INFREP, a European network for the monitoring of earthquake's induced disturbances in the lower ionosphere

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Abstract

In this communication we present a recently installed network of VLF/LF receivers which covers the Central and Eastern Europe for the follow up of the Signal propagation of a suitable number of VLF/LF transmitters on the purpose to detect in real time pre- co- and post- earthquake ionospheric perturbations induced by the tectonic activity which occur in the above mentioned area. In addition the method of analysis of the collected data at the station of Thessaloniki is exposed and an example of the operation of the system is given.

Key words: *VLF/LF radio transmission, Hilbert-Huang transformation, Earthquake precursors*

1. Introduction

No matter the so called Lithosphere-Atmosphere-Ionosphere- Connection (LAIC) mechanism works, either by the generation during the earthquake preparation period of Atmospheric Gravity Waves at Acoustic frequencies (AGW), in the area of the epicenter which subsequently move upwards, enrich the turbulent content of the ionosphere over the epicenter and initiate Gravity Waves which propagate in the waveguide of the Ionosphere (Liperovsky et al. 2000, Molchanov et al. 2004), or by the ion exhalation and subsequent variations of the electric field at the site of the earthquake preparation area which produce variations of the Ionosphere over the epicenter area (Pulinet and Ouzounov 2010), a great amount of research in the last twenty years by means of ground- based experiments (Molchanov et al. 2004; Molchanov et al. 2005; Liperovsky et al. 2002; Shvets et al. 2004; Rozhnoi et al. 2004;Contadakis et al. 2007; Contadakis et al. 2008, Tsolis and Xenos 2010, Rozhnoi et al. 2009; Biagi et al. 2009), space-born studies (Parrot 2006; Hayakawa et al. 2000) and combined space- born and ground- based studies (Rozhnoi et al. 2007; Muto et al. 2008) as well, indicate the existence of pre-, co- and post- earthquake ionospheric perturbations at all the levels (E,D,F layers).

It has been observed long ago (Gogberg 1989, Molchanov et al. 1998) that the VLF/LF electromagnetic signals, which propagate in the Earth-ionosphere waveguide are greatly influenced in amplitude and phase by the plasma condition of the lower ionosphere and can be used as an integrate diagnostic for lower ionosphere (D layer) variations over the propagation path. For this reason the follow up of VLF/LF electromagnetic signals propagation is considered as a reliable diagnostic mean for pre-, co- and post-earthquake ionospheric perturbations for earthquakes which may occur along the propagation path of the signal.

In this communication we present a recently installed network of VLF/LF receivers which covers the Central and Eastern Europe for the follow up of the signal propagation of a suitable number of VLF/LF transmitters on the purpose to detect in real time pre- co- and post- earthquake ionospheric perturbations induced by the tectonic activity which occur in the above mentioned area. In addition the method of analysis at the station of Thessaloniki is presented and an example of the operation of the system is given.

2. The International Network for Frontier Research on Earthquake Precursors (INFREP)

The INFREP is a scientific cooperation among different international research groups. The cooperation aims to build up a network for measuring various physical parameters in order to search and study effects possibly related to the occurrence of earthquakes. In particular the first network consists of eight receivers able to meas-

Table 1: *The eight receivers*

	Site	*Country*	*Longitude*	*Latitude*	*Receiver*
1	Bari	Italy	16° 53′E	41° 06′N	OmniPal
2	Torre Canne	Italy	17° 28′E	40° 49′N	Elettronica
3	Andro Doco	Italy	13° 05′E	42° 25′N	Elettronica
4	Gratz	Austria	14° 45′E	47° 36′N	OmniPal
5	Thessaloniki	Greece	23° 00′E	40° 56′N	Elettronica
6	Dobrogea	Romania	26° 63′E	44° 07′N	Elettronica
7	Sivas	Turkey	37° 23′E	39° 14′N	Elettronica
8	Moscow	Russia	37° 37′E	55° 45′N	OmniPal

ure the intensity of VLF/LF radio signal from various broadcasting stations located throughout Europe.

