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A possible preseismic anomaly in the ground wave of a radio broadcasting (216 kHz) during July–August 1998 (Italy)

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Abstract. On February 1996, a receiver able to measure the electric field strength of LF radio broadcastings, with a sampling frequency of ten minutes, was put into operation in a site (AS) located in central Italy. One of the broadcasting stations selected is MCO (f=216 kHz), located in southeast France, 518 km far from the receiver. The MCO data collected since February 1996 up to September 2004 were examined and, at first, the night time data and the day time data (in winter and summer) were separated. Then, the wavelet analysis on the night and day time data was applied. The main result of the analysis was the appearance of a very clear anomaly during summer (July–August) 1998, at day time and at night time. The anomaly is a strong exaltation of the signal components with period in the 25–40 days range. Theoretical calculations of electric field strength were made and the only way to justify this anomaly seems to be the occurrence of an increase of the ground wave propagation mode of the radio signal. Such an increase could have been produced by an increase of the ground conductivity and by modifications of some parameter of the troposphere, mainly the refractive index. On 15 August 1998 a seismic sequence started with 17 earthquakes (M=2.2–4.6) on the Reatini mountains, a seismogenic zone located 30 km far from the AS receiver along the path MCO-AS. In this paper, the possibility that the previous radio anomaly can be a precursor of this seismic sequence is proposed.

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1 Introduction

For many years, research into the interaction between seismic activity and disturbances in radiobroadcasts has been carried out. Recently, pre-seismic disturbances in the Omega and Loran radio waves, that lie in the VLF (3–30 kHz) frequency band, have been presented (Gokhberg et al., 1989; Hayakawa and Sato, 1994; Morgounov et al., 1994; Hayakawa et al., 1996; Molchanov and Hayakawa, 1998). These radio signals are used for worldwide navigation support and propagate in an earth-ionosphere wave-guide mode along great circle propagation paths. The analysis is based on the amplitude and the phase variations of the radio signals propagating from different transmitting stations. The anomalous variations detected several days before strong earthquakes have been explained by disturbances in the lower ionosphere produced during the preparatory phase of strong earthquakes.

Since 1996, the electric field strength of LF (150–300 kHz) broadcasting stations is sampled by receivers located in central Italy. Some decreasing of the electric field strength of the radio signals was revealed and it has been explained by defocusing in the troposphere caused by the preparation of moderate (M=3.0–3.5) earthquakes located nearby the receivers (Bella et al., 1998; Biagi et al., 2001a, b). Then, a significant increase (6–8 dB) in the electric field of a radio signal (f=270 kHz) was observed and it was proposed as a precursor of a strong seismic sequence (M=5.1–6.0) occurred over 400 km far from a receiver but in the middle of the

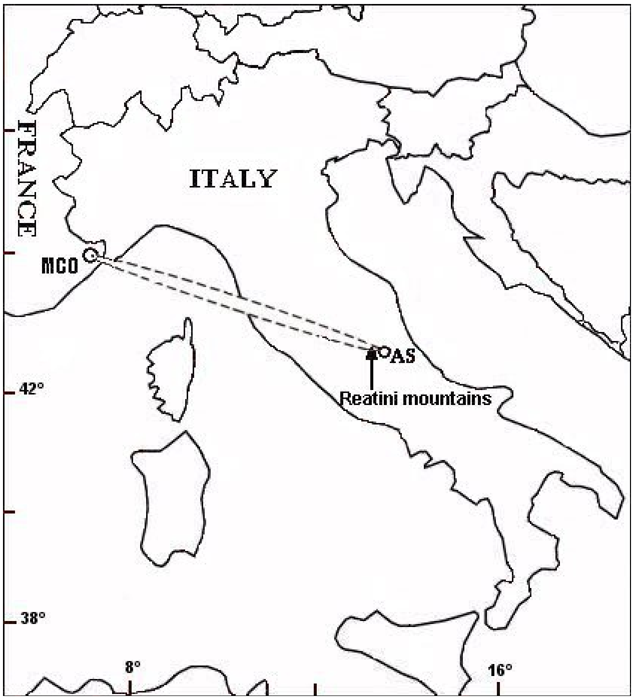

Fig. 1. Map showing the location of the receiver AS and of the MCO transmitter. The first Fresnel zone is indicated by a dotted line. The location of the Reatini mountains seismogenetic area is shown too.

transmitter-receiver path (Biagi and Hayakawa, 2002; Biagi et al., 2003). The increase was explained by the occurrence of some disturbances in the ionosphere during the preparatory phase of the seismic sequence.

