Bitlis Eren Univ J Sci &
Technol
5 (1), 18 - 23, 2015

E - ISSN 2146-7706

Research Article

Precursory Anomaly in VLF/LF Recordings Prior to the Çaglayan (Erzincan-Turkey) Earthquake on July 30th, 2009

Aydın Büyüksaraç [1*], Ali Pınar [2], Sinan Koşaroğlu [3]

[1] *Bitlis Eren University, Department of Civil Engineering, TR-13000 Bitlis, Turkey*
[2] *Boğaziçi University, Kandilli Observatory and ERI, Çengelköy, TR-34684 İstanbul, Turkey*
[3] *Cumhuriyet University, Department of Geophysical Engineering, TR-58140 Sivas, Turkey*
[*] *Corresponding author: abuyuksarac@beu.edu.tr*

Abstract

An international project network consisting of six receivers for sampling LF and VLF radio signals has been going on to record the data in Europe from different transmission stations around the World. One of them was established in Resadiye, Turkey, located just on the North Anatolian Fault Zone. The receiver works in VLF and LF bands monitoring ten frequencies (16.4, 21.75, 37.5, 45.9, 153, 180, 183, 216 and 270 kHz) with one minute sampling interval.

An earthquake of Mw = 4.9 took place 225 km away from the VLF/LF station at the eastern tip of the Erzincan basin at 4 km depth on July 30, 2009. We observed some anomalies on the radio signals (37.5 and 153 kHz) that initiated about 7 days before the earthquake and disappeared soon after the earthquake. We attribute this anomaly to the Mw=4.9 earthquake as a seismo-electromagnetic precursor. The radio anomaly that appeared 7 days before the occurrence of the 2009 Caglayan (Erzincan) earthquake is in good agreement with other results indicating precursory anomalies in the project network mostly observed in seismically active countries such as Italy and Greece.

Keywords: Earthquake precursors, VLF/LF, Erzincan, Resadiye, NAFZ.

1. Introduction

Turkey is located on a seismically active area and has numerous big scale earthquakes due to the relative movements of Eurasian Plate, African Plate and Arabian Plate. Main sources of seismic activity in Turkey are North Anatolian Fault system, one of the most seismically active right-lateral strike slip faults in the world, the East Anatolian Fault, an active left-lateral strike slip fault which extends from Antakya to Karlıova, and the Western Turkey Graben Complex, an area of intense seismic activity which is related to the graben complexes in the Aegean region. Turkey has suffered significant losses of life and property due to earthquakes. There have been nearly 100 large earthquakes since 1900, 14 with casualties more than 10.000 with magnitudes M>7.0 in Turkey. Each year an average of around 800 people died as a result of those earthquakes during the period between 1903 and 1999. The latest destructive two earthquakes were in 1999 and totally around 30.000 people were killed by the earthquakes in Gölcük (M=7.4) and Kaynaşlı (M=7.2).

Since the short term earthquake prediction studies are to be effective in saving the life of people rather than reducing the damage such studies is to play vital role in countries such as Turkey where the rate of loss of life is high.

Earthquake prediction can be evaluated in three terms; Long Term (a few hundred years), Medium Term (hundreds to a few years) and Short Term (a few months to a few days). However, Short-term earthquake prediction is of essential importance for people beings in order to mitigate the earthquake disasters. The detection of ionospheric perturbations associated with earthquakes, seems to be very promising for short-term earthquake prediction because the ionosphere is very sensitive to seismic effects (Hayakawa 2007).

We have proposed a possible use of VLF (very low frequency, 3-30 kHz) / LF (low frequency, 30-300 kHz) radio sounding of the seismo-ionospheric perturbations. The anomalous electric field in the ionosphere emerge before the main seismic shock and it can be considered as ionospheric precursors (Pulinets & Boyarchuk 2004).

Rozhnoi et al. (2004) have studied the percentage occurrence of anomalous days for different conventional earthquake magnitudes. After examining different effects (solar flares, geomagnetic storms etc.), they have succeeded detecting the seismic effect in subionospheric VLF/LF propagation when the earthquake magnitude exceeds 5.5.

