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LF radio anomalies revealed in Italy by the wavelet analysis: Possible preseismic effects during 1997–1998

P.F. Biagi [a,b,*], L. Castellana [a], T. Maggipinto [a], R. Piccolo [a], A. Minafra [a], A. Ermini [c]
S. Martellucci [c], C. Bellecci [c], G. Perna [d], V. Capozzi [d], O.A. Molchanov [e], M. Hayakawa [f]

[a] Department of Physics, University of Bari, Via Amendola, 173-70126 Bari, Italy
[b] Inter-Department Centre for the Evaluation and Mitigation of the Volcanic and Seismic Risk, University of Bari, Italy
[c] Department of Engineering of Enterprise, University of Roma Tor Vergata, Via di Tor Vergata, 00133 Rome, Italy
[d] Department of Biomedical Sciences, University of Foggia, Via L. Pinto-71100 Foggia, Italy
[e] United Institute of the Earth's Physics, Russian Academy of Science, Bolshaya Gruzinskaya 10, 123995 Moscow, Russia
[f] Department of Electronic Engineering, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu City, Tokyo 182-8585, Japan

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Abstract

Since 1996, the electric field strength of the broadcasting station CZE (Czech Republic, $f = 270$ kHz) has been sampled each ten minutes, by a receiver (AS) located in central Italy, 818 km far from the transmitter. Here, we present the results obtained by a detailed analysis applied on the data recorded from February 1996 up to September 2004. At first, we separated the day time data and the night time data in the radio signals; then, in the day time data we separated the data collected in winter from the data collected in summer. Finally, we applied the wavelet analysis on the previous trends. The first result was the appearance of a very clear anomaly during February–March 1998, at winter day time and at night time. This result confirms an anomaly revealed previously in the same data but analysed with a different approach. The anomaly was related to a strong ($M = 5.1$–6.0) seismic sequence occurred in a zone (Slovenia) lying in the middle of the transmitter–receiver path. The present result reinforces the hypothesis of the occurrence of some disturbances in the ionosphere during the preparatory phase of the Slovenia seismic sequence. The second result came from the wavelet analysis applied to the summer day time data and it was the appearance of a very clear anomaly during August–September 1997. On September 26 the Umbria–Marche (central Italy) seismic sequence started with two earthquakes with magnitude $M = 5.6$ and $M = 5.9$ and the seismic activity lasted for more than six months. We consider the August–September 1997 radio anomaly as a precursor of the previous earthquakes and a possible explanation model is proposed.

Keywords: Low frequency; Radio-waves; Wavelet; Anomalies; Precursors

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1. Introduction

In 1995 some of the authors designed and built a receiver, able to measure the electric field strength of LF radio signals at field sites, where the noise is very low. It was planned to sample radio signals used for broadcastings and it was decided to collect data in central Italy. A setting place (AS), that is the mouth of a natural cave located in the central Apennines on the southern slope of the Gran Sasso chain, was located. On the basis of the best reception, the LF broadcasting stations MCO (France, $f = 216$ kHz) and CZE (Czech Republic, $f = 270$ kHz) were selected. On February 1996, the measurements, with a sampling frequency of ten minutes, started. The receiver is located 518 km far from the MCO broadcasting station and 818 km far from the CZE broadcasting station. Fig. 1 shows the location of the transmitters and of the receiver.

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[*] Corresponding author. Address: Department of Physics, University of Bari, Via Amendola, 173-70126 Bari, Italy. Tel.: +390805442343; fax: +390805442434.

E-mail address: biagi@fisica.uniba.it (P.F. Biagi).

