Observational and Analysis Techniques for Studying the Ionosphere – A Precursor Zone for Detection of Earthquakes

R.C. Sharma[1] and Niharika Sharma[2]

[1]Department of Applied Sciences and Humanities, Dronacharya College of Engineering, Khentawas, Gurgaon – 123506, Haryana (India)
[2]Government Senior Secondary School Kakoria, Rewari, Haryana (India)
E- mail: [1]ramchhavisharma@yahoo.com

Abstract—*It has been detected that there are distinct ionosphere anomalies located over area of seismic activity. There is supporting evidence that electromagnetic emission propagate from the ground causing these turbulence. This paper accumulates the recent advances in scientific understanding of the problem of seismo – ionosphere coupling related. It analysis the physical mechanism, main features of ionosphere variations associated with earthquakes and observational and analysis techniques of studying the ionosphere. For this purpose, the L'Aquila earthquake occurred on Monday, 6 April 2009 at 01:32:39 UTC has been selected. The exact coordinates of the event were 42.334^0 N and 13.334^0 E, which correspond to a point 85 km northeast of Rome. This earthquake was the main shock of a series of pre-seismic events, which started in February and continued through March 2009. This event analyzed using two different techniques i.e. using cross-correlation coefficient method combined with Empirical Mode Decomposition and by using Fourier wavelets and bi-spectral method. The study reveals that the electromagnetic effects associated with plasma turbulence in the ionosphere can be one of the significant indicator.*

Keywords: *Ionosphere, earthquakes, seismo- ionospheric interaction, satellite*

1. INTRODUCTION

The earthquake is a sudden and rapid shaking of the earth caused by the breaking and shifting of fault lines/collision of tectonic plates beneath the earth surface. This results in being able to observe the signs that are possible precursors of earthquakes by monitoring tension of the rocks [1]. Monitoring emissions of excessive unexpected radon gas in the cracks or breaks in the fault lines can be defined as possible precursors of earthquakes [2]. Excessive emission of radon gas in the time frames prior to the earthquakes and the changing magnetic field of the earth present another method group of possible precursors. Magma movements setting off earthquakes and the movements of earth layers cause changes in magnetic field of the earth [3]. This change in magnetic field will have an influence on ionosphere height [4]. Height of ionosphere will determine reflection height of VLF signal and the unexpected changes in this will be able to be related to external factors. Changes in magnetic field of the earth will also have an impact on the ionization of ionosphere. Generation of Acoustic gravity waves and anomalous electric field due to earthquake may be responsible for turbulence in the Ionosphere. Electron density and ionization of ionosphere is directly related to losses on the signals as the ionizing effect of radon gasses is quite high [5].It is there for crucial to study the perturbation in the ionosphere using versatile observational and analyzing techniques. In the present paper, a brief introduction about the ionosphere, the observational techniques for studying the ionosphere and peculiarities in the observational techniques for ionosphere precursor registration, the processes involved in the physical mechanism of seismo-ionospheric coupling and analysis techniques applied on the L'Aquila earthquake occurred on Monday, 6 April 2009 are discussed.

1.1 IONOSPHERE

The ionosphere is a large region of the upper atmosphere ranging from 80 to 1000km and contains atoms consisting of O_2, N_2 and O. This layer is known to be very energetic as these atoms absorb solar radiation causing them to become ionized. As a result the atoms transition into the plasma state (ions and free elections) and become susceptible to electromagnetic fields. Radio waves entering this region get affected in much the same way as one entering a region of differing dielectric constant and conductivity. Layer in the atmosphere was first postulated in the middle of nineteenth century in order to explain the daily variation of Earth's magnetic field at the ground level [6]. This hypothesis was revived by Kennelly and Heaviside to explain Marconi's transmission of radio signal across

the Atlantic over the curvature of earth [7]. In 1926, Appleton and Barnett demonstrated a path difference between the continuous wave signals travelling directly over the ground and those reflected from the ionized layer and thus established directly the existence of ionized region. In 1931, Chapman provided theoretical explanation of the formation of the ionospheric layers as due to the ionization of atmospheric gases by solar radiations.

