STUDY OF IONOSPHERIC ANOMALY DURING SEISMIC ACTIVITY BY USING WAVELET ANALYSIS

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ABSTRACT

In this research, we introduced a wavelet-based approach designed to identify and analyze ionospheric anomalies linked to seismic events by utilizing hourly foF2 ionosonde data. We employed wavelet transform and cross-wavelet analysis techniques to uncover and characterize the spatio-temporal fluctuations of ionospheric anomalies related to the 6.3 magnitude earthquake that struck L'Aquila, Italy, on April 6, 2009, as well as another significant event with a magnitude of 7.8 that occurred in Indonesia on October 25, 2010. To deepen our understanding of the dynamic interactions between the variability of ionospheric anomalies and geophysical indices, we analyzed 30 days of data both prior to and following the earthquakes. This paper presents the details of the algorithm and the findings of our analysis.

Keywords:

Wavelet power spectrum; ionospheric anomalies; foF2; solar and geomagnetic activity.

1 INTRODUCTION

Until now earthquake is a mysterious phenomena and there is no method that successfully predicted or forecast the earthquake phenomena. Scientists are trying to discover more reliable earthquake precursors so that earthquake prediction may be possible in future. Form last few decades the methods for earthquake predictions mainly focuses on searching abnormal variation in various geophysical quantities produced during earthquake preparation process. More than 100 years ago, the relationship between geomagnetic abnormal variation and earthquakes was noticed. At the end of

1950's, because the proton precession Magnetometer with high precision and good stability was invented and widely used, the observation technique for geomagnetic field was greatly improved and some earthquakes were convincingly predicted.

According to Lithosphere-atmosphere-ionosphere coupling (LAIC) model, geochemical, atmospheric and ionospheric parameters are united by a common physical mechanism (Pulinets, 2009). Using IAP (ionospheric plasma analyzer) and ISL (Langmuir probe) on DEMETER satellite and GPS data analysis Akhoondzadeh *et al.* (2010) and Shailesh Raghuwanshi et al. (2013) showed electron and ion density variations in the ionosphere occurred over locations prior to strong earthquakes. Jain *et al. (*2010) reported the anomalies in slab thickness of ionospheric F-region for some days before the main seismic event. They concluded that it may be due to the seismogenic electric field developed above the surface of the earth. Recent investigation has shown that major earthquake ($M \geq 6.0$ Richter scale) occurrence within 48 hrs is expected when geomagnetic index Kp attains its minimum value (Midya et al., 2011).

Scientists keep searching new methods for detecting the geomagnetic precursors before earthquakes for many years and some of them have been put into use for earthquake prediction in China. Among them, both the methods "Geomagnetic Transfer Function" and "Abnormal Daily Variation" are proved to be successful in earthquake prediction. However, "Geomagnetic Transfer Function" can only be used to middle and long term earthquake prediction and "Abnormal Daily Variation" can predict the possible date of an earthquake, but not the exact location. Some attempts are already taken by different scientist throughout the world. No satisfying methods are found until now, and it is important to apply new methods to detect the earthquake precursors. This is due to the fact that most of the earthquake prediction is based on traditional Fourier Transform (FT) method or the statistical methods. But it is well established that the numbers of data in geophysical domain consists of short duration transients and are highly non-linear and non-stationary in nature. Therefore performance of FT and statistical methods are diminished. To overcome these difficulties or limitations Wavelet Transform based methods are generally used now a day.

The wavelet analysis is a mathematical technique which is very useful for numerical analysis of time series data in geophysics. Therefore the use of wavelet techniques in geophysical data analysis has grown since it represents a synthesis of old techniques associated with robust mathematical results and efficient computational algorithms under the interest of a broad community (Daubechies et al., 1992). It is a rapidly developing field. Overviews of papers are particularly very useful for the understanding of this method and several good ones concerning wavelets are already available (Daubechies et al., 1992; Chui 1992). In geophysical domain the main characteristic of the wavelet based methods is the interpretation of the time-frequency decomposition. For the better understanding of such feature, let us consider an example of musical structure where it has been interpreted as events localized in time. Although it belongs to a more complex structure, a piece of music can be understood as a set of musical notes characterized by four parameters: frequency, time of occurrence, duration and intensity (Daubechies et al., 1992; Lau and Weng, 1995).