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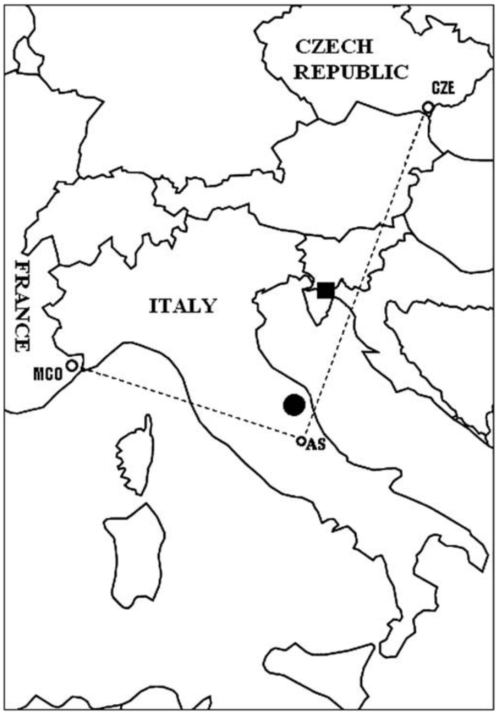

Fig. 1. Map showing the location of the receiver AS and of the two transmitters MCO and CZE. The two radio-paths are indicated by dotted lines. The black square represents the location of the Slovenia seismic sequence. The black circle indicates the location of the $M = 5.6$ and $M = 5.9$ Umbria–Marche earthquakes.

In 2000–2001 some of the authors, studying some parts of the LF data recorded by the AS receiver, revealed some decreases of the radio signals probably related to moderate seismic activity occurred nearby the receiver (Biagi et al., 2001a,b). Then, the whole of the data recorded since January 1997 up to March 2000 was examined (Biagi and Hayakawa, 2002). Firstly, a 7-day high pass filter was applied to the raw data to remove high frequency components and then the long term smoothed trend of the filtered data was determined by a 9th order polynomial fitting. Afterwards, a working file was created as the difference between each filtered set and its polynomial fit. The standard deviation σ over each entire work data set was calculated. Plots of the MCO and CZE radio-signals obtained are shown in Fig. 2. The horizontal dashed lines in each series represent the $\pm 3\sigma$ level. If an anomaly is considered to be a value occurring over 3σ, then from Fig. 2 it is possible to note that: (1) no anomaly appears on the MCO data trend; (2) an anomaly, that is an increase of the order of 6–8 dB, appears on the CZE trend during February–March 1998. At the end of the increase, a strong seismic crisis started in Slovenia ($M = 5.2$, on March 13; $M = 6.0$, on April 12; $M = 5.1$, on May 6), in a zone lying in the middle of the transmitter–receiver path. The location of the Slovenia earthquakes is shown in Fig. 1 and the time occurrence of the first shock is indicated in Fig. 2. The possibility that the CZE increase pointed out in Fig. 2 could be a precursor of the Slovenia seismic activity has been proposed in previous papers (Biagi and Hayakawa, 2002; Biagi et al., 2003).

Now, with a four years longer data set, we have gone over again the CZE data and we have used a more detailed method of analysis.

2. Theoretical computations and data analysis

The LF signals are characterised by the ground-wave and the sky-wave propagation modes. The ground-wave,