Conventionally, the ionosphere is considered as divided broadly in to three layers which are called bottom to top, the D, E and F-layers. D-region is the lowermost region of the ionosphere and is situated in the altitude range of 80 to 90 Km. Being the lowermost and in a relatively dense part of the atmosphere, the recombination rate is highest and the layer is present only during day light hours. D-region is believed to result from photo-ionization of nitric oxide by Lyman- α radiation from the sun. The peak density of this region occurs near 80 Km altitude and is of the order of $3x10^3$ e/cm^3. This region is capable of reflecting very long waves, the critical frequency being around 100kc/s. the D-region is known mostly as the absorbing layer for short wave signals. The lowest layer that affords long distance communication is in the E-region which extends from about 90km to 120km. above the earth. It is a region of fairly high atmospheric density and consequently the ionization varies with the height of the sun. It is formed by the ionization of all major atmospheric constituents by solar photons in different bands. This region has a day time maximum of ionization of about 10^5 e/cm^3 around 100km, the ionization level drops rapidly after sundown, when ions and electrons recombine in the absence of sunlight. The critical frequency of E-layer lies in the range 3 to 5 Mc/s at noon. Superimposed on the normal E-layer and sometimes obscuring it in conventional ionograms, may be one or more ledges of additional ionization. Their rather random appearance on the conventional apparatus led to their designation as sporadic E-layer. Most long distance communication results from ionization which takes place in the F-region. It is the uppermost region, being situated at the top of the E-region at a height of about 140km and above. There is no generally accepted upper height limit for it. Its principal area is the F2 layer which varies considerably in ionization level and in height. It may be anywhere from 210 to 420 km above the earth depending on season, latitude, time of day, and the portion of the sunspot cycle prevalent at a given time. At these heights the atmosphere is very thin, and so the ions and electrons are slow to recombine. Because of this the level of ionization is not so responsive to the height of the sun, it reaches a maximum shortly after noon local time, but tapers off quite gradually thereafter. The ionization continues to remain at a fairly high level throughout the night though decreasing and reaching a minimum just before sun rise. At sun rise it increases rapidly and attains the day time level in the course of an hour or two. During the day the F-region sometimes splits in to two layers. The lower and weaker one occurring at a height of about 180 km is designated the F1 layer. It has a day time maximum of about $2x10^5$ e/cm^3 near 180 km. During night F1-layer disappears and the ionosphere takes the form of a single layer called the F2-layer, with a maximum of about 10^5 e/cm^3 in the vicinity of about 350 km. The region below F2- layer is known as the ‘ Bottom side’ ionosphere and the region above as the ‘ Topside’ ionosphere.

The atmospheric lay out indicating the temperature and electron density are shown in Fig. 1.

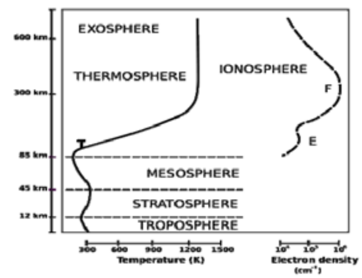

Fig. 1: The Atmospheric lay out indicating the Temperature and electron density.

2. OBSERVATIONAL TECHNIQUES OF STUDYING THE IONOSPHERE

2.1 GROUND BASED IONOSONDE

The radio sounding technique is a basic tool of Ionosphere research [8]. The sounder is a type of radar which is capable of obtaining echoes from the ionosphere over a wide range of operating frequencies. The method is based on measuring the time taken by a pulse of radio waves to travel to the ionosphere and back as a function of frequency. The equipment used is called Ionosonde and the measurements made with it are used to deduce the electron density distribution up to the height of maximum of electron density. In a typical mode of operation, the sounder is swept from 1-25 MHz in 13.5 sec. using a pulse repetition frequency of about one hundred per second and a peak power of up to 30 kilowatts. The new Ionosonde has been designed and built on the basis of the theory of radar systems [9,10]. A synthetic description of the Ionosonde, which is a simplified functional diagram of the whole system is given in fig. 2. The Ionosonde has been divided into functional blocks representing the main functions; one block does not necessarily correspond to physical blocks or circuits. The thicker lines refer to digital buses The blocks are grouped into two sections corresponding approximately to the transmitting and the receiving sections: on the left, there is a power amplifier, a frequency synthesizer and the code generator; on the right there is the radio receiver, the Analog to Digital Converter and the Digital Signal Processor. Every block is controlled by a personal computer (PC Control and storage), which can store and display data. The antennas complete the system. In order to increase signal-to-noise ratio without increasing the transmitted peak power, the pulse compression technique (encoded pulse) is applied. After the echo is received, it is compared to the transmitted code by means of a correlation process.

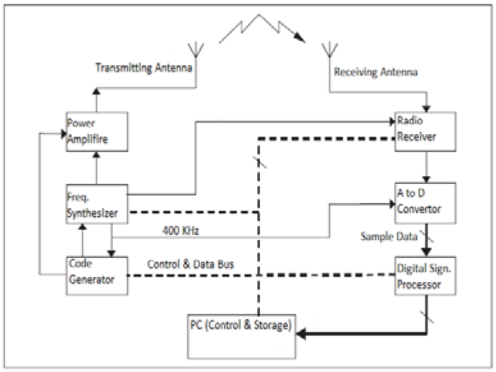

Fig. 2: Simplified Functional diagram of a digital Ionosonde.

