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The INFREP Network: Present Situation and Recent Results

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Abstract

VLF/LF (20 - 300 kHz) radio waves propagation is affected by different factors such as meteorological conditions, solar bursts and geomagnetic activity. At the same time, variations of some parameters in the ground, in the atmosphere and in the ionosphere occurring during the preparatory phase of earthquakes can produce disturbances in the propagation of the previous signals along their radio paths: these disturbances are the radio precursors. Since 2009, several VLF/LF radio receivers have been installed throughout Europe in order to realize a European (VLF/LF) radio network for studying the VLF/LF radio precursors of earthquakes, called the INFREP network. In this paper, at first the description of the present situation of the INFREP network is presented, that is: the location of the receivers, the location of the VLF/LF transmitters whose signal is sampled, the daily download of the data collected by the receivers on the INFREP server and the method of data analysis used in order to individuate possible radio precursors. Then the results obtained on the occasion of recent (2016-2017) seismic activities which occurred in the "sensitive" zone of the INFREP network are presented. The first case examined is the October 30, 2016 earthquake with M_w = 6.5, which occurred in Central Italy, near Norcia small town; this earthquake was preceded by a strong shock (M_w = 5.9) which occurred 4 days before. The second case presented is the strong (M_w = 6.7) offshore earthquake which occurred on July 20, 2017, near the coast of Turkey and Kos island (Greece) and the third case is the August 8, 2017 earthquake with M_w = 5.0, which also occurred near the coast of Turkey and Kos island (Greece). In all the previous cases radio anomalies were revealed in some radio signals collected by the receiver located in Cyprus. The influence of causes different from seismicity as geomagnetic activity and solar burst, meteorological conditions, malfunction of the receiver and/or the transmitters has been examined and none convincing connections appeared. So, the possibility that the previous anomalies are radio precursors of the earthquakes seems realistic. Finally, some discrepancy of some of these anomalies with respect to the general peculiarities of the radio precursors is presented and discussed.

Keywords

Earthquakes, VLF/LF Radio-Waves, Precursors

1. Introduction

The VLF radio signals lie in the 20 - 80 kHz frequency band. These radio signals are used for worldwide navigation support, time signals and for military purposes. The LF radio signals lie in 150 - 300 kHz frequency band and are used for long way broadcasting by few (this type of broadcasting is going into disuse) transmitters located all over the world. The VLF signals propagate in the earth-ionosphere wave-guide mode along great circle propagation paths. The LF signals are characterized by a ground-wave and a sky-wave propagation mode. The first one generates a signal that propagates in the channel ground-troposphere, while the second one generates a signal which propagates using the lower ionosphere as a reflector.

VLF/LF radio signal propagation is affected by different factors such as meteorological condition, solar bursts and geomagnetic activity. At the same time, variations of some parameters in the ground, in the atmosphere and in the ionosphere, occurring during the preparatory phase of earthquakes, can produce disturbances in the previous signals and these disturbances are the radio precursors. Radio precursors are reported in many previous studies [1]-[20]. These anomalies are pointed out in the intensity and/or in the phase of the radio signals and generally they are connected to earthquakes located within the 5th Fresnel zone defined by transmitter and receiver location. Mainly, the precursors were revealed in the night time data because the VLF/LF radio signals propagation is less disturbed during the night than during the day, due to the dynamic status of the lower atmosphere. According to the most convincing models [2] [9] [10] [21] [22] [23] [24] [25] the processes occurring during the preparatory phase of strong earthquakes determine a particular lithosphere, atmosphere, and ionosphere coupling and cause the variation of the medium in which radio signals propagate, affecting especially radio propagation in the VLF/LF bands.

The INFREP network has been developed in 2009 in order to study the VLF/LF radio precursors and some results have been published [26]-[31]. In the recent years the INFREP network was implemented and modified.

Here at first the current situation of the INFREP network is presented; then the results obtained recently on the occasion of seismic activities occurred in 2016-2017 are reported.

2. Status Quo of INFREP Network

A web site [32] has been organized; the site shows the network, describes the research Teams involved and indicates the main references.

The network currently consists of nine receivers located as follows: two in Italy, Romania and Greece; one in Austria, Portugal and Cyprus. The radio receivers were manufactured by an Italian factory and measure the intensity (electric field strength) of 10 radio signals in the bands VLF (20 - 80 kHz) and LF (150 - 300 kHz), with 1 minute sampling rate. The signals radiated by existing VLF-LF broadcasting stations located in Europe are used. Generally, each receiver collects 5 VLF and 5 LF signals; in any case, the selection of the signals to collect is based on the quality of local reception. The location of the transmitters and receivers is shown in **Figure 1**. The labels and frequencies of the transmitters are reported in **Table 1**. The data collected are transmitted every day to the server located at the Department of Physics of the University of Bari (Italy) that is the central node of the network. The different temporal trends (10 for each receiver), can be seen using the INFREP web site where also the sampled data are stored protected by username and password.