In the last decades, the wavelet technique has been extensively adopted in atmospheric science (Gambis ,1992, Krankowski et al. , 2005). In last decade numerous attempts were made to compare TEC values obtained from different ground- and space-based observations (Codrescu et al., 2001; Orus et al., 2002; Balehaki et al., 2003). An extensive database of TEC measurements has become available from GPS and VLBI. The GPS satellites continuously provide TEC data (since 1994) through the world-wide network of GPS ground receivers. Earlier than GPS the VLBI technique has provided TEC data for more than 20 years (since 1984), collected at IVS (Hobiger et al., 2005).

In this work, the Morlet Wavelet Transform (MWT) is used to determine the wavelet time-Frequency spectra of foF2 data above the earthquake region of Italy, Indonesia, Newzealand and Papua New Guinea for the time period of 30 days for different earthquakes.

2. CHARACTERISTICS OF EARTHQUAKES

We used five different earthquake cases for seismic precursor study. The characteristics of these earthquakes were summarized in Table [1].

Table [1] Characteristics of earthquakes

S. N.	Date	Time (UT)	Name of Earthquake	Epicenter	Mag	Focal Depth	Name of nearest Ionosonde	Position of Ionosonde	Distance from Epicenter (KM)
1	06/04/2009	01:32:39	Italy: L'aquila	42.33^0N /13.33^0E	6.3	9	Rome	41.8^0N/ 12.5^0E	90
2	25/10/2010	14:42:22	Indonesia	3.49^0S /100.08^0E	7.8	20	Cocos island	12^0S /96.8^0E	1012

3. THE DATA

In this study we have collected the foF2 hourly data for the ionosonde situated within the earthquake preparation zone with the help of NOAA Space Environment Center (http:// http://www.ngdc.noaa.gov)and various earthquake data with their characteristics we retrieve from Survey (http://www.usgs.gov/natural_hazards).We have find out numbers of earthquakes in these region within time limit but due to unavailability of proper foF2 data we had selected only few for study. To examine the various geomagnetic effect imparted at this observed data we used OMINI web data server (http://omniweb.gsfc.nasa.gov) ,which provide the Dst ,Kp and ap parameters value at the given time period.

4. METHODOLOGY

In this section short overview of wavelet transform is given in the context of work done in this chapter. It is very essential for the understating of the work done here.

4.1 WHY WAVELET?

The main concern of this work is to study the variation in ITEC during earthquake which we can consider as earthquake precursor. Consequently we need to use a spectral analysis tool to decompose the original ITEC data into various frequency bands and still keep the localized information in time domain. The wavelet analysis is very advanced and suitable method for such data with impulsive, multiscale, and non stationary spectral features. It has a wide range of tools, such as wavelet transform, multi resolution analysis, timescale analysis, time-frequency representations, matching pursuit decompositions and other powerful tools. It allows decomposing the ITEC data into the different timescales of variations, which are localized in time. Wavelet transform provides the opportunity to separate the variations according to the timescales of their drivers, which are from the ionospheric parameter in the ionosphere and magnetosphere. It also provides the possibility to reconstruct the data according to variations of specific timescales and frequencies after filtering process.

4.2. COMPARISON BETWEEN WAVELET TRANSFORM AND FOURIER TRANSFORM

As spectral analysis tool wavelet analysis has some similarities and dissimilarities as compared to the Fast Fourier Transform (FFT), which is widely used in geophysical research as basic tool for the spectral analysis. They are both linear operations that generate a data structure that contains $\log_2$ (n) segments of various lengths, usually filling and transforming it into a different data vector of length 2n. The mathematical properties of the matrices involved in both the transforms are similar as well. The inverse transform matrix for both the wavelet transform and the FFT is the transpose of the original. As a result, both transforms can be viewed as a rotation in function space to a different domain. For the FFT, new domain contains basis functions that are sines and cosines. For the wavelet transform new domain contains more complicated basis functions called wavelets, mother wavelets, or analyzing wavelets. Another similarity is that the basic functions are localized in frequency making mathematical tools such as power spectra (how much power is contained in a frequency interval), useful at picking out frequencies and calculating power distributions.

