Normalization and processing of VLF signals for the detection of seismic-ionospheric precursor phenomena using the Empirical Mode Decomposition Method and Neural Networks.

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Abstract

The scope of this paper is to present a method for enhancing the detection abilities of seismic-ionospheric precursor phenomena using VLF radio signals. Therefore, a normalization of the VLF signals received is applied prior to their analysis by the Empirical Mode Decomposition in order to bring forth the impact of the attributes of the ionosphere on the disturbance of VLF waves and also bring in line the detected disturbances across multiple stations of different characteristics such as the transmitted power and the distance between transmitter and receiver. Finally, artificial neural networks are applied to automatically detect seismic-ionospheric precursor phenomena.

1. Introduction

It is well established that the earthquake activity contributes to ionospheric variability(Xenos et al., 2009,2010). Extensive studies point to the conclusion that the Earth's lithosphere interacts with the atmosphere prior to a strong seismic event, resulting in the generation of an anomalous electric field that affects the electron content of the ionosphere(Pulinets et al., 1997,2004).However, the seismo-ionospheric interaction is considered a local event, in the sense that only a certain area over the ground is affected by the earthquake, and its size is a function of the magnitude of the event.
On the contrary, solar activity, which is the primary contributor to ionospheric variability, affects the ionosphere as a whole, producing, more or less, global effects compared to the localized phenomena of seismo-ionospheric coupling. The challenge therefore is to distinguish between the seismic-generated D-layer fluctuations and the fluctuations attributed to solar activity. The problem becomes more and more complicated when other smaller magnitude disturbances of undefined origin appear in the received signal, usually characterized as geophysical or ionospheric noise.

2. Data and Analysis

VLF signals transmitted by number of VLF transmitters (Table I) located in Europe are monitored for over a year in Thessaloniki (40.69N 22.78E). The received signal is sampled (sampling rate 1 sample per second) and stored for off line processing. For the purpose of this study the data collected for the period of one month is chosen (1-3-2011 up to 31-3-2011).

Table I

Frequency (Hz)	Station Call	Location	Country	Lat/Lon
19.580	GBZ	Anthorn	UK	54.912, -3.277
20.270	ICV	Tavolara	Italy	40.923, 9.731
23.400	DHO	Rhauderfehn	Germany	53.082, 7.616
37.500	ICE	Keflavik	Iceland	63.959, -22.542

Then, a normalization of the VLF samples is applied prior to their analysis by the Empirical Mode Decomposition method. The procedure is based on the method of calculating the amplitude of the electric field of the received signal as stipulated by Wait (Wait, 1957). According to that method, for signals received from VLF transmitters on the same receiver at the same time the variables that influence the amplitude of the electric field received signal (E) depend on the transmitter power (P) , the wavelength of the transmitted signal (λ) and the normalized distance of the transmitter (d/α) (where α is the radius of the earth) and the receiver as provided by the great circle distance, as well as a factor due to the ionospheric influence (A) (1).

$$E=\sqrt{(P)}*\left[\frac{5*\sqrt{(\lambda)}}{a*\sin(d/a)}\right]*A \qquad (1)$$

Thus, a normalization factor is obtained minimizing the influence of the constant parameters taken into account in (1) with the exception of the ionospheric characteristics of the path between the receiver and the transmitter. Consequently, the disturbances due to precursor phenomena monitored in the time series of the received signals can be accentuated. Then, to reduce the effect of regional ionospheric phenomena and to accentuate the localized phenomena in the direct path of the stations, the previously processed signal is being divided by the previous15 minutes average of the amplitudes of the four VLF stations (figs1 and 2)