Here, we present the result of a detailed analysis applied on the electric field strength data of a radio signal recorded by a receiver from February 1996 up to September 2004. The broadcasting station, named MCO, is located in southeast France and it transmits a LF (f=216 kHz) radio signal with a radiated power of 1400 kW. The receiver, named AS, is into operation at the mouth of a natural cave located in central Italy on the southern slope of the Gran Sasso chain, 518 km far from the transmitter. The receiver samples the electric field strength (instrumental zero equal to 0.2 mV/m) each ten minutes and it is detailed in Bella et al. (1998). Figure 1 shows the location of the transmitter and of the receiver.

2 Theoretical computations and data analysis

The LF signals are characterised by the ground-wave and the sky-wave propagation modes. The ground-wave, for distances lesser than 500–1000 km, provides a stable signal that can be a significant one. On the contrary, the sky-wave is greatly variable between day and night and, at day time, between winter and summer. At first, by considering the MCO radio signal we calculated the theoretical electric field strength of the ground-wave propagating over a curved earth with a troposphere whose refractive index varies according to an exponential way with the height (Rotheram, 1981a, b). Then, for the same signal we calculated the theoretical electric field strength of the sky-wave at night time and at day time during winter and summer, using the wave hop approach (Knight, 1973; CCIR, 1990a). According to the wave hop propagation theory, the sky-wave signal received by an antenna can be considered as a ray starting from the transmitter and reflected one or more times (hops) by the lower ionosphere and by the ground. The distance MCO-AS is consistent with only one hop, where the reflection point of the lower ionosphere is located in the middle of the radio path. All the previous theoretical values are reported in Table 1.

Table 1. Experimental (Exp) and theoretical (Theo) values of the electric field strength (mV/m) for the MCO (216 kHz) radio signal at AS receiver.

ELECTRIC FIELD STRENGTH (Exp. values)		SKY WAVE (Theo. values)	
Day time			
winter	summer	winter	summer
0.79	0.52	0.50	0.02
Night time			
3.65		3.10	
GROUND WAVE (Theo. value)			
0.54			

Then we analysed the MCO electric field strength data (ten minutes sampling time). At first, we separated the day time data and the night time ones. In order to obtain at first data sets always related to the day time and to night time, regardless the seasons, and then each set with the same number of data per day, we selected the range from 09:00 a.m. to 02:00 p.m. (local solar time) for the day time and the range from 09:00 p.m. to 12:00 p.m. (local solar time) for the night time. This last choice is resulted, in addition to the previous conditions, from the fact that the MCO broadcasting station interrupts the transmissions for 3–4 h after midnight. Then, in the day time data we separated the data collected in winter (21 December–21 March) from the data collected in summer (21 June–21 September). Figure 2 shows the night time, day time, winter day time and summer day time trends of the MCO electric field strength from February 1996 up to September 2004. We calculated the mean value of each data set and these values, represented by horizontal dashed lines in the Fig. 2, are reported in Table 1.

