Pre-seismic anomalies revealed analyzing the radio signals collected by the European VLF/LF network from July 2009 until June 2011

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Abstract: During 2008 a radio receiver working in VLF (20-60 kHz) and LF (150-300 kHz) bands was developed by an Italian factory. The receiver can monitor 10 frequencies distributed in these bands measuring, for each of them, the electric field intensity. Since 2009 these radio receivers were installed throughout Europe in order to realize an "European VLF/LF Network". At present, two of them are into operation in Italy and other four are located in Greece, Turkey, Portugal and Romania, respectively. In this study, the radio data collected during two years have been analysed. At first, for each radio signal, the day-time data and the night-time ones have been separated. Then, the earthquakes with M≥5.0 located in a 300 km radius around each receiver/transmitter and within the 5th Fresnel zone related to each transmitter-receiver path, have been selected. The radio data collected were studied using the Wavelet spectra and the Standard Deviation trends as different methods of analysis. In many cases evident precursor phases were pointed out. As an example, the case of the May 19, 2011 earthquake that occurred in Simav (Turkey) with magnitude M_w= 5.7 is here presented in details.

1. Introduction

Since 1980, studies about the interaction between seismic activity and disturbances in radiobroadcasts have been carried out. Pre-seismic disturbances in VLF radio signals, that lie in the 20-60 kHz frequency band, have been presented mainly by Japanese and Russian researchers (Hayakawa and Sato, 1994; Hayakawa et al., 1996; Hayakawa et al., 2006; Morgounov et al., 1994; Molchanov and Hayakawa, 1998). At the same time, pre-seismic disturbances on LF (150-300 kHz) radio broadcasts were proposed mainly by Italian researchers (Biagi et al., 2001a,b; Biagi and Hayakawa, 2002, Biagi et al., 2005, 2006). Generally, the radio data have been collected by receivers located on the ground. Recently, some possible seismic disturbances revealed by VLF radio signals collected on board of the French DEMETER satellite were presented by Molchanov et al. (2006) and Rozhnoi et al. (2007).

All the previous disturbances are related to variations of some parameters in the ground, in the atmosphere and in the ionosphere. The ground variations such as

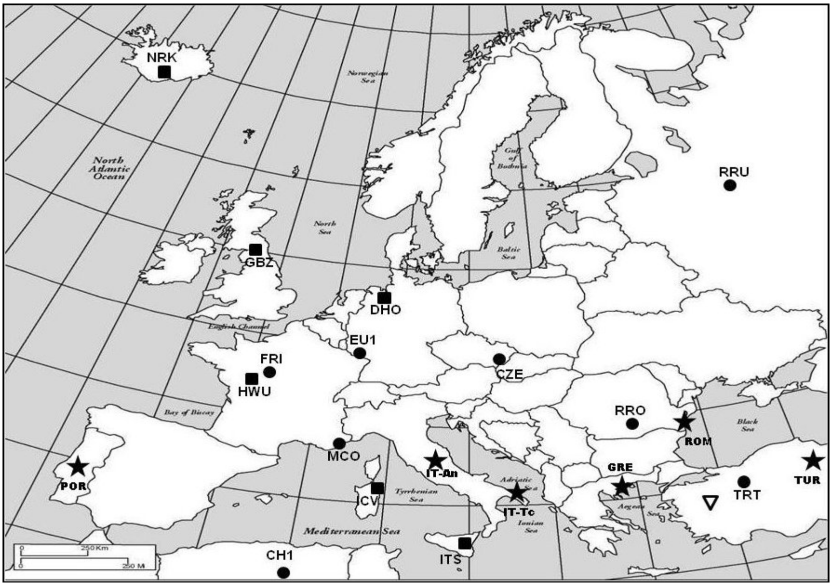

Figure 1 Map showing the receivers and the transmitters of the European VLF/LF Network. The stars show the location of the receivers; the circles indicate the LF transmitters, the signals of which are collected by the different receivers; the squares are referred to the VLF transmitters. The triangle indicates the location of the Simav (Turkey) earthquake.

uplift and tilt, gas emissions, underground water level fluctuations, changes in groundwater chemistry and changes in the electrical resistivity of rocks are clearly related to the microfracturing processes occurring during the preparatory phase of earthquakes. On the other hand, in order to justify the atmospheric (mainly ionospheric) disturbances two different models have been proposed. The first one assumes a direct effect that is the ionising radiation from gases (mainly radon), aerosol or electromagnetic emissions from the ground (Alperovitch, 1997; Biagi et al. 2001b; Hayakawa and Sato, 1994; Pulinets et al., 1998); the second model assume an indirect effect, that is the production of gravity waves in the atmosphere-ionosphere (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998) as a consequence of pre-seismic processes in the ground. This model overcomes the problem, present in the first model, of the transport up to the ionosphere of particles or electromagnetic waves from the ground.

