Neural network based tomographic approach to detecting the ionospheric anomalies prior to the 2007 Southern Sumatra earthquake

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Abstract

In this paper, neural network based ionospheric tomography was performed to investigate the detailed structure that may be associated with earthquakes. The 2007 Southern Sumatra earthquake (M8.5) is selected because significant decreases in the Total Electron Content (TEC) have been confirmed by GPS data analysis. With respect to the analyzed earthquake, we detected significant decreases at heights of 250-400 km, especially at 300 km. The global tendency is that the decreased region expands to the east with increasing altitude and concentrated in the Southern hemisphere over the epicenter. Furthermore, obtained results are consistent with other satellite observation.

1. Introduction

The ionospheric anomalies possibly associated with large earthquakes have been reported by many researchers [1-3]. However, a physical mechanism of pre-earthquake ionospheric anomalies has not been clarified. To understand the mechanism, it is believed that monitoring of three-dimensional ionospheric electron density distributions is effective. In this study, to investigate the three-dimensional structure of ionospheric electron density prior to the earthquake, the Residual Minimization Training Neural Network (RMTNN) tomographic approach [4] is adopted for data of GPS ground receivers and ionosonde. The advantage of this method is model-independence and flexibility in reconstruction. We investigate the three-dimensional structure of possible earthquake-related ionospheric anomalies of the 2007 Southern Sumatra earthquake (M8.5) by GPS data analysis. As for the 2007 Southern Sumatra earthquake, significant decreases of TEC is detected [5]. To verify the reliability of results obtained by the developed RMTNN method, we compared estimated electron densities with the occultation data observed by FORMOSAT-3/C.

2. Application to the 2007 Southern Sumatra earthquake

The Southern Sumatra earthquake (M8.5 and depth 34 km) occurred on 12 September 2007. The epicenter was located at 4.520°S, 101.374°E, off the south coast of Sumatra, Indonesia. Before applying the proposed RMTNN method, we confirm the existence of possible TEC anomalies before the earthquake. After reconstruction of the electron density, we compare the results with GPS occultation data obtained by FORMOSAT-3/C.

2.1 TEC anomalies before the earthquake

In order to estimate the TEC anomaly associated with the 2007 Southern Sumatra earthquake, we used TEC data sets from the global ionosphere map (GIM) published by the Center for Orbit Determination in Europe (CODE). We hereinafter refer to *GIM-TEC* as TEC from GIM data. The computation of the *GIM-TEC* is performed as follows. The original spatial resolution of GIM is 2.5° in latitude and 5.0° in longitude, and the temporal resolution is 2 hours. We performed linear interpolation to obtain a resolution of 1 hour at a certain resolution. We computed the mean *GIM-TEC* values for the previous 15 days and the associated standard deviation as a reference at specific times. Then, the normalized *GIM-TEC (GIM-TEC*)* is defined as follows:

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$$GIM\_TEC^*(t) = \frac{GIM\_TEC(t) - GIM\_TEC_{mean}(t)}{\sigma(t)} \quad (1)$$

where *GIM_TEC (t)* is the extracted GIM data at time *t*, $GIM\_TEC_{mean}(t)$ is the mean value for the previous 15 days, and $\sigma(t)$ is the associated standard deviation. Geomagnetic conditions are found to be relatively quiet during the analyzed period. As the result, *GIM_TEC** around the epicenter exceeded the lower threshold of -2σ on 4 and 9 September, which are eight and three days before the earthquake. In particular, the decrease at 07:00-08:00 UT (14:00-15:00 LT) on 9 September is significant and the disturbed area is extends 10 degrees in latitude and 40 degrees in longitude. Based on the above results, there is a possible TEC anomaly before the earthquake. Therefore, the proposed RMTNN method is applied to the earthquake in order to investigate the structure of pre-seismic ionospheric anomaly.

