

Ionospheric Total Electron Content Response to the December 26, 2004 North Sumatra Earthquake

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Abstract: Problem statement: Ionospheric precursors of earthquake have been studied by scientists and seismologists. This study aims at examining the relationship between the ionosphere and earthquake precursors. The effects of the anomalous electric field that penetrates the ionosphere on the electron concentration can be measured experimentally. This study reports on the variability of the Total Electron Content (TEC) during the December 26, 2004 earthquake in North Sumatra (epicentre: 3.295°N, 95.982°E) which measured 9.3 on the Richter scale. **Approach:** The ionospheric TEC near North Sumatra between December 19 to 31 was calculated between 22:00 and 24:00 and between 02:00 and 06:00 local time (LT) using a dual frequency Global Positioning System (GPS) receiver. It was recorded for a period of 13 days, which is seven days before and five days after the earthquake. The GPS data was taken from the Department of Survey and Mapping Malaysia in the north of Malaysia (4.1°N, 99.8°E), which is near North Sumatra. Four sets of data were selected from different GPS satellites that passed near the epicentre. **Results:** Results show good agreement with the existence of earthquake precursors. TEC variability was detected at night and in the early morning of 21 December 2004 (five days before the earthquake) and 25 December 2004 (a day before). Findings show an increase in the electron concentration level at the station closest to the epicentre and the TEC varies from 2-10 TEC unit. **Conclusion/Recommendations:** The findings correspond with previous research and literature in this field. Further studies on the parameters that cause the change in the ionospheric TEC due to earthquakes are needed if this is to be used as part of an earthquake early warning prediction system.

Key words: Ionosphere, TEC, earthquake, Global Positioning System (GPS)

INTRODUCTION

The variability of electron concentration in the ionosphere (measured by ground based ionosondes and dual system GPS receivers) around the time of earthquake has been studied by scientists and seismologists. This variation is generally known as ionospheric precursors of earthquake, which appears one to five days before the time of seismic shock^[1]. These phenomena can be explained by the interaction of the acoustic-gravity waves generated by the lithospheric perturbations during the seismic event preparation, with cold dense ionospheric plasma in the presence of ambient electric and magnetic fields.

Earthquake prediction: Ionospheric precursors of earthquakes were registered in 73% of the cases for earthquakes with a magnitude of 5 and in 100% of the seismic shock with a magnitude 6 on the Richter scale. Therefore, magnitude of 5 is considered as the threshold of the ionosphere sensitivity of earthquake preparation^[2]. The explanation on how this situation can be predicted is based on the Dobrovolsky formula^[2] in Eq. 1:

$$R = 10^{0.43M} \quad (1)$$

Where:

R = Radius of earthquake preparation zone

M = Earthquake magnitude (where M = 9.3 in this study)

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Precursory phenomenon of earthquake and the seismic shock: One of the main sources of atmosphere-ionosphere modification over the regions, during the preparation of earthquakes, is the emanation of different chemical substances from the earth^[3]. Among them are radon, light gases (hydrogen and helium) and sub-micron aerosols with high metal content^[4]. Recent experimental studies^[5] indicated a direct connection between the stress applied to rocks and the generation of charge carriers, causing the formation of electric currents and thus affecting surface potentials. The rock inside the earth's crust contains a formation of H₂O that has been there for a long time. After going through several processes, the crystallization in H₂O is transformed into OH peroxy^[6]. During the preparation of the earthquake, the peroxy bond breaks, hence positive holes are released. These charge carriers are highly mobile and change the mineral or rock momentarily into a p-type semiconductor^[5]. When they intersect with the Earth's surface, the ground potential is expected to become very highly positive^[5,9]. The normal ground potential varies between 0.1-100 V m⁻¹, but, in the areas of impending earthquakes, the value can increase up to 1000 V m⁻¹^[4]. The gas emanation including radon which is released from the ground can affect the aerosol content and cause the conductivity to increase up to fivefold above the original level. The loading-unloading process during the earthquake preparation is the reason for the variation of radon concentration before earthquakes. Radon is an ideal indicator in geological research because it is generated continuously in any geological structure^[4].