In order to reveal possible radio precursors, the data had to be analyzed for discovering "anomalies", which differs from normal variations of the data trends. In INFREP, analysis of the radio data is performed only on the night-time data for all VLF/LF radio bands, between 21.00 and 24.00 (UTC). Each day is therefore represented by 3 hours, that is, taking into account the 1 min sampling rate used, 180 data (minutes). For the analysis of the data sets and detection of potential anomalies, there are several methods available that can be used [33] [34] [35] [36]. INFREP employs the Wavelet analysis [36]. Using the "Morlet function", the Wavelet transform of a time signal is a complex series that can be usefully represented by its square amplitude, *i.e.* considering the so-called Wavelet power spectrum. The power spectrum is a two dimensions plot (**Figure 2**) 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, color from blue to red indicates increase in the power strength; so, red zones define anomalies. INFREP has implemented a software able to apply the Wavelet analysis on the radio data automatically at the end of each day. The analysis is performed on those 15 days [2700 data (minutes)] or 20 days [3600 data (minutes)] preceding each day; this day is indicated on the spectrum by a vertical white line (**Figure 2**); the part of the spectrum after the day is related to 15 days data without any frequency added to avoid border effects. At the moment, the software operates on the night time data of four signals collected by each of the receivers: CIP, CRE, GRE and IT-Aq. Referring to **Figure 1** and **Table 1** the situation is the following: CIP (using DHO, GBZ, EU1, MCO transmitters); CRE (using DHO, EU1, FRI, MCO transmitters); GRE (using CZE, GBZ, EU1, RRO transmitters); IT-Aq (using DHO, GBZ, EU1, MCO transmitters). The results obtained with the Wavelet analysis are protected in the INFREP web site by a further username and password.

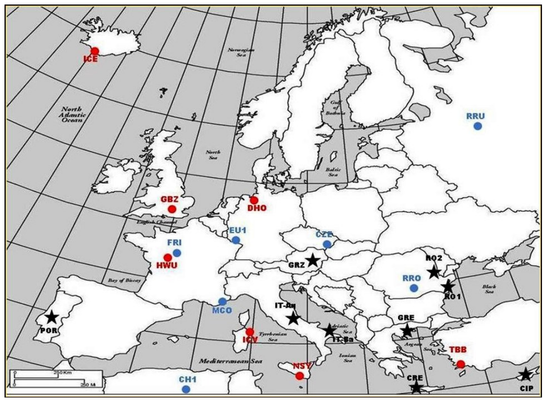

Figure 1. Map showing the receivers and the VLF-LF transmitters of the INFREP Network. The stars show the location of the receivers; the circles indicate the transmitters (blue: VLF, red: LF) the signals of which are collected by the different receivers.

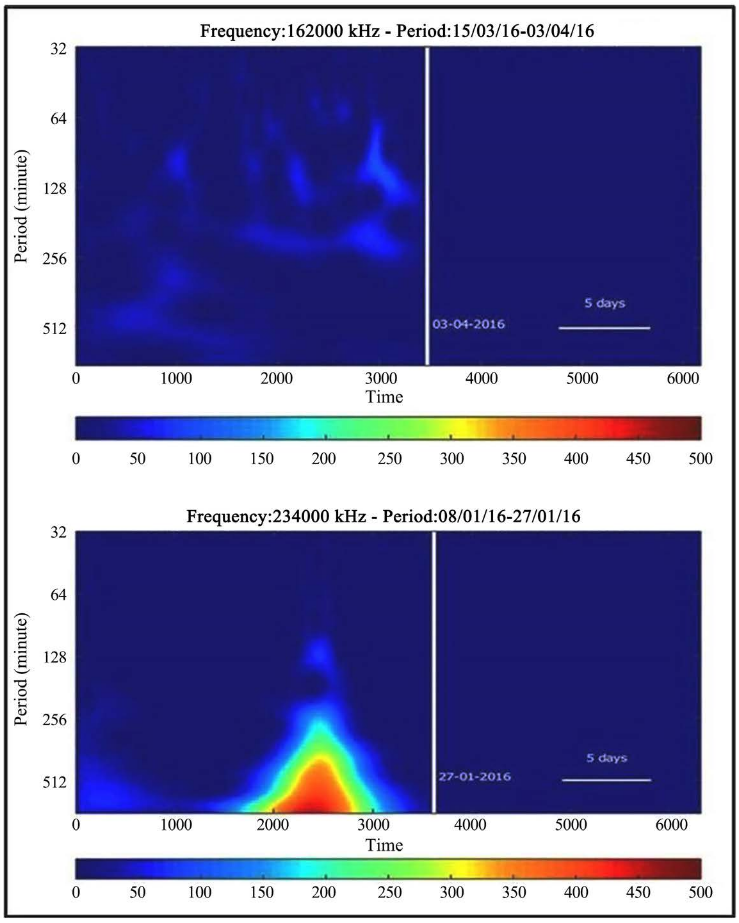

Figure 2. Two examples of Wavelet power spectra; at the top a normal situation; at the bottom an anomaly appears.

Table 1. Labels and frequencies of the VLF-LF transmitters used in the INFREP network.

VLF	Frequency (kHz)	LF	Frequency (kHz)
GBZ	19.58	RRO	153
ICV	20.27	FRI	162
HWU	21.75	EU1	183
DHO	23.4	CH1	198
TBB	26.7	MCO	216
ICE	37.5	RRU	261
NSY	45.9	CZE	270

3. Recent Results

3.1. Central Italy

On October 26, 2016 an earthquake with $M_w = 5.9$ occurred in Central Italy, near Norcia small town; followed by the main shock ($M_w = 6.5$), which occurred 4 days later (October 30, 2016). The focal depth reported was equal to 8 km and 9 km, respectively. The epicenter of the main shock was 12 km shifted towards a south west direction with respect to the first one. The earthquakes occurred in the "sensitive" area of the INFREP network.