The receiver OmniPal is of Japanese origin (Biagi et al. 2008 and reference therein) and can measure the electric field intensity and the phase of five

VLF/LF radio signals simultaneously, while the receiver Elletronica is of Italian origin (Biagi et al. 2009 and reference therein) and can measure the electric field intensity of ten VLF/LF radio signals. Both receiver are equipped with acquisition systems and the data, which are collected at a desired sampling gap, are organized in daily text files and are available to the authorized people either from the central site of the network (http://beta.fisica.uniba.it.//infrep/) for all the receivers or from the sites of the network receivers. The real time analyzed signals of the receiver of Thessaloniki is available to anyone from the site http:// 87.203.232.9/

This network is practically an extension of a local network which covers the peninsula of Italy and part of North Balkan, which was installed by Prof. Pier Franceso Biagi (see for instance Biagi et al. 2001) who had the initiative of the creation of INFREP. Table 1 displays general informations about the eight receivers of the network and Table 2 general informations about the transmitters in use. All transmitters are long range transmitters for intercontinental receiving, regularly in use for transmitting Time or meteorology informations or finally transmitting for civil or military purposes. Figure 1 shows the position of both, receivers and transmitters in Europe and Figure 2 displays the photos of the two receivers which are in use.

Table 2: *The VLF/LF transmitters which are monitored by Thessaloniki receiver*

Station Code	*Frequency (kHz)*	*Site*	*Country*	*Longitude*	*Latitude*
ICE	37.500	Keflavic	Iceland	22° 34′ W	64° 01′ N
GBZ	19.580	Anthorn	Great Britain	03° 16′ W	54° 54′N
MCO	216.000	Roumoules	Monaco	06° 09′E	43° 47′N
EU1	183.000	Felsberg - Berus	Germany	06° 40′E	49° 16′N
DHO	23.400	Rhauderfehn	Germany	07° 36′E	53° 04′N
ICV	20.270	Tavolara	Italy	09° 42′E	40° 54′N
NSY	49.500	Niscemi	Italy	14° 26′E	37° 26′N
CZE	270.000	Topolna	Chech Republic	17° 30′E	49° 07′N
ROM	153.000	Brasov	Romania	25° 36′E	45° 45′N
TRT	180.000	Polatli	Turkey	32° 25′E	39° 45′N

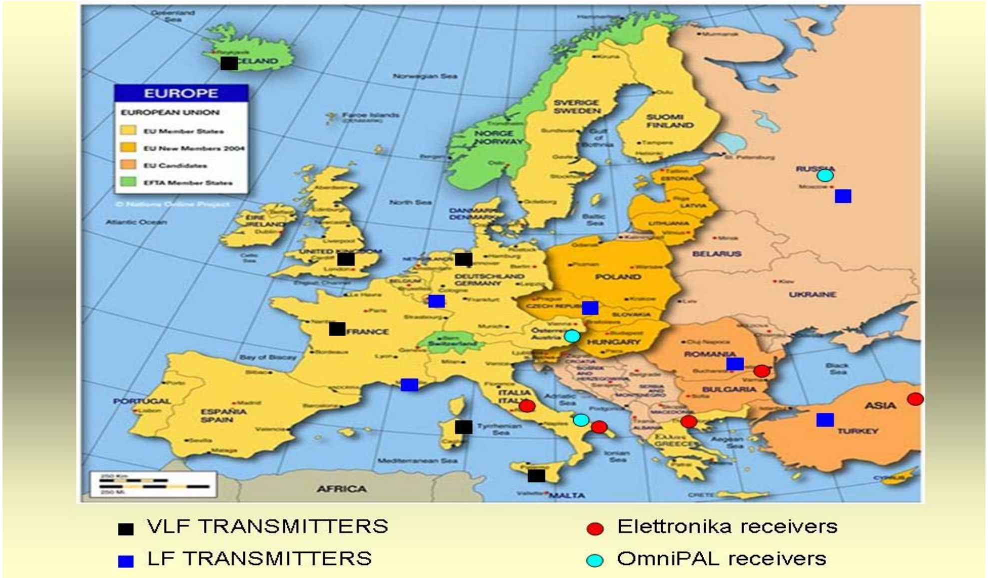

Figure 1: *The sites of the receivers and the transmitters of the network*

Figure 2: *The Japanese OmniPAL receiver and the Italian Elettronika receiver*

Each station of the network can identify a particular transmission path with unusual signal disturbances by comparing the signals which receive simultaneously from the transmitters at different directions. The intersection of more than two transmission paths, the signals of which present similar unusual disturbances and received by different receivers, spot at the tectonically active area which possibly is responsible for the observed signal disturbances.