Good quality of the ionograms recorded accompanied by a good background noise level as compared to analog Ionosonde, functions to recognize the polarization of the echo, Doppler analysis, improvement in signal to noise ratio, digital signal processing, the software adaptation for remote access and better results at the lower frequencies (E - layer) are the main advantages.

2.2 TOPSIDE SOUNDER

This technique makes it possible to study the ionosphere above the F-layer peak. Topside sounder is a satellite-borne Ionosonde, which sounds the topside of the ionosphere from the height of the satellite down to the F2 layer peak. The basic theory of the topside sounder is the same as for the ground based sounders except that the pulsed radio waves propagate downwards from the satellites. The sounder used to investigate the upper ionosphere are of two different types, namely, swept frequency sounders and fixed frequency sounders. Above the F_2 layer peak the electron concentration decreases approximately exponentially with height so that low frequency radio waves transmitted from the satellite are reflected in the vicinity of the satellite and higher frequency waves are reflected near the F_2 layer peak. The time-delays between the transmitted pulses and their echoes received back from the ionosphere are telemetered to and recorded on magnetic tape / data acquisition stations distributed throughout the world. These recordings are subsequently processed to produce ionograms.

2.3 Incoherent Scatter Sounding.

It provides an enormously powerful tool for studying the ionosphere from the ground. In principle, high frequency radar pulses are transmitted and the power frequency spectrum or auto-correlation function and polarization of the scattered signal returned from the free electrons in the ionosphere are measured. The amount of power scattered back by free electrons in the ionosphere is directly proportional to the electron density. The basic requirement is that the electronic mean free path should exceed the propagating radio wavelength and scale size of the irregularities. This happen at meter wavelength at heights above 100 Km. and thus electron density throughout F-region can be obtained. Since the electrons are in thermal motion, the scattered echo is generally Doppler shifted and hence the information regarding electron temperature can be deduced from it. The advantage of this technique is that its coverage is not limited to altitudes below the peak of F_2 layer.

2.4 Satellite Beacon Studies

The advent of artificial satellites ushered in a new era in ionosphere studies because of made to order radio sources that can be placed in the satellite with a choice in polarization, modulation depth, frequency etc. in addition, the orbiting satellites are most suitable for studying the latitudinal variation, while the satellites are best suited for studying the diurnal, seasonal and other long term variations at any particular place. The narrow band width of satellite signals makes it possible to study small scale variation in frequency, that accompany scintillations due to concentration of electron content [11]. The fixed polarization of the radio waves emitted by a satellite beacon makes it possible to study the polarization scintillations of signals from satellite. Satellite beacons consists of plane polarized un-modulated waves of frequencies greater than the F-layer critical frequency. Ground stations deduce information about the ionosphere by analyzing received signals from the satellite. The characteristics of the satellite radio signals such as amplitude, frequency, phase and direction of arrival may all undergo significant changes during passage through the ionosphere. The important effects on the electromagnetic wave traversing the ionosphere can be:

(a) The change in the direction of arrival of wave due to refraction.
(b) Change in the polarization angle of the wave (magnetic-ionic effect).
(c) Shift in the frequency of received wave (Doppler Effect).
(d) Change in wave amplitude by absorption and by interference from different ray paths due to refraction effects.

Magnitudes of all these effects are dependent upon the frequency of the wave transmitted by the beacon abroad the satellite. One of the techniques of investigating the ionosphere by means of beacon satellites involves the deduction of the integrated electron density or total electron content from the measurements of dispersive Doppler frequency shift resulting from the change of phase path length between the satellite and receiver due to the ionosphere [12]. This can be done by measuring the departure from harmonic relationship of the received signals from harmonically related transmitted frequencies. The reduction of the phase path length is dependent upon the electron content along the ray path.