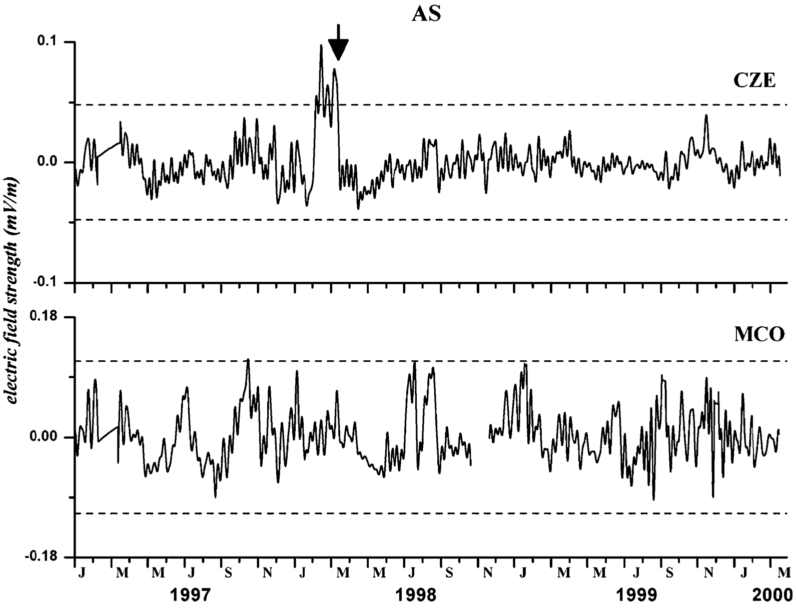

Fig. 2. Difference between the filtered data and smoothed trends of the CZE and MCO radio-signals from January 1, 1997 to March 15, 2000. The dashed horizontal lines represent the $\pm 3\sigma$ level (where σ is the standard deviation). The black arrow represents the occurrence of the first Slovenia earthquake ($M = 5.2$, March 13).

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 from day to night and, at day time, from winter to summer.

At first, we calculated for the CZE radio signal the theoretical electric field strength of the ground-wave propagating over a curved earth with a troposphere whose refractive index varies in an exponential way with the height (Rotehram, 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 CZE-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.

Then we analysed the CZE electric field strength data (ten minutes sampling time). At first, we separated the day time data from the night time ones. In order to obtain both data sets always related to the day time and to night time, regardless of the season, and each set with the same number of data per day, we selected the range from 8.00 a.m. to 1.00 p.m. (UT) for the day time and the range from 8.00 p.m. to 11.00 p.m. (UT) for the night time. This last choice resulted, in addition to the previous conditions, from the fact that the CZE broadcasting station interrupts the transmissions for 3–4 h after midnight (local time = UT + 1 h). Then, in the day time data we separated the data collected in winter (December 21–March 21) from the data collected in summer (June 21–September 21). Fig. 3 shows the night time, day time, winter day time and summer day time trends of the CZE electric field strength from February 1996 up to September 2004. We calculated the mean value for each data set and these values, indicated as horizontal dashed lines in Fig. 3, are reported in Table 1.

Table 1
Experimental (Exp) and Theoretical (Theo) values of the electric field strength (mV/m) for the CZE radio signal

	Experimental value	Theoretical value
Sky wave		
Day time		
Winter	0.31	0.40
Summer	0.21	0.02
Night time	1.49	1.60
Ground wave		0.22

Then, since the statistical characteristics of the signals 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 signal in both time and frequency simultaneously. A picture, the spectrogram, showing both the amplitude of the signal versus the wavelet

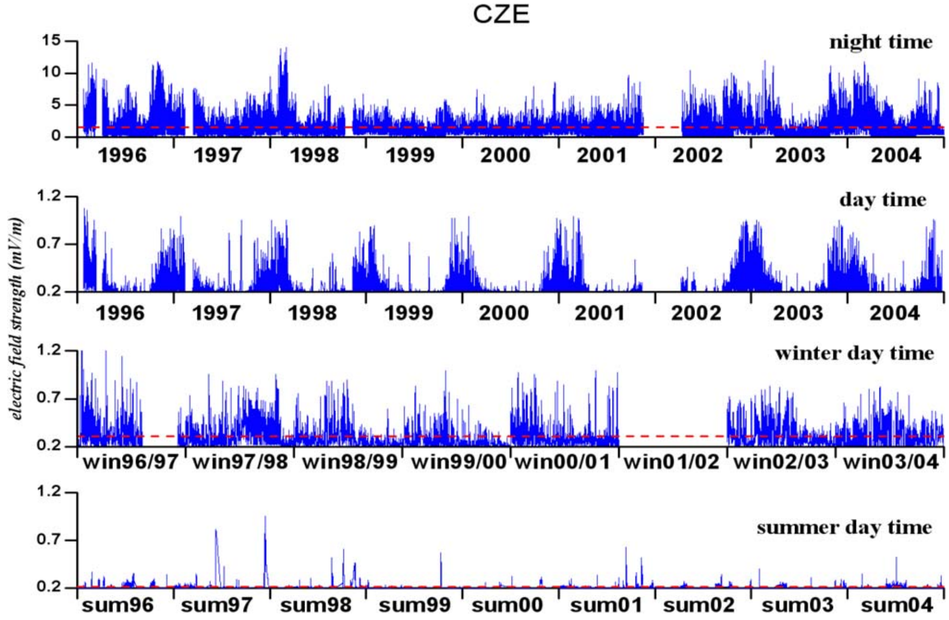

Fig. 3. From the top reading downwards, the CZE electric field strength at night time (8.00–11.00 p.m., UT), at day time (8.00 a.m.–1.00 p.m., UT), at winter day time and at summer day time, from February 1996 to September 2004. The dashed horizontal lines represent the mean values of the relative data set (Table 1). The gaps in the trends correspond to interruptions in the data collection.

