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Unusual behavior of *D*-region ionization time at 18.2kHz during seismically active days

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Abstract We have been monitoring the VTX3 station at Vijyanarayanam which transmits Very Low Frequency (VLF) signal at 18.2 kHz using the Stanford University made receiver stationed at our Centre We observe significant anomalies of the formation time of the *D*-region of the ionosphere at the Sunrise during the seismically active days. We have analyzed this data for over five months (1st November 2006 to 28th April 2007) and have noticed that during or before the earthquakes which took place in the neighboring region, the formation time is very anomalous in comparison to the normal days and therefore this may be used as a precursor to the earthquakes. We suspect that this abnormal behavior is due to the Lithosphere-Ionosphere coupling. To our knowledge this anomalous behaviour has never been reported before

Keywords · Physics of the ionosphere, radiowave propagation, D region, ionospheric disturbances, earthquakes

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1. Introduction

The physics of earthquake is very complex. The occurrence of earthquake is connected with the earth's crystal dynamics involving the structure of tectonic plates, and with the microscopic processes involved in the friction, electric discharges and release of various gases from the cracks.

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Can earthquake be predicted and the associated tragedies be averted ? A variety of prediction methods have been tried for centuries, ranging from accounts of 'earthquake weather' to arrangements of the planets and uneasiness of animals. All these have been unsuccessful. Beginning in the 1960s, a major scientific effort towards reliable earthquake prediction grew rapidly in seismically active lands particularly in Japan, the former Soviet Union, China and United States. Among different precursory phenomena mentioned in the literatures on earthquake prediction, the ionospheric ones are probably the youngest. The first publications concerning the ionospheric effects connected with the earthquakes were published just after the Alaskan 'Good Friday' earthquake in 1964 (Bolt, 1964; Davis & Baker, 1965).

The ionosphere is a part of the upper atmosphere where there are enough electrons and ions to effectively interact with the electromagnetic fields. As a conducting medium, it plays an important role in the global electric circuit, and as a partly ionized gas, it is subjected to the laws of plasma physics. Due to its electromagnetic properties, the ionospheric plasma interacts with the Earth's magnetic field and to a considerable extent, is controlled by it. Ionosphere is sometimes referred to as magneto-active plasma.

The ionosphere plays a major role in radio propagation, that varies strongly with frequency. At extremely low frequency (ELF, 3-1000 Hz) and very low frequency (VLF, 3-30 kHz) the ionosphere strongly affects propagation over even shorter paths. ELF and VLF waves have long been used for subsurface remote sensing and geophysical prospecting, and sub-ionospheric VLF propagation irregularities and unusual ELF-VLF generation have even been suggested as precursors to major earthquakes (Molchenov and Hayakawa, 1998; Parrot, 1994).

There are several papers in the literature, which recognize that some electromagnetic phenomena would take place prior to an earthquake. Two possible methods have been proposed for the study of sub-ionospheric VLF/LF propagation data to understand seismo-ionospheric perturbation. The first one is based on the analysis of night time amplitude and/or phase anomalies (Horic, 2007). The second method is called the 'terminator time' method, which is based on the determination of characteristic times of minima in the amplitude/phase diurnal variations during sunrise and sunset (see, Hayakawa, Molchenov, Ondoh, Kawai, 1996; Hayakawa, Molchanov, Shima, Shvets and Yamamoto, 2003; Maekawa and Hayakawa, 2006). This method has been used to interpret the results prior to the Sumatran earthquake of December 26th, 2004 (Chakrabarti *et al* 2005).

The Centre for Space Physics VLF receiving station in Kolkata (22°34' N, 88°24'E) has been monitoring VLF signals almost continuously at 18.2kHZ transmitted by the VTX3 station located at Vijayanarayanam (8°26' N, 77°44' E), which is at a distance of 1943 km from the receiver. Some preliminary results involving the monitoring of the sudden ionospheric disturbances (SID) and meteor showers have been reported (Chakrabarti *et al* 2002; 2003). There, we used CSP-made single loop antennas. More recently, we have installed a receiver made by the Stanford University which is capable of monitoring multiple VLF stations. In the present paper, we report the narrowband results from this receiver.