2.2 Results of RMTNN tomography

The 24 selected GPS receivers, including 22 stations from SuGAr and two stations from IGS, and the ionosonde station (Kototabang) for the restriction. In the present paper, we focus on the period of 07:30-07:45 UT (14:30-14:45 LT) on 9 September 2007, during which an abnormal TEC decrease was detected by *GIM-TEC**. In order to clarify the anomalous changes in three-dimensional electron density distributions, the difference between the reconstructed data on September 9 and the model data that is constructed by the median value through 15-day backward computations. The reconstructed region is 10°S-10°N in latitude and 90°E-110°E in longitude and 100 to 700 km in altitude. Fig. 1(a) shows the Integrated Electron Content (IEC) at altitude intervals of 150 km from 100 to 700 km. The IEC over altitudes of 100 to 250 km indicates that the density decreases in the southwest region, including the epicenter. On the other hand, an increase occurs over the Sumatra-Java islands. The IECs at altitudes of 250 to 400 km and 400 to 550 km decrease significantly around the epicenter. The IEC at altitudes of 550 to 700 km decreases slightly, except in regions east of the epicenter. The ionospheric electron density profile above the epicenter obtained from the tomographic data is shown in Fig. 2(a). The solid line indicates the profile on September 9, and the dashed line represents the median profile computed from the reconstructed data during August 25 and September 8. The observed electron density on September 9 is 40% of the median value at the peak electron density. And, hmF2 is similar in both cases at an altitude of 330 km. Moreover, observed electron density profile on September 9 is lower than first quartile value except below 230 km altitude. Figs. 1(b) and (c) shows the longitude-altitude and latitude-altitude cross sections, which include the epicenter. The results show a significant decrease in the electron density at approximately 300 km. The area of this decrease expands eastward with altitude and is concentrated in the Southern hemisphere over the epicenter.

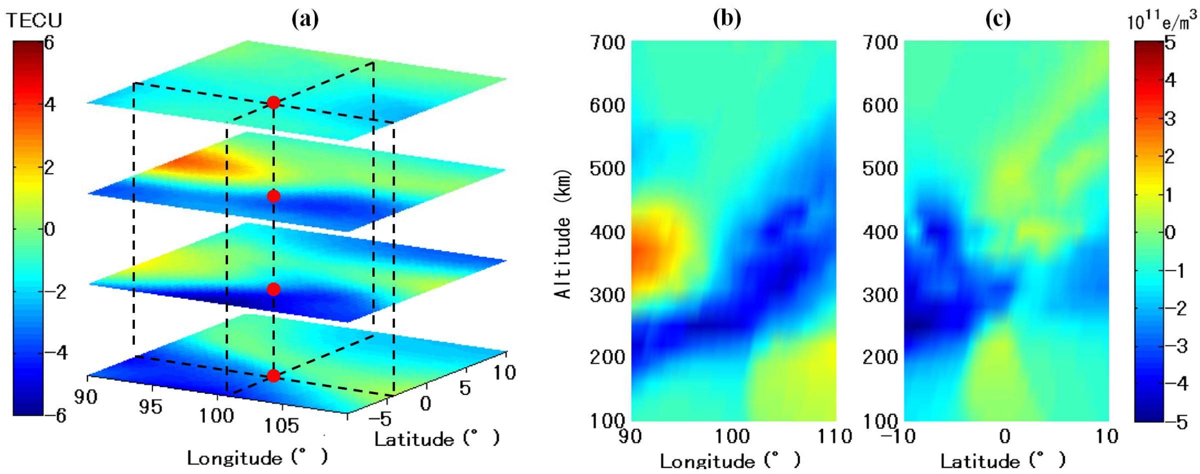

Fig. 1. Example of electron density distributions (07:30-07:45 UT).

(a) Differences in the integrated electron content (IEC) between the observed and the reference data at 150 km intervals from altitudes of 100 to 700 km. The red dots indicate the projection of the epicenter.

(b) Longitudinal difference in electron density between the observed data and the reference data at the same latitude of epicenter (4.520°S).

(c) Latitudinal difference in electron density between the observed data and the reference data at the same longitude of the epicenter (101.374°E).

2.3 Evaluation of the estimated electron density by FORMOSAT-3/C data

In order to validate the electron density distribution obtained by the RMTNN algorithm, we compare the vertical electron density profiles derived by tomography with FORMOSAT-3/C radio occultation measurements. FORMOSAT-3/C is composed of six microsatellites, each of which houses a GPS occultation experiment. The accuracy of the ionospheric electron density profile observed by FORMOSAT-3/C is extremely high. However, the observable time and space depends on the positional relationship of the satellites. In this study, we analyze the occultation data for the afternoon period of 06:00-09:00 UT (13:00-16:00 LT) during August 25 and September 9. These data provide the electron density profile on September 9 and the 15-day backward median for the day. The investigated orbits of