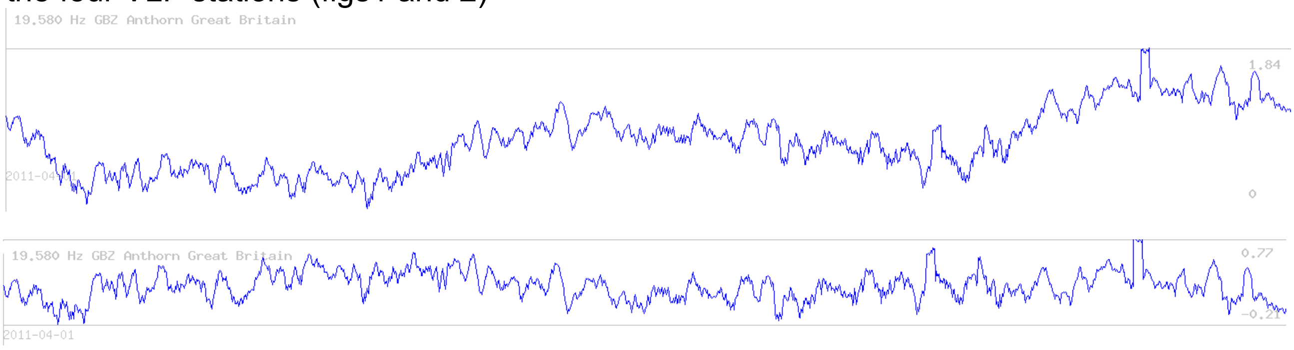

Fig.1. Amplitude diagrams of the received from the GBZ station signal on 1 April 2011: raw data (upper diagram), normalized data (lower diagram)

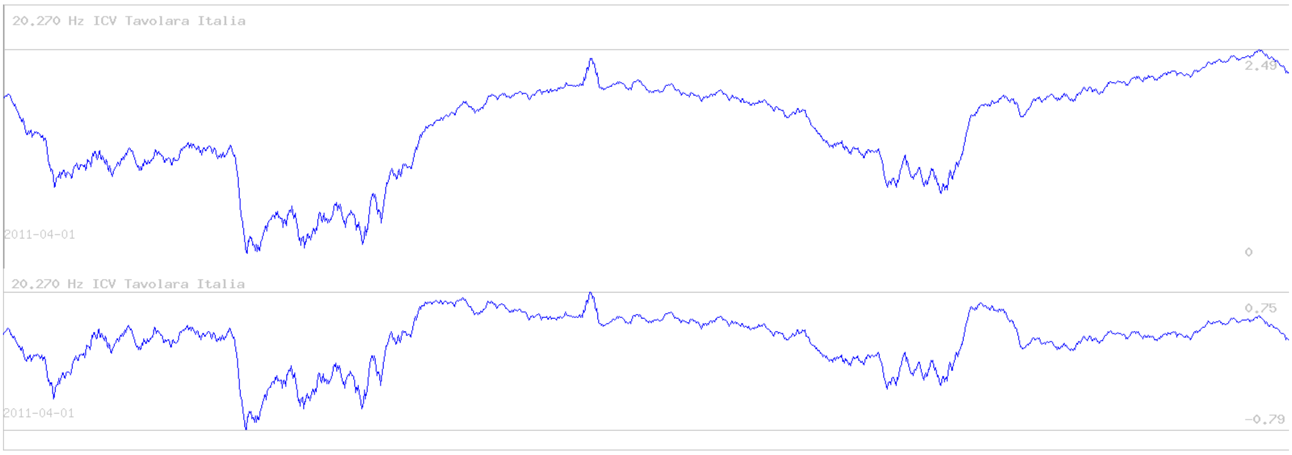

Fig.2. Amplitude diagrams of the received from the ICV station signal on 1 April 2011: raw data (upper diagram), normalized data (lower diagram).

In order to bring forth those disturbances and to facilitate their detection the use of Hilbert-Huang Tranform (Huang et al. 1998,2005) is then applied, or rather part of it described by the Empirical Mode Decomposition method. (fig 3). This is an adaptive method for processing non-linear and non-stationary signals. In fact, EMD decomposes a real signal into its functional components, known as Intrinsic Mode Functions (IMF). The process can be compared to a filter bank (Flandrin et al. ,2004) and this can provide a high pass filter, that can provide a clear image on abnormal disturbances on the signal that are not part of the normal noise content.

