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Study the Anomalous Behavior of VLF Signal during Earthquake by D-Layer Preparation Time (DLPT) and D-Layer Destruction Time (DLDT) Method

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ABSTRACT
VLF (Very Low Frequency) radio waves are partially reflected and partially absorbed by the lowest region of the ionosphere (the D-layer), which begins at about 40km altitude. By measuring the amplitude and phase of radio signals after they have reflected from the ionosphere, it is possible to detect various kinds of ionospheric and space activities. It has been established that the ionosphere may be perturbed due to seismic activity. The effects of this perturbation can be detected through the VLF wave amplitude variations. There are several methods to find these correlations and these methods can be used for the prediction of these seismic event. We present the unusual VLF signal amplitude variation for the NWC transmitter of 19.8 kHz signal received at Ionospheric and Earthquake Research Centre (IERC), Sitapur, Midnapore for a period of 6 months for the year 2011. In this project, we present the effects of the seismic activities on D-Layer Preparation Time (DLPT) and the D- Layer Destruction Time (DLDT). We identify those days in which DLPT and DLDT shows anomalous value from the average and we correlate those anomaly with seismic events.

Keywords: .Very Low Frequency, ionosphere, radio signal, seismic activity, D-Layer Preparation Time, D- Layer Destruction Time,

1. INTRODUCTION
The occurrence of earthquake is leads by the earth's crustal dynamics which involves the movement of the tectonic plates, and as a result various gases and magma release from the cracks. From ancient period people are trying to predict earthquake by some weakly scientifically justifiable methods such as arrangements of planets and the uneasy behavior of the animals etc. But these methods are not successful either. Meanwhile in 1960s, scientist found that some electromagnetic phenomena occurred a few days before the earthquake which may perturb the ionosphere. So far, only phenomenology has been done based on observations, but no rigorous theory has been proposed on it as the perturbation of the ionosphere due to the seismic wave is a complicated process. Even then, scientists are trying to find this correlation between the ionosphere and the seismic wave. In this paper we will present some of the methods which are currently pursuing at Indian Centre for Space Physics (ICSP), Kolkata.

2. Very low frequency (VLF)
Very low frequency or VLF refers to radio frequencies (RF) in the range of 3 Hz to 30 kHz. Since there is not much bandwidth in this band of the radio spectrum, only the very simplest signals are used, such as for radio navigation. Also known as the myriameter band or myriameter wave.VLF waves can penetrate water to a depth of roughly 10 to 40 meters (30 to 130 feet), depending on the frequency employed and the salinity of the water. VLF is used to communicate with submarines near the surface (for example using the transmitterDHO38). VLF is also used for radio navigation

3. The Ionosphere and observing it with VLF signal
The ionosphere is the uppermost part of the atmosphere. It plays an important part in atmospheric electricity and forms the inner edge of the magnetosphere. It has practical importance because, among other functions, it influences radio propagation to distant places on the Earth. In the ionosphere the electrons and electrically charged atoms interact with the electromagnetic fields. The

photo-ionization process produces ionospheric plasma and this ionospheric plasma interacts with the earth's magnetic field. The ionosphere is made up of different layers with different compositions, electron densities, ionization sources, and predominant chemical processes. The three major layers are the D-layer (60-90) km, E-layer (90-150) km, and the F-layer (150-800) km. Here is some short introduction about these layers.