scale and the dependence between amplitude and time can be drawn (Daubechies, 1992; Strang and Nguye, 1996). In our analysis we have considered the "Morlet function" as wavelet function (Torrence and Compo, 1998), and we have plotted in Fig. 4 and in Fig. 5 the wavelet power spectrum normalized with respect to the power of the white

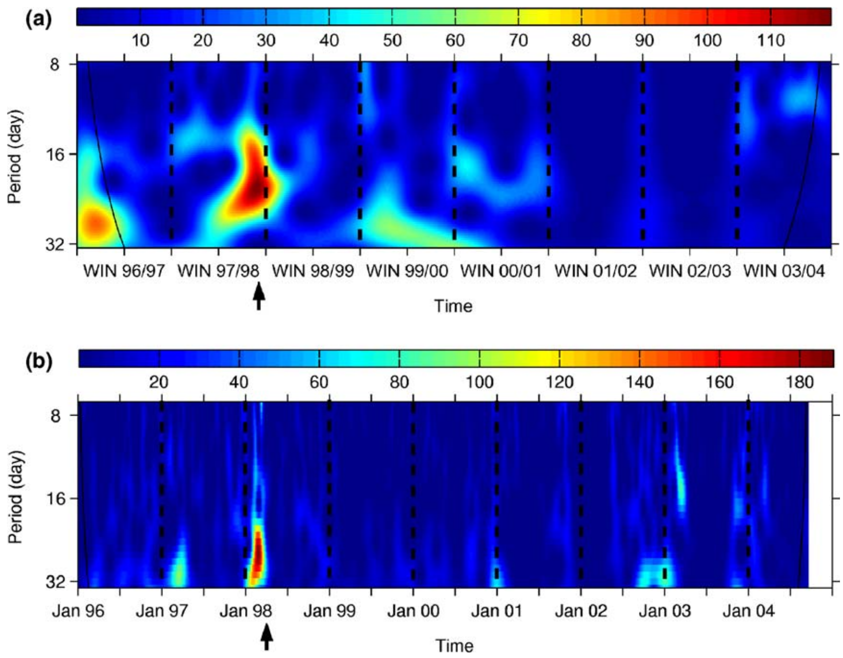

Fig. 4. Normalized wavelet power spectrum from February 1996 to September 2004 of the CZE electric field strength in the range 16–64 days at: (a) winter day time, (b) night time. The left axis is the Fourier period (in day), the bottom axis is time. For each panel wavelet power level (arbitrary scale) is represented with a colour scale from dark blue to dark red. The black arrow in each plot represents the time occurrence of the first Slovenia earthquake ($M = 5.2$, March 13.) (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

