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A study of the behavior of the terminator time shifts using multiple VLF propagation paths during the Pakistan earthquake ($M = 7.2$) of 18 January 2011

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Abstract. On 18 January 2011, at 20:23 UTC, an earthquake of magnitude 7.2 occurred in southwestern Pakistan (latitude 28°44′ N, longitude 63°56′ E) at a depth of 68 km. We present the results of the analysis of very low frequency (VLF) radio signals, received at three stations located in India. We analyze the VLF signals around this earthquake day and look for possible precursory effects of this earthquake. For our analysis, we use four different VLF propagation paths. These propagation paths are DHO–IERC (Sitapur), VTX–Pune, VTX–ICSP (Indian Centre for Space Physics, Kolkata) and NWC–IERC. We observed significant shifts of the "sunrise terminator time" (SRT) for DHO–IERC and VTX–Pune paths. For DHO–IERC path, the SRT of the VLF signals shifted towards nighttime three days before the earthquake day, and in the case of VTX–Pune path it shifted towards nighttime just one day before the earthquake day. For VTX–Kolkata path, the shift of SRT is four days before the earthquake day, but here the shift is not so strong, somewhere between 2σ and 3σ lines. For the other two paths, namely, DHO–IERC and VTX–Pune, the terminator time shifts crossed the 3σ line. We found no significant shifts of SRT for NWC–IERC propagation path. Higher deviation in the VTX–Pune path as compared to VTX–ICSP path could be due to the proximity of the former to the epicenter. Similarly, DHO–IERC path is over the epicenter while NWC–IERC path is totally away from the epicenter. This could be the reason why the effect in DHO–IERC path is stronger than that in NWC–IERC path.

1 Introduction

Prediction of earthquakes is one of the most challenging jobs for the scientific community. Numerous attempts have been made over the centuries, and yet a definite answer is still alluding us. It is postulated that the ionosphere could undergo changes well before earthquakes so that certain anomalies in the very low frequency (VLF) signals may be used for short-term earthquake prediction. In this regard, the first attempt was taken by Bolt (1964) after the "Alaskan earthquake" (Bolt, 1964). Using ionosonde method, he first reported a possible seismo-ionospheric correlation. After that several papers were published supporting seismo-ionospheric correlations (e.g., Davis and Baker, 1965; Row, 1967; Yuen et al., 1969). In 1989, Gokhberg et al. published a paper on the basis of their study of the signals received by Omega navigation transmitter (10.2–13.6 kHz) during 1983–1986, and they found that 250 out of 350 earthquakes with magnitude (M) greater than 4 were associated with phase and/or amplitude variations (Gokhberg et al., 1989). These studies on the ionospheric perturbations due to seismic events are mainly based on the anomalous variations of the phase and amplitude of the signals.

In 1996, after the "Kobe earthquake", Hayakawa et al. (1996, hereafter H96) introduced a new method, namely the "terminator time method" for earthquake prediction. They showed that both the sunrise and sunset terminators times shifted towards the nighttime a few days before the earthquake. Molchanov et al. (1998) analyzed VLF signals around the ten large earthquake (magnitude greater than 6) days and generally supported the observation of H96. They found five cases where the terminator times were shifted a few days before the earthquake. According to them, the reasons for the absence of the terminator time shifts in the other five cases could be due to the long distance of the epicenter of the earthquakes from the propagation paths and also the larger depths of the earthquakes. This method was also examined by Clilverd et al. (1999) who used the data of 6 yr during 1990–1995. However, for a very few cases they found that the terminators of the VLF signals shifted before the earthquake, and in most of the cases they found no strong association between terminator time shifts and earthquakes. In a response to this conclusion, Soloviev et al. (2004) performed the full-wave computation and showed that a perturbation in the lower ionosphere during day/night transmissions would exhibit a significant change in the terminator time. Just after the 2004 devastating earthquake of Indonesia, the seismo-ionospheric correlation was examined by Chakrabarti et al. (2005), who came to the conclusion that a definite shift towards the night is present a few days before the earthquake. Subsequently, using the VLF signal from the Indian Navy station VTX (latitude 8.43° N, longitude 77.73° E) to Indian Centre for Space Physics (ICSP), Kolkata (latitude 8.43° N, longitude 77.73° E), Sasmal et al. (2009) showed that the "VLF day length" (defined as the time difference between the two terminator times) becomes anomalously high typically two days before the earthquakes. Subsequently, Ray et al. (2010) reported that the "VLF day length" obtained from the VLF signals for VTX–Malda propagation path become anomalously high one day before the earthquake. These two works also support the "terminator time method" for earthquake prediction.