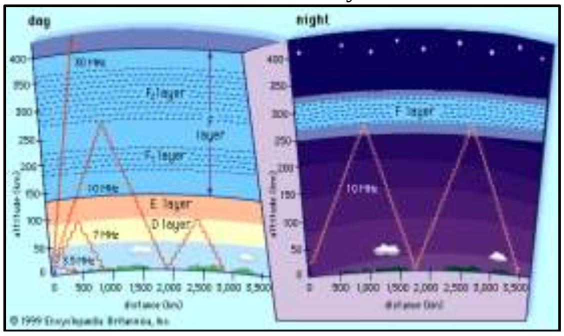


Fig 1: Reflection of VLF waves from the Ionosphere

4. D-layer

The D layer is the innermost layer, 50 km to 90 km above the surface of the Earth. Ionization here is due to Lyman series-alpha hydrogen radiation at a wavelength of 121.5 nm ionizing nitric oxide (NO). When the sun is active with 50 or more sunspots hard X-rays (wavelength <1 nm) ionize the air (N_2, O_2).During the night cosmic rays produce a residual amount of ionization. Recombination is high in the D-layer, thus the net ionization effect is very low and as a result high-frequency (HF) radio waves are not reflected by the D layer. The D layer is mainly responsible for absorption of HF radio waves, particularly at 10 MHz and below, with progressively smaller absorption as the frequency gets higher. The absorption is small at night and greatest about midday. The layer reduces greatly after sunset.

During solar proton events, ionization can reach unusually high levels in the D-region over the high and polar latitudes. Such events are known as Polar Cap Absorption (or PCA) events, because the increased ionization significantly enhances the absorption of radio signals passing through the region. In fact, absorption levels can increase by many tens of dB during intense events, which is enough to absorb most (if not all) transpolar HF radio signal transmissions. Such events typically last less than 24 to 48 hours.

5. E -layer

The E layer is the middle layer, 90 km to 120 km above the surface of the Earth. Ionization is due to soft X-ray (1-10 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen (O_2). Normally this layer can only reflect radio waves having frequencies lower than about 10 MHz and have a negative effect on frequencies above 10 MHz due to its partial absorption of these waves. At night the E layer begins to disappear because the primary source of ionization is no longer present. This results in an increase in the height where the layer maximizes because recombination is faster in the lower layers. The increase in the height of the E layer maximum increases the range to which radio waves can travel by reflection from the layer. This region is also known as the Kennelly - Heaviside layer or simply the Heaviside layer.

6. Es – layer

The E_s layer or sporadic E-layer. Sporadic E propagation is characterized by small clouds of intense ionization, which can support radio wave reflections from 25 – 225 MHz Sporadic-E events may last for just a few minutes to several hours and make radio amateurs very excited, as propagation paths which are generally unreachable, can open up. There are multiple causes of sporadic-E that are still being pursued by researchers. This propagation occurs most frequently during the summer months with major occurrences during the summer, and minor occurrences during the winter. During the summer, this mode is popular due to its high signal levels. The skip distances are generally around 1000km (620 miles). VHF T V and FM broadcast D X'ers also get excited as their signals can be bounced back to earth by Es. Distances for short hop events can be as close as 500 miles or up to 1,400 (or more) for a long, single hop. Douple-hop reception over 2,000 miles is possible, too.

7. F-layer

The F layer or region, also known as the Appleton layer, is 120 km to 400 km above the surface of the Earth. It is the top most layer of the ionosphere. Here extreme ultraviolet (UV, 10–100 nm) solar radiation ionizes atomic oxygen. The F layer consists of one layer at night, but in the presence of sunlight (during the day), it divides into two layers, labeled F1 and F2. These F layers are responsible for most sky-wave propagation of radio waves, facilitating high frequency (HF, or shortwave) radio communications over long distances. From 1972 to 1975 NASA launched the AEROS and AEROS B satellites to study the F- region.