3. Method of data analysis

It is well known that in the case of the VLF/LF frequencies radio transmission the received signal is the composition of the ground wave i.e. the wave which is propagating parallel to the ground and the sky waves of different orders, which reach the receiver after one or more successive reflections at the lower ionosphere and the earth, as they are propagating in the waveguide of the earth-ionosphere. Figure 3 displays a simplified schematic picture (ignoring the earth curvature) in which the received signal is the composition of the ground wave and a one reflection sky wave, the so called one hop wave. Although for distances shorter than 1000km only the contribution of the one hop sky wave is important (Biagi et al. 2006, Yosida et al. 2008) for larger distances the contribution of more than one hop sky waves should be taken in account.

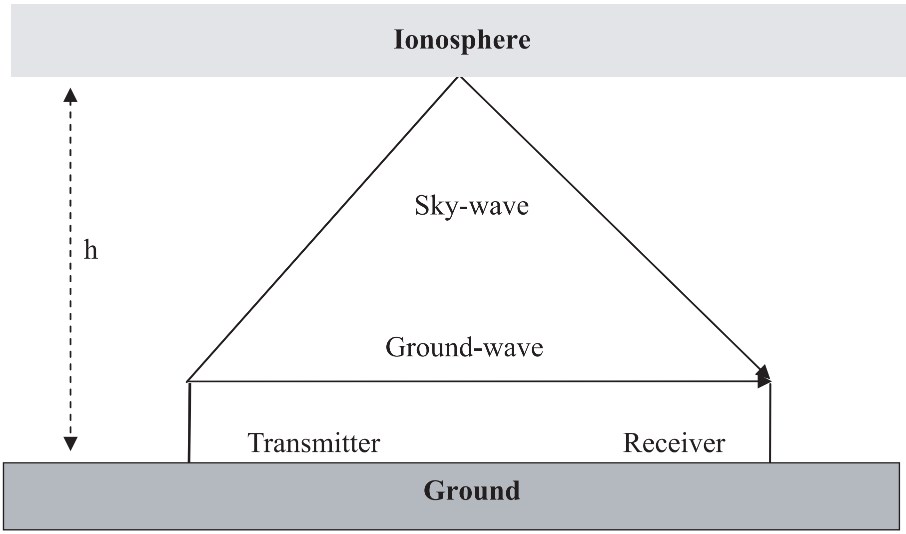

Figure 3: *A simplified model for VLF/LF transmission*

The total intensity of the received signal is the sum of the intensity of the two waves and will depend on the phase lag φ between the ground and the sky wave which is:

$$\varphi = (2\pi / \lambda)(L - d)$$

where: λ = wavelength of the signal, d = distance transmitter-receiver, L = total path of the sky wave.

The path of the ground wave d is constant while the path of the sky wave, L, depend on the height, h, of the lower limit of the ionosphere. The mean height of the lower ionosphere is about 85km, and varies between 75 km at day time and 95 km at night time. There are also annual variations. As a results the intensity of the received signals undergo daily and annual variations. In addition any variation in the lower ionosphere which may be produced by variations of the geomagnetic field, tropospheric storms, volcanoes, planetary storms, tectonic activity etc. result to variations of the signal intensity. On the absence of all other causes we attribute the unusual VLF/LF radio signal variations to the tectonic activity.

Two methods of VLF/LF signal analysis has been proposed so far.

(1) The terminator time method in which one observe the shifting of the minimum in VLF/LF signal intensity around sunrise and sunset (see for instance Molchanov et al. 1998) and
(2) the nighttime fluctuation method (see for instance Rozhnoi et al. 2004, Svets et al. 2004).

In the station of Thessaloniki we introduce a new method in which we analyze the whole day signal for checking the fluctuations by de-signalizing the total signal using the method of Hilbert-Huang Transformation (see also Tsolis and Xenos 2009) which is described in the following. In this method the day-time signal are included in the analysis too.