2.5 GPS TEC Technique

Geographical Positioning System (GPS) has great importance in scientific applications. The GPS satellites that are orbiting the Earth transmit signals that propagate through the ionosphere that exists at about 60 –1500 km above the Earth's surface. The signals from the GPS satellites travel through the ionosphere on their way to receivers on the Earth's surface. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their velocity and direction of travel. Due to the in-homogeneity of the propagation medium in the ionosphere, the GPS signal does not travel along a perfectly straight line. The effects of the ionosphere can cause range-rate errors for users of the GPS satellites who require high accuracy measurements. The parameter of ionosphere that produces most of the effects on radio signals is Total Electron Content (TEC). By modeling TEC parameter, the evaluation of the ionospheric error and the correction of these ionospheric errors for differential GPS can be done. The ionosphere causes GPS signal delays to be proportional to TEC along the path from the GPS satellite to a receiver. TEC is defined by the integral of electron density in a 1 m^2 column along the signal transmission path. TEC is a key parameter in the mitigation of ionospheric effects on radio system. The TEC measurements obtained from dual frequency GPS receivers are one of the most important methods of investigating the Earth's ionosphere. GPS sensors, distributed over the globe, are currently being used in ionospheric measurements, tectonics and earthquake monitoring, Precision receivers can be used to calibrate these distributed sensor networks in a deterministic manner. Several ionospheric experiments would be made possible by the use of these precision receivers. The tomographic reconstruction can be performed with various separation distances between the receivers, revealing smaller spatial and temporal scales associated with gravity waves and electric and magnetic field perturbations. 3-D irregularity structures in the ionosphere can be imaged and tracked, providing valuable insight into plasma structuring and their movements.

All these techniques used for ionosphere monitoring: vertical sounding, topside vertical sounding and GPS TEC have advantages and disadvantages but reveal similar properties in ionospheric precursors. The first misunderstanding results from the complexity of spatial and temporal dependence of ionospheric precursors. According to theoretical calculations.[13], the deviation of the electron concentration in the ionosphere may be positive or negative depending on the direction of the anomalous electric field. This result in the complex shape of the temporal variations of the critical frequency before earthquakes registered by Ionosonde situated within the area of the earthquake preparation [14]. The shape of a precursor depends not only on the process itself (seismo-ionospheric coupling) but on the relative position of the impending earthquake epicenter and Ionosonde as well [15]. Taking into account that GPS TEC records have very high correlation with Ionosonde critical frequency record, this conclusion relates to the GPS TEC single station measurements too. Another scenario can be observed from the topside sounding data. It is possible using the records of satellite consecutive orbits to make an LT-map of the ionosphere over the earthquake preparation zone. This technique gives an opportunity to obtain a snapshot of the ionosphere revealing real distribution of electron density for a given local time. It is one of the great advantages in using a satellite as it gives reading prior to ground based measurements. However, the increasing number of GPS receivers all over the world opens up the possibility of making a GPS map of the ionosphere, including periods of earthquake preparation. This technique has an advantage over topside sounding, because it permits the production of time-lapse maps, showing ionosphere dynamics in real time. At the same time GPS technology has similar limitations as it is applicable only for land based registration. If an epicenter is situated in the ocean which is the case for the most of Pacific coast earthquakes in Mexico, a large probability of missing the precursors exists. This situation is aggravated by the fact that precursors are generally observed over geomagnetic field lines in an equatorial direction and not exactly over the epicenter area. More also needs to be said regarding recent developments of occultation technology or GPS MET technology. Occultation profiles obtained by one satellite are distributed chaotically in space and time and cannot completely fit the requirements of ionospheric precursor tracking. This type of tracking requires profiles be obtained at least once a day at the same local time as is the case in topside sounding in the same geometric configuration, or temporal evolution of precursors should be tracked as in the case of ground based Ionosonde or GPS receivers. A new perspective, however, will open up when the multi-satellite constellations are created, the COSMIC project, to provide continuous monitoring of the same place in the same configuration. As a conclusion it needs to be stated that for high confidence in results all three techniques should be used simultaneously. Taking into account the encouraging results obtained using the topside sounding technique; the launch of satellites with topside sounders onboard is an urgent requirement of short-term earthquake prediction.

3. PHYSICAL MECHANISM OF SEISMO-IONOSPHERIC COUPLING

All the processes involved in the Physical mechanism of seismo - ionospheric coupling are schematically presented in Fig. 3.

One can see that the near ground layer of the atmosphere become real plasma with particle concentration comparable with some regions of the Earth's ionosphere. In addition, this plasma is posed in a strong electric field, where one should expect particle acceleration and excitation of plasma instabilities. An estimation of the plasma frequency for the cluster ion NO_3. $(H_2O)n$, where n is the number of H_2O molecule in the cluster, is given here. When n = 6, the atomic mass will be M = 190 amu, which is equivalent to m = 3.15×10^{-22}g and with the concentration of the charged particle of the order of 10^{6} cm^{-3} this gives $f = \omega/2\pi = 16.9$ KHz which lies just in VLF frequency band.