We will concentrate on the variation of the *D*-layer preparation time (DLPT) on each day during the sun-rise and demonstrate that just before or during earthquake activities, the time taken is anomalously high. In fact, we see anomalous behaviour, especially a large scale fluctuation of this time around seismically active days. To our knowledge, this has

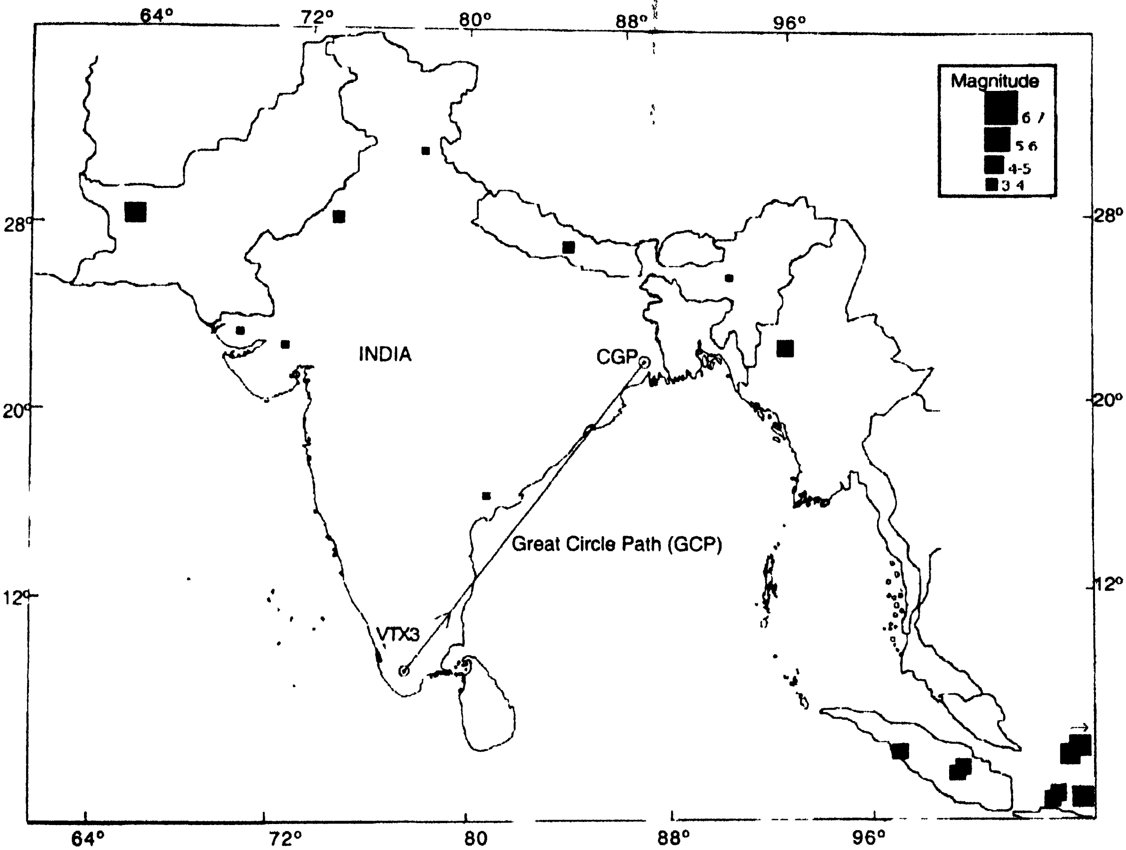

Figure 1. The Great Circle Path (GCP) between the receiver and the transmitter. The locations of the approximate earthquakes are also shown schematically.

never been pointed out in the literature. The deficiency of our method is that while we can predict with pretty much certainty that earthquake will take place, we cannot be certain of its exact location. However we believe that an accurate prediction would be possible by placing several antennas at strategic locations. We are in the process of installing such antennas and the results will be reported in due course.

In the next Section, we present a brief description of the receiving system at CSP. In Section 3, we present the results of seismologically passive and active days, in order that the distinction may be made. The DLPT is found to be significantly different just before and during earthquakes. Indeed, one could expect DLPT to be higher or lower than the average value. These results are also presented in this section. Finally, in Section 4, we draw concluding remarks.