For many years, research on the interaction between seismic activity and disturbances in radiobroadcasts has been carried out. Recently, pre-seismic disturbances in the Omega and Loran radio waves, which lie in the VLF (3–30 kHz) frequency band, have been presented (Gokhberg et al. 1989; Hayakawa & Sato 1994; Morgounov et al. 1994; Hayakawa et al. 1996; Molchanov & 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 the strong earthquakes.

Received 24 February 2015
Available online June 2015

Since 1996, the electric field strength of LF (150–300 kHz) broadcasting stations is sampled by receivers located in central Italy. Decrease in 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 small (M=3.0–3.5) earthquakes located nearby the receivers (Bella et al. 1998; Biagi et al. 2001a, b).

The existence of the ionospheric anomalies /ionospheric precursors is well established not only by physical modeling but statistically as well (Pulinets et al. 2002; Liu et al. 2004; Chen et al. 2004). For the ionospheric precursors of earthquakes, both approaches are used. One way is to track the specific ionosphere parameters trying to detect the recently revealed main features of the ionospheric precursor (Pulinets et al. 2003). The other way is to use the statistically established behaviour of some parameter (for example, the critical frequency foF2) as a signature of the impending earthquake (Pulinets et al. 2002). Both approaches have their advantages as well as their drawbacks. The first method could fail in magnetically disturbed conditions, while the second requires an a priori knowledge of the precursor behaviour, which must be acquired through many years of observations.

2. Data collection and measurement network

An international cooperation attending six countries to study earthquake precursors was planned. The network started to operate in March 2009. The data are collected separately by different teams (Biagi et al. 2011). The data centre is at the Department of Physics of the University of Bari, which is headquartering of the network.

A radio receiver, made by the factory Elettronika (Palo del Colle, Bari, Italy), is shown in Fig. 1a, b. The equipment is powered through AC power supply. It works in VLF (20–50 kHz) and LF (150–300 kHz) bands monitoring ten frequencies distributed in these bands (Fig. 2); for each of them, the apparatus saves the power level detected on a non-volatile memory at a customizable sampling time interval. The receiver is connected to two different antennas with the corresponding preamplifier located near the relative antenna. The preamplifier converts low impedance to the high impedance of the low-frequency antennas and to amplify the captured signal level introducing very low noise. The huge amount of data collected by the receiver is organized in text files, one for each day (Biagi et al. 2010).

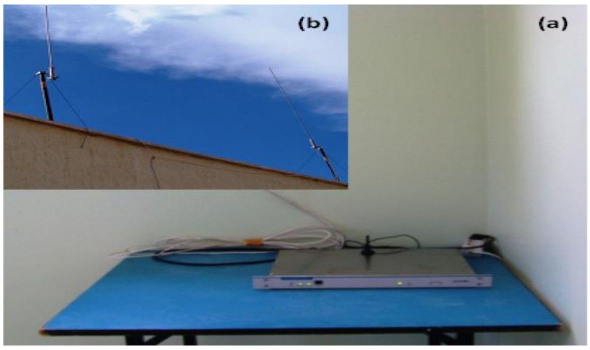

Figure 1. (a) The radio receiver in Turkey, made by the factory Elettronika (Palo del Colle, Bari, Italy) and **(b)** the antennas with the corresponding preamplifier.