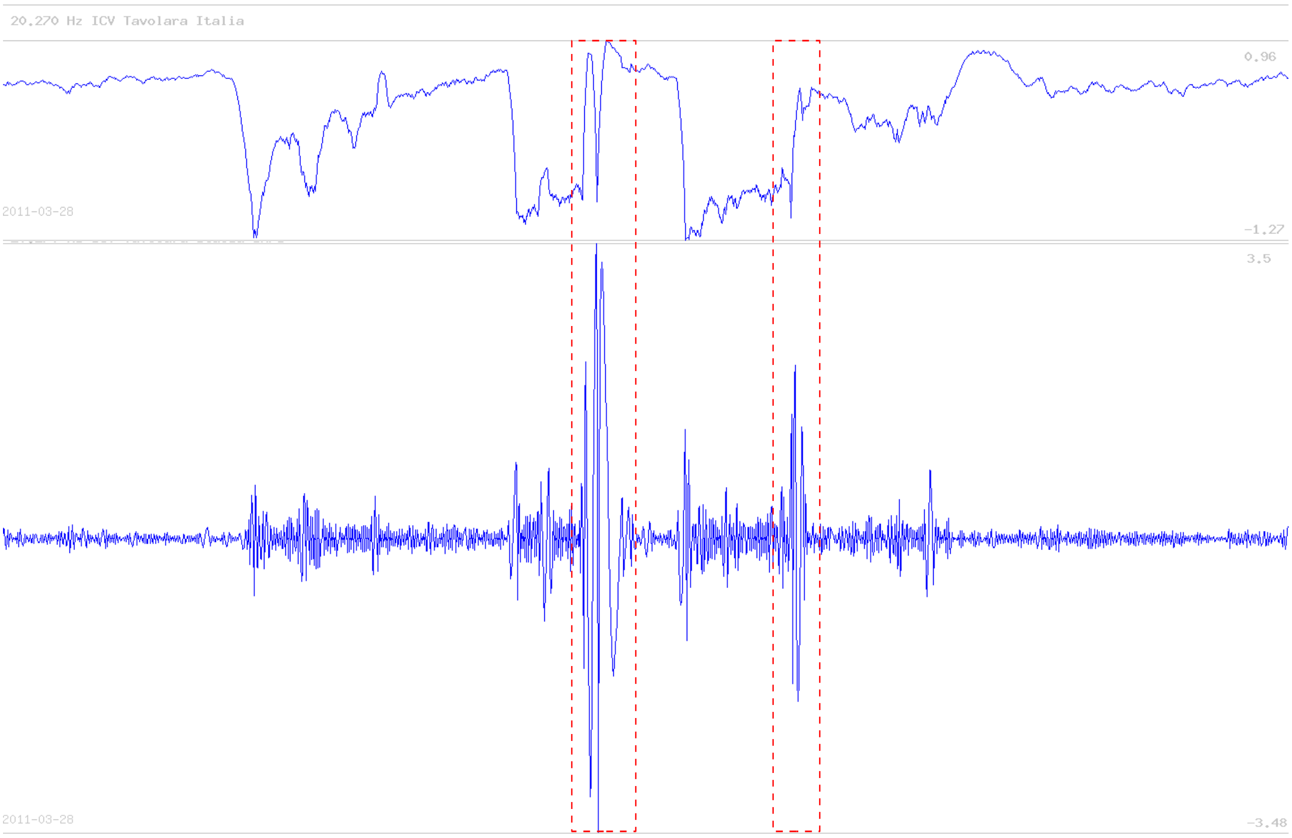

Fig3. Disturbance on the normalized amplitude data(upper) and the IMF1 diagram (lower) on the ICV station Tavolara, Italy 19.58kHz recorded on 28-03-2011.