2. Brief description of the receiver

The VLF laboratory consists of a cross-loop receiving antenna with a pre-amplifier and a GPS system attached to it for time stamp. The signals are fed into the AWESOME (Atmospheric Weather Educational System for Observation and Modeling of Effects) receiver made at Stanford University Star Laboratory. The software supplied (SUVLF-DAQ) is capable of separately storing broadband (0 to 50kHz) and narrowband data. Narrowband data from up to eight stations from the east-west and north-south antennas are stored. Figure 2 shows the antenna on the CSP laboratory.

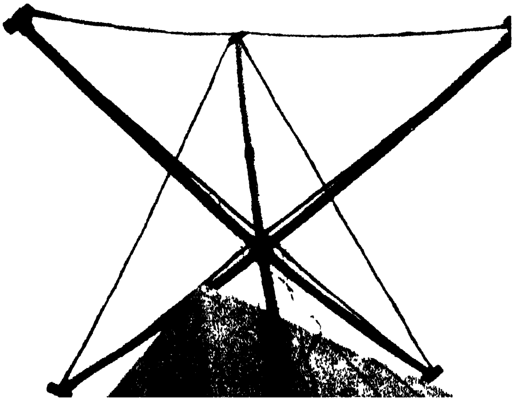

Figure 2. Cross-loop antenna at CSP.

The data is continuously stored in the ISRO sponsored data bank for future analysis. The block diagram of the system is shown in Figure 3.

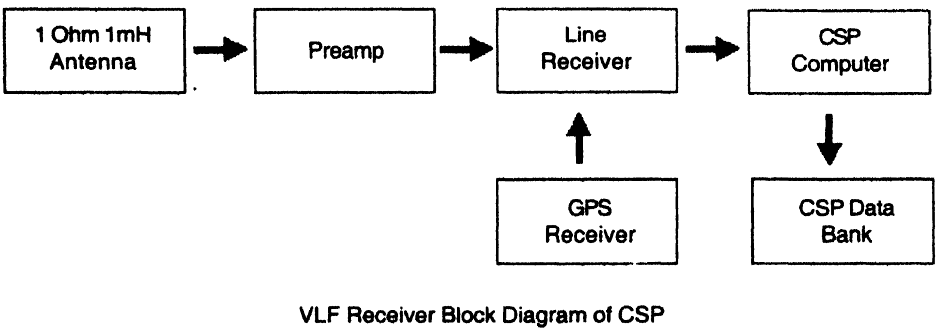

Figure 3. Block Diagram of the VLF receiving system at Centre for Space Physics.

3. Results and analysis

Figures 4a and 4b show the usual whole day pattern of the VLF amplitude data for 00:00 hrs to 24:00 hrs without any interruption. Along *X*-axis we plot time in minutes and along *Y*-axis, we plot the amplitude of the signal in decibel. In the day time, the effects are mainly due to solar irradiation on the ionosphere. At nighttime, the perturbations occur due to scintillation effects. During the sunrise, the signal amplitude drops and reaches a minimum value. This is called the sunrise terminator. The time taken, *i.e.*, $T_A - T_B$ is our *D*-Layer preparation time or DLPT.

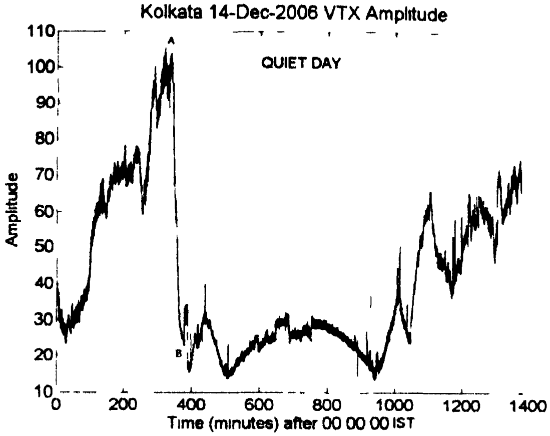

Figure 4a. VLF data from VTX3 on a seismically quiet day.