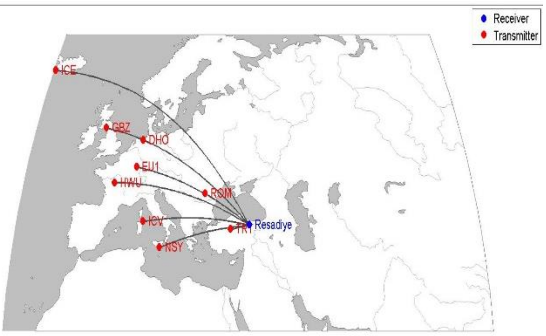

Figure 2. Map of VLF/LF transmitters and place of receiver, Resadiye in Turkey. Lines show the wavepaths. **JXN**: 16.4 kHz (Helgeland, Norway), **HWU**: 21.75 kHz (LeBlanc, France), **DHO**: 23.4 kHz (Rhauderfehn, Germany), **ICE**: 37.5 kHz (Keflavik, Iceland), **NSY**: 45.9 kHz (Niscemi, Norway), **ROM**: 153 kHz (Brashov, Romania), **TRT**: 180 kHz (Polatlı, Turkey), **EU1**: 183 kHz (Felsberg, Germany), **MCO**: 216 kHz (Roumelous, France), **CZE**: 270 kHz (Topolna, Czech Republic)

3. Data processing applied to the LF/VLF records

The Çağlayan earthquake (Mw=4.9) occurred near Erzincan city, East Anatolia on 30 July 2009 (GMT 10:37:49) (Fig. 3).

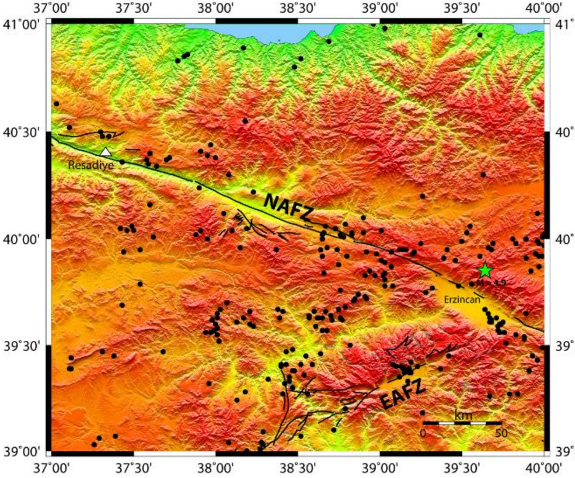

Figure 3. The Caglayan earthquake (Mw=4.9) occurred on 30 July 2009 (GMT 10:37:49) and place of Resadiye VLF/LF station. The black circles show earthquake epicentres M≥3.0 around Resadiye and Erzincan. The biggest magnitude was 4.9 between March 2009 and December 2010. NAFZ: North Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone.

That has the largest earthquake during registration period since March 2009. The area is seismically very active and the epicentre of the first major earthquake (M=7.9) of a series of eight M>7 events during 1939-1999, was the province of Erzincan at 01:57 am (GMT 11:57 pm) on December 27, 1939. 32,962 people had been killed by this earthquake. The last killing earthquake (M=6.9) in Erzincan was in 1992 where the loss of life was 450.

Observing different signal phases on different frequency components of the radio signals (VLF and LF) that emerged a week before the earthquake on 30 July 2009 made us investigate any possible relation between the event and the phases (Fig. 4a and b). Several data processing stages were applied to the VLF and LF data.