The most important dissimilarity between wavelet transform and Fourier transform is that individual wavelet functions are localized in space (time domain in geomagnetic data analysis). This localization feature along with wavelets localization of frequency makes many functions and operators using wavelet transform when transformed into the wavelet domain. This results in a number of useful applications such as data compression, detecting features in the original data and removing noise from the time series, which is suitable for the geomagnetic data analysis.

Another advantage of wavelet transforms is that the windows vary. In order to isolate signal discontinuities, one would like to have some very short basis functions. At the same time in order to obtain detailed frequency analysis, one would like to have some very long basis functions. A way to achieve this is to have short high frequency basis functions and long low frequency ones. This provides the possibility of separate specific timescale of variations, which are contained in the original data.

4.3 THEORY OF WAVELET TRANSFORM

A wavelet is a small wave in which energy is concentrated in time. It gives a tool for the analysis of transient signal, non-stationary or time-varying phenomena. In wavelet analysis method it is possible to represent the signal as time-localized oscillatory function, which is called Mother Wavelet. This function is continuous in time and frequency and act as a source function by which scaled and translated basis function are constructed. In Fourier analysis we used sine and cosine function as orthogonal basis function. But wavelet analysis consists of decomposing a signal or an image into a hierarchical set of approximations and details. From an algorithmic point of view, Wavelet analysis offers a harmonious compromise between decomposition and smoothing techniques.

General overview of Wavelet analysis may be found in Chui (1992), Daubechies et al. (1992), Sone and Yamamoto (1997). Wavelet analysis uses a time localized oscillatory function as a Mother Wavelet. Using the Mother Wavelet function $\psi(t)$ the continuous wavelet transform of a signal $f(t)$ is defined as:

$$Wf(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\bar{\psi}\left(\frac{t-b}{a}\right)dt \qquad [1.1]$$

Where,

a =dilation parameter

b = translation parameter

$\bar{\psi}$ = complex conjugate of $\psi(t)$

To ensure the existence of inverse wavelet transform mother wavelet satisfies the condition of admissibility given by:

$$C_{\psi} = \int_{-\infty}^{\infty} \frac{|F_{\psi}(\omega)|^2}{|\omega|} d\omega < \omega \qquad [1.2]$$

Where,

$F_{\psi}(\omega)$ = Fourier transform of $\psi(t)$

The signal $f(t)$ may be synthesized or reconstructed by an inverse wavelet transform of $Wf(a,b)$ as defined by:

$$f(t) = \frac{1}{C_{\psi}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Wf(a,b)\, \psi\left(\frac{t-b}{a}\right) \frac{1}{a^2}\, dadb \qquad [1.3]$$

A wavelet family associated with mother wavelet $\psi(t)$ is generated by two operation dilation and translation, which are denoted by parameter a and b. The dilation parameter indicates the width of wavelet window, smaller the value of a higher the filter resolution and translation parameter b indicates the wavelet window. In the wavelet transform shifting the wavelet window along the time axis examine the signal in neighborhood of window's current location. In this way the information remain in the time domain.