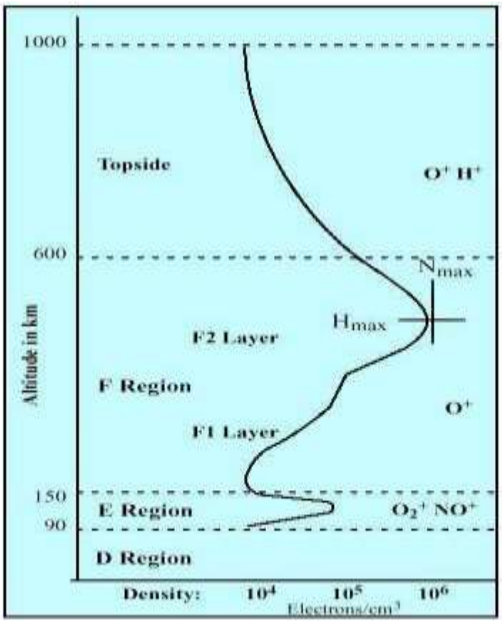


Fig 2: Layers of the ionosphere

8. Radio wave propagation through the ionospher

The ionosphere plays a major role for the radio wave propagation. The region 50-250km of the atmosphere can be studied neither by sending balloons nor by satellites. The only way is the radio wave propagation method. The surface of the earth and the lower ionosphere behaves as a waveguide through VLF (3-30 kHz) can propagate. During the propagation through these layers, the VLF signal amplitude is affected and it carries information about the ionospheric changes. VLF radio waves are partially reflected and partially absorbed by the lowest region of the ionosphere (the D-layer).By measuring the amplitude of radio signals after they have reflected from the ionosphere, it is possible to detect various kinds of ionospheric and space activity taking place. It has been reported that certain electromagnetic phenomena area associated with seismic activities which can directly perturb the ionospheric plasma and change the charge density profile.

9. Propagation of VLF signal through ionosphere- Theory of Eccles and Larmor

Let the ionized medium contain N_e electrons per cm^3, each of charge e and mass m. The motion of the electrons is influenced by the E field of the passing wave.

Equation of motion of an electron as

$m\,(d\Omega/dt)=E_0\, e \,\text{Sin}\, pt$

Ω=instantaneous velocity of the electron

$\Omega= -(E_0 e/mp)\text{Cos}\, pt$

p=VLF frequency

The motion of the electrons produces a convection current, the of which is given by –

$N_e e\Omega= -(E_0 N_e e^2/mp)\text{Cos}\, pt$

Now, at the point under consideration, there is also a displacement current due to the fluctuation of the field intensity given by –

$(K/4\pi)(dE/dt) = (KE_0/4\pi)\, p\, \text{Cos}\, pt$ ………….. (1)

K=dielectric const. of the medium without electrons.

The total current is therefore given by -

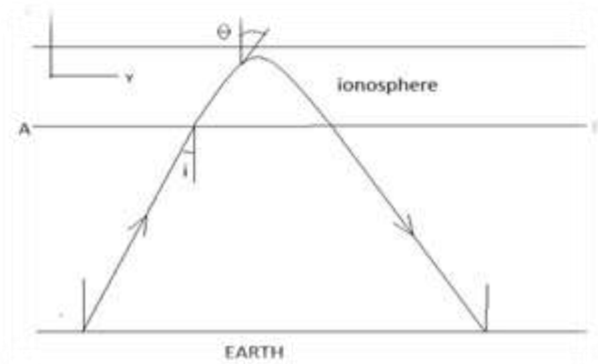
$(K - (4\pi N_e e^2/mp^2))\,(E_0 p/4\pi)\, \text{Cos}\, pt$ ………… (2)

Hence presence of electrons in an otherwise empty space thus reduces the dielectric const. from unity to $1-(4\pi N_e e^2/mp^2)$ and alters the phase velocity from C to U.

$U=C/(1-(4\pi N_e e^2/mp^2))^{0.5}$ ……......................... (3)

The reduction of dielectric constant to a value less than unity is that EM waves

Fig 3: Path of the Reflected ray from the



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sent upward may be bent down by reflection from the ionized region.

The ionization increasing from bottom to upwards in ionosphere. Let the wave be incident on AB at an angle i to the vertical, r.i (μ) of the region just below AB is unity, the angle θ which the refracted ray would make with the vertical at that point then

$\sin i = \mu_0 = [1-(4\pi N_e^0 e^2/mp^2)]^{0.5}$ ………………..(4)

Where N_e^0 is the electron density at the point of total reflection where μ_0 is the r.i.

This shows that μ_0 is inversely proportional to Ne. So from eqn. (3) & (4) we can say that velocity of VLF is higher when it goes from denser to rarer medium. That is why the fluctuations in VLF signal is much high in day time than night time, because of the presence of D-Layer, and the day time signal is also perturbed in the presence of seismic wave.