Unfortunately, at the time of the earthquake, part of the INFREP network was undergoing a major reorganization. Among the data collected by the 4 receivers where the Wavelet analysis is automatically performed each day only those from CIP receiver are available (Figure 3). Starting several days before the first earthquake, two anomalies appeared one after the other in the two VLF signals, the night time intensity of which is analyzed online. The two signals are radiated by the DHO transmitter (23.4 kHz) and by the ICV transmitter (20.27 kHz). The 5th Fresnel zones of the radio paths brush the border of the Dobrovolsky area [37] of the previous main shock (Figure 3). The power spectra related to DHO transmitter in the period 17-30 October are reported in Figure 4; the anomaly starts at October 19. The power spectra related to ICV transmitter in the same period are reported in Figure 5; here the anomaly starts at October 23.

The power spectra related to the other two signals (EU1 and MCO), automatically analyzed at this site, were controlled and they did not show any clear disturbance in the considered period. So, the possibility of a malfunction of the receiver is very low.

3.2. Western Turkey

On July 20, 2017 a strong ($M_w = 6.7$) earthquake occurred offshore, near the coast of Turkey and Kos island (Greece); on August 8 an earthquake with $M_w = 5.0$ occurred practically in the same zone. The focal depth was 10 km for both the events. The epicentres are inside the "sensitive" area of the INFREP network. In this case the online Wavelet power spectra of four radio-signals for each one of the CIP, CRE, GRE and IT-Aq receivers are available.

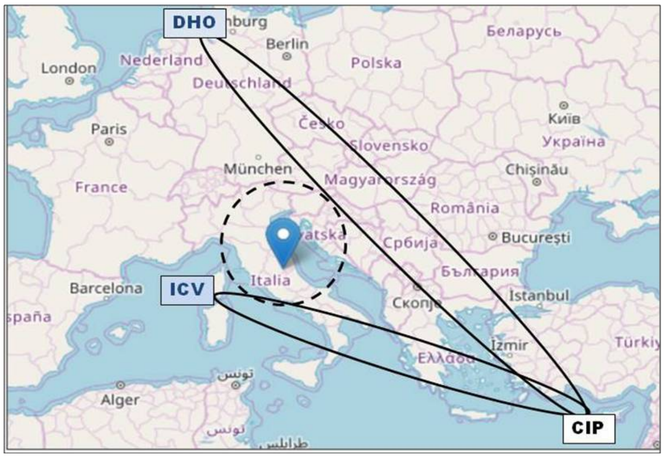

Figure 3. Location of the Norcia (Central Italy) earthquakes occurred at the end of October 2016. The dashed line encloses the Dobrovolsky area of the main shock (M_w = 6.5, October 30); the ellipses define the 5th Fresnel zones of the two radio paths.