In practice discrete wavelet transform is used in which the dilation parameter a and the translation parameter b are discrete. These procedures become much more efficient, if dyadic values of parameters a and b are used.

$$a = 2^j, b = 2^j k \qquad j, k \in Z \qquad [1.4]$$

Where Z = set of positive integer

For a special cases of $\psi(t)$, corresponding discredited wavelets $\psi_{jk}(t)$ is used, which is given by:

$$\psi_{jk}(t) = 2^{\frac{j}{2}}\psi(2^j t - k) \qquad [1.5]$$

Which constitute an orthogonal basis for $L^2(R)$ (Mallat, 1991; Daubechies, 1992; Jawerth and Sweldens, 1994). Using $L^2(R)$ the wavelet expansion of a function $f(t)$ and the wavelet expansion coefficient are defined as:

$$f(t) = \sum_j \sum_k \alpha_{jk}\psi_{jk}(t) \qquad [1.6]$$

and

$$\alpha_{jk} = \int_{-\infty}^{\infty} f(t)\bar{\psi}_{jk}(t)dt \qquad [1.7]$$

DETAILS AND APPROXIMATIONS

In discrete wavelet transform a signal can be represented by its approximations and details. The details at level *j* are defined as:

$$D_j = \sum_{k \epsilon Z} a_{jk}\psi_{jk}(t) \qquad [1.8]$$

And approximation at this level

$$A_j = \sum_{j=J} D_j \qquad [1.9]$$

It’s become obvious that

$$A_j - 1 = A_j + D_j \qquad [1.10]$$

and

$$f(t) = A_j + \sum_{j \leq J} D_j \qquad [1.11]$$

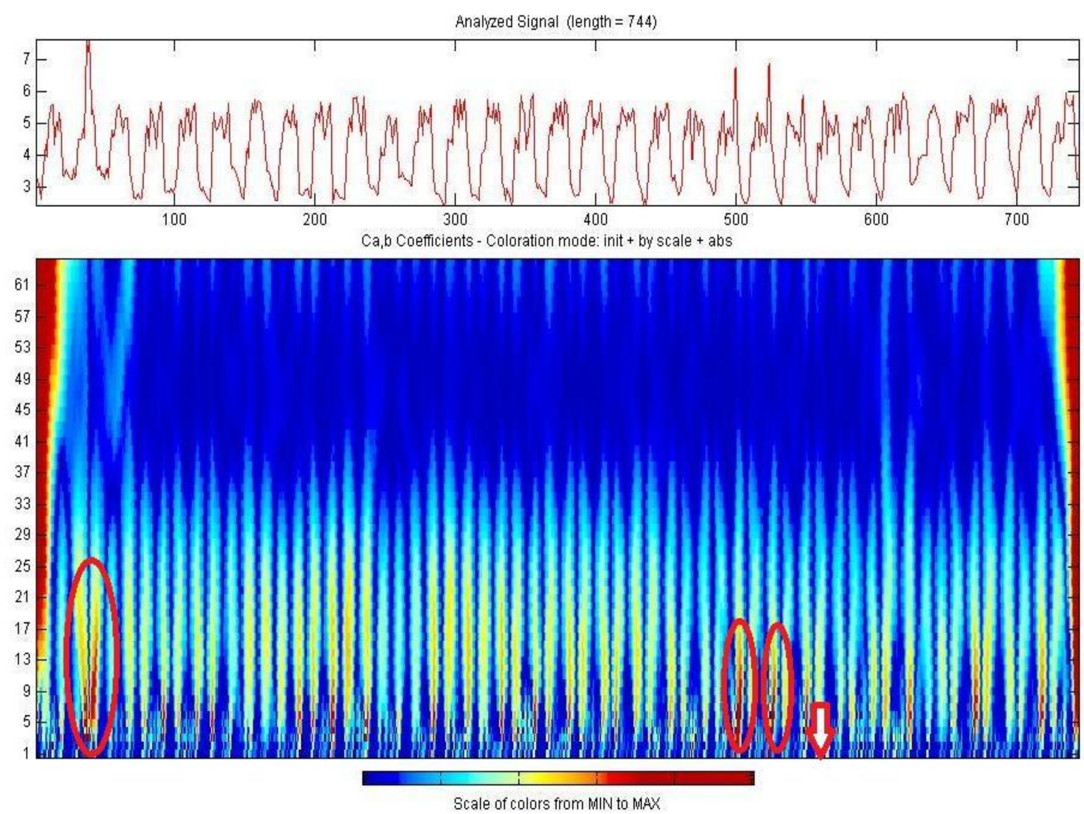
These equations provide a tree structure of a time series and also a reconstruction process for the series.