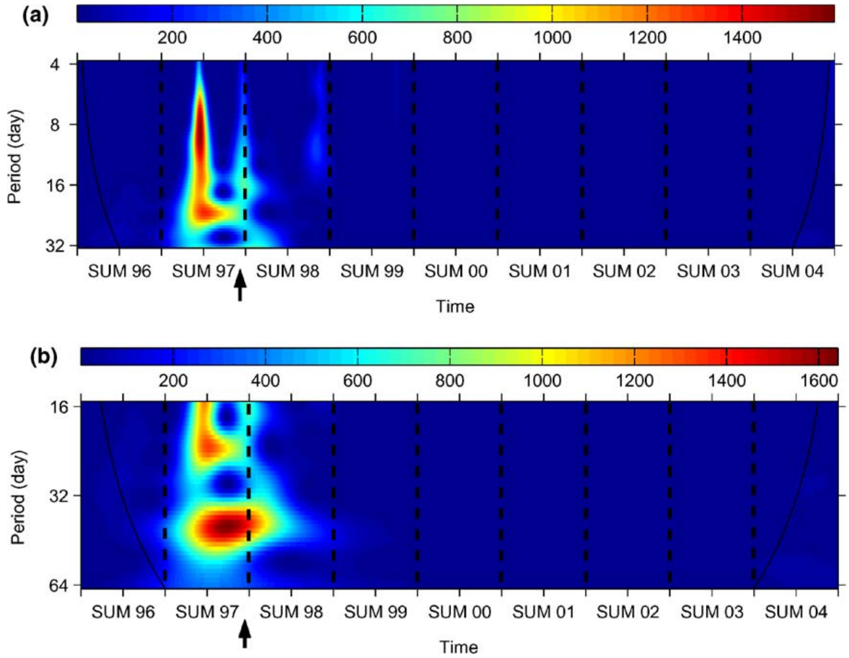

Fig. 5. Normalized wavelet power spectrum from February 1996 to September 2004 of the CZE electric field strength in the range 4–32 days at the top (a) and 16–64 days at the bottom (b). In each plot the left axis is the Fourier period (in day), the bottom axis is time. For each panel wavelet power level (arbitrary scale) is represented with a colour scale from dark blue to dark red. The black arrow represents the time occurrence of the two earthquakes ($M = 5.6$ and $M = 5.9$) happened on September 26, 1997 in the Umbria–Marche. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

noise. The main results of this analysis are: (a) at night time and at winter day time, a clear anomaly, that is a strong exaltation of the components with period in the 18–30 days range, appears during February–March 1998 as it is shown in Fig. 4(a) and (b); (b) at summer day time, a clear anomaly, that is an exaltation of the components with period in the 6–50 days range stands up during August–September 1997 as it shown in Fig. 5.

In the same way, the data of the other (MCO) radio signal were analysed too. The results of this study are published by now (Biagi et al., 2005) and here it must be mentioned only that the previous anomalies do not appear in the MCO electric field strength data.

3. Discussion

From the Table 1 and taking into account that our receiver has an instrumental zero equal to 0.20 mV/m, the following statements can be made: (1) the ground wave has a theoretical value near the instrumental zero of our receiver so that the recording of the ground wave at our receiver is generally doubtful; (2) the sky wave at night time and at winter day time has values clearly over the instrumental zero which can be recorded by our receiver and in these cases the agreement between theoretical and experimental values is excellent; (3) the sky wave at summer day time has a value (ten times lesser than the instrumental zero) that surely cannot be recorded by our receiver.

Now, let us examine the anomalies pointed out in the previous session.

The anomaly at the item (a) of the previous session confirms the increase pointed out in the study we summarized in the introduction. This anomaly appears at winter time and it is clear both in the day time data and in the night time ones. So, on the basis of the previous statements, the anomaly is related to the sky wave and indicates an exalting of its intensity. According to the wave hop theory this exalting might be explained by a 2–3 times increase of the reflection coefficient of the ionosphere in a zone lying in the middle of the transmitter–receiver path. This increase should be connected with the emission of radon, ions, electromagnetic waves, etc. (Biagi and Hayakawa, 2002; Hayakawa et al., 1996; Morgounov et al., 1994) from the focal zone of the forthcoming Slovenia earthquakes.

The anomaly at the item (b) of the previous session is a new result pointed out in this study. This anomaly, revealed by the wavelet analysis, is related to the appearance of the two large signals with a duration of 10–20 days, evident in the trend at the bottom of the Fig. 3 during the summer 1997. The first enhancement starts on July 30 and the second one on September 14. These enhancements are characterised mainly by values of 0.6 mV/m, with some spikes up to 0.8 mV/m. Looking at the summer day time trend, it is possible to note the presence of other signals similar to the previous ones, but with lesser amplitude and lesser time duration. These last ones are related to summer storms (lightings) as we checked by the data of a local meteorological station. Then the anomalous signals are responsible of a clear exalting in the amplitude spectrum (Fig. 5) while no effect on the spectrum is produced by the other ones. So, according to our opinion, the anomaly under study is related to CZE radio signal increase. Taking into account that the anomaly appears at summer and only at day time, from the previous statements the sky wave cannot be involved. We propose that the anomaly is related to an increase of the ground-wave propagation mode. In fact, such an increase could produce an electric field strength recordable clearly at day time during the summer. At night time the ground wave is superimposed to the sky wave, that it is more intense, and some interference process could drop the increase of the total electric field strength; so, no anomaly could be revealed at night time.