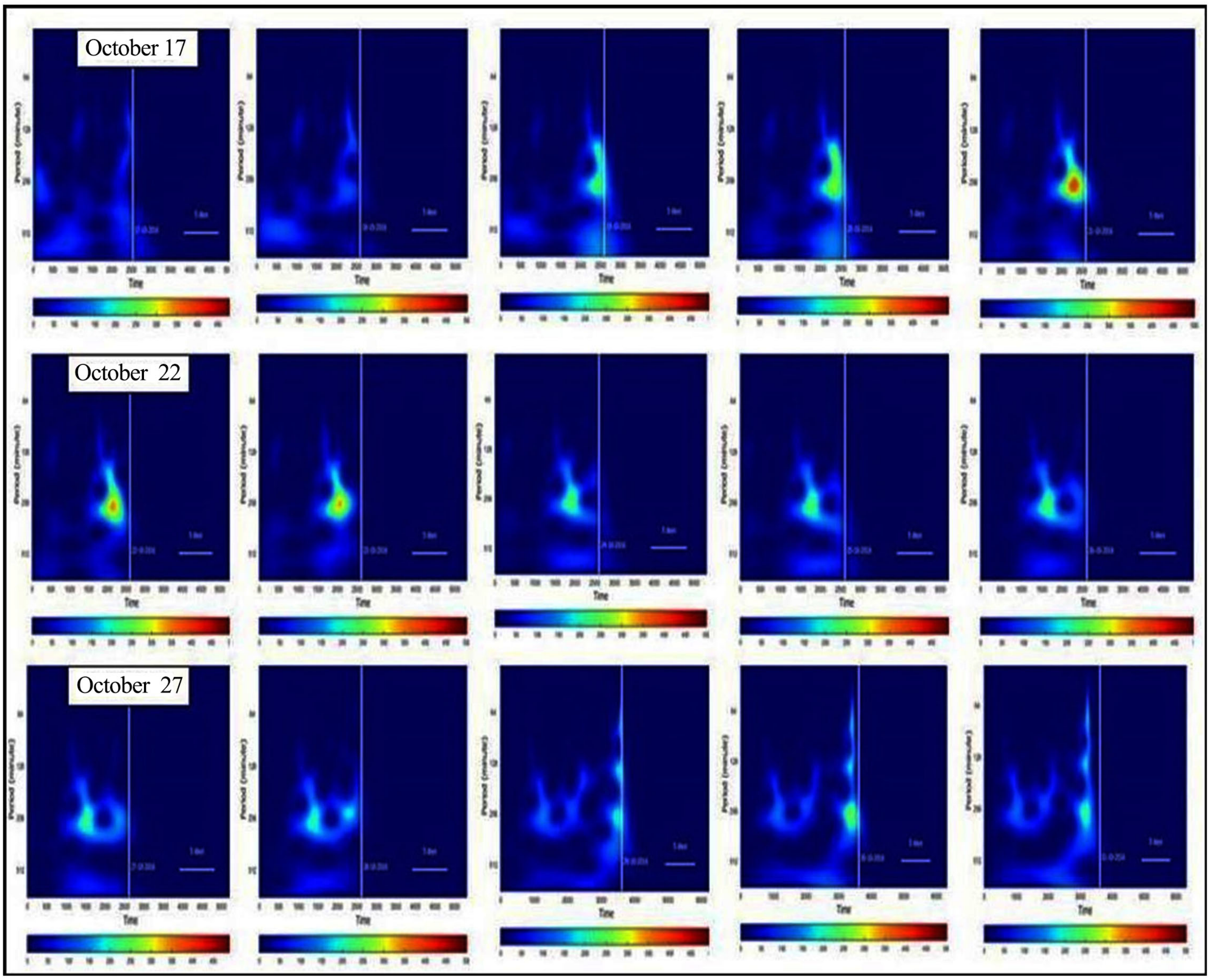

Figure 4. The power spectra of the DHO (23.4 kHz) radio signal collected by CIP receiver from 17th to 31st of October 2016. In the time interval between 17th and 28th October, the Wavelet analysis is performed on the 15 days [2700 data (minutes)] preceding the reference day (vertical white line); in the last three days, analysis is performed on the 20 days [3600 data (minutes)].

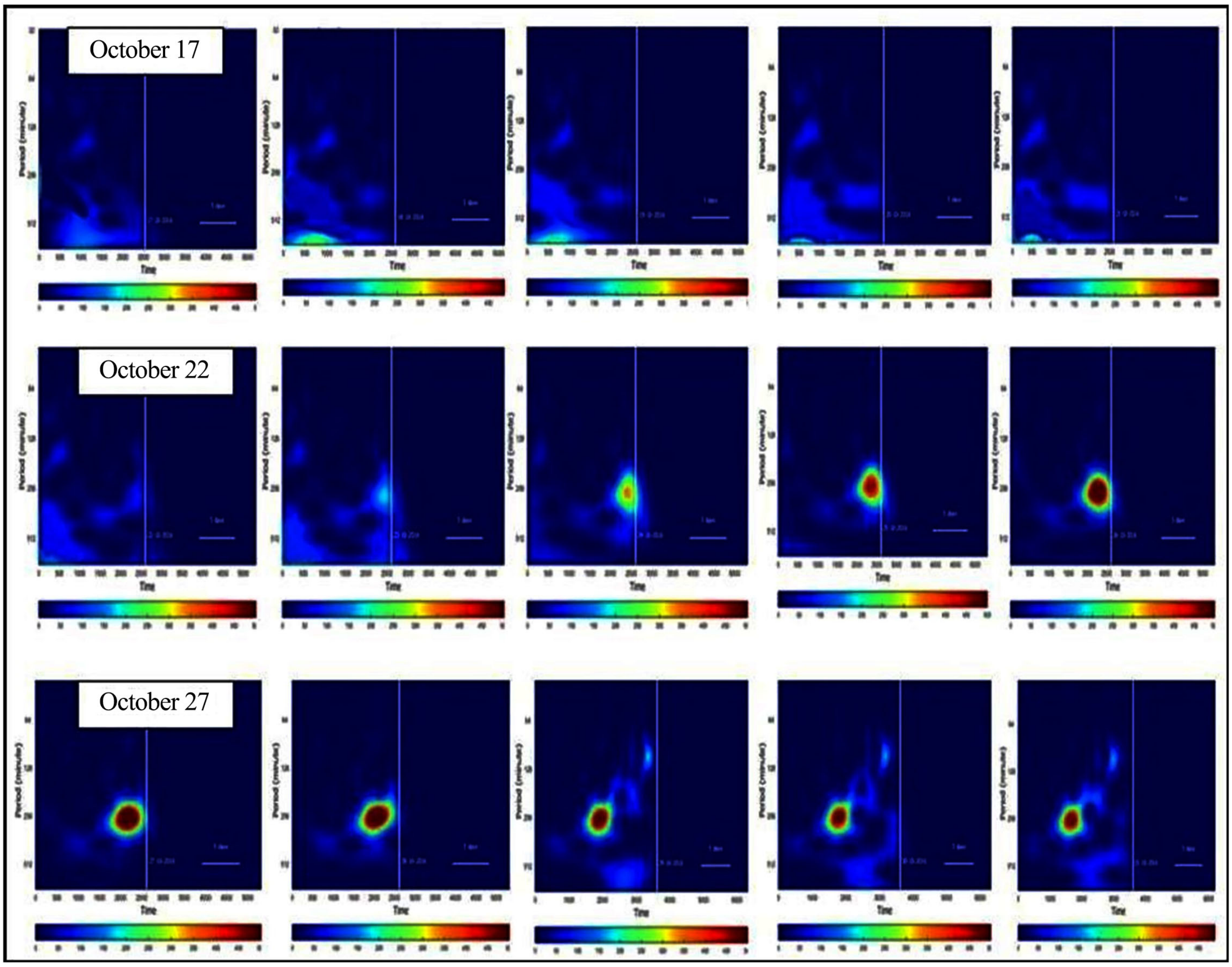

Figure 5. The power spectra of the ICV (20.27 kHz) radio signal collected by CIP receiver for the time interval between the 17th and 31st of October 2016. In the time interval between the 17th and 28th of October, the Wavelet analysis is performed on the 15 days [2700 data (minutes)] preceding the reference day (vertical white line); in the last three days the Wavelet analysis is performed on the 20 days [3600 data (minutes)].