Other affected gases are aerosols. Aerosols in the atmosphere can lead to the formation of large-scale electric fields up to several kV m⁻¹^[6]. The normal ground potential varies between 0.1-100 V m⁻¹, however in cases of thunderstorms or in areas of impending earthquakes, it can rise up to 1000V m⁻¹^[4].

Raleigh wave during the occurrence of seismic shock: After a large earthquake, the vertical displacement due to Raleigh wave propagation induces upward-propagating acoustic waves in the atmosphere through the continuity of displacement at the surface. The amplitude of the atmospheric wave increases exponentially with altitude, leading to large vertical oscillations in the upper atmosphere and ionosphere^[3]. This seismic wave in the ionosphere can be detected by using existing dual frequency GPS satellites.

TEC from GPS: The signals from the GPS satellites travel through the ionosphere on their way to receivers on or near the earth's surface. The free electrons

populating this region of the atmosphere affect the propagation of the signals, changing the velocity and the direction of travel^[7]. By processing the data from a dual-frequency GPS receiver, it is actually possible to estimate just how many electrons were encountered by the signal along the travel path - the TEC. Over the past two decades, ionospheric noise on dual frequency GPS observations has been exploited to derive the information on the ionosphere and for the advanced research in ionospheric studies; whereby time delay has been used as data for analysis^[7].

The difference between the two-frequency measurements can be used to calculate the TEC along the signal path between the GPS satellite and the ground-based GPS receiver. In fact, a regional network of ground-based GPS receivers can be used to construct a map of TEC above the region. This is because the propagation velocity and direction of the GPS signal changes in proportion to the varying electron density along the line of sight between the receiver and the satellite as GPS signals propagate through the ionosphere.

Total Electron Content (TEC): The parameter of the ionosphere that produces most of the effects on GPS signal is the Total number of Electron Content (TEC)^[3]. TEC is a measure of the total amount of electrons along a particular line of sight. Unit of TEC is 10¹⁶ per square metre. TEC can be measured by using either GPS receivers or ionosonde (indirectly). In this study, the TEC is measured by using GPS receivers.

The TEC normally varies smoothly from day to night as earth's dayside atmosphere is ionized by the Sun's extreme ultraviolet radiation, while on the night side, the ionosphere electron content is reduced by chemical recombination^[8]. GPS satellites transmit electromagnetic waves for positioning on two frequencies: L1 (1.57542 GHz) and L2 (1.2276 GHz). The velocity of an electromagnetic wave at GHz band is frequency dependent on the ionosphere. This enables us to extract the ionospheric TEC along the line of sight between the satellite and the receiver.

Calculation of slant and vertical TEC: Slant TEC is a measure of the TEC along the ray path from the satellite to the receiver^[3], shown in Fig. 1 as the quantity TECs. Vertical TEC enables the TEC to be mapped across the surface of the earth. The slant TEC, from Eq. 2 can be calculated using GPS signal as given in Freund *et al.*^[4]:

$$TEC = \frac{1}{40.3} \left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right) (P_1 - P_2) \quad (2)$$

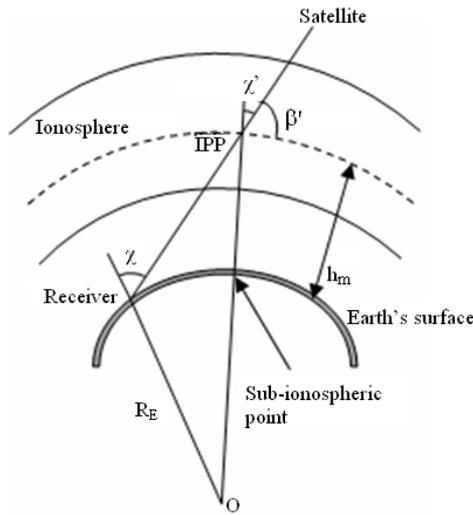


Fig. 1: Ionospheric single layer model

Vertical TEC (TEC_v) can be regarded as^[3]:

$$vTEC = TEC(\cos \chi') \quad (3)$$

with

$$\cos \chi' = \sqrt{1 - \sin^2 \chi}$$

$$\sin \chi' = \frac{R_E}{R_E + h_m} \sin \chi \quad (4)$$

where:

χ and χ' = Zenith angles at the receiver site and at the ionospheric pierce point, IPP

R_E = Mean earth radius

h_m = Height of maximum electron density (450 km)

This study reports on the TEC changes due to seismic activity specifically according to the earthquake event. TEC variations before and after the occurrence were observed using GPS data. Findings show an increase in the variability of electron concentration level at the station closest to the epicentre. In order to develop an earthquake precursor, further study is needed to check on the parameters that cause the change in the ionospheric TEC.