In Fig 3 precursor phenomena to the three earthquakes observed on the 31 March 2011 in Ionian Sea, Greece (38.14 N, 20.60 E) M=3.2 and in Sicily, Italy (38.28 N, 15.15 E) M=3.2 , and finally in the Ionian Sea, Greece (39.62 N, 20.34 E) M= 3.2 three days later).

The red lines indicate the seismic events.

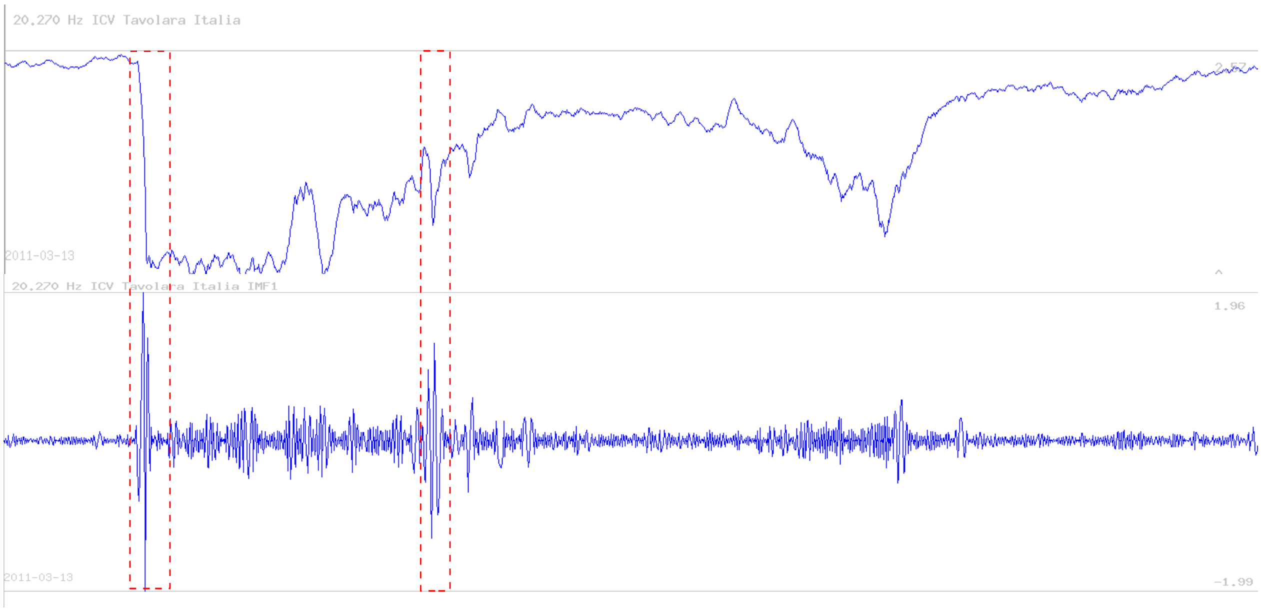

Fig. 4. Disturbance on the normalized amplitude data(upper) and the IMF1 diagram (lower) on the ICV station Tavolara, Italy 19.58kHz recorded on 13-03-2011

Further on, the application of Artificial Neural network is investigated in order to explore the possibility of automatic prediction future seismic precursor phenomena or at least provide a preliminary discrimination among the received disturbances. In fact, artificial neural networks were employed to provide a method for quickly scanning the Intrinsic mode Functions (IMF), derived by the application of the EMD method, in order to provide real time discrimination of disturbances due to precursor phenomena. Thus the implementation of a back propagation feed-forward neural network (NN) was selected (Table II). The NN configuration was selected after testing an extensive variety of possible configuration of feed forward neural networks.