Apart from following this approach, two other methods were introduced by Chakrabarti and collaborators. In Chakrabarti et al. (2010), it was shown that the time taken to form the D-layer or to destroy it also becomes anomalous about a day before the earthquake. In Ray et al. (2011) it was pointed out that the nighttime amplitude of the VLF signal fluctuates anomalously three days before the earthquakes. This was further verified in the case of Pakistan earthquake (Ray et al., 2012) of magnitude 7.2, which occurred in southwestern Pakistan (latitude 28.9° N, longitude 64° E) on 18 January 2011.

One of the problems in the approaches given above is that while the precursors may have been observed, no inference could be drawn about the location of the epicenter, since only one receiving station was used. If a multiple number of stations could be used, then there is a possibility to compare relative anomalies and perhaps some possible hints about the epicenter may be obtained. In the present paper, we use the "terminator time method" to analyze the same Pakistan earthquake mentioned above. However, we consider the VLF signals for four different propagation paths to study if the shifts of the terminators closer to the epicenter are higher. The major source of our data is the data received at the Ionospheric and Earthquake Research Centre (IERC)

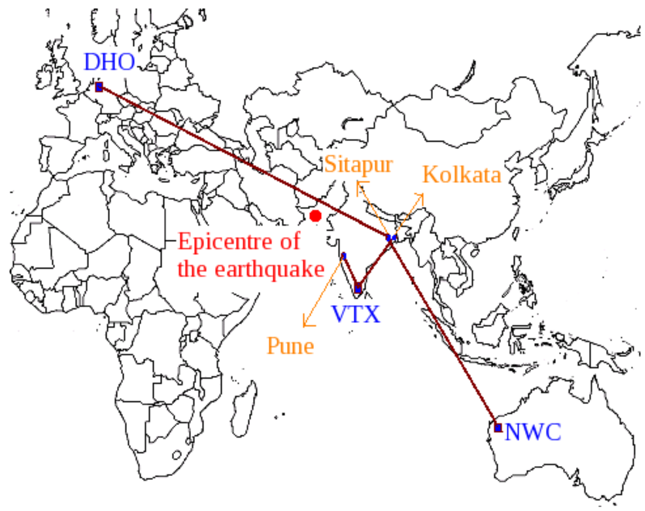

Fig. 1. VLF propagation paths and the epicenter of the Pakistan earthquake considered for analysis. Transmitters and receivers are marked with filled squares and small filled circles, respectively. The epicenter of the earthquake is marked by a large filled circle.

under Indian Centre for Space Physics (ICSP) located at Sitapur (latitude 22.51° N, longitude 87.79° E), though the ICSP (Kolkata) data and Pune data were also used. The propagation paths that we used are DHO–IERC, VTX–Pune, VTX–ICSP and NWC–IERC. We found significant shifts of the SRT for DHO–IERC and VTX–Pune paths (see Fig. 1 below), and for the other two paths, no significant shifts of SRT were found. For the present analysis we mainly concentrate on the "sunrise terminator time" (SRT), because the "sunset terminator times" were not very prominent for all the paths.

The plan of the paper is following: in the next section we show the propagation paths, and in Sect. 3, we present our analysis and results. Finally, in Sect. 4, we draw our conclusions.

2 The transmitters and the receivers

For the present analysis, we use the VLF signals received at three different receiving stations, located in Pune (latitude 18.51° N, longitude 73.85° E), ICSP, Kolkata (latitude 22.56° N, longitude 88.4° E) and IERC/ICSP, Sitapur (latitude 22.51° N, longitude 87.79° E). We use three different types of the receivers at these three stations. In Pune, we use ICSP-made Gyrator-III type receiver. The Gyrator-III type receiver is capable of tuning with a single transmitter. Sixteen turns of wire around a 1 m × 1 m square frame act as a loop antenna. This loop detects the fluctuations in magnetic field component of the signal. The data are obtained through the sound card and are logged automatically in the computer as an ASCII file.

At ICSP, Kolkata, we use the AWESOME receiver made at Stanford University, which receives VLF signals transmitted from several transmitting stations, located all over the world. In the present work, we concentrate only on the VLF signals transmitted from VTX at 19.2 kHz, the data of which were clean. In an AWESOME receiver, the antenna has two cross loops that detect fluctuating magnetic field components and can also locate the direction of the signal. After receiving the data by this antenna, they are pre-amplified and time-stamped by a GPS unit. The data are automatically stored in the computer. The MATLAB software is used to convert these data into a text file.