At first the situation related to the July earthquake is described. In Figure 6, the 5th Fresnel zones of the four radio-signals DHO (23.4 kHz), GBZ (19.58 kHz), EU1 (183 kHz) and MCO (216 kHz) collected by the CIP receiver and automatically analyzed are reported. The epicenter of the earthquake is also indicated. The relative online power spectra obtained on July 20, 2017 are reported in Figure 7. Starting 3 - 4 days before the earthquake above mentioned, an anomaly appears on the signal radiated by the DHO transmitter (a weak disturbance appears also on the signal radiated by GBZ transmitter, that is the other VLF signal on line analyzed); on the contrary, the power spectra related to the EU1 and MCO (LF signals) don't show any clear disturbance. The presence of a clear anomaly only in one radio signal among the four automatically analyzed minimizes the possibility of a malfunction of the receiver. In order to exclude a possible malfunction of the DHO transmitter (the signal of which shows the anomaly) the power spectrum related to this signal obtained in the same day in CRE and IT-Aq site were considered. Take into account that this signal is not collected by the GRE receiver. The situation is described in Figure 8, showing that none disturbance is present on both the power spectra of the DHO signal.

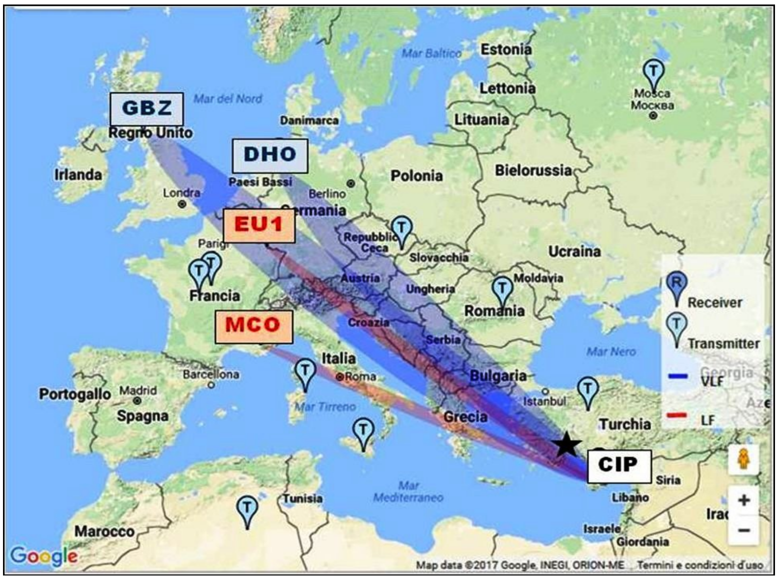

Figure 6. The ellipses represent the 5th Fresnel zones of the four radio-signals DHO (23.4 kHz), GBZ (19.58 kHz), EU1 (183 kHz) and MCO (216 kHz) collected by the CIP receiver and automatically analyzed. The star shows the epicenter of the July 20, 2017 (M_w = 6.7) earthquake.