10. A Brief review of seismo-ionospheric phenomena

The scientific work on the seismo-ionospheric perturbation started on 1960s.Since those countries like Japan, China, Soviet Union, and United States made several scientific efforts to find the precursor of Earthquake. Several models were proposed by the scientists to explain this seismo-ionospheric correlation which may change the ionospheric characteristic. These include:-

(1) Anomalous electric field in the atmosphere (Jianguo 1989;Vershinin et al.,1999; Rulenco,2000).
(2) Heating of the ionosphere (Kim and Hegai 1997;Sorokin et al, 2000).
(3) Increase in the conductivity of the ionosphere, emission of radioactive gases (Wattananikorn et al., 1999).
(4) Irregularities along the geomagnetic field lines into the magnetosphere(Larkinaet al., 1989; Kim and Hegai,1997) which may scattered the VLFemissions.
(5) Changing the gravity waves (Artru et al.,2004) due to the plate movements whichmay change the shape of the ionosphere.

The first successful observation of the seismo-ionospheric coupling takes place after the Alaskan “Good Friday” earthquake on 1964. Bolt in 1964firstpublish a paper on this phenomena. Leonard and Barnes (1965) observed ionospheric disturbances due to Alaskan earthquake using the ionosonde method. After that Devis and Baker(1965),Row (1966,1967),Yuen et al (1969), Tanaka et al. (1984) successfully publish some paper on it.At the time of Caucasus earthquake on 30 December, 1983Gufeld and Marenco successfully found the anomalies in the nighttime VLF signals two days and one day before the earthquake. Just before the Kobe earthquake (magnitude-7.3) on 17 January 1995 a very interesting result usingVLF wasobtained by Hayakawa et al (1996), the sun rise and sunset terminator shifted significantly a few days before the earthquake. Subsequently Molchanov and Hayakawa,(1998); Cliverd, Rodger, and Thomas (1999); Molchanov and Hayakawa,(2000); Hayakawa et al (2003); Maekawa et al (2006), etc. publish several paper regarding the terminator shifting during earthquake.

Indian Center for Space Physics (ICSP) continuously monitoring VLF signal since 2002.After the devastating Sumatran earthquake it pays attention to the possible association of earthquake with Seismo-ionpospheric phenomena using different techniques. This group successfully observed strong correlation between VLF signal fluctuations and earthquake using different methodology since 2004 to till now for several earthquakes around Indian sub-continent (Chakrabarti et al., 2005, Chakrabarti et al., 2007, Sasmal et al., 2009, Chakrabarti & Sasmal, 2010, Ray et al, 2011, Ray et al., 2012, Sasmal et al., 2012).

11. The Transmitter and Receiver

Fig 4: The position of the transmitter and receiver and the wave path between them

Ionospheric and Earthquake Research Centre (IERC), a new branch of Indian Centre for Space Physics (ICSP), Kolkata located at Sitapur, Midanpore (Lat. 22°30N, Long. 87°47E) which is about 64 kilometer away from the main receiving station ICSP, Kolkata. This place is electrical noise free and the data coming from this station is very quiet in quality. In this project we used the data received from the IERC for the year 2011. We use the NWC (Lat. 21˚47′S, Long. 114˚09′E) of Australia transmitting frequency 19.8 kHz.

Figure-3 shows the wave path between NWC and Sitapur. The great circle distance from Sitapur to NWC is about 5693 km. In this paper, we present the data received from the SoftPAL (Software Phase and Amplitude Logger) VLF antenna/ receiver system. In this system we use an electric field antenna. The signal received from this antenna is fed into a pre amplifier and then into a service unit. Both the amplitude and phase information has been obtained from receiving System. The data acquisition is taken place by a USB Dongle and the Lab-chart software and automatically stored to the computer after getting time stamp by a GPS unit. The whole process is shown by a block diagram below:

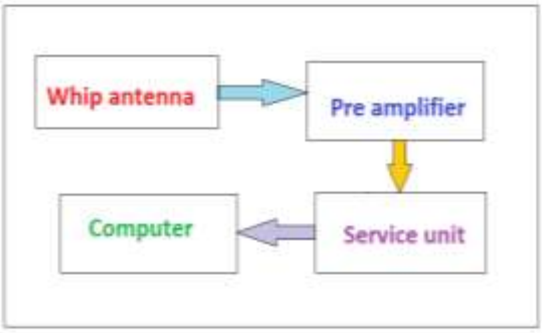

Fig 5: **Block diagram of data receiving process**

12. Typical VLF Signals from NWC at IERC, Sitapur

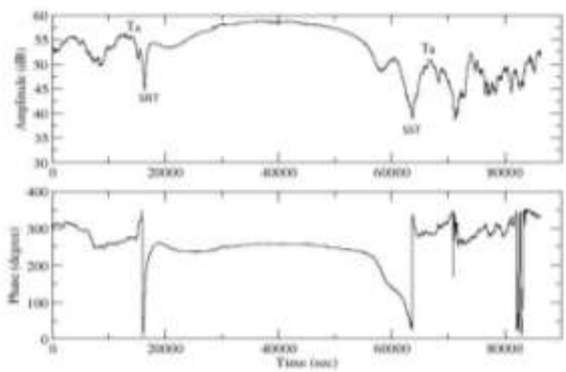

Fig 6: Variation of the signal amplitude and phase of NWC as a function of time in second for 7th July 2011.

In fig-6, we present typical NWC 19.8 kHz. Signals Amplitude and Phase as a function of time for the whole day. We present signal amplitude and phase for the 7th July 2011.The amplitude signal strength shows a minimum just around the sunrise and the sunset. This is known as the terminators. SRT and SST are the sunrise terminator and the sunset terminators respectively. SRT is defined by the first minimum which occurs just after the decrease of the signal amplitude during the formation of the D-Layer in the morning. We define SST by the last weak minima just before the increase (recovery) of the signal amplitude during the disappearance of the D-Layer in the evening. Typically, under the normal circumstances, the sunrise and sunset terminators are good measures of the sunrise and sunset times. The formation of the D-Layer during the sunrise is represented by the strong attenuation of the signal amplitude, and the disappearance of the D-Layer during the sunset is represented by the increase of the signal amplitude. We mark with T_A to denote the time from where the signal starts to attenuate towards the sunrise terminator in the morning and T_B to denote the time when the signal is fully recovered after the sunrise terminator. Actually T_A is the time from which the D-Layer starts to form and T_B is the time when the D-Layer is totally disappears. Thus (SRT- T_A) can be treated as D-Layer preparation time or DLPT, and (T_B –SST) can be treated as D-Layer disappearance time or DLDT.

13. Earthquake statistics

We collect the data of different Earthquakes from July 2011 to December 2011, took place on India and its neighboring subcontinents like Andaman & Nicobar Islands, Pakistan, Afghanistan, Indonesia, Sumatra, etc from www.imd.gov.in , and draw two histograms of the effective magnitude of the Earthquakes and depth of the epicenter.

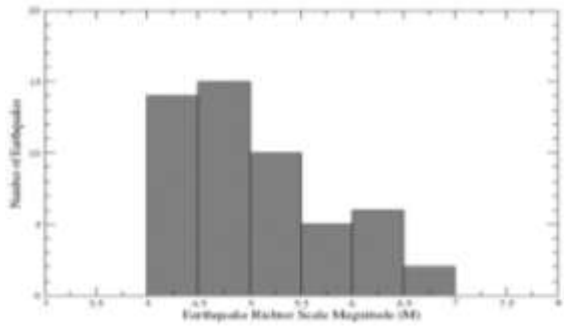

Fig 7: Histograms of the effective magnitude of the Earthquakes

In fig-7 we draw histograms of the effective magnitude of the Earthquakes. It is clear that the majority of Earthquakes happened between magnitudes 4.5 to 5. The next most number of Earthquakes happened in magnitude range 4 to 4.5. The least number of Earthquakes have magnitude range 6.5 to 7. We found no Earthquake having magnitude >7. So we found no much devastating Earthquakes in the period of July 2011 to December 2011.