For the IERC (Sitapur) receiving station, we use "SoftPAL" receiver, which receives signals from several transmitting stations. For the present analysis we used the VLF signals transmitted from NWC (latitude 21.8° S, longitude 114.15° E) and also from DHO (latitude 53.06° N, longitude 7.6° E). These two transmitting stations transmit at 19.8 kHz and 23.4 kHz, respectively. For a "SoftPAL" receiver, an electrical antenna is needed that measures the electrical field components of the VLF signals. After receiving the data by this antenna, first they are pre-amplified and time-stamped by a GPS unit. Here also the data are automatically stored in the computer. The "Lab Chart" software is used to convert the data into text file.

We monitor signals along four propagation paths: DHO–IERC, VTX–Pune, VTX–ICSP, and NWC–IERC. The data received at different receiving stations are normalized before they are compared using the Long Wavelength Propagation Capability (LWPC) model. This normalization is done with the data obtained at noon. In Fig. 1, we plot the propagation paths that are used in the present analysis. The transmitters are marked with filled squares, and the receivers are marked with small filled circles. We also mark the epicenter of the earthquake by a large filled circle. With the amplitude of the signals being highly dependent on the propagation paths, we obtained totally different diurnal signals in these paths.

3 Results

We analyze the amplitude variations of the VLF signals at the four propagation paths on days before, on and after 18 January 2011 (UTC) (hereafter E-day). At 20:23 (UTC), 18 January, an earthquake of magnitude 7.2 occurred in the southwestern Pakistan at a depth of 68 km. For convenience we shall present the data in Indian Standard Time or IST (= UTC+5:30). This is because, since IST is ahead of UTC by 5.5 h and sunrise time at the receiving stations is also at around 5:30 a.m., the diurnal variation of the data is roughly symmetric with respect to the local noon. In IST, the earthquake occurs on 19 January 2011 at 1:53 a.m. and it will be marked as such in all the figures. In passing we may just mention that conventional earthquake preparation zone (Dobrovolsky et al., 1979) is about 1250 km of radius around the epicenter. It is a measure on the ground, and it is not directly related to the size of the perturbed area of the ionosphere. However, it still gives a rough idea of the length scales one needs to keep in mind while determining the influence of an earthquake.

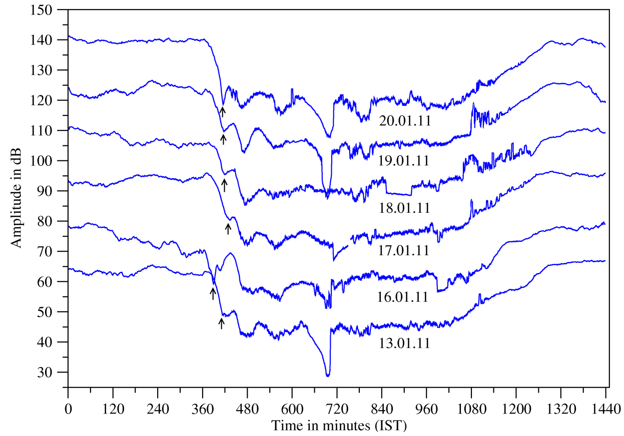

Fig. 2. Variation of the amplitude of VLF signal in various days around the E-day (19 January 2011 IST). SRTs in each day are marked by an "arrow". Note that the SRT of the data of 16 January 2011 shifted towards nighttime by about 40 min.

3.1 DHO–IERC path

Let us first discuss the results for the DHO–IERC propagation path. The distance between the transmitting station (DHO) and the receiving station (IERC) is 7380 km. The mid-point of this propagation path is situated 1865 km away from the epicenter of the earthquake. In Fig. 2 we plot the amplitude of the VLF signal. The amplitude of the VLF signal is plotted as a function of time in minutes for a few days around the E-day. The sunrise terminator times (SRTs) of each day are marked by the "arrow" symbol. We define the SRT by the first weak minimum that occurs after the weakening of the signal at dawn. We find that the SRT of the VLF signal of the data of 16 January 2011 is shifted towards nighttime. This may be the precursor effect of the earthquake on the E-day. To elaborate this point, we have plotted the SRTs as a function of day number in Fig. 3. In this figure, the solid curve represents the average value of the terminator times while the dotted and dashed curves represent the 2σ and 3σ line, respectively. The vertical dashed line represents the earthquake day. The SRTs are marked by the circles connected by a solid line. We find that three days before the E-day, SRT crossed the 3σ line. We checked that no solar flare, lightning or any other ionospheric disturbance event occurred on that day. The shift is also towards night as observed in several previous occasions. This led us to believe that this terminator time shift could be the precursor effect of the earthquake.