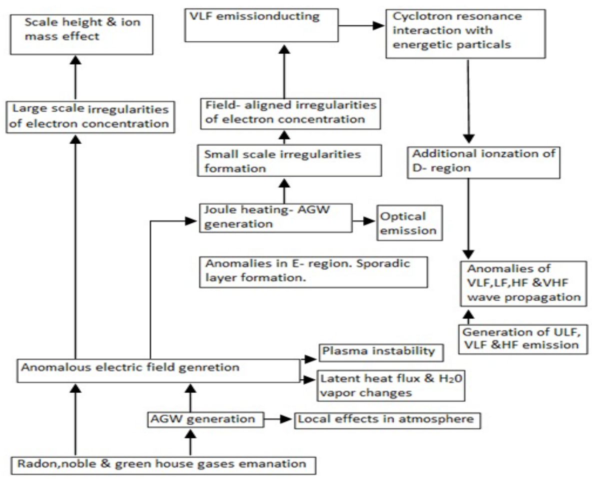

Fig. 3: Physical Mechanism of seismo – ionospheric coupling.

Taking in to account that plasma concentration, one can expect the coverage of the whole ULF – ELF – VLF band. Anomalous electric field penetrating into E – region of the ionosphere creates irregularities registered experimentally [16]. In the F- region, two main effect should be noted. In the area of maximal conductivity due to Joule heating acoustic gravity waves will be generated giving rise to the small scale density irregularities with in the ionosphere [17]. These processes are manifested in periodic electron density oscillations registered at different ionospheric heights by radio physical techniques of the ionosphere and are well supported by experimental data[18].. The other, probably main and well documented effect is formation of the large scale irregularities of electron concentration in the F_2 region of the ionosphere [19] . They were registered by satellite and from the ground by the ground based Ionosonde and ground networks of GPS receivers [20]. A typical intensity observed spectra showing amplitudes fluctuation during earthquake is shown in Fig. 3,[21].

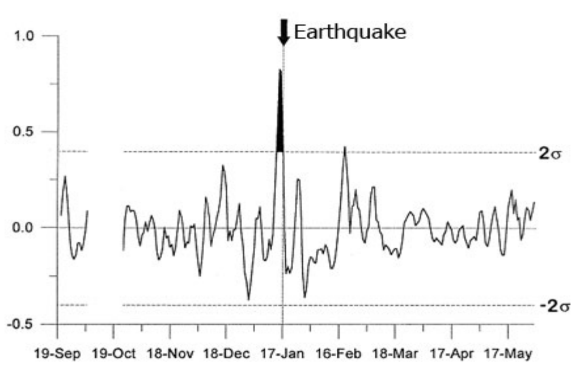

Fig. 4: Typical intensity spectra showing amplitudes fluctuation during earthquake

4. ANALYSIS TECHNIQUES

4.1 Cross Correlation-EMD Analysis

The method used in this study is a combination of the Cross Correlation Analysis method proposed by Pulinets (22), and the Empirical Mode Decomposition proposed by Huang [23]. The Cross Correlation method is just a correlation coefficient calculation of the foF_2 measurements from a station that it is located within the earthquake preparation area, compared with a similar foF_2 signal from an ionospheric station located outside the seismo-ionospheric precursors of the 6 April 2009 earthquake in L'Aquila the preparation area. The idea is that when the two stations are located relatively close together, solar activity-oriented disturbances will affect each station's foF_2 measurements in the same way, and therefore the cross correlation coefficient is expected to be high in the absence of a seismic event. On the other hand, when a seismic event occurs in the vicinity of one of the two stations, the cross correlation coefficient drops, since the measurements from the station inside the earthquake preparation area are the only ones affected. However, the selection of the two stations requires careful consideration, as the distance between them must ensure that they are both equally subject to the same solar activity ionospheric disturbances, maintaining at the same time consistency with the in and out requirements of the earthquake preparation area for the seismo-ionospheric precursors to appear. The second part of the technique requires de-noising the foF_2 signals collected from the two stations using Empirical Mode Decomposition (EMD), an adaptive method for processing non-linear and non-stationary signals. EMD basically decomposes a real signal into its functional components, which are known as Intrinsic Mode Functions (IMF). This process derives information about the decomposition of the signal itself, without the requirement for a predefined basis. This means that the decomposition is driven itself and there are no a-priori decisions that may affect the final result. A typical decomposition of a real signal using EMD results in a filter bank wavelet-like breakdown of the signal having a higher to lower frequencies hierarchy. Since the decomposition is executed in the time domain without losing time resolution as the order of scale increases, the initial signal can be reconstructed perfectly by just adding together the IMFs. This is actually the property that allows for an adaptive de-noising of a noisy signal. In other words, the noisy components being captured by the higher order IMFs, are left out during the reconstruction, and only the IMFs that contain the signal energy are added to form the de-noised signal.