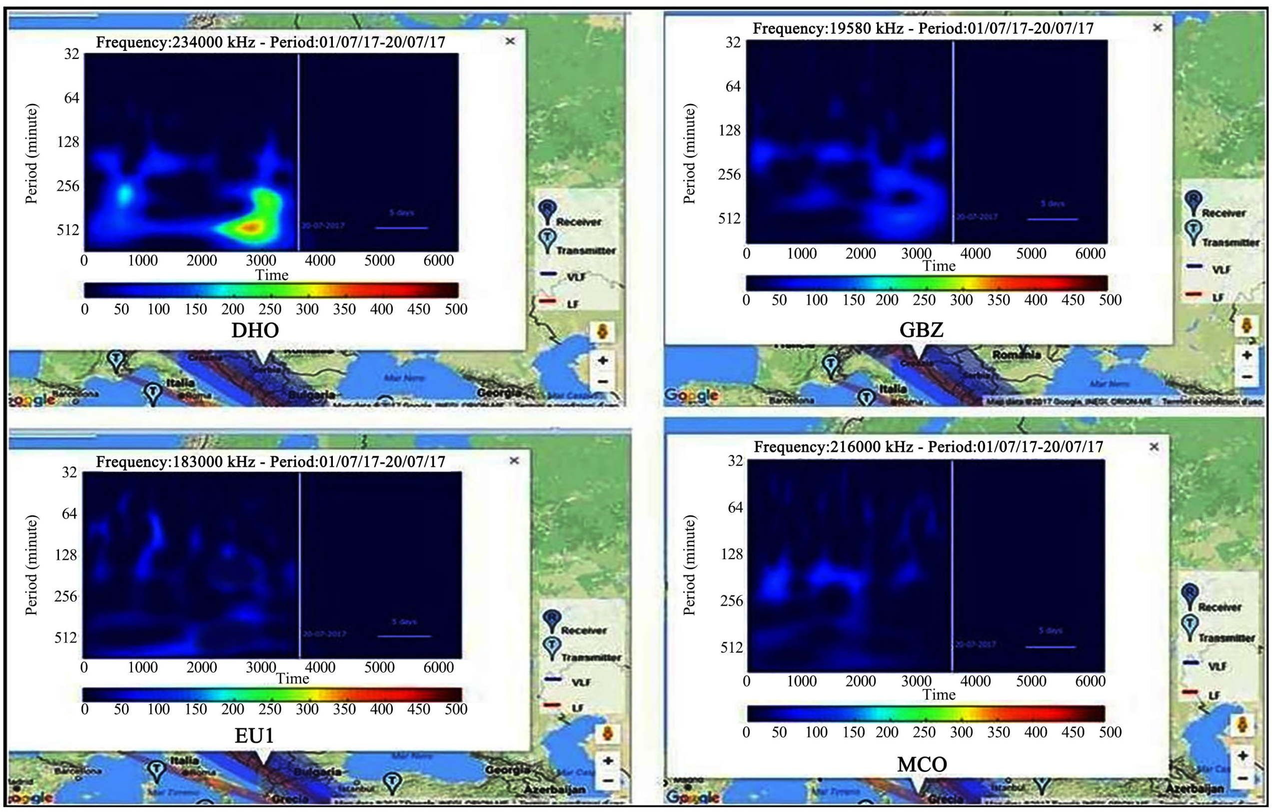

Figure 7. The on-line (July 20, 2017) power spectra of the four radio signals represented in Figure 6 are shown.

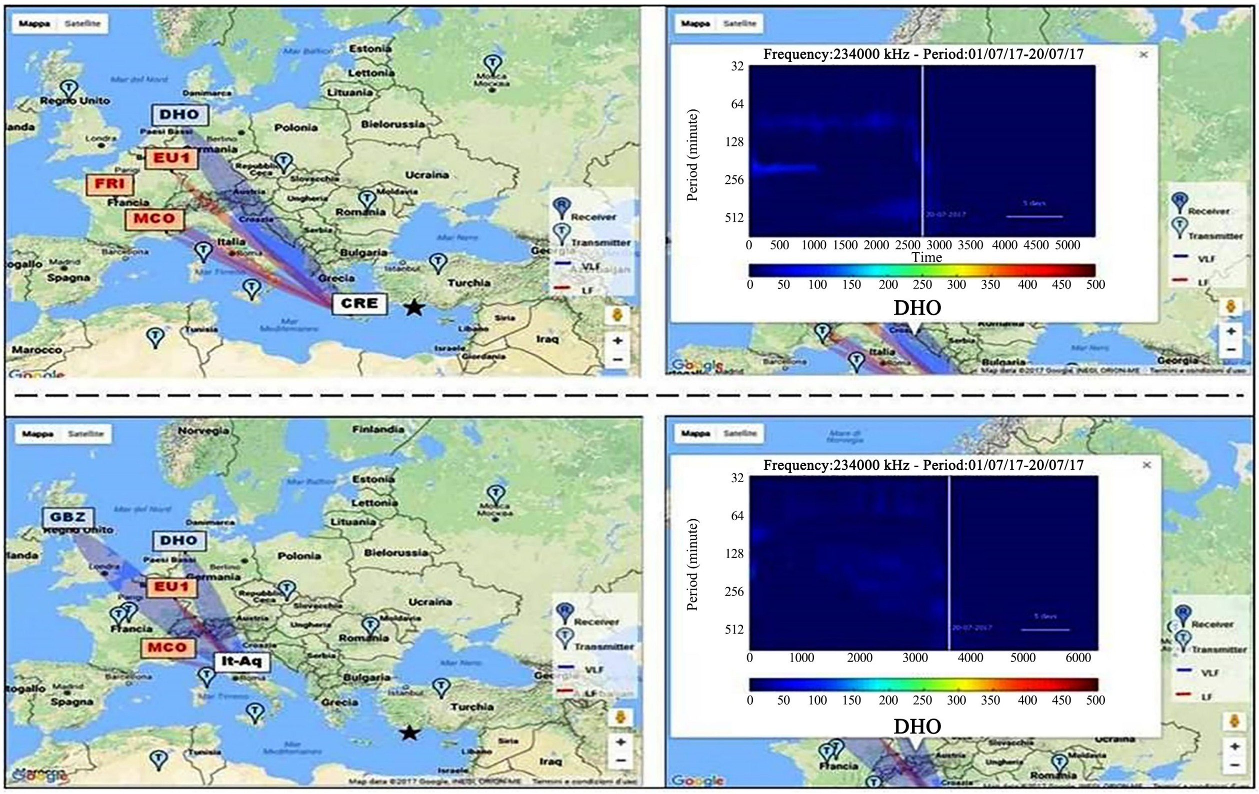

Figure 8. The top panel is related to the CRE receiver: on the left the ellipses represent the 5th Fresnel zones of the four radio-signals collected by the CRE receiver and automatically analyzed and the star shows the epicenter of the July 20, 2017 (M_w = 6.7) earthquake; on the right the on-line (July 20, 2017) power spectrum of DHO signal is shown. The bottom panel is the same one but related to the IT-Aq receiver.