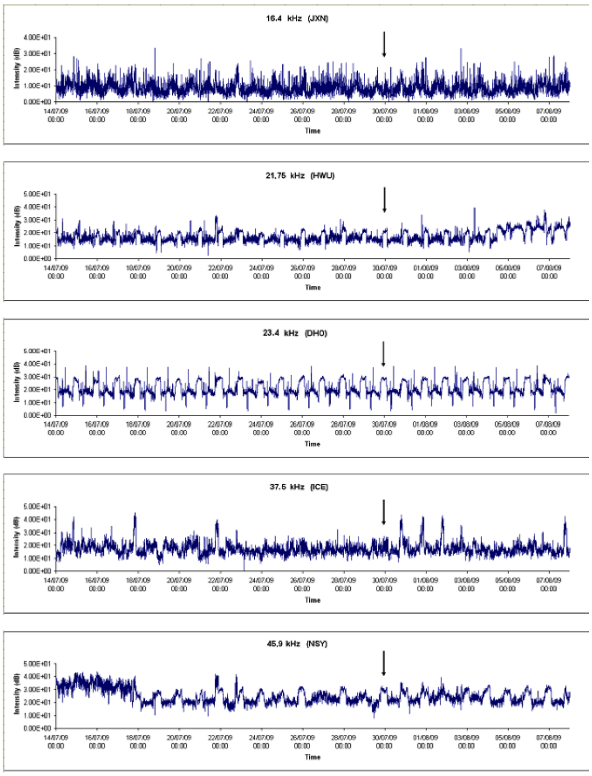

Figure 4. Time series of recordings **(a)** VLF recording in 5 frequency. Arrows show the earthquake date.

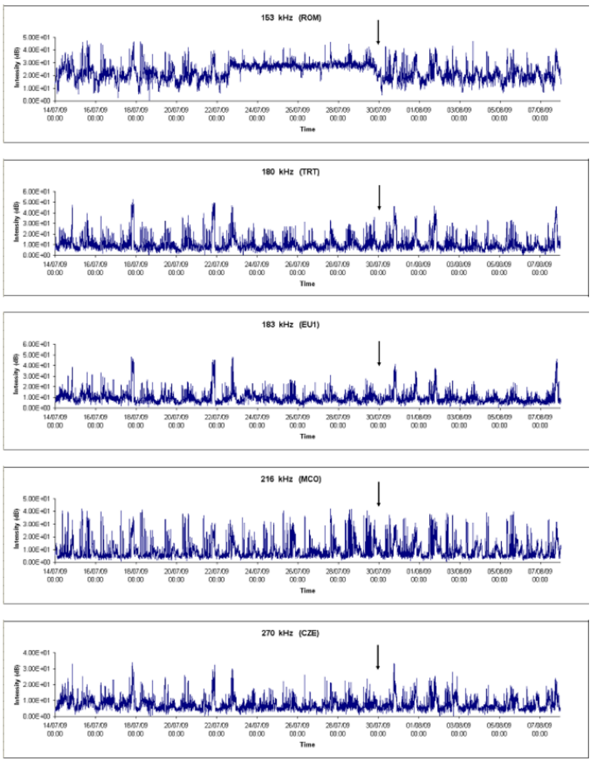

Figure 4. Time series of recordings **(b)** LF recording in 5 frequency. Arrows show the earthquake date.

Firstly, we processed the time series of the radio signals to understand how the frequency content of the anomaly differs from that of the normal trend. For this purpose we selected two time windows; one covering the anomaly period and the other spanning a normal period. The selected time window length was a 6 day. The sampling interval and the length of the time window limit the observed spectra from 120 seconds to six days. We identified a significant bias (drop) for the signal energy of the anomaly period at the whole frequency band.

Secondly, in order to clearly depict the anomaly we estimated the daily Rayleigh Energy of the calculated spectra following the Parseval's theorem (Fig. 5).

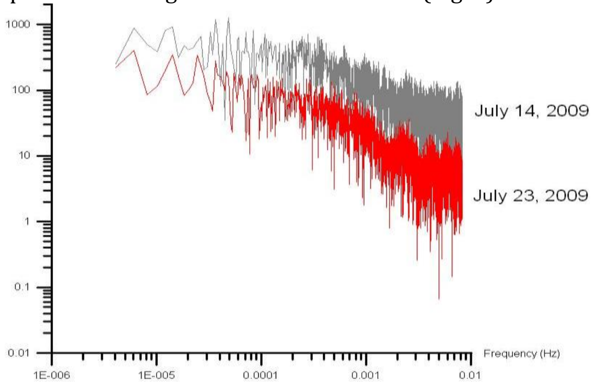

Figure 5. Rayleigh Energy of the calculated spectra.

We initiated the estimations well before the anomaly period. Such calculations gave an obvious sign for the impending event (Table 1).