5. RESULTS AND DISCUSSION

Analysis of ionospheric F2 layer critical frequency (foF2) for several strong earthquakes in Italy, Indonesia, Newzealand and Papua New Guana revealed the common feature of ionospheric anomalies observed before earthquakes. These anomalies are expressed in the form of sharp changes of foF2 few days before the seismic shock. We present five cases of earthquakes in which ionospheric perturbations were observed before the earthquake. Results related to these earthquakes are described below.

5.1. ITALY – L'AQUILA EARTHQUAKE OCCURRED ON APRIL 06, 2009

An earthquake of magnitude 6.3 was occurred in Italy – L'Aquila in the month of April 2009**.** Epicenter of this earthquake was [42.33^{0}N, 13.33^{0}E]. This was a type of shallow earthquake with focal length of 9 km. we have analyzed the abnormal variation in ionospheric foF2 signal over the epicenter observed by ionosonde located at Rome [41.8^{0}N, 12.5^{0}E] during 15 March-15 April 2010.For the analysis ionospheric of foF2 parameter wavelet transform is used and the result of analysis is shown in Figure [1.1].



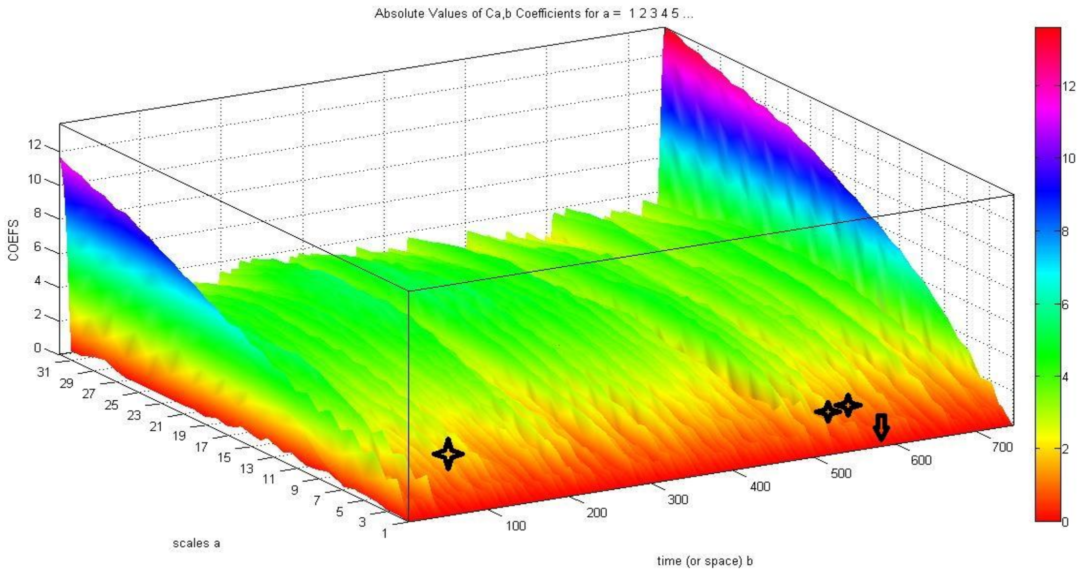


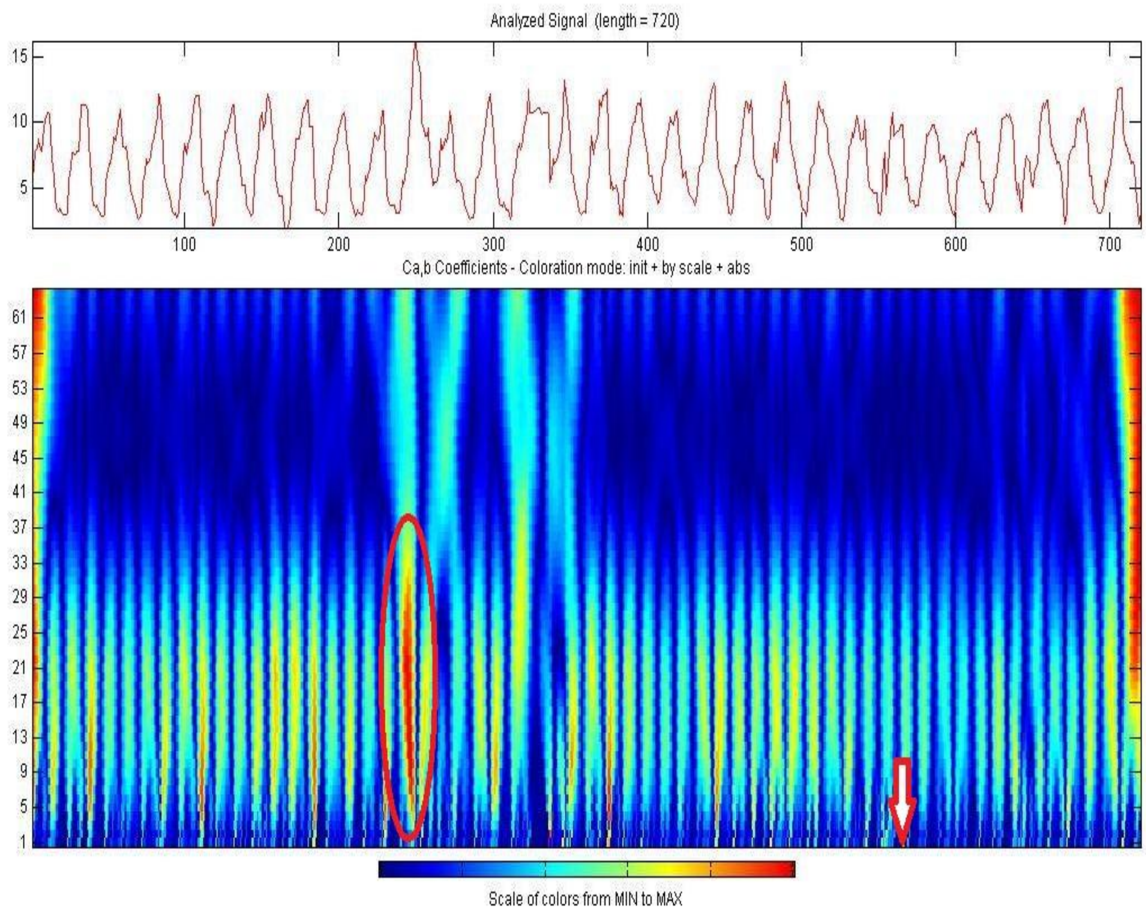
Figure [1.1] Continuous wavelet transforms study of foF2 signal for the Italy earthquake [42.33^{0}N, 13.33^{0}E] occurred on 6/04/2009.

The upper panel shows the variation in foF2 within given time interval. Middle panel shows the Wavelet power spectrum to analysed coefficient result of these signals and last panel represent the three dimensional wave patterns for the analysed CWT. It found that the continuous wavelet power spectrum shows anomalous variations and significant enhancements in fof2 signal few days before the shock. We observed anomalous variations in foF2 signal before twenty days, two days and one day before the main seismic shock which was represented by circle and the day of seismic event are denoted by an arrow. In last panel stars indicate the lower values of wavelet coefficient which shows the precursor phenomena. The large values at either end of the spectrum are due to the scale smoothing operator reaching the scale boundaries.

5.2. INDONESIA EARTHQUAKE OCCURRED ON OCTOBER 25, 2012

During the month of October 2012, an earthquake occurred in Indonesia on 25 with magnitude 7.8 and focal length of 20 km. Epicenter of this earthquake was [3.49^{0}S, 100.08^{0}E]. The variation of the ionospheric foF2 signal observed at Cocos Island [12^{0}S, 96.8^{0}E] is studied using wavelet transform over the epicenter during 1 October-30 October 2012.