In this framework, during 2008 a new radio receiver, operating both in the VLF and in the LF band and able to monitor the electric field intensity of 10 frequencies, was developed by an Italian factory named Elettronika (Palo del Colle, Bari). Up to 2011, six receivers have been put into operation, two of them operating in Italy and the remaining four in Greece, Turkey, Portugal and Romania respectively, giving rise to the first "European VLF/LF Network" (Biagi et al., 2011). A sampling rate of 1 minute is used; the electric field intensity of the signals is expressed in dBm as dBm=20log(VmVpp). Figure 1 describes the network.

2. Data analysis

As a first step, the day-time data from the night-time ones were separated. As regard the VLF signals, different time ranges have been selected in order to obtain data related at proper night time conditions (basically related to darkness) along all the paths. As regard the LF signals, the range from 8.00 to 13.00 (UT) for the day-time and the range from 20.00 to 22.00 (UT) for the night-time were selected; this last choice is forced by the occurrence of an interruption of 3-4 hours in some radio broadcasts generally after the local 24.00.

The mentioned data have been analysed using the Wavelet spectra and the Standard Deviation trends The Wavelet transform allows to highlight the spectral components of a signal by using variable-width time windows and by considering that the frequency content of these windows is in inverse relation to the time widths; so, the localization of the signal is simultaneously obtained both in time and in frequency. In this study, the "Morlet function" was adopted as Wavelet. In this case the Wavelet transform of a time signal is a complex series that can be usefully represented by its square amplitude, i.e. the so-called Wavelet power spectrum can be considered. The power spectrum is a two dimensions plot that, once properly normalized with respect to the power of the white noise, gives information on the strength and precise time of occurrence of the various Fourier components which are present in the original time series. Generally, colour from blue to red indicates increase in the power strength; so, red zones define anomalies.
For a sample of n data, the Standard Deviation (SD) is calculated as follows:

$$SD = \frac{\sqrt{\sum_{1}^{n}(x_i - x_m)^2}}{n-1}$$

where x_m is the mean value of the x_i values. SD shows how much variation or "dispersion" there is from the mean. A low SD value indicates that the data points tend to be very close to the mean, whereas high SD value indicates that the data points are spread out over a large range of values. The SD can be calculated for each set of day-time data and night-time data and particularly low/high values define anomalies, that is low or high dispersion of the data. For a larger evidence we used the % value defined as $SD\text{-}SD_m/SD_m$ where SD is the value of each day/night-time data an SD_m is the mean value of the SD data set in the whole time interval analyzed. The related trends are the Standard Deviation trends and the values over $\pm 2\sigma$ (standard deviation) in these trends were assumed as low/high values defining an anomaly.

3. Earthquakes selection

In order to reveal possible seismic effects on the radio signals, at first it was necessary to select the pertinent earthquakes. The European Mediterranean Seismological Centre bulletin from July 2009 to July 2011 has been used (EMSC website: http://www.emsc-csem.org). The three following criteria in the earthquakes choice have been adopted: a) earthquakes with $M_w \geq 5.0$ located inside the 5th Fresnel zone of the different radio paths; b) earthquakes with $M_w \geq 5.0$ occurred inside a circle with 300 km radius around each receiver; c) earthquakes with $M_w \geq 5.0$ occurred inside a circle with 300 km radius around each transmitter. The rule a) takes into account several results which indicate that the area inside the 5th Fresnel zone is the most sensitive as for the seismic disturbances on the radio propagation (Molchanov and Hayakawa, 1998; Molchanov et al. 2006; Rozhnoi et al., 2004). The rules b) and c) are based on the dimension of the area interested by possible pre-seismic effects (Dobrovolsky et al., 1979; Kingsley et al., 2001).