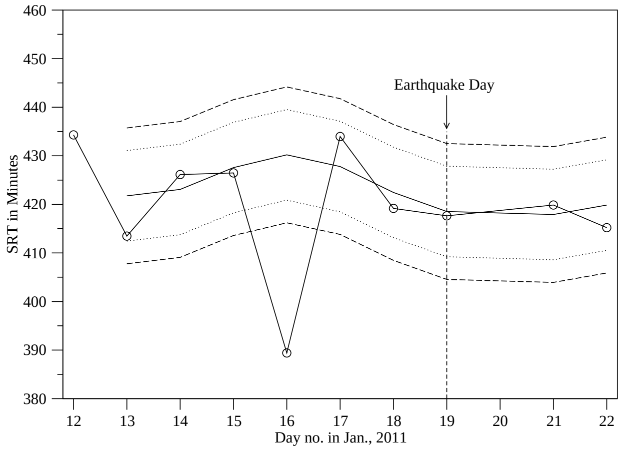

Fig. 3. SRTs of the VLF signals for the DHO–IERC propagation path are plotted as a function of the day number. SRTs are marked by the open circles connected with a solid line. The mean value of the SRT is plotted by the solid line. The dotted and the dashed curves represent the 2σ and 3σ lines, respectively. The vertical dashed line is plotted to indicate the earthquake day. Note that three days before the earthquake the SRT crossed the 3σ line.

3.2 VTX–Pune path

The distance of the VTX–Pune propagation path is 1203 km. The mid-point of this propagation path is situated 2107 km away from the epicenter of the earthquake. In Fig. 4, the amplitude of the signal is plotted as a function of time in minutes. Only the data obtained a few days around the E-day are plotted. In this case, the wave propagates from the east to the west. Due to the attenuation effects, the amplitude of the nighttime signal is very low (Chakrabarti et al., 2012). For this reason, the nature of the signal is quiet different. To be consistent with the earlier case, we define the SRT as the last minimum point in the morning after which the signal rises almost vertically. From Fig. 4 we see the significant shift of the SRT in the data of 18 January 2011 (IST), which may be considered to be the precursor of the earthquake. In Fig. 5, we plot the SRT as a function of day number. Here we use the data of 20-day data around the earthquake day. The SRTs are indicated by the open circle, while the mean, 2σ and 3σ lines are represented by the solid, dotted and dashed curves, respectively. The vertical dashed curve represents the E-day. It is clear that one day before the earthquake the SRT crossed the 3σ line. The net shift of the SRT is about 100 min towards the night. Thus this anomalous shift may be considered to be the precursor of the earthquake. Here also we check that no solar flare, lightning or any other event that may cause ionospheric disturbances occurred on that day.

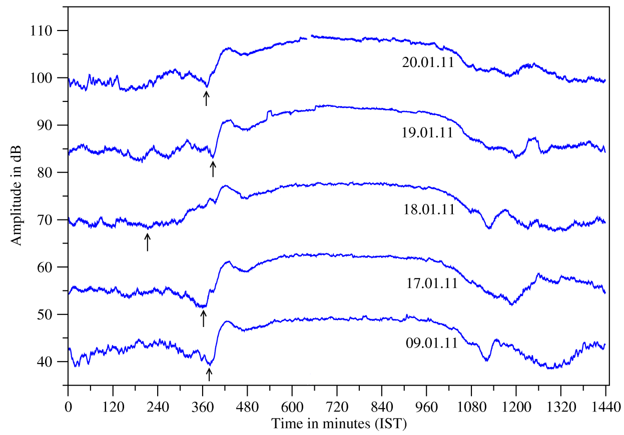

Fig. 4. The diurnal VTX–Pune signal variation. A total of five days data are plotted around the E-day. The "arrows" indicate the SRT of the signal for each day.