Table 1. Rayleigh Energy of the calculated spectra

Event	Moment Mag. (Mw)	Seismic Moment (Mo)	Standard Deviation of Mo (std Mo)	Corner Freq (fc)	Standard Deviation of fc (std fc)
30.07.2009 07:37	4.9	0.264^{24}	0.496^{23}	0.9	0.10
Brune stress= 41.7			Brune energy = 0.146E+13 Joul		

Thirdly, we constructed a spectrogram including the whole frequency band of the data from fortnight before the earthquake to a week after the earthquake. The strongest anomaly in the spectrogram was identified for the periods larger than 60 hours (Fig. 6).

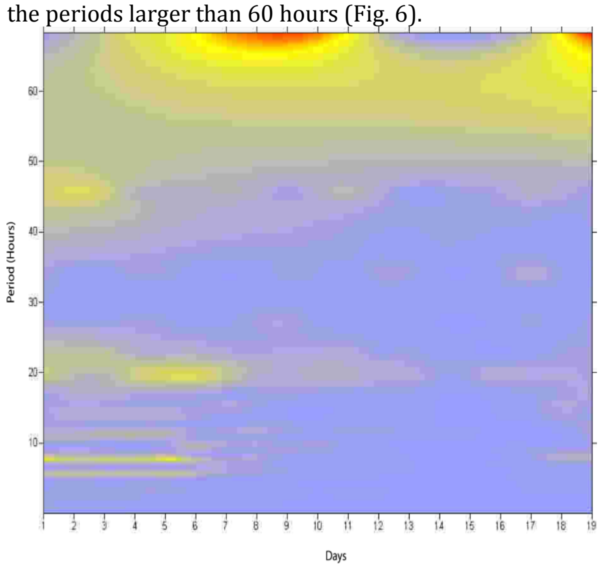

Figure 6. A spectrogram estimated from the VLF/LF data.

4. The source parameters of the Çağlayan (Erzincan) Earthquake on July 30th ,2009 (Mw=4.9)

In earthquake prediction studies it is good to understand the source of an anomaly recorded by an observation system. We generally consider that the likely sources of the anomalies we are interested in are the earthquakes; therefore, it is essential to derive information on the properties of the earthquake that generated the anomaly we observed in the radio signals. Within this frame, we analyzed the broadband data at several local seismic stations that recorded the event and estimated its source parameters such as centroid moment tensor, source radius and stress drop. To retrieve the kinematic source parameters of the earthquake we used the method developed by Kuge (2003) which is based on waveform modelling of displacement seismograms at one or more stations at local distances. In the method a centroid location can be searched for in a 3D-grid scheme by achieving the best fit between observed and synthetic displacement seismograms. Our analysis of the broadband records of the July 30th, 2009 event shows that the event took place at shallow depth showing predominantly normal faulting mechanism and was associated with extremely high stress drop with an average value of about 250 bars.

We estimated the stress drop through modelling the source spectra. The source spectrum of the seismic ground motion is characterized by 3 parameters: 1) the low frequency level, proportional to seismic moment; 2) the corner frequency, proportional to the source size; 3) the power of high-frequency asymptote. Each region of a spectrum is related with a different source parameter. There are various source models that relate the spectral parameters to the source parameters. In this study the Brune's source model was used (Brune 1970). It can be summarized in the following way:

1.The seismic moment is determined from the flat portion of the spectra at low frequency asymptote using the eq. (1)

$$Mo = 4\pi\rho V^3 R\Omega_0 / R_\theta \qquad (1)$$

where ρ is the density at the source region, V is the velocity at the source region, R is the hypocentral distance, Ω_0 is the low frequency asymptote, and R_θ is radiation pattern determined from the mechanism of an earthquake.