4. Results and the Simav earthquake

In totally 27 cases for analysing were found and successes, i.e. radio anomalies preceding the subsequent earthquake and clearly related to the event, were obtained in 70% of the cases. It must be noted that increasing the value of the M_w threshold the percent of the successes increases up to 80% for $M_w \geq 5.5$ reaching 100% for $M_w \geq 5.8$.

As an example of analysis, the case of the May 19, 2011 earthquake occurred in Simav, Kutahya (Turkey) with magnitude $M_w = 5.7$ is here reported. The location of this earthquake is indicated in Figure 1. An intense aftershocks activity occurred for more than one month releasing an energy equivalent to an earthquake with the same magnitude of the main shock. The area belongs to one of the most important tectonic units of the Western Anatolia extension regime. In general, in this region the seismic activity occurs on the E-W tectonic line and on its branches and strong earthquakes are expected. The most intense and damaging recent earthquakes happened in 1928 with M (Richter) of 6.2 and in 1970 with M = 7.2. The epicentre is inside the 300 *km* radius circle around the TRT (180 *kHz*) transmitter, the signal of which is sampled by three receivers (GR, IT-An, IT-Tc) of the Network. With regard to the VLF radio signals, the earthquake is inside the 5th Fresnel zone defined by the ITS (45.9 *kHz*) transmitter and the TUR receiver of the Network.

Figure 2a shows the results of the analysis of the TRT radio data collected at daytime by the GR, IT-An and IT-Tc receivers during April-May 2011. Top and bottom of Figure 2a refer respectively to the Wavelet Spectra and the Standard Deviation trends. Both the Wavelet Spectra and the Standard Deviation trends reveal anomalies during the first fifteen days of April and the anomalies seem to be correlated. Figure 2b shows a similar analysis done on the night-time data. Also in this case the indication of the Wavelet Spectra and of the Standard Deviation trends are well correlated, i.e. for all the receivers, some anomalies appear in the first fifteen days of April mainly in the period 10-15 April; then a clear anomaly stands up in the data related to the GR receiver before the time occurrence of the Turkey earthquake.

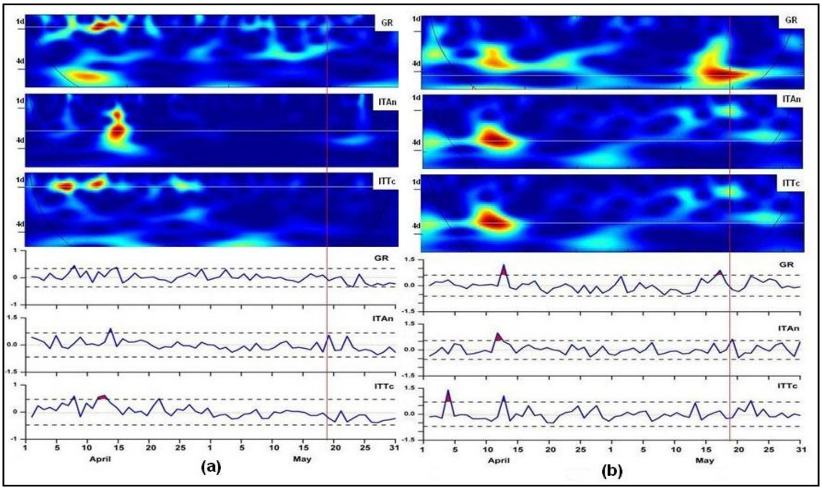

Figure 2 **(a)** Results of the analysis of the TRT radio data collected at day-time. At the top the Wavelet Spectra and at the bottom the Standard Deviation trend, where the zones over 2σ are filled in red**.**
(b) The contents are the same of Figure 2a but related to night-time data. In both the panels the vertical line indicates the occurrence of the Turkey earthquake.