Then, since the statistical characteristics of the signal under analysis change in time, the wavelet transform on the night time data and on the day time data at winter and at summer, was applied (Torrence and Compo, 1998). In this way it has been possible to highlight the spectral components of the signal by using variable-width time windows, by considering that the frequency content of these windows is in inverse relation to the time widths. This allows the localization of the

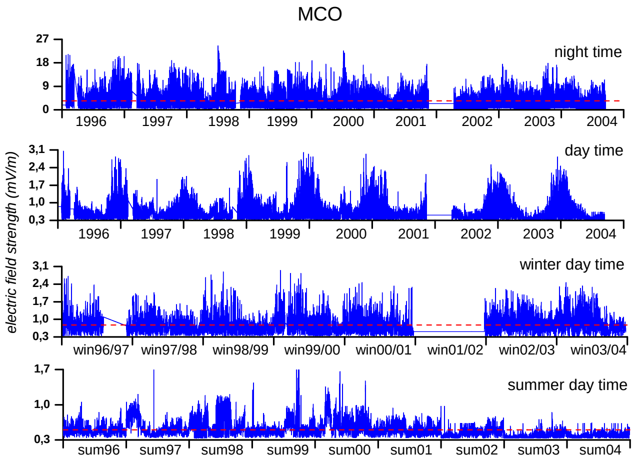

Fig. 2. From the top reading downwards, the MCO electric field strength at night time (09:00–12:00 p.m., local solar time), at day time (09:00 a.m.–02:00 p.m., local solar time), at winter day time and at summer day time, from February 1996 to September 2004. The dashed horizontal lines represent the mean values (Table 1) of the relative data set.

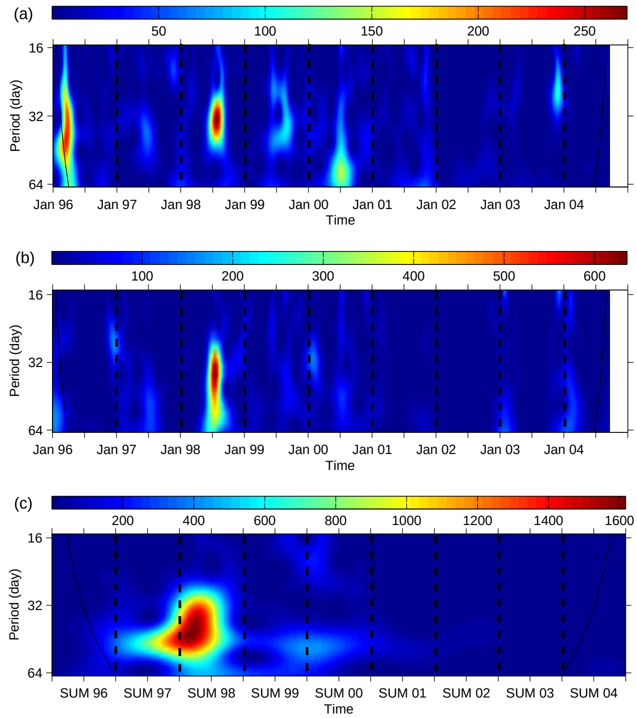

Fig. 3. Normalized wavelet power spectrum from February 1996 to September 2004 of the MCO electric field strength in the range 16–64 days at: **(a)** night time, **(b)** day time, **(c)** summer day time. The left axis is the Fourier period (in day), the bottom axis is time. For each panel wavelet power level (arbitrary scale) is represented with a colour scale from dark blue to dark red.

signal in both time and frequency simultaneously. A picture, the spectrogram, showing both the amplitude of the signal versus the wavelet scale and the dependence between amplitude and time can be drawn. (Daubechies, 1992; Strang and Nguyen, 1996). In our analysis we have considered the "Morlet function" as wavelet function (Torrence and Compo, 1998), and we have plotted in the Fig. 3 the wavelet power spectrum normalized with respect to the power of the white noise. The main result is the appearance of a very clear anomaly during summer (July–August) 1998, at day time and at night time. The anomaly is a strong exaltation of the signal components with period in the 25–40 days range.