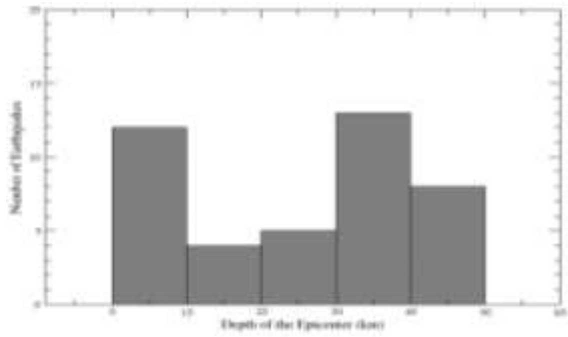

Fig 8: Histogram for the Earthquakes with the depths of the epicenter

In fig-8 we draw the cross correlation incorporating the depth of the epicenter of the Earthquakes. We take those Earthquakes having depths < 50. We found for most number of Earthquakes the depth of the epicenter lies between 30 km to 40 km.

We do not take those Earthquakes for which depth is >50, as in those cases the effect on DLPT and DLDT is very low. These earthquakes may predict using different methods.

14. DlPT/DLDT method

During the seismo-ionospheric coupling or gravity waves it is expected that the lower boundary of the ionosphere may be perturbed more. Thus whether the seismic event changes the ion density and thereby shifting the lower boundary of the ionosphere, it will change the characteristics of the D-Layer. We anticipate that this time taken for the formation of D-Layer (DLPT) during sunrise and the time for destroying the D-Layer (DLDT) during sunset may also be affected by the seismic events. This is because, in the presence of the extra ionizing source, the time taken for such activities may be changed significantly.

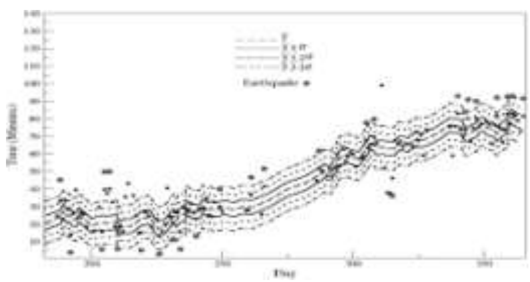

Fig 9: The variation of DLPT and as a function of days for the six months of data. The small dots are the calculated values of the DLPT for each day and the big circles represents earthquakes which are 'associated' with the anomalous data through the Earthquake may have occurred 2-3 days later. The big dashed curve is the average of the DLPT and the solid line and dotted and small dashed lines are drawn at $\pm1\sigma$, $\pm2\sigma$, $\pm3\sigma$ apart respectively

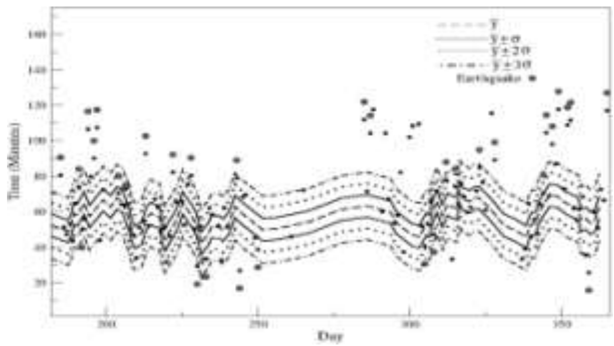

Fig 10: The variation of DLDT as a function of days for the six months of data. The small dots are the calculated values of the DLDT for each day and the big circles represents earthquakes which are 'associated' with the anomalous data through the Earthquake may have occurred 2-3 days later. The big dashed curve is the average of the DLDT and the solid line and dotted and small dashed lines are drawn at $\pm1\sigma$, $\pm2\sigma$, $\pm3\sigma$ apart respectively

In this paper we present the correlation between the seismic events and the DLPT and DLDT. We use six months of data (NWC signal of 19.8 kHz) from July 2011 to December 2011 and we plot the DLPT and DLDT as a function of days (fig-9 & fig-10). Typically, the DLPT varies between 30-50 minutes and the DLDT varies between 50-70 minutes. However, in a number of days, these values are anomalous. We found that the value of DLPT and DLDT become anomalously high or low during the earthquakes. We found that the deviation from the mean value of DLPT is larger than 3σ for most of the Earthquakes where for DLDT the value is larger than 3σ to 4σ.