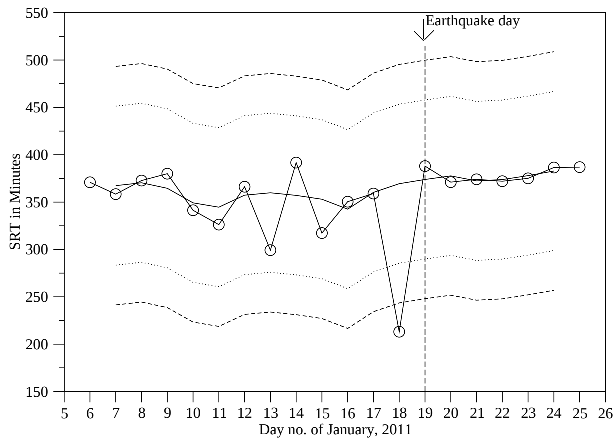

Fig. 5. Variation of SRTs is plotted as a function of day number. The circles represent the value of the SRT on each day. The mean, 2σ and 3σ lines are marked by solid, dotted and dashed curves, respectively. The vertical dashed line represents the E-day. One day before the earthquake, the SRT shifted towards nighttime by about 100 min, indicating that this could be taken as the precursor.

3.3 VTX–ICSP path

For VTX–Kolkata propagation path, the effect is not so strong. The distance of this path is 1944 km, and the distance between the mid-point of this propagation path and the epicenter of the earthquake is 2441 km. This distance is comparatively longer than the previous two propagation paths. In Fig. 6, we plot the amplitude of the VLF signals of this propagation path as a function of time in minutes. From this plot, one can see a very small amount of shift of the SRT (defined as the first weak minimum occurring after the weakening of the signal at dawn) in the VLF signals four days before the earthquake. In Fig. 7, these SRTs (marked by open circle

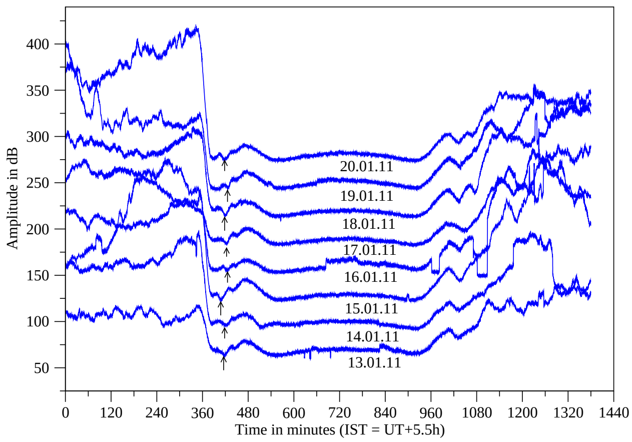

Fig. 6. Variation of the signal amplitude for VTX–ICSP propagation path. The "arrow" symbols indicate SRT on each day.

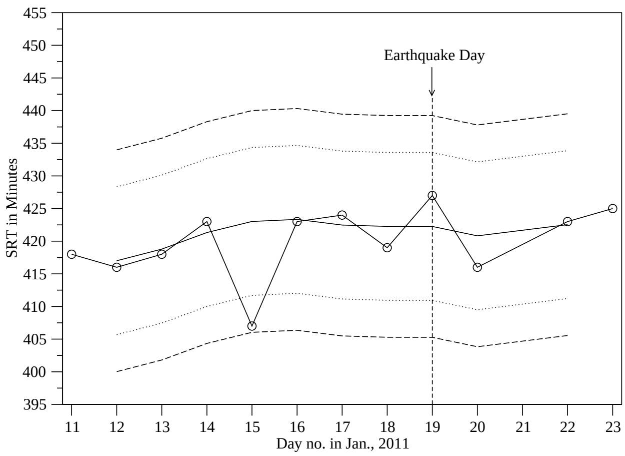

Fig. 7. Variations of the SRTs as a function of day (IST). SRTs are marked by the circles and are connected with lines. The mean, 2σ, 3σ lines are plotted by solid, dotted and dashed curves. The vertical dashed line denotes the E-day. The deviation of SRT three days before the earthquake is at about 3σ level.

connected by a solid line) are plotted as a function of day (IST) along with the mean, 2σ and 3σ lines, represented by solid, dotted and dashed curves, respectively. We use the data of 12 days around the E-day. We find that four days before the earthquake, the SRT is just about 3σ level away from the expected mean value indicating a weak precursory effect. The shift is only about 15 min towards the night. The reason for the absence of the strong precursor effect may be the long distance of the epicenter of the earthquake from the mid-point of this propagation path.