3 Discussion

By considering the results reported in Table 1 and by taking into account that our receiver has an instrumental zero equal to 0.20 mV/m, the following statements can be made: 1) the sky-wave at night and at winter day time has values which can be recorded by the AS receiver; on the contrary at summer day time it cannot be recorded by the receiver; 2) the ground-wave is recorded by the AS receiver; 3) at night time and at winter day time the ground-wave is superimposed to the sky-wave; at summer day time practically it represents the recorded signal. The radio anomaly we revealed is related to an increase of the electric field strength during summer; so, taking into account that the anomaly appears not only at night time but also at day time, from the previous statements the sky-wave cannot be involved. On the contrary, these statements suggest the possibility that the anomaly is related to an increase of the ground-wave propagation mode. The anomaly revealed by the wavelet analysis can be investigated clearly on the day time data. Looking at the trend at the bottom of the Fig. 3, it is evident that the quoted anomaly is related to the appearance of the large signals during the middle summer 1998. These anomalous signals are characterised mainly by values of 0.8 mV/m, with some spikes up to 1 mV/m. The theoretical electric field strength of the MCO ground wave at the AS receiver is 0.54 mV/m (Table 1). The experimental mean value (summer day time) from 1996 to 2004 is in good agreement with the theory (Table 1). If the ground-wave electric field strength would undergo a 50% increase or so on, the anomalous signals responsible of the anomaly under study could be justified. Several parameters as the scale height of the troposphere, its refractive index, the relative permittivity and the conductivity of the ground, control the ground-wave propagation of a radio signal. The most influent ones are the ground conductivity and the refractive index of the troposphere. If the value of one or both the previous parameters increases in some zone or at all along the radio path then, as a result, the electric field strength of the ground-wave increases. The conductivity of the ground is strongly affected by the water content. In many cases a small increase in the percentage of water steps up the conductivity enormously (Telford et al., 2002). The refractive index of the troposphere varies primarily with height, as previously mentioned. An important parameter to take into account is the value of the refractive index at the surface of the ground (CCIR, 1990b). Such a value is affected by the chemical

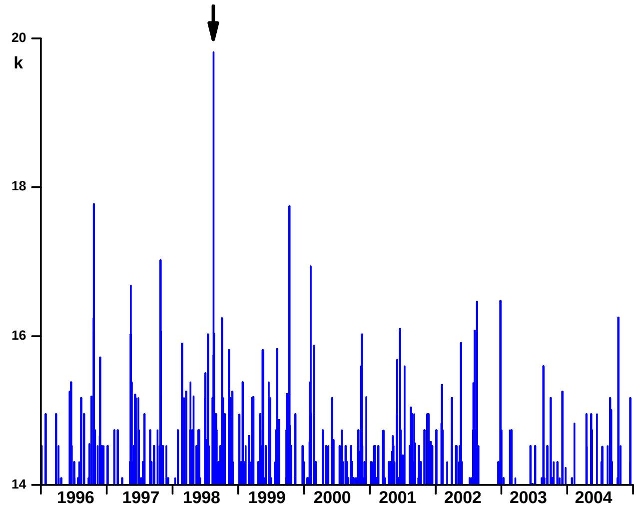

Fig. 4. Temporal trend of the k (energy (erg)=10^k) values of the earthquakes occurred in the Reatini mountains seismogenetic area. The arrow represents the occurrence of the 15 August 1998 seismic sequence.

composition of the air and it changes when variations, also small ones, in this composition happen.

In order to justify the radio anomaly described in the previous session, at first, we checked the meteorological conditions and the rainfall in the area of the radio path. The data of the meteorological stations located along radio path in Italy and in France were checked and we did not discover any anomalous situation during July–August 1998.

On the contrary, from the Seismic Bulletins of the INGV (National Institute of Geophysics and Volcanology) it results that on 15 August 1998, i.e. practically at the end of the radio anomaly, a seismic sequence started with 17 earthquakes (M=2.2–4.6), in a zone located 30 km far from the AS receiver exactly along the MCO-AS path. The seismic sequence lasted for about one week and it was the most large seismic activity occurred in Italy from July to September 1998. The sequence is set in the seismic activity of the Reatini mountains seismogenetic area. This area, located in the central Apennines (Fig. 1), is approximately a rectangle, with a diagonal 40 km long in the northeast direction.

The possibility that the previous radio anomaly was a precursor of this seismic sequence can be considered and we have investigated this possibility.