Next, the August 8, 2017 (M_w = 5.0) earthquake is described. Note that **Figure 6** can be referred also to this earthquake (the epicenter is about the same of the previous earthquake). In **Figure 9** the power spectra on August 7, 2017 related to DHO, GBZ, EU1 and MCO signals collected by the CIP are reported. From **Figure 9**, an anomaly appears on the signal radiated by the DHO transmitter, starting 6 - 7 days before the earthquake mentioned above; on the contrary, the power spectra related to the GBZ, EU1 and MCO don't reveal any clear disturbance. As before, the presence of anomaly only in one signal minimizes the possibility of a malfunction of the receiver. In order to exclude a possible malfunction of the DHO transmitter (the signal of which shows the anomaly) the power spectra related to this signal obtained in the same day in CRE and IT-Aq site were examined. The situation is described in **Figure 10**, showing that there is no disturbance present on both the power spectra of the DHO signal.

4. Discussion

Disturbances in VLF-LF radio waves can be connected to adverse meteorological conditions around the receiver location or to anomalous geomagnetic activity as reported in previous analyses [15] [16] [26] [38] [39]. These causes have been checked as regards the periods when the anomalies presented above occurred

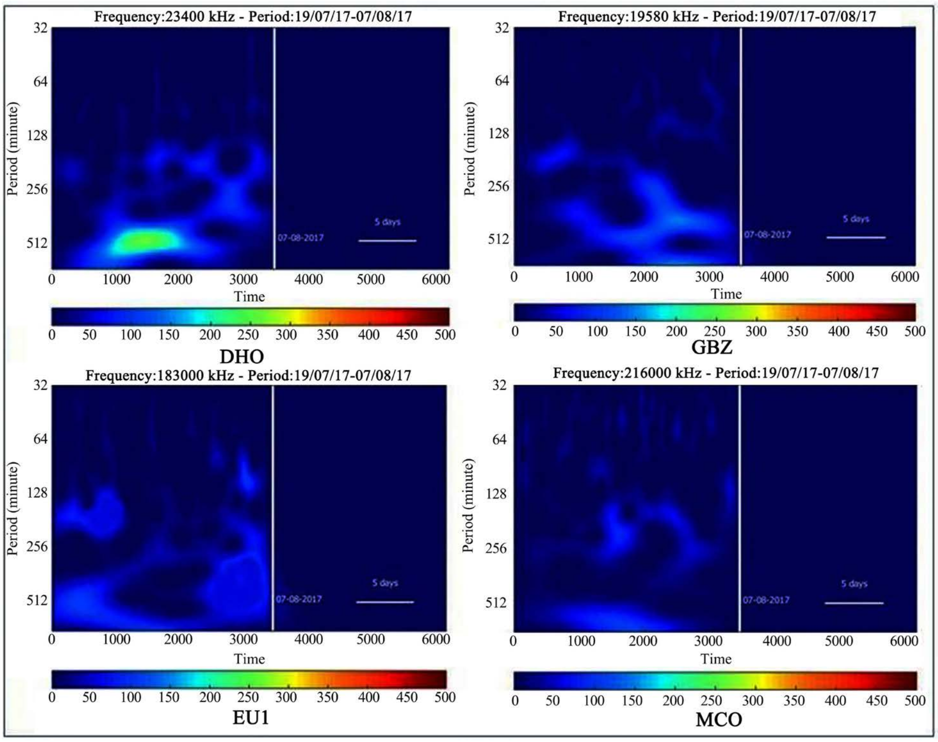

Figure 9. The power spectra obtained on August 7, 2017 of the four radio signals represented in Figure 6.

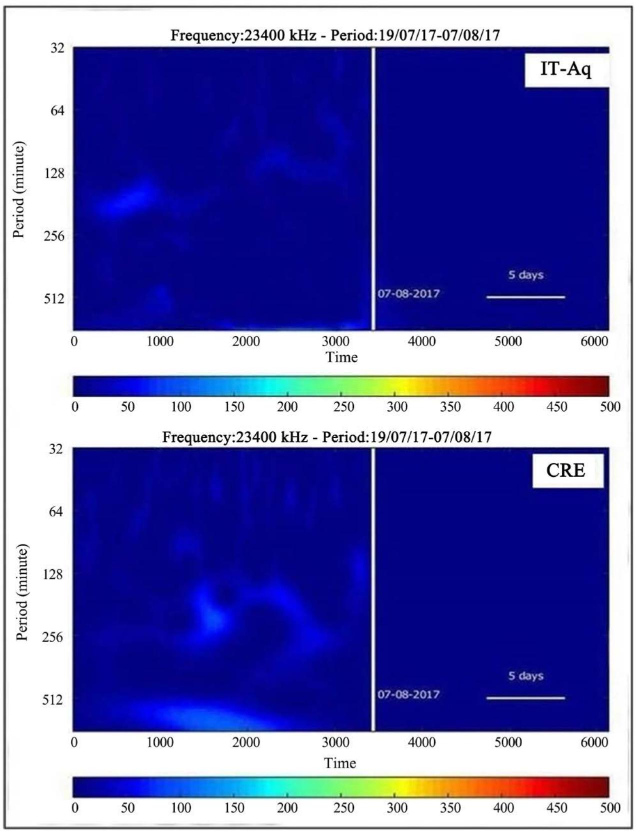

Figure 10. The DHO power spectra obtained on August 7, 2017 at IT-Aq and CRE receivers are shown. The relative maps are the same reported in Figure 8.

and no clear correspondence was noticed in all the cases. The Wavelet analysis performed at each site on four signals and, when possible, on the same signal at different sites allows to reduce the possibility that the anomalies presented are related to problems connected to the transmitter or to the receiver. So, a connection of the anomalies with the seismicity can be considered.