4.1.1 Data analysis

The L'Aquila earthquake occurred on Monday, 6 April 2009 at 01:32:39 UTC. The exact coordinates of the event were 42.334^{0} N–013.334^{0} E, which correspond to a point 85 km northeast of Rome. This earthquake was the main shock of a series of pre-seismic events, which started in February and continued through March 2009. The earthquake preparation area is calculated as 511 km according to the Dobrovolsky equation [24].

$$r = 10^{0.43M}\ \text{km} \text{ ---------------------} \qquad (1)$$

Where M is the magnitude of the earthquake and r is the size of the area in km.

In an effort to increase the validity of the results of this study, we used data from three ionospheric stations, all of which were selected to ensure that their data was affected in a similar fashion by the solar activity-related phenomena. At the same time, the selection of the stations was such that the two, namely the Rome and San Vito stations, were located inside the earthquake preparation area, whereas the third, the Athens station, was located outside of it. According to the correlation coefficient theory we expect the Rome and San Vito measurements to show the disturbances caused by the earthquake, whereas the Athens measurements should be unaffected. Following this line of reasoning, the cross correlation coefficient of the Rome and San Vito signals is expected to be high, in contrast to the correlation coefficient of either station's readings with the Athens measurements. The foF2 signals used were one-hour sample measurements from 10 March to 13 April 2009. This corresponds to a timeframe of 35 days, of which 27 days were prior to the event and 7 days were after the event. The data were downloaded from both the Space Physics Interactive Data Resource (SPIDR) and the Digital Ionogram Databases **(DIB)** . Geophysical noise was removed from the signals using EMD, and then their de-noised versions were used for the calculation of the respective correlation coefficients. The results of computation are shown in Fig.5

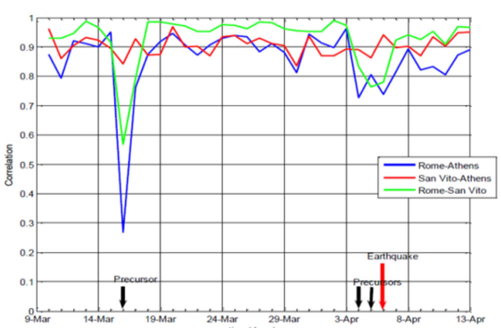

Fig. 5: Plot of correlation coefficient between Rome-Athens, San Vito Athens and Rome San Vito.

It can be seen that, the Rome station measurement were affected by the earthquake, producing precursors 22 days, 2 days, and 1 day prior to the event. The ionosphere over a station located close to the border defined by the theoretical estimated earthquake preparation area, may not be affected adequately by the event, for the seismo-ionospheric precursors to appear. When a series of intense seismic activities prior to the main shock is reported, precursors may appear more than 12 days prior to the event, which exceeds the maximum time frame reported so far regarding the appearance of seismo-ionospheric precursors.

4.2. Wavelet and Bi-spectrum Analysis

The traditional Fourier analysis is not relevant to study turbulence. The Fourier transform spreads information about the localized features over all scales making it impossible to study the evolution of different scale structures simultaneously. The important property of the wavelet transform is that the square of the wavelet coefficients can be interpreted as local energy and their statistics is easy to visualize and understand. The usefulness in studying the turbulence has been underlined by Farge [25] in the context of coherent structures. The main advantage of using the wavelet transform is that it preserves the information about local features of the signal and allows reconstruction of the signal over a given range of scales. This property is of particular importance in studying turbulence, which often shows coherent structures apparently related to nonlinear processes. Extensive discussion of the wavelet transform, and its applications in turbulence can be found in a number of books and review articles [26], [27]. Applications of the wavelet analysis to study turbulence in the space plasma were discussed by [28].

The complex Morlet wavelet to analyze data is represented by the following function of time t and central frequency $\boldsymbol{\omega}_0$:

$$\boldsymbol{\psi}(t) = e^{\left(i\omega_o t - t^2/2\right)} - \sqrt{2}e^{\left(i\omega_o t - t^2 - \omega_o^2/4\right)} \text{ -- } \qquad \text{--- (1)}$$

The Continuous Wavelet Transform (CWT) of the signal x(t) is a convolution of the signal x(t) with the wavelet function and the result of the integration over time in the infinity interval. Therefore, CWT is a function of the time shift τ and a scaling parameter a as

$$\int_{-\infty}^{\infty} x(t)\, \boldsymbol{\psi}^* \left(\frac{t-\tau}{a}\right) dt = CWT(\tau, a) \qquad \text{-------- (2)}$$