MATERIALS AND METHODS

The 2004 December 26 North Indonesian Earthquake was chosen as the case of this study since it is the largest earthquake recorded in the century,

measuring 9.3 on the Richter scale. Another reason is its location, which is near Malaysia. The effect of ionospheric precursor locality is used for the data analysis at several observation times. In order to detect the earthquake precursor, TEC is extracted using data from GPS dual frequency system. In order to estimate TEC from GPS observations, the ionosphere was approximated by a spherical shell at a fixed height of 400 km above the earth's surface. Geometric factor of Eq. 3 was used to convert the slant TEC (TECs) into a vertical TEC (TEC_v). TEC_v was used since its value is not dependent on the location of satellite receiver compared to TECs. High-precision phase measurements were used to remove the phase ambiguities by fitting the phase measurements to the code data collected along an individual satellite pass. The observation was made seven days before the earthquake and five days after, which were from 19 to 31 December 2004. Four sets of data, which were taken from four different GPS satellites, were used. The satellites were chosen based on their track location closest to the epicentre (3.295°N, 95.982°E) in North Indonesia. The observed TEC was taken from the receiver station at University Sains Malaysia (USM), Pulau Pinang (4.1°N, 99.8°E), supplied by Department of Survey and Mapping Malaysia (Jabatan Ukur dan Pemetaan Malaysia, JUPEM) in Receiver Independent Exchange (RINEX) format. The daily TEC was calculated using Matlab Programming Language and plotted to observe the daily TEC variation before and after the earthquake.

Recent researches^[1,2,9,10] stated that earthquake precursor could be seen according to the changes variation of TEC reading and exceeding the average of maximum and minimum daily TEC from five days to a few hours before the earthquake.

RESULTS

The first data set in Fig. 2, which is TEC_v reading observed from satellite PRN 16 and Fig. 3 for PRN 8, does not show any peculiarities that can be regarded as precursor phenomena in its daily variation from 19-31 December 2004. Figure 4 shows the daily variation of PRN 16, which gave maximum TEC_v value of 20 detected on 21 December. On 23 December, the TEC_v fell to a minimum value of 7.5. However, both signs cannot be assumed as earthquake precursors, since the difference (max and min TEC_v value) between the days is considered small (that is less than 10 TEC_v).

Figure 5 shows the TEC_v reading for satellite PRN 13 and the daily variation shown in Fig. 6 shows that one precursor was detected on 22 December, 4 days before the occurrence of the earthquake. On that day,