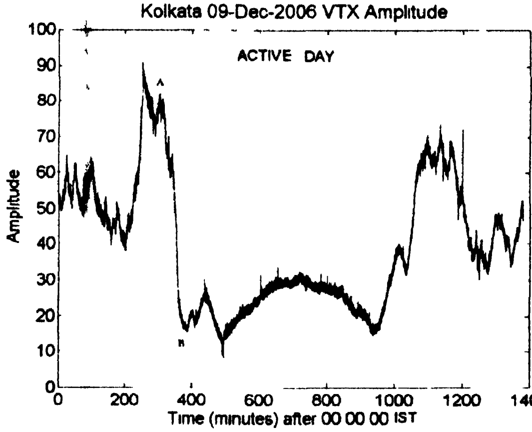

Figure 4b. VLF data from VTX3 on a seismically active day

From these figures, it is clear that DLPT is different in the two days. We call a day seismologically active if DLPT is very far from the average. We observe that this DLPT fluctuates erratically immediately before, during and immediately after the earthquakes. Otherwise, it is a quiet day. Figure 5 shows the variation of DLPT with date from 5th

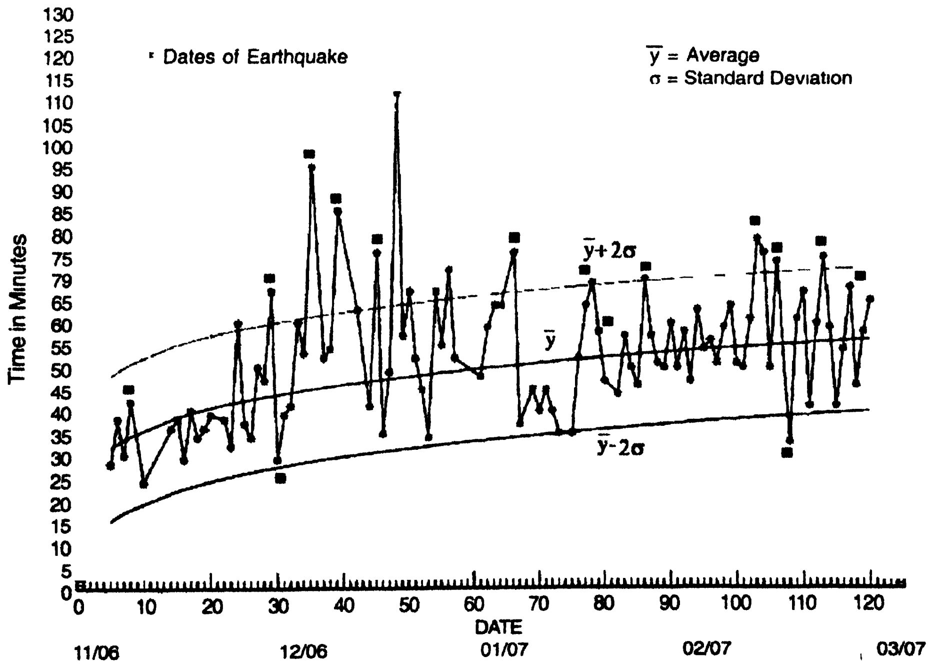

Figure 5a. Ionization time with date for 1st November 2006 to 28th of February 2007. The central curve is the mean and the one above and below are 2σ away from the mean. Filled squares represent the seismically active days.

November 2006 to 28th February, 2007. The mean curve is drawn removing the data of the days on which there has been earthquakes with magnitude 3.5 or higher. The curves representing ± 2 σ (where σ is the standard deviation around the mean) are also plotted.