3.4 NWC–IERC path

We have also analyzed the VLF signal for the NWC–IERC path. The distance between the NWC and IERC is 5698 km,

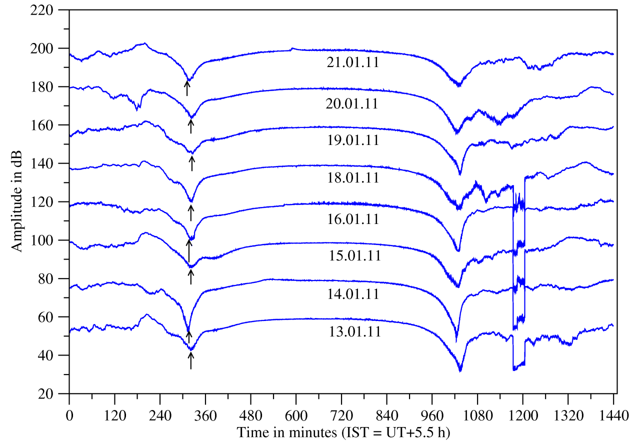

Fig. 8. Diurnal variation of the amplitude of VLF signal along NWC–IERC is plotted for a few days around the E-day. The "arrows" indicate the SRTs on each day.

and the epicenter of the earthquake is situated 5049 km away from the mid-point of this propagation path. NWC is a powerful and stable transmitter. Thus the NWC–IERC data are relatively clean. The interference between the sky wave and the ground wave causing the minimum at the terminators is also very prominent. From these data, we obtained the SRT from the VLF signal on each day and found no change of the value of SRT around the earthquake day. In Fig. 8, we plot the amplitude of the VLF signals for a few days. Here the amplitude is plotted as a function of time in minutes. It is clear that there is no change in the SRT around the E-day. To show this more clearly, we plot the SRT as a function of day (IST) in Fig. 9. Here we use 24 days of data around the E-day, and we found that the SRT for each day is within the 2σ line, not significantly deviating from the mean. So the precursor effect is very weak in the data of NWC–IERC propagation path.

4 Conclusions

The search for the correlation between the seismic events and ionospheric signal anomaly has been ongoing for about half a century, and yet a definite answer to this tantalizing problem is not in hand. The reason is that the problem is multi-parametric and highly non-local. The effect is also non-linear. For instance, in four propagation paths, the deviation was *not* found to be proportional to the distance of the epicenter from the mid-point of the propagation path. As of yet, there is no definite theory that quantifies to a specific type of anomaly. It is not even clear whether it is the lower ionosphere that alone is perturbed, or the possible perturbation in ground conductivity (which enters into the picture from the second hop onwards of the signal) is also responsible. In these circumstances, the best goal would be to analyze as many cases as possible and get a good amount of statistics of

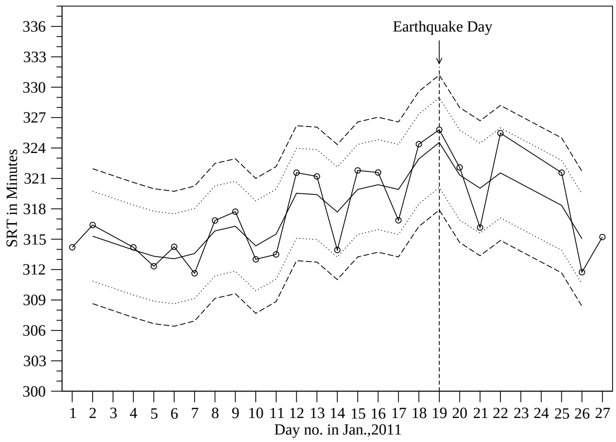

Fig. 9. SRTs are plotted as a function of the day (IST). They are marked by the open circles connected with a solid line. The mean, 2σ, 3σ lines are plotted by the solid, dotted, dashed curves and the E-day is marked with a vertical dashed line. Note that the SRTs on each day are within 2σ line, not enough to consider as a precursor.

what we observe and what we do not observe. In a previous analysis from our group, we presented the anomalies of terminator time shifts, formation/disappearance time of D-layer and the nighttime fluctuations from a given propagation path. However, in this paper, for the first time, we compared the effects of the same earthquake in four paths and found very exciting results. We find, in particular, that the anomalous terminator time shifts are higher when the distance of the mid-point of the propagation path is lower. The VTX–Pune path exhibited the highest anomaly, even though the distance of the mid-point is more than that of DHO–IERC. Nevertheless, our study indicates that the effect *is* propagation path dependent, and with more observations one could look for a pattern that may lead to successful prediction of earthquakes in the future.

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