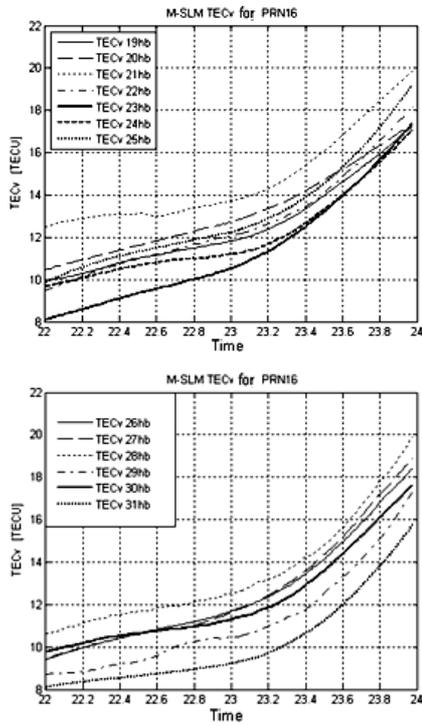


Fig. 2: TECv variation for satellite PRN 16

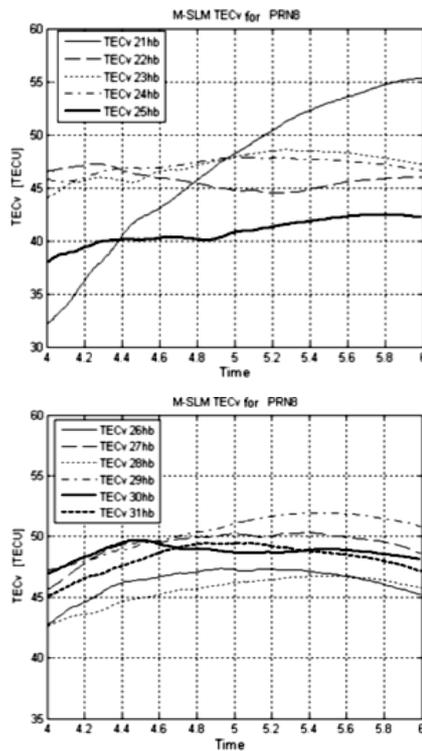


Fig. 3: TECv variation for satellite PRN 8

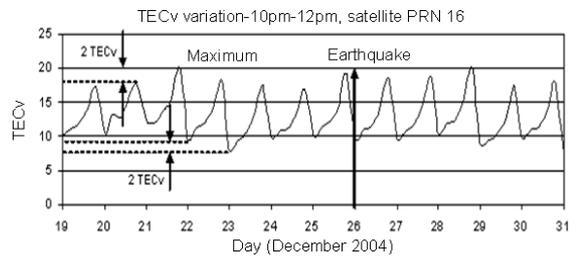


Fig. 4: Overall TECv variation for satellite PRN 16 from 19 to 31 December 2004

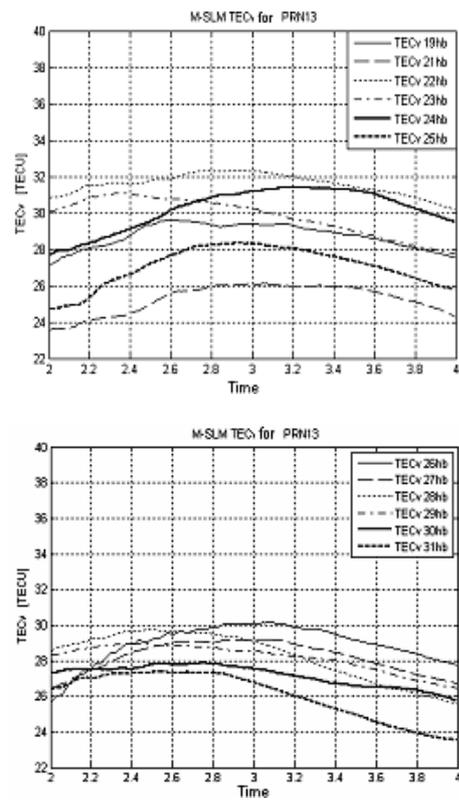


Fig. 5: TECv variation for satellite PRN 13

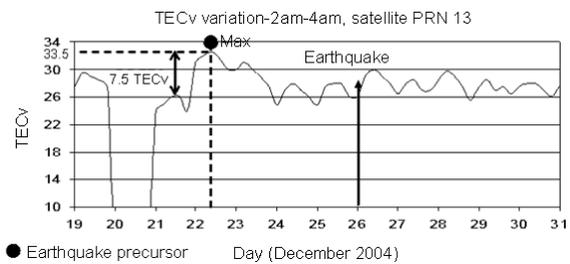


Fig. 6: Overall TECv variation for satellite PRN 13

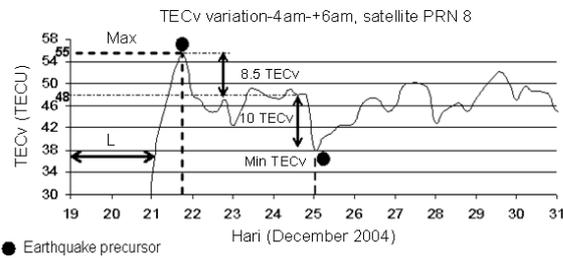


Fig. 7: Overall TECv variation for satellite PRN 8

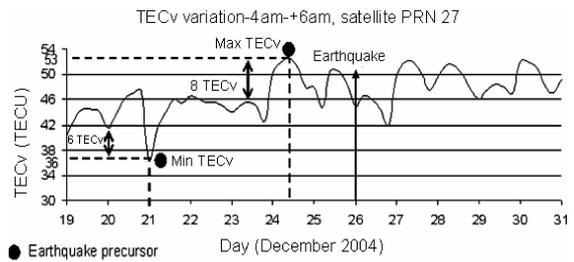


Fig. 9: Overall TECv variation for satellite PRN 27

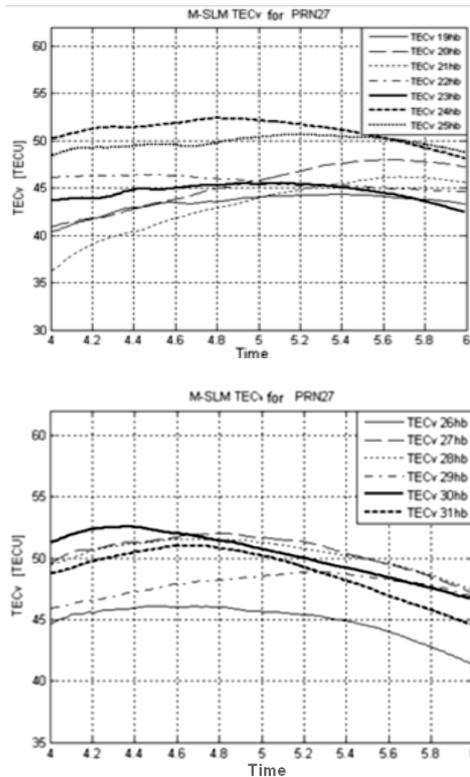


Fig. 8: TECv variation for satellite PRN 27

the TECv reading was 33.5, which was a 7.5 increase from 26 TECv recorded on 21 December. The reading on 20 December could not be recorded due to ionospheric scintillation.

TECv variation for satellite PRN 8 in Fig. 7 shows two signs of earthquake precursor on 21 and 25 December. The observation started on 21 December since the data for 19 and 20 December were not available. The maximum value of 55 TECv was recorded on 21 December. On 25 December, the TECv fell to a minimum value of 38 TECv. Both precursors were detected five days and one day before the earthquake.

Figure 8 shows the TECv variation from satellite PRN 27 from 19 to 31 December 2007. Figure 9 shows two indications of earthquake precursors, which were detected on 21 and 25 December 2004.

TECv first fell into minimum value on 21 December and then maximum TECv value of 53 was recorded on 25 December.

DISCUSSION

The ionospheric precursor could be observed between five days and a few hours prior to an earthquake^[4,9]. In this study, the precursor is detected five days and one day before, which were on 21 and 25 December 2004. It was demonstrated that the variations of electron concentration could be stimulated by the atmospheric electric field within the ionosphere.