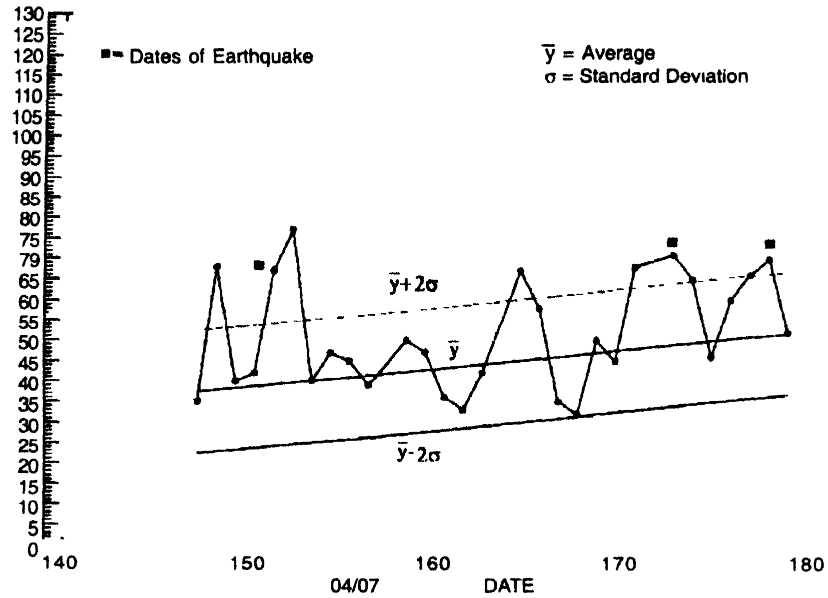

Figure 5b. Same as Figure 5a for the month of April, 2007.

Days of the major earthquake events are marked with squares. It is clearly seen that close to seismologically active days, the fluctuations are either very high or very low. The correlation of earthquakes with anomalous DLPTs is thus established. Table 1 shows the deviation of DLPT from the mean in σ on all the days during this analyzed period.

We note from the table that generally speaking, anomalous DLPTs (be they very much above or below the average) occur 'around' earthquakes. However, we do not find any correlation between the magnitudes of the earthquake and the DLPTs. This is mainly because we ignore two vital parameters such as the distance of the epicenter from the great circle path and the depth under the earth's surface in which the earthquakes occur.

4. Discussions and Concluding Remarks

In this paper, we have presented examples of unusual behaviour of the formation time of the *D*-layer around seismologically active days. We find that the so-called *D*-Layer Preparation Time or DLPT shows large scale fluctuations. For instance if the degree of ionization due to 'seismo-electric' effects is less and diffused, then the VLF radio wave will have to enter deeper inside the *D*-layer for an effective reflection to take place resulting in a longer value of DLPT. On the other hand, if the ionization is strong and concentrated in a thin layer below the E-layer then the reflection will occur by this layer much before the normal time. Thus DLPT is could be expected to be lower also. This additional effect on and above the average effect due to the solar irradiation causes the DLPT to be

Table 1. The observed deviation of DLPT from the mean around seismically active days

Date	Earthquake Magnitude	Observed DLPT in minutes	Deviation in σ	Country of the Earthquake
7/11/06	5 0	42	1 0	Pakistan
29/11/06	3 9	67	2 8	India
30/11/06	6 2	29	1 9	Indonesia
05/12/06	5 0	95	4 2	Myanmar
09/12/06	5 2	85	3 5	North Sumatra
*15/12/06	3 5 (16/12/06)	76	2 9	India
*18/12/06	5 7 (17/12/06)	112	5 2	North Sumatra
*05/01/07	3 4 (07/01/07)	76	2 6	India
17/01/07	5 9	69	2 04	South Sumatra
*25/01/07	4 0 (24/01/07)	70	2 05	India
11/02/07	5 0	79	2 6	North Sumatra
14/02/07	4 0	74	2 2	Indonesia
*16/02/07	4 8 (15/02/07)	33	2 5	Nepal
21/02/07	3 6	75	2 3	India
27/02/07	3 5	58	1 7	India
1/04/07	7 5	67	3 0	Solomon Islands
21/04/07	6 1	71	2 5	Papua New Guinea
27/04/07	6 0	70	2 3	North Sumatra

* Anomalous DLPT before or after the earthquake which occurs on dates in second column

** The earthquake data is taken from the website http //www imd ernet in

sometimes very high or very low. We find that these extreme values are often deviated from the mean by more than 2 σ, *i.e.*, our conjecture is valid above 95% confidence level.

The subject of earthquake prediction through VLF effects is in its infancy. We suspect that what we observe is due to Lithosphere-Ionosphere coupling, but quantitative explanations are still lacking. It is possible that some kind of exchange between the ionization and neutral bubbles could be responsible for such anomalous behaviour.

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