Hilbert – Huang Transformations

The analysis of the received time series is based on the Empirical Mode Decomposition (Hilbert Huang transform), which is a modern method of analysis still evolving. It is well known that the traditional signal processing methods (e.g. the Fourier transform) are based on the basic assumption that the analyzed signals are linear and stationary in time. Hence, the basic problem encountered in modeling a non-linear signal is the use of harmonics, with a direct result the appearance of the negative frequencies, which of course have no physical significance. Moreover, the modern methods of signal processing focus in algorithms capable of solving either non-linear or non-stationary signals, but which are incapable to analyze signals belonging to both categories. The wavelets and the Wagner – Ville methods of analysis for instance, can be used successfully to analyze non-stationary signals, yet they both are linear analysis techniques.

Contrary to these methods, the Empirical Mode Decomposition Method, although it lacks in mathematical validation, gives very good results when analyzing non-linear and non-stationary signals especially when a precise representation of the signal energy and its frequency content in time is required.

The EMD is a method encompassing two discrete phases. In phase 1 the signal is being analyzed in its structural components the so-called Intrinsic Mode Functions (IMF) whereas in phase 2 a Hilbert transform for each IMF is applied and hence for each temporal components an amplitude/power component is being provided.

The results are presented in two dimensions (time – frequency) the amplitude being expressed by colour variations (spectrogram). This representation is called the Hibert spectrum. Adding all signal amplitudes corresponding at the same time or at the same frequency component the Marginal Hilbert Spectrum is obtained. The final product is a very precise, compared to the traditional techniques, signal spectral representation in time. The signal analysis to IMFs, is the base of the Hilbert – Huang transform. Its basic assumption is that in every random signal, high frequency components are to be found, superposed on the low frequency ones. Therefore, the IMFs of the signal, which are the final results of the analysis process, must fulfill the above mentioned criteria, so that the instantaneous frequency values, obtained through the Hilbert transform, are physically acceptable.

Consequently, a signal is characterized as IMF when:

- The number of the maxima and minima equals to the number of its zeros minus one at most.
- At each point, the average value defined by the maximum and minimum envelopes equals zero.

First, an iterative process known as sifting, which detects all local extrema and distinguishes them between local maxima and minima, is applied to the initial signal. Then, using an interpolation algorithm, usually cubic splines, the maxima $E_{max}(t)$ and minima $E_{min}(t)$ envelopes are defined respectively whence their average value $m_1(t)$ is calculated. This value is then subtracted from the original signal values $x(t)$ and the result $h_1(t)$ is then tested whether it can be characterized IMF or not. If it does not, the $h_1(t)$ is subject to the same iterative process as $x(t)$ until the answer is positive. It has to be mentioned that gradually the average value of the maxima and minima envelopes is becoming smaller tending to zero.

Then the first IMF is subtracted from the initial signal and the result r_1 is sifted again. The first IMF contains the higher frequency components since it is obtained from the initial extrema of the signal. The second, third etc IMFs contain lower frequencies considering that the signal extrema are gradually becoming fewer and fewer; when the number of remaining extrema is less than three, the process is terminated and the initial signal can be written as:

$$x(t) = \sum_{i=1}^{n} IMF_i + r_n$$

where r_n is the final residual, a constant or a monotonous function with no extrema.

The number of the resulting IMFs equals $\log_2 N$, where N is the number of the signal samples. The resulting approximation is very high, usually to a 10^{-15} deviation, which is due to the cubic spline interpolation.

The orthogonality of the process is proved by:

$$IO = \sum_{0}^{T} \frac{\sum_{j=1}^{n+1} \sum_{k=1}^{n+1} IMF_k IMF_j}{x^2(t)}$$

where j and k are two randomly selected IMFs and n is the number of the IMFs, in this process no residuals are considered.