2. The corner frequency f_c, which marks the boundary between the low and high frequency regions, is related with the size of an earthquake source and decreases with increasing seismic moment value, Mo. The source radius, r, is given by Eq. (2)

$$r = \frac{2.34V}{\pi f_c} \qquad (2)$$

Following Hanks & Wyss (1972) corrections to the observed seismic spectra were made to get the source spectra at each station. Then, using the Brune (1970) source model, the source parameters were obtained through non-linear fitting of the observed and calculated spectra (Ambeh & Fairhead 1991). The theoretical curve of a spectrum was calculated from the following relation (Eq.3):

$$S(f) = \frac{\Omega_0}{[1+(f/f_c)^2]^{\gamma/2}} \qquad (3)$$

Where γ is a constant that controls the high-frequency decay of the spectrum.

5. Discussions and conclusions

When we record an anomaly and attribute it to a specific earthquake we need to determine the kinematic and dynamic source parameters of the earthquake so as to understand whether some specific source parameters are causatives for an anomaly on the radio signals. Thus, we are to establish a series of anomaly-earthquake pairs. Such pairs may provide clues on the sources of the observed anomalies on the radio signals. In this frame, we have recorded the first anomaly since the installation of the Resadiye station. We attributed it as a precursor before the July 30th 2009 earthquake (Mw=4.9) which took place 225 km to the east of the station. We analysed the broadband waveform records at several nearby seismic stations to derive the kinematic and dynamic source parameters of the event. The moment tensor inversion analysis yield results showing predominantly normal faulting event at shallow depth of 4 km located at the eastern side of the Erzincan basin. On the other hand, the source spectrum modelling suggests a source model with a radius around 800 m and relative high stress drop (Fig. 7).

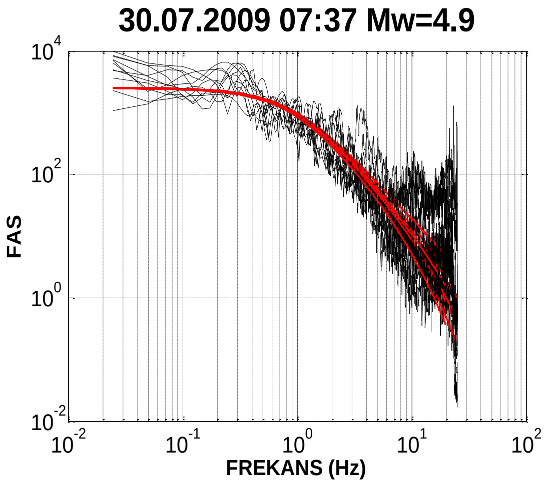

Figure 7. A Brune (1970) source spectrum model for the July 30th, 2009 event.

The energy loss during the anomaly period is observed at the whole frequency range as observed in the Fourier amplitude spectrum shown in Fig. 7. The significance of such an energy loss is that the anomaly initiated about a week before the earthquake which corresponds to the minimum frequency in the observed spectrum. On the other hand, the anomaly was not a piece wise continuous but rather it was a steady continuous signal that was apparent during the whole anomaly period covering the time range from the whole observing period to the sampling interval time.

On the contrary of the amplitude spectrum, the spectrogram shown in Fig. 6 suggests that the signal is not so homogeneous at the whole frequency band but rather it is stronger at some certain frequencies. The spectrogram shows that the signal at periods larger than 60 hours is obvious but is missing or weak at lower periods.

The anomaly before the earthquake was shown only in two frequencies, 37.5 kHz and 153 kHz. Changes before the earthquake were started on the data one week ago. Amplitude of the signals was lower during the anomaly period on both frequencies (Fig. 8).

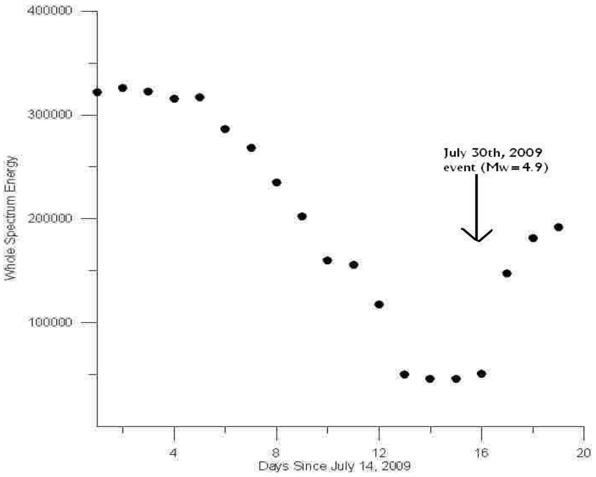

Figure 8. Rayleigh Energy of the calculated spectra estimated according to Parseval's rule.