Table II. Artificial Neural Network characteristics

Learning method	**Layer structure**	**Transfer Function**	**Output Functions**	**Number of neurons h-layer**
Back-propagation	4 Input 1 Hidden 1 Output	tangent sigmoid	g(x), tangent sigmoid	6

For the ICV station in Tavolara, Italy, for a period of one month (March 2011) a day was selected with clearly observed disturbances (7 March 2011) as a precursor to the 09 March 2011 Sicily,Italy (39.62 N, 20.34 E) M=3.7 earthquake. The data base of this day had 1440 samples; 20 minute intervals were selected for every sample and from that interval certain factors of the IMF were selected such as the number of peak values, their sum, etc. The intervals were selected after empirical observation of learning and success rates. With the selected configuration for a random permutation of 70% training values and 30% testing values a consistent 98% of correct detection of disturbances across multiple different executions of the training process, with a false positive rates of 0.2%.
Applying the so trained neural network for the whole selected month, we detected 17 reported disturbances that can all be attributed to earthquakes with magnitude higher than M=3 in the region between Greece and Italy.

3. Results and discussion

The application of NNs proved very satisfactory. In fact in geographical latitudes higher than Peloponnese (fig. 5) , 96% of successful predictions were achieved and zero false or negative predictions, whereas for the whole Ionian Sea area the successful prediction reached 50% with a 2% of false predictions. This can be explained by the fact that the NNs employed were trained with prototype patterns obtained by precursor phenomena of earthquakes occurring in geographical latitudes higher than Peloponnese. Therefore, it is obvious that more prototype patterns are required to enhance the prediction accuracy of the NNs.

Fig 5. Ionian Sea map

4. Conclusions

From the analysis we can conclude that the normalization process can provide a better overview of the received signal and can facilitate in the process of locating disturbances on that signal. As such it can provide a clearer view of the disturbances that can be attributed to the ionosphere.
Furthermore the processing of the signal through the use of EMD can accentuate the disturbances encountered and can provide a clearer view of the phenomena that are being monitored as well as provide a starting input for the use of Neural Networks. That use of NN with the proper training procedure can lead to a system that could aid in the automatic detection of seismic precursors.
The above processes have been intergated on a real time on line experimental system which can be found at http://79.129.26.170:81/

References

Flandrin, P., Rilling, G., and Goncalves, P.: Empirical Mode Decomposition as a filter bank, IEEE Signal Proc. Lett., 11(2), 112–114, 2004a.
Flandrin, P., Goncalves, P., and Rilling, G.: Detrending and denoising with Empirical Mode Decompositions, Eusipco, 12th European Signal Processing Conference, Vienna, Austria, 6–10 September 2004b.
Huang, N. E., Shen, Z., Long, S. R.,Wu, M. L., Shih, H. H., Zheng,Q., Yen, N. C., Tung, C. C., and Liu, H. H.: The empirical mode decomposition and Hilbert spectrum for nonlinear and nonstationary time series analysis, P. Roy. Soc. Lond. A Mat., 454, 903–995, 1998.
Huang, N. E. and Attoh-Okine, N. O.: The Hilbert-Huang transform in engineering, Taylor & Francis, 2005
Pulinets, S. A.: Alekseev, V. A., Legenka, A. D., and Hegai, V. V.: Radon and Metallic Aerosols

Emanation before Strong Earthquakes and their Role in Atmosphere and Ionosphere Modification, Adv. Space Res., 20(11), 2173–2176, 1997.
Pulinets, S. A.: Ionospheric Precursors of Earthquakes; Recent Advances in Theory and Practical Applications, Terr. Atmos. Ocean. Sci., 15, 413–435, 2004
Tsolis, G. S. and Xenos, T. D.: Seismo-ionospheric coupling correlation analysis of earthquakes in Greece, using empirical mode decomposition, Nonlin. Processes Geophys., 16, 123–130, 2009,http://www.nonlin-processes-geophys.net/16/123/2009/
Tsolis, G.S. and Xenos, T.D. : A qualitative study of the seismo-ionospheric precursors prior to the 6 April 2009 earthquake in L'Aquila, Italy, Nat. Hazards Earth Syst. Sci., 10, 133–137, 2010 www.nat-hazards-earth-syst-sci.net/10/133/2010/
Wait, J. R.: The Attenuation vs Frequency Characteristics of VLF Radio Waves, Proc. I.R.E. 45 (1957), p. 760