fig. 12 shows a schematic view of the mechanism.

4 Conclusions

The method of diagnostics applied on this study has the advantage to be global thanks to the world-wide positioning of the powerful VLF transmitters and to the satellite reception. Anyway, it has the specific disadvantage to require rather long time period of analysis, because the longitudinal distances among the satellite orbits are too large. Above a fixed area, the satellite appears at the same local time only once per day. So, at least one month period of registration is necessary for the longitudinal spacing of about 1000 km.

In any case, this study has revealed the existence of "scattering spots" in VLF radio signals related to large earthquakes and it has approximately defined the size of the perturbed area as function of the earthquake magnitude.

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