In order for the signal to be characterized IMF the symmetry, around zero, and the zero average of the maxima and minima envelopes criteria must hold. Yet, when the sifting process, in order for the second criterion to be fulfilled, is repeated, an over-decomposition of the signal occurs and then the resulting IMFs have no significance. Therefore, an iteration termination criterion is necessary. He first criterion proposed by N. Huang himself states that the process id terminated when the constant deviation between two successive iterations becomes very small, i.e.

$$SD = \sum_{0}^{T} \left[\frac{|h_{k-1}(t) - h_k(t)|}{h_{k-1}} \right]^2$$

The iteration can be terminated when SD lies between 0.2 and 0.3. Yet, this criterion had to be slightly modified, since the SD can be strongly affected by very small local values of the signal also the SD is strongly affected even when the IMFs are not strictly characterized as such. Therefore, the denominator is changed and the new formula is:

$$SD = \frac{\sum_{0}^{T} |h_{k-1}(t) - h_k(t)|^2}{\sum_{0}^{T} h_{k-1}^2(t)}$$

Nowadays a rather empirical criterion is used; it guaranties an almost zero value of average of the maxima and minima envelopes but it also permits some small local variations around the average in areas where the signal has very high frequencies. Therefore, the mode amplitude value $a(t)$ is defined as:

$$a(t) = \frac{E_{\max}(x) - E_{\min}(x)}{2}$$

Then an evaluation function sx is defined by:

$$sx = \left| \frac{m(t)}{a(t)} \right|$$

where $m(t)$ is the above defined average. The sifting is terminated when sx becomes less than a predefined threshold Th_1 for a large percentage of the signal samples defined as $1-a$; for the rest of the samples a second threshold exists (Th_2) usually ten times larger than Th_1. The usual choices for Th_1, Th_2 and a are 0.05, 0.5 and 0.05 respectively.

4. An Example

As an example we present the earthquake precursory disturbances which were observed in the case of an earthquake of magnitude 5.4 at Peshkopia of Albany at 21h 49 m and 40 sec Universal Time of 06/09/2009 (Anastasiadis et al. 2010). No significant for-shock was observed while a sequence of aftershocks with magnitudes ranging between 3 and 3.9 follow the main shock. The precise location was: Longitude = $20^{o}.41$E and Latitude = $41^{o}.62$E. The depth of the earthquake was 10 km while the epicentral distance from the receiver of Thessaloniki was 242.455 km. Figure 4 shows the sites of Peshkopia and Thessaloniki together with the sites of the transmitters of the network. Figure 5 displays the total signal as well as the two first Intrinsic Mode Functions (IMF) which were computed by Hilbert –Huang Transformation analysis for the transmission of the Roumoules Station in Monaco (MCO). In this Figure the time of the main shock is marked by a thunder sign and the precursory disturbances on the signal are marked by arrows.

The precursory disturbances appear first at 6 o'clock Local Time i.e 16 hours before the shock. In this particular case similar disturbances are present in the signals of all the transmitters who lie northern of Thessaloniki. This happened because

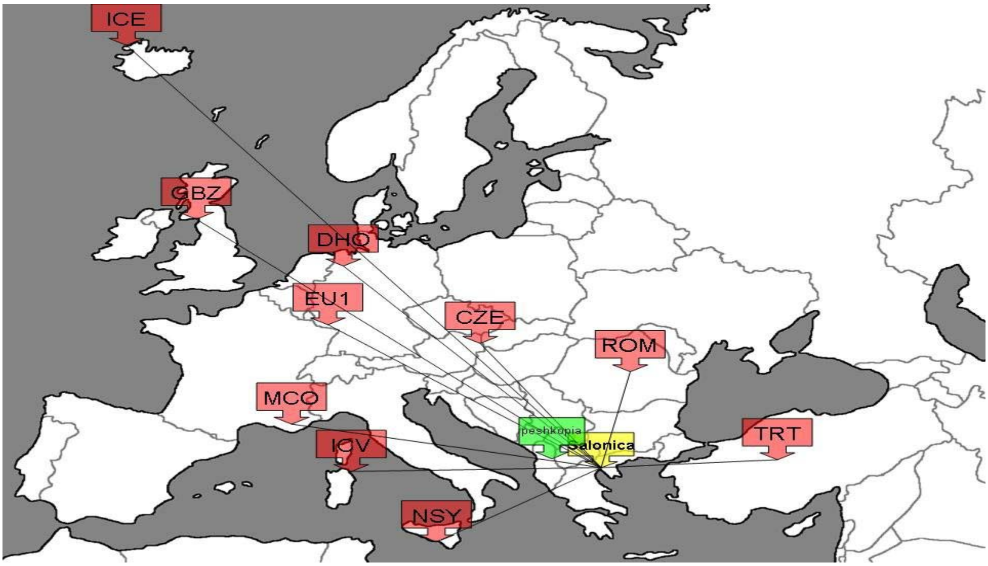

Figure 4: *The sites of Thessaloniki, Peshkopia of Albany and Network Transmitters*