Now, it must be noted that the previous anomaly occurred during the two months before the two earthquakes ($M = 5.6$ and $M = 5.9$) happened on September 26, 1997 in the Umbria–Marche (central Italy) region. Their location is indicated in Fig. 1. These earthquakes started an intense seismic sequence lasting more than six months. So, the possibility that the radio anomaly is a precursor of the Umbria–Marche seismic sequence can be considered.

The theoretical electric field strength of the CZE ground wave at the AS receiver is 0.22 mV/m (Table 1) and, as previously specified, the ground wave is generally not clearly recorded by our equipment. If the ground-wave electric field strength would increase three–four times, its value, being over the instrumental zero, should be clearly recorded by our receiver and the anomalous signals responsible of the anomaly under study could be justified.

At first we have tried the following model. 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. Anyway, the most influent parameters are the conductivity of the ground and the refractive index of the troposphere. 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 composition of the air and it changes when variations, also small ones, in this composition happen.To evaluate the CZE 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, 1990b). In particular for the CZE-AS path in Italy, 75 km long (Fig. 1), we assumed the ground conductivity equal to 3 mS/m. For the refractive index of the troposphere at the surface of the earth we used the standard value 1.000315 (Rotehram, 1981b). In the attempt to increase the ground-wave value, we have repeated the evaluation of the CZE ground-wave electric field strength using the value

30 mS/m for the ground conductivity in the Italian part of the path and increasing up to 1.000600 the value of the refractive index of the troposphere at the surface of the earth in the same part of the radio path. An increase of the underground waters in the surface layers and the emissions of gases, particles and so on (atmosphere–lithosphere coupling) in a wide zone during the preparatory phase of the Umbria–Marche seismic sequence, could justify the changes adopted for the previous parameters. Greater increases of the values are not realistic ones. We have obtained for the ground-wave electric field strength at the AS receiver the value 0.34 mV/m, i.e. an increase of about one half with respect to the normal value. So, the ground wave becomes clearly recordable at AS receiver, but its intensity remains one-two times lesser than the intensity of the signals responsible of the anomaly under study.

Then, we have tried another model. The ground-wave propagation of a radio signal can be affected by irregularities (ducts, reflecting layers, scattering zones and so on) in the troposphere. If we assume the formation of a tropospheric reflecting layer (CCIR, 1990c; Rue, 1987) or a tropospheric duct (CCIR, 1990c; Crane, 1981) in the zone of the Umbria–Marche earthquakes, as a consequence of emissions of gases, particles and so on, during the preparatory phase of the quoted earthquakes, then reflected rays can arrive in the different zones and they can intersect each others producing interference. As a consequence, in the constructive interference areas the radio signal level is very high, while in the destructive interference areas (radio holes) the radio signal level is very low. If we assume the formation of an area of constructive interference nearby the AS receiver, the large CZE signals responsible of the anomaly under study can be justified.It must be noted that the absence of a concurrent similar effect on the MCO data (Biagi et al., 2005) can be justified by the lacking of such an area nearby the AS receiver for the MCO radio signal.

According to our opinion the last previous model alone or both the models together can be considered to justify the anomaly under study.

4. Conclusions

From this study we can infer that the LF radio signals contain two different types of information: one related to the sky wave and the other one related to the ground wave. In particular: (a) preseismic anomalies appearing mainly on the sky wave seem to be related to disturbances in the ionosphere; (b) preseismic anomalies appearing mainly on the ground wave seem to be related to disturbances in the ground and/or in the troposphere. In any case an atmosphere–lithosphere coupling must be claimed to justify the radio anomaly related to the earthquakes.

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