On the basis of the many papers (see references in the introduction), the VLF-LF radio signals anomalies have the following general peculiarities: 1) they appear at least 10 - 15 days before the subsequent earthquake, 2) the magnitude M_w of the earthquake is equal-greater than 5.5, 3) the epicenter is located inside the 3rd-5th Fresnel zone of the radio path in the central zone or near the receiver. As concerns the Central Italy earthquakes (M_w = 5.9 and M_w = 6.5) occurred on October 2016, the anomalies revealed conform to both the precursory time and the magnitude threshold; in fact they appear 8 - 4 days before the first earthquake and 12 - 8 days before the second one and the M_w = 5.9 - 6.5 values are well above the threshold. On the contrary, the epicenter location is ruled out, mainly because the earthquake occurred outside the relative Fresnel zones. Unfortunately, as mentioned before, in addition to the data of the Cyprus receiver, the data of other receivers are not available in order to validate the anomalies revealed. But, it can be noted that in DHO signal the anomaly starts on October 19, while in ICV signal on October 23. The ICV radio path lies along a different direction (**Figure 3**) with respect to the DHO radio path; so, this 4-day-time shift is in agreement with the time occurrence of the two earthquakes, taking into account the location of the two epicenters indicated in paragraph 3. The previous observation seems to confirm the possibility that the anomalies considered are related to the earthquakes. On the occasion of the main (October 30, M_w = 6.5) earthquake, the Norcia small town was destroyed. The reason that there were no victims is mainly due to the fact that after the first (October 26, M_w = 5.9) earthquake, the population was outside, so, this earthquake practically produced a forecast of the main shock. The localization of the incoming earthquake is a basic problem in earthquakes forecast; so, the diversity that appeared here, might be taken into account in the future developments. Now, let us consider the situation related to the Western Turkey earthquakes occurred on July-August, 2017. In these cases, it has been possible to validate the anomalies revealed on the path DHO-CIP minimizing the possibility that they are connected to a malfunction of the DHO transmitter or to a malfunction of the receiver. So, the possibility that these anomalies are connected to the previous earthquakes is more significant. As concerns the earthquake (M_w = 6.7) occurred on July 20, 2017, the anomaly revealed on the path DHO-CIP receiver (confirmed by the weak effect on the path GBZ-CIP) is in agreement with all the peculiarities of the radio precursors mentioned above; in fact the epicenter is located near the receiver, inside the 5th Fresnel zone of the radio path, the magnitude is well above the threshold value and the precursory time (3 - 4 days) is within the upper limit. Regarding the earthquake (M_w = 5.0) occurred on July 20, 2017, the anomaly revealed is compliant with the standards as concerns the precursor time (6 - 7 days) and the location of the epicenter (near the receiver inside the 5^{th} Fresnel zone of the radio path), but not for the magnitude value, that is under threshold (5.5). It is possible that the unperturbed meteorological condition in that period has increased the sensitivity of the method. Also, the definition of the magnitude of the incoming earthquake is a basic problem in earthquakes forecast; so, a possible influence of the meteorological conditions on the magnitude threshold might be taken into account in the future developments.

5. Conclusion

Currently, the INFREP network consists of: a) nine receivers (two in Italy, Romania and Greece and one in Austria, Portugal and Cyprus); each one collects the intensity of 10 VLF-LF radio signals, with 1 minute sampling rate; b) the data collected are transmitted every day to the server located at the Department of Physics of the University of Bari (Italy), that is the central node of the network; c) in order to discover anomalies, a software able to apply the Wavelet analysis on the radio data automatically at the end of each day has been planned and realized. Actually we are working to reduce the possibility of losing the INFREP data as it occurred two times recently. The results obtained on the occasion of the Central Italy earthquakes (M_w = 5.9 and M_w = 6.5) which occurred on October 2016 and of Western Turkey earthquakes (M_w = 6.7 and M_w = 5.0) which occurred on July-August 2017 confirm the sensitivity of the network for revealing radio precursors of earthquakes, but they confirm also the importance of increasing the number of the receivers in order: 1) to confirm the interpretation of the anomalies revealed as precursors of earthquakes; 2) to reduce the inaccuracy of the location of the epicenter. We have prepared and are preparing projects at the purpose to obtain financial support. The electromagnetic observations, recently (February 2018) increased by the launch of the first CSES (China Seismo-Electromagnetic Satellite) satellite, need the support of valid ground-based data in order to increase the validity of the future results. In any case, it is unlike that the electromagnetic data could produce some realistic forecast of strong earthquake by themselves; at this purpose the information related to some other parameter as seismic activity, uplift and tilt, gas emissions and so on, might be added to the electromagnetic information. Our future program moves also in this direction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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