At first we calculated the first Fresnel zone of the MCO radio signal related to the AS receiver. This zone is the area delimited by the dashed ellipse reported in the Fig. 1. The Fresnel zones are considered the sensitive zones to the seismo-atmospheric effects and, as it concerns earthquakes with magnitude up to 5.0, the first zone is generally considered (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Molchanov et al., 1998; Rozhnoi et al., 2004). Recently, it was proposed to reach up to the fifth Fresnel zone, but it could be possible for earthquakes like 2004 Sumatra one with M=9.0 (Horie et al., 2005). We checked the location of the epicentres of the August 1998 seismic sequence and we found that they are located inside the first Fresnel zone (Fig. 1).

Then, we extracted, from the Seismic Bulletins of the INGV, the earthquakes occurred in the Reatini mountains seismogenetic area from 1996 to 2004. For each earthquake, we calculated the k value (energy (erg)=10^k) from the magnitude M, using the relationship (Kanamori and Anderson, 1975):

$$k = 11.8 + 1.5M\,. \qquad (1)$$

The trend of the k values in the period 1996–2004 is reported in Fig. 4. In the days in which more than one earthquake occurred, the energies were added and the total k value was derived. From Fig. 4, a clear spike stands up on the occasion of the 15 August 1998 seismic sequence.

Finally, we extracted, from the Seismic Bulletins of the INGV, the earthquakes occurred in the first Fresnel zone of Fig. 1 from 1996 to 2004. It must be noted that the seismic activity of the French part of this zone is included in the previous Bulletins. The trend of the k values in the period 1996–2004 continues to reveal the previous spike on 15 August 1998.

All these statements considered, the connection between the radio anomaly under study and the August 1998 seismic sequence in the Reatini mountains is reasonable and the following interpretation of the radio anomaly as a precursor can be proposed: a) during the preparatory phase of these earthquakes, an increase of the underground waters in the surface layers of a zone around the epicentres happened, producing a consequent increase of the local surface ground conductivity; b) at the same time, emissions of gases, particles and so on happened in this zone and, as a consequence, variations in some of the parameters of the troposphere, mainly an increase of the refractive index at the surface, occurred. It must be noted that variations in the level of the underground water as well as emission of gases and particles have been observed from long time before the occurrence of earthquakes (Heinicke et al., 1995; King, 1984/1985; King et al., 1995; Kovach et al., 1975; Ouzounov and Freund, 2004; Roeloffs, 1988; Roeloffs and Quilty, 1997; Steinitz et al., 2003; Wakita et al., 1988).

The previous increases of the ground conductivity and of the surface refractive index produced an anomalous zone along the MCO-AS path able to increase the electric field strength of the ground-wave at the AS receiver. As an example, we have tried a quantitative estimation. For the evaluation of the MCO theoretical ground-wave electric field strength at the AS receiver we used the values of the ground conductivity reported on the world Atlas of ground conductivities (CCIR, 1990c). In particular for the MCO-AS path in Italy, 250 km long (Fig. 1), we assumed the ground conductivity equal to 1 mS/m. For the refractive index of the troposphere at the surface of the earth we used the standard value 1.000315 (Rotheram, 1981b). Now, we have repeated the evaluation of the MCO ground-wave electric field strength introducing, in corrispondence with the Reatini mountains area, a radio path (40 km long) with a ground conductivity equal to 10 mS/m and a refractive index of the troposphere at the surface of the earth equal to 1.000600. In such a way, we have obtained for the ground-wave electric field strength at the AS receiver the value 0.80 mV/m, i.e. an increase of about 50% respect the previous value. This increase is representative of the radio anomaly under study.

4 Conclusions

From this study we can infer that the LF (200–300 kHz) radio signals recorded as far as 500–1000 km from the transmitter, contain information related to the ground-wave. In particular, anomalies appearing on this wave could be related to variations in some parameters of the ground and of the troposphere which control the ground wave propagation mode. Such variations can be produced by the processes which take place during the preparatory phase of earthquakes occurring inside the first Fresnel zone of these radio signals.

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