In the Taiwan earthquakes (1997-1999), the pre-ionospheric anomalies appeared from 18:00 to 22:00 local time^[11]. In this study, the anomaly was detected also during the early morning hours between 2 AM and 6 AM.

To have a better view of the anomalies, the percentages of the anomalies appearing around the earthquake days is compared with the associated earlier ones^[12]. Anomalous variations of TEC which were derived from the records of GPS permanent receivers were detected within seven days before the Colima earthquake of 21 January 2003^[12]. In this study, anomalies appeared around the north Sumatra earthquake five days before occurrence.

The duration of seismo-ionospheric perturbations is about 4-6 h^[3]. The duration of the North Indonesia seismo-ionospheric perturbations was about 4 h continuously (2 -6 AM).

The TECv value at preparation time of the earthquake compared to normal days differ around 10-20 TECv^[4]. In this study, the maximum TECv difference was from 2 to 10 TECv. This could be due to the location of GPS receiver or satellite track that was not at the epicentre of the earthquake.

CONCLUSION

The results obtained shows that it is possible to perceive the earthquake precursors a few days before an earthquake occurrence. Further studies on this investigation should be undertaken to examine this finding. Some researches on predicting and modelling of the natural disasters (earthquake, tsunami, volcano, flood and storm) system can be considered for future enhancement. This result is useful in providing an early warning of an earthquake and therefore, the casualties caused by earthquake could be minimised.

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