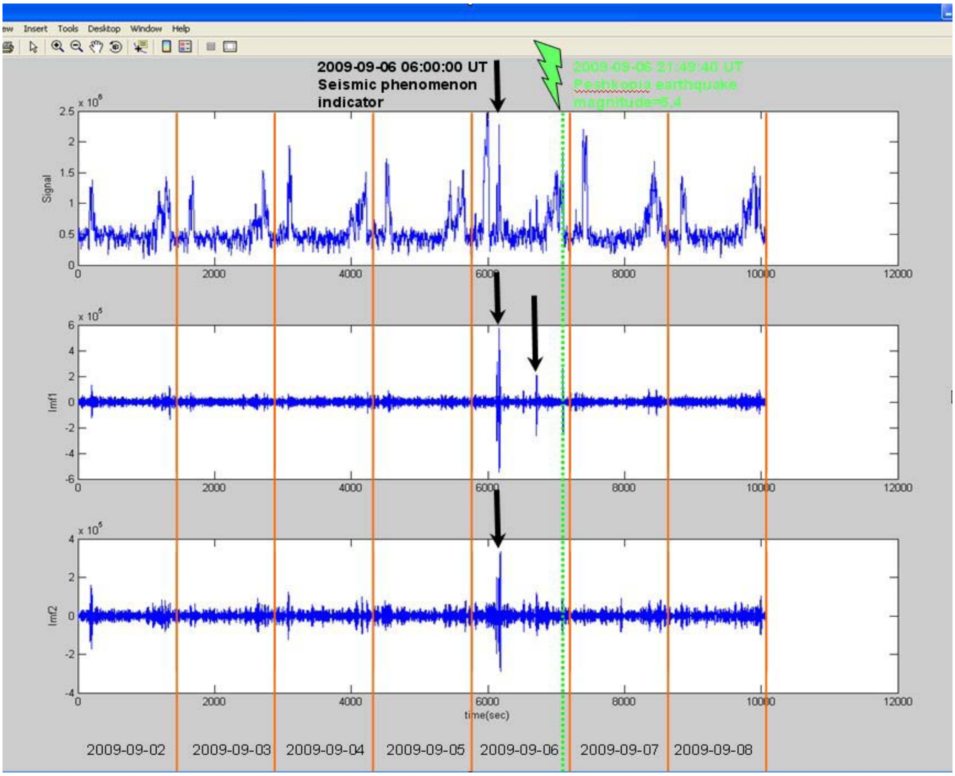

Figure 5: *The signal and the two first IMF of the MCO signal around the date of Peshkopia earthquake*

Thessaloniki lies in the limit of the earthquake preparation area of the Peskopia shock, which according to the theory of Dobrovolsky (Dobrovolsky et al.1979) has a radius 210 km around the epicenter, and consequently Ionosphere over Thessaloniki is also influenced.

As a result we may detect a relative proximity of the epicenter of an oncoming earthquake but we cannot determine the direction in which the earthquake will happen. In this case the observations of the other network receivers will help to spot the epicenter.

5. Concluding Remarks

Continuous research during the last decades indicate an unquestionable influence of the earth lithosphere upon the ionosphere. Tectonic activity which may result to an earthquake induces disturbances on the earth ionosphere. VLF/LF radio transmission is a very good diagnostic mean for lower ionosphere disturbances and consequently for earthquake precursors. INFREP network is dedicated to the study of these phenomena, the so called seismo-electromagnetic phenomena, with the hope that our knowledge on that will help to the mitigation of the earthquake loses in life and infrastructions. The present network will be extended to cover the whole Europe and is already connected with a similar network which is in operation in Japan during the last decade.

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