The following remarks are the consequence of the previous results. A possible cause of the anomalies appearing in both the day-time and night-time data during the first fifteen days of April could be the meteorological situation in the zone where the transmitter is located. These meteorological conditions were examined and they do not appear so critical; so, the meteorological justification of the previous radio anomalies is not convincing. Another possible cause of these anomalies could have been some malfunction of the broadcasting station, but it was ruled out by station manager. So, the possibility that the radio anomalies are connected with the Turkey earthquake of May 11 could be realistic. In such a case these anomalies should be considered a middle term precursor of the earthquake. Then, as it concerns the anomaly appearing some days before the occurrence of the earthquake in the TRT radio signal recorded by the GRE receiver at night time (Figure 2b) it must be noted that: a) the other LF signals collected by this receiver coming from Nord and West (Figure 1) do not reveal any disturbance in the same period, so the cause of the anomaly is in the East area with respect to the receiver; b) the anomaly appears only at night time, so it should be related mainly to an ionosphere disturbance; c) the GRE receiver is the nearest (Figure 1) to the TRT transmitter. As a consequence, it seems reasonable to consider the previous anomaly a precursor of the Turkey earthquake, a short term precursor, i.e. related to the final processes of the preparation of earthquake.

Figure 3a shows the results of the analysis of the radio signals collected at night-time by the TUR receiver and radiated by the VLF transmitters GBZ and ITS. The 5th Fresnel zones defined by the transmitters and the receiver are reported in Figure 3b. As usual, in Figure 3a at the top the Wavelet Spectra and at the bottom the

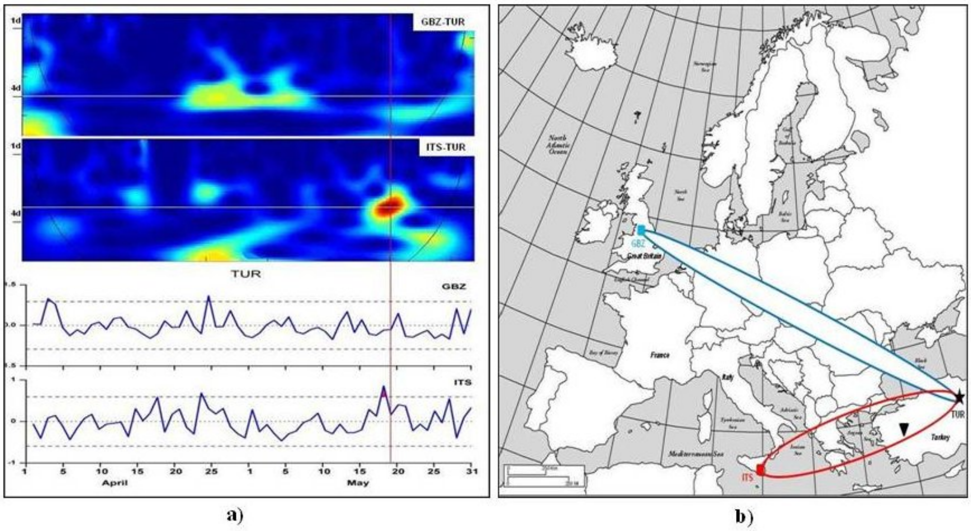

Figure 3 **(a)** Results of the analysis of the GBZ and ITS radio data collected by the TUR receiver at night-time. At the top the Wavelet Spectra and at the bottom the Standard Deviation trends where the zones over 2σ are filled in red. The vertical line indicates the occurrence of the Turkey earthquake.
(b) Map of the 5th Fresnel zones defined by GBZ transmitter-TUR receiver and ITS transmitter-TUR receiver. The epicentre of the earthquake is indicated by a triangle.

Standard Deviation trends, are reported. Again the two methods are in agreement reveal mainly the presence of a clear anomaly some days before the occurrence of the earthquake in the ITS data.

From this result, the following remarks can be done. The anomaly appears on the ITS radio signal while the GBZ radio signal does not reveal any similar effect. Figure 3b shows that the epicentre of the Turkey earthquake is inside the 5th Fresnel zone of the ITS-TUR path, while is out the same zone related to the GBZ-TUR path. So, the possibility that the previous anomaly is a precursor of the Turkey earthquake is consistent. Probably, the anomaly is related to the same disturbance in ionosphere responsible of the LF radio anomaly (the short term one) described in the previous item.

5. Conclusions

This study has confirmed that the VLF and LF radio signals can give information on the preparatory phase of earthquakes with M_w greater than 5.0; but, if the threshold of magnitude increases the percent of successes increases. The anomalies are related to disturbances produced in ionosphere, lower atmosphere or both. The Wavelet spectra and the Standard Deviation trends seem valid methods of data analysis for revealing these anomalies.

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