When we discuss the development of the plasma turbulence and cascade of the energy in the spectrum, the first step in this cascade and the fundamental process which is involved is the 3- wave interaction. The resonance conditions for these processes are:

$$\omega_1 + \omega_2 = \omega_3 \text{ --------} \qquad \text{--------------- (3)}$$

$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 \text{ \_\_\_\_\_\_\_\_\_\_\_\_\_\_} \qquad \mathbf{(}4)$$

where ω_1, ω_2 and ω_3 are the wave frequencies and $\mathbf{k_1}$, $\mathbf{k_2}$ and $\mathbf{k_3}$ are the wave vectors of the interacting waves. Verification of these conditions is possible using the so called bi-spectral analysis. This method for the studies of the plasma processes was first proposed by Kim and Powers [29]. It allows finding the nonlinearly interacting wave modes by computing the bi-spectrum of the signal which gives the information about phase coherence of these waves. The bi-spectrum of the signal x(t) is defined by:

$$B(k,l) = E[X_k X_l X^*_{k+l}] \text{ ------ } \qquad \text{--------- (5)}$$

Where X is the FFT (Fast Fourier Transform) of x(t) and Xk, Xl, and Xk+l are the spectral components at frequencies k, l and k+l, respectively. E[..] denotes an averaging over the time interval**.**

A quantitative measure of the phase coherency may be obtained using the bi-coherence spectrum which is defined in terms of the bi-spectrum as:

$$b^2(k,l) = \lim_{T\to\infty} \frac{1}{T}\frac{|B(k,l)|^2}{x_k x_l x_{k+1}}\ldots\ldots\ldots\ldots \qquad (6)$$

Where T is the time interval of averaging. The computer procedures for applications of the methods of wavelet and bi-spectral analysis have been developed in the package SWAN [30]. The results are presented in Fig. 6.

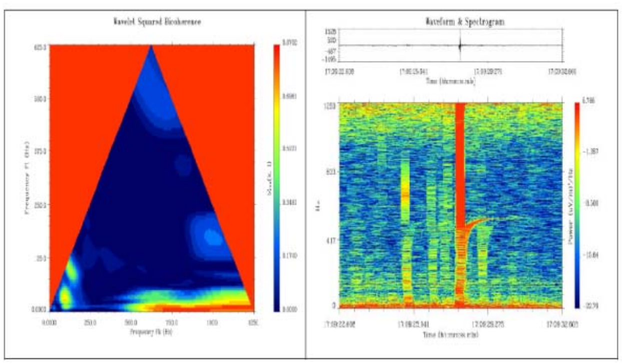

Fig. 6: Wavelet and Bio-coherence spectrum.

5. CONCLUSION

Efforts have been made in this paper to establish correlation between ionospheric anomalies and earthquake. It has been detected that there are distinct ionospheric anomalies located over areas of seismic activity. There is supporting evidence that electromagnetic emissions propagate from the ground causing these anomalies. Advantages and disadvantage are regarded concerning different techniques of ionospheric monitoring in relation to ionospheric precursor registration. The unpredictability of earth quakes and the impact of their devastation cause a need to use more than one technique simultaneously in the same earthquake preparation area and improvement in existing techniques and development of new technology in hopes that one day, accurate earthquake warnings will be available well in time.

6. ACKNOWLEDGEMENT

The Author Dr. R.C.Sharma is very thankful to Management and Administration of Dronacharya College of Engineering Gurgaon for providing research environment and constant encouragement during the course of this work.

REFERENCES

[1] URL-3, 2011. http://deprem.itu.edu.tr/?file=harici. 10 Mart 2011

[2] Sac. M, Camgoz. B. Izmir'de J. Commun.Res. Lab. Say:43,169-180(2005)

[3] Liu. J, Chuo. Y, Shan. H, Tsai. C, and Pulinets. S.A., Preearthquakes ionospheric anomalies registered by continuous GPS TEC measurements. Annales Geophysicae,1585-1593(2004).

[4] Yamauchia, T., Maekawaa, S., Horiea, T., Hayakawaa, M., Solovievb, O., Subionospheric VLF/LF monitoring of ionospheric perturbations for the 2004 Mid-Niigata earthquake and their structure and dynamics, Journal of Atmospheric and Solar-Terrestrial Physics.(2007).

[5] Muto, F,. Horie, T., Yoshida, M., Hayakawa, M., Rozhnoi, A., Solovieva, M., Molchanov, O. A., Ionospheric perturbations related to the Miyagi-oki earthquake on 16 August 2005, as seen from Japanese VLF/LF subionospheric propagation network, Physics and Chemistry of the Earth, s. 449-455(2009).