The result of analysis is shown in Figure [1.2]. In which upper, middle and lower panel shows variation in observed foF2 signal for the given time period ,wavelet power spectrum and three dimensional wave patterns for the analysed signal using CWT method respectively. It was notice that anomalous variations in foF2 signal before fourteen days from the main seismic shock which was represented by circle and seismic event is denoted by an arrow. It shows that the continuous wavelet energy power spectrum of ionospheric anomaly variations exist many significant enhancements before the shocking. In last panel star indicate the lower value of wavelet coefficient which shows the precursor phenomena.



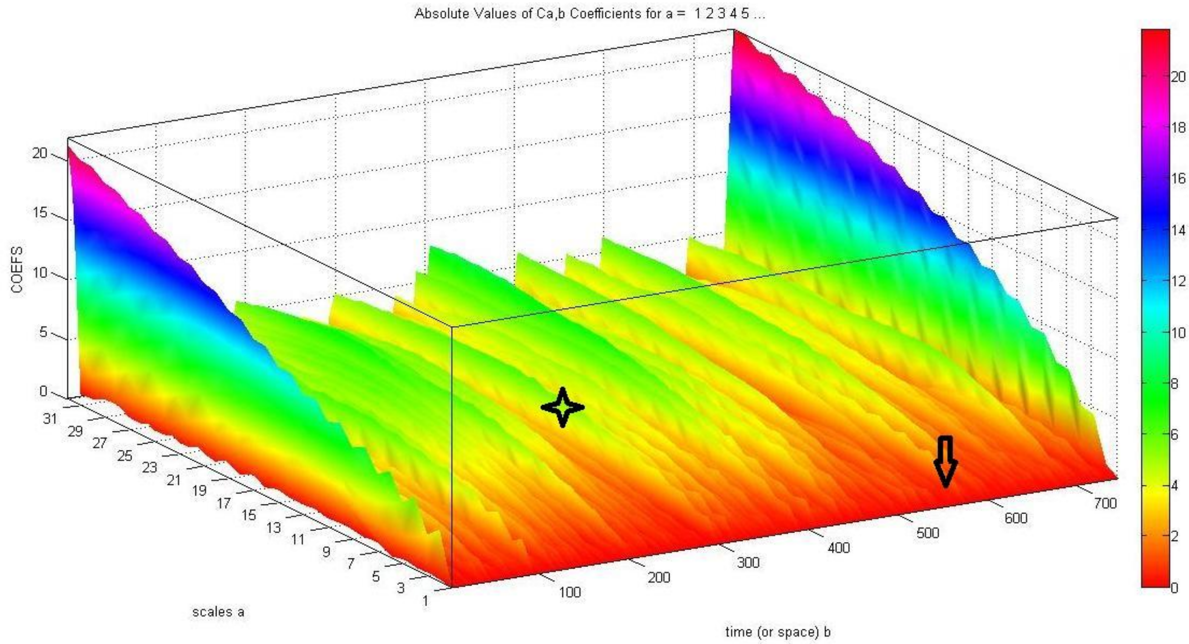


Figure [1.2] Continuous wavelet transforms study of foF2 signal for Indonesia earthquake [3.49^0S, 100.08^0E] occurred on 25-10-2012.

Here anomalous variations in foF2 signal is observed before fifteen days from the main seismic shock which was represented by circle and seismic event is denoted by an arrow. It shows that the continuous wavelet energy power spectrum of ionospheric anomaly variations exist many significant enhancements before the shocking. In last panel stars indicate the lower values of wavelet coefficient which shows the precursor phenomena.