Here we incorporate the effective magnitude of the Earthquake concept as well as we use the original magnitude of the earthquake. In the figures, small dots are actual observed values of DLPT and DLDT on a given day. The big circles represents Earthquakes which are believed to be associated with anomalous data, even when the Earthquake may have taken place 2-3 days later. The big dashed curve is the average of the DLPT and DLDT values, computed by removing days which show anomalies of more than 3σ. The solid line and dotted and small dashed curves are drawn at ±1σ, ±2σ, and ±3σ apart respectively. To check whether the anomalies in the DLPT and DLDT are also observed or not in prior to the Earthquakes, we make a table by taking data of different Earthquakes and correlate this data with our DLPT and DLDT result.

15. List of earthquakes in INDIA and its neighboring subcontinents from JULY 2011 to DECEMBER 2011

TABLE

Date	Magnitude	Region
04/07/2011	5.5	NORTHERN SUMATRA, INDONESIA
16/07/2011	4.6	NICOBAR ISLANDS, INDIA
21/07/2011	5.2	INDONESIA
28/07/2011	4.5	INDIA (W.DINAJPUR)-BANGLADESH BORDER REGION
28/07/2011	4.4	DISTRICT KISHTWAR, J &K
03/08/2011	5.3	NORTHERN SUMATRA, INDONESIA
10/08/2011	5.8	PAKISTAN
13/08/2011	4.0	KACHCHH REGION, GUJARAT
22/08/2011	6.2	SOUTHWEST OF SUMATRA,INDONESIA
23/08/2011	4.8	HIMACHAL (DISTT-LAHUL&SPITI) J&K (DISTT-LADAKH) BORDER REGION
04/09/2011	4.2	UKHRUL, MANIPUR
05/09/2011	6.5	NORTHERN SUMATRA, INDONESIA
07/09/2011	4.2	DELHI-HARYANA(DISTT - SONIPAT)REGION
18/09/2011	6.9	NEPAL--INDIA (SIKKIM) BORDER REGION
18/09/2011	5.0	INDIA(SIKKIM)--NEPAL BORDER REGION
18/09/2011	4.5	INDIA(SIKKIM)--NEPAL BORDAR
18/09/2011	4.2	INDIA(SIKKIM)--NEPAL BORDER REGION
23/09/2011	4.5	IMPHAL
24/09/2011	4.3	JAMMU & KASHMIR,INDIA
28/09/2011	4.7	ANDAMAN SEA
01/10/2011	5.0	ANDAMAN SEA
11/10/2011	4.9	NORTH ANDAMAN SEA
16/10/2011	5.6	NORTHERN SUMATRA INDONESIA
20/10/2011	5.3	DISTRICT JUNAGADH, GUJARAT
21/10/2011	4.5	IMPHAL,MANIPUR
12/11/2011	4.3	JUNAGADH, GUJARAT
15/11/2011	4.5	ANDAMAN SEA
19/11/2011	4.7	LACCADIVE SEA,INDIAN OCEAN REGION
21/11/2011	5.8	MYANMAR-INDIA BORDER ,REGION

27/11/2011	5.5	NORTHERN SUMATRA, INDONESIA
05/12/2011	4.5	OFF EAST COAST OF ANDAMAN ISLANDS
06/12/2011	4.8	ANDAMAN ISLANDS
14/12/2011	4.5	INDIA (SIKKIM) - NEPAL BORDER REGION
16/12/2011	4.6	OFF EAST COAST OF NICOBAR ISLANDS
16/12/2011	4.8	OFF EAST COAST OF NICOBAR ISLANDS
27/12/2011	4.8	NICOBAR ISLANDS REGION

16. Conclusion

Earthquake is a natural disaster which takes away thousands of lives and leave behind its destruction. Their prediction is thus of great importance. In this paper we analyze the data of Sitapur, Midanpore (Lat. $22^{\circ}30$N, Long. $87^{\circ}47$E) for six months and calculate DLPT and DLDT from the data amplitude. Then we have plotted the value and observe anomalous data, and correlate this with the Earthquake in India and its neighboring subcontinents. It is observed that the anomalous fluctuations in the data is directly correlates the seismic event. To improve this correlation we have to analyze the data for a longer period of time. Finally it can be said that though this subject is in its infancy, it show a lot of promises.

17. Acknowledgement

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