[6] Stewart. B, Encyclopaedia Britannica,16,181(1978).

[7] Kennely, A.E. Electrical world and Engineer, 39, 473(1902).

[8] Breit. G and Tuve. M.A., Nature, 116, 357(1925).

[9] Hunsucker R.D., Radio Techniques for probing the Terrestrial Ionosphere in Physics and chemistry in space, Springer-Verlag Berlin Heidelberg Vol 22(1991).

[10] Skolnick M.I., Radar Handbook, Mc Graw-Hill New York (1997).

[11] Kitchen ,F.A. and Joy, R.R. Nature, 181, 1759(1958).

[12] Roas, W.J. J. Geophysical Res., 65, 2601(1960).

[13] Pulinets S.A,Boyarchuk K.A, Khegi V.V, Kim V.P. and Lomonosov A M, Quasielectrostatic model of atmosphere-thermosphere- ionosphere coupling, Adv. Space Res.,26 pp 1209-121 (2000).

[14] Chuo Y.J, Chen Y.I, and Pulinets S.A, Ionospheric foF2 variations prior to strong earthkuake in Taiwan area Advances in Space Res. 27, 1305-1310 (2001).

[15] Pulinets S.A., Liu J.Y, Safronova A.I, Interpretation of statistical analysis of variation of foF2 critical frequency befoee earthquakes based on data from Chung Li ionospheric station (Taiwan) Geomagn. Aeronam., 44,102-106 (2004a).

[16] Liperovsky V.A., Pokhotelov O.ALiperovaskaya E.V, Parrot M., Meister C.V.,and Alimov A.O., Modification of sporadic E-layer caused by Seismic activity, Surveys in Geophys,. 21, 449-486 (2000)

[17] Molchanov, O., Hayakawa, M., Oudoh, T., Kawai, E., Precursory effects in the subionospheric VLF signals for the Kobe earthquake. Physics of the Earth and Planetary Interiors, s. 239-248(1998).

[18] Hegai, V. V., V. P. Kim, and L. I. Nikiforova: A possible generation mechanism of acoustic-gravity waves in the ionosphere before strong earthquakes. *J. Earthquake Predict. Res.*, 6, 584-589(1997).

[19] Chmyrev, V. M., N. V. Isaev, O. N. Serebryakova, V. M. Sorokin, and Y. P. Sobolev: Small-scale plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region. *J. Atmos. Solar-Terr. Phys.*, 59, 967-974(1997).

[20] Pulinets, S. A., and A. D. Legen'ka: Spatial-temporal characteristics of the large scale disturbances of electron concentration observed in the F-region of the ionosphere before strong earthquakes. *Cosmic Res.*, 41, 221-229(2003).

[21] Molchanov, O., Hayakawa, M., Oudoh, T., Kawai, E., Precursory effects in the subionospheric VLF signals for the Kobe earthquake. Physics of the Earth and Planetary Interiors, s. 239-248(1998).

[22] Pulinets S.A., Boyarchuk K.A, Ionosphere Precursors of Earthquakes, Springer Verlag Publication (2004).

[23] Huangs C.S., Foster J.C., Goncharenka L.P., Ericson P.J., Rideout W., and Coster A.J., A strong positive correlation of ionospheric strom observed by the Millston Hill incoherent scatter Radar and globle GPS network, J.Geophys. Res. 110, A06303 (2005).

[24] Dobrovolsky I.R., Zubkov S.I., Myachkin V.I., Estimation of the size of earth quake preparation zones Pageoph., 117, 1025-1044 (1979).

[25] Farge, M., N. Kevlahan, V. Perrier, and É. Goirand, 1996, Wavelets and turbulence, Proc. IEEE, **84**, pp. 639-669.

[26] Murray, W.A.S., Hargreaves, J.K., Nature,173, 944(1954).

[27] Browne,I.C., Evans, J.V.,Hargreaves,J.K., Murry,W.A.S.,Proc. Phy. Soc.,B69,901(1956).

[28] Pulinets, S. A., T. B. Gaivoronska, and A. Leyva Contreras: Correlation analysis technique revealing ionospheric precursors of earthquakes, EGU General Assembly, Nice, France., Geophys. Res. Abs., Vol. 6, 01055(2004b).

[29] Kim Y.C. and E. J. Powers, Digital bispectral analysis of self-excited fluctuation spectra. *Phys. Fluids,* **21,** pp. 1452–1453 (1978).

[30] Lagoutte, D., J.Y. Brochot and P. Latremoliere, SWAN Software for Waveform Analysis, Analysis Tool version 2.3, LPCE/NI/003.D — Part 1, Part 2 Part 3 (1999).