6. CONCLUSIONS

The problem of variability in the ionosphere is one of the most actual and complex problem in modern Ionospheric Physics. This is due to the fact that it is impossible to determine the main cause of this effect. A lot of different factors make a contribution to this phenomenon making it unpredictable in a deterministic sense. In addition, there is no commonly accepted way of quantitative description of this ionospheric variability. It exists more in an intuitive rather than in a well determined manner. To know the reason of ionospheric variability, we can divide the sources into two large categories the effects on the ionosphere from above and from below. These effect were observed by many scientist (Davies, 1990;Afraimovish et al.,2002; Pulinets et al., 1996,1998 ;Kazimirovski , 2002; Forbes et al.,2000; Rishbeth and Mendillo.,2001) ; Shailesh Raghuwanshi et al. (2013).

The results discussed in the above section shows significant ionospheric perturbations several days before and few days after the main shock observed by various ionosonde stations. The observed anomalous variations might be correlated with the seismic effect due to isolation from any known solar or magnetic activities. All ionosonde stations show anomalous variation in foF2 around the time of main shock. Others in agreement with those report the present results and hence it can be concluded that ionospheric behavior changes a few days before a major seismic shock within or far from the earthquake preparation zone. The cause explaining these ionospheric disturbances are related to the action of upward propagating electric fields generated due to the stress of rocks. Many authors proposed the hypothesis on the possible internal gravity waves or Acoustic Gravity Wave (AGW) generation before earthquakes (Garmash et al., 1989; Linkov et al., 1990 and Shalimov, 1992). Taking in to account that morphological features of the ionospheric precursors of earthquakes make a foundation of the development of the techniques of short-term earthquake prediction. On the average seismo ionospheric variations increased or decreased up to 10% to 30% and not depend on the magnitude of earthquake or focal depth etc. The seismo ionospheric variation has an effect on vertical distribution of the plasma leading to an increase of the height scale of the ionosphere. Variations are observed only related to earthquake preparation zone.

The main idea we present in this research is that the joint multi resolution wavelet analysis of self-potential signals and support data related to environmental forcing can represent a suitable basis to extract environment-induced electrical fluctuations. Wavelet transform translates the complexity of mixed global behaviors and transient patterns described by the electrical signals in simpler time sequences of coefficients over several resolutions or scales. We focused on hourly self-potential variability driven by earthquake by exploiting hourly measures as support data. Such data, transformed in the wavelet domain, were used to mark the time-scale regions where earthquakes act influencing self-potential variability. We showed that in these regions excited wavelet coefficients of the signal are detectable. Moreover, these coefficients can be filtered out, removing distortions with a mildly invasive technique. We think that our methodological approach is promising. However, there liability of the recovering procedure is strictly related to the quality of the support data and their ability to represent the actual mechanisms we are interested in.

In the analysis, wavelet techniques are basically used in two ways: as an integration nucleus of the analysis to get information about the processes and as a characterization basis of the processes. Some selected papers, here shortly described, reveals applications in a wide range of phenomena. Ranging from issues related to atmospheric-ocean interactions to nearby space conditions, all aspects are related to the atmosphere as a whole.

Several authors have discussed the problem of choosing the Daubechies orthogonal wavelet functions for turbulent signals, for example Katul and Vidakovic (1996, 1998); Vidakovic (2000). They have found that the best choice is a function that produces less unbalance on the signal energy, i.e., in which less coefficients are needed to represent the signal. These authors have developed a threshold procedure, that they denominate as Lorentz threshold, to identify the most relevant coefficients. Liu (1994) has defined a coherence wavelet function using a Morlet wavelet to study the interactions between the wind and the oceanic waves. Torrence and Compo (1998) have discussed the practical applicability of such information in characterizing the cross correlation, since there are some difficulties in the analysis of the resulting information. In this study, the conventional treatment given to the Fourier analysis affects the temporal localization of the wavelet analysis. The shape of the chosen wavelet function must translate the characteristics of the time series. For example, to represent a time series with abrupt variations or steps, the Haar wavelet may be the most convenient. In the analysis of time series with smoother variations, the mexican-hat and Morlet wavelet can be recommended.

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