However, we checked the other receivers near Turkey such as Greece, Romania, Italy to correlate if our records were anomaly due to seismo-electric effect or a kind error belong to transmitter. The receiver in Romania was off the record. But the receivers in Italy and Greece had the records for the same period with Turkey. When we looked at the records there was no anomaly on the frequencies 37.5 kHz and 153 kHz or the other frequencies before the Çağlayan earthquake (Fig. 9). It means precursor anomalies were happen on the frequencies 37.5 kHz and 153 kHz before the Çağlayan earthquake.

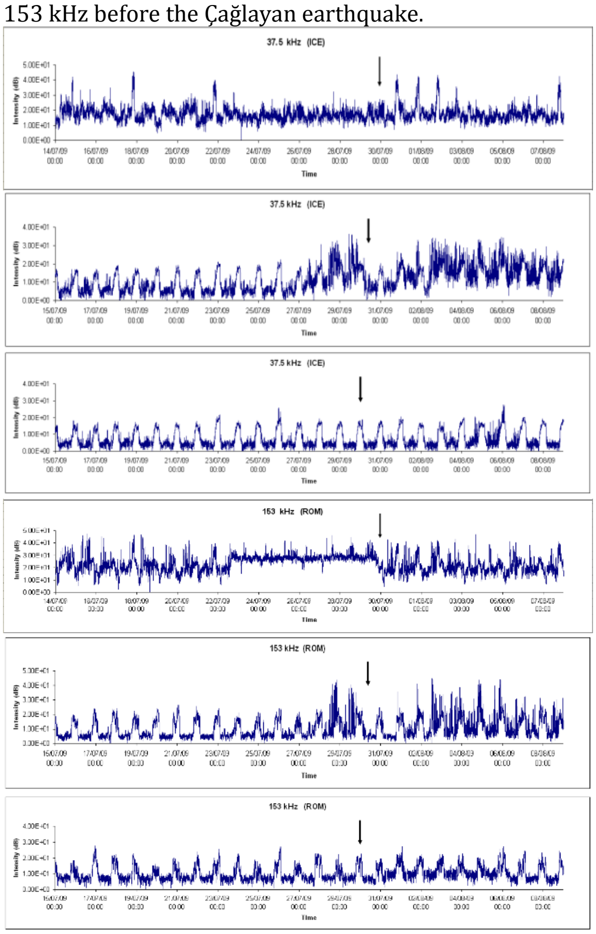

Figure 9. Comparison of the records on the frequencies 37.5 kHz and 153 kHz recorded by the receivers in Italy and Greece. Arrows show the earthquake date.

Acknowledgements

This research was realised by the equipment VLF/LF Band Receiver manufactured by the factory Elettronika in Italy. It was donated by Bari University, Physics Department.

References

Ambeh WB, Fairhead JD (1991). Spectral characteristics and source parameters of micro earthquakes from the Mt Cameroon volcanic region, West Africa. Geophys. J. Int. 106, 229–237.

Bella F, Biagi PF, Caputo M, Cozzi E, Della Monica G, Ermini A, Plastino W, Sgrigna V (1998). Field strength variations of LF radio waves prior to earthquakes in Central Italy. Phys. Earth Planet. Int. 105, 279–286.

Biagi PF, Piccolo R, Ermini A, Martellucci S, Bellecci C, Hayakawa M, Capozzi V, Kingsley SP (2001). Possible earthquake precursors revealed by LF radio signals. Nat. Hazards Earth Syst. Sci. 1, 9-14.

Biagi PF, Castellana L, Maggipinto T, Loiacono D, Schiavulli L, Ligonzo T, Fiore M, Suciu E, Ermini A (2010). A pre seismic radio anomaly revealed in the area where the Abruzzo earthquake (M=6.3) occurred on 6 April 2009. Nat. Hazards Earth Syst. Sci. 10, 215–216.

Biagi PF, Maggipinto T, Righetti F, Loiacono D, Schiavulli L, Ligonzo T, Ermini A, Moldovan IA, Moldovan AS, Buyuksarac A, Silva HG, Bezzeghoud M, Contadakis ME (2011). The European VLF/LF radio network to search for earthquake precursors: setting up and natural/man-made disturbances. Nat. Hazards Earth Syst. Sci. 11, 333–341.

Brune JN (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes. J. Geophy. Res. 75, 4997–5010.

Chen YI, Liu JY, Tsai YB, Chen CS (2004). Statistical tests for pre-earthquake ionospheric anomaly. Terr. Atm. Ocean Sci. 15, 385–396.

Gokhberg MB, Gufeld IL, Rozhnoy AA, Marenko VF, Yampolsky VS, Ponomarev EA (1989). Study of the seismic influence on the ionosphere by super long-wave probing of the Earth-ionosphere waveguide. Phys. Earth Planet. Inter. 57, 4–67

Hanks TC, Wyss M (1972). The use of body wave spectra in the determination of seismic source parameters. Bull. Seism. Soc. Am. 62, 561-589.

Hayakawa M, Sato H (1994). Ionospheric perturbations associated with earthquakes, as detected by subionospheric VLF propagation, in: Electromagnetic Phenomena Related to Earthquake Prediction, (Eds) Hayakawa, M. and Fujinawa, Y., Terrapub, Tokyo, 391–397.

Hayakawa M, Molchanov OA, Ondoh T, Kawai E (1996). Anomalies in the subionospheric VLF signals for the 1995 Hyogo-ken earthquake. J. Phys. Earth 44, 413–418.

Hayakawa M (2007). VLF/LF Radio Sounding of Ionospheric Perturbations Associated with Earthquakes. Sensors 7, 1141-1158.

Kuge K (2003). Source modeling using strong-motion waveforms: Toward automated determination of earthquake fault planes and moment-release distributions. Bull. Seismo. Soc. Amer. 93, 639-654.

Liu JY, Chuo YJ, Shan SJ, Tsai YB, Pulinets SA, Yu SB (2004). Pre-earthquake ionospheric anomalies monitored by GPS TEC. Ann. Geophys. 22, 1585–1593.

Molchanov OA, Hayakawa M (1998). Subionospheric VLF signal perturbations possibly related to earthquakes. J. Geophys. Res. 103, 17489-17504.

Morgounov VA, Ondoh T, Nagai S (1994). Anomalous variation of VLF signals associated with strong earthquakes (M≥7.0), in: Electromagnetic Phenomena Related to Earthquake Prediction, (Eds) Hayakawa, M. and Fujinawa, Y., Terrapub, Tokyo, ISBN: 4887041136,9784887041134.

Pulinets SA, Boyarchuk KA, Lomonosov AM, Khegai VV, Liu JY (2002). Ionospheric precursors to earthquakes: a preliminary analysis of the foF2 critical frequencies at Chung-Li ground-based station for vertical sounding of the ionosphere (Taiwan island). Geomag. and Aeron.42, 508–513.

Pulinets SA, Legenka AD (2003). Spatial-temporal characteristics of the large scale disturbances of electron concentration observed in the F-region of the ionosphere before strong earthquakes. Cosm. Res. 41, 221–229.

Pulinets SA, Boyarchuk KA (2004). Ionospheric Precursors of Earthquakes, Springer, Berlin, ISBN: 978-3-540-20839-6.

Rozhnoi A, Solovieva MS, Molchanov OA, Hayakawa M (2004). Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions. Phys. Chem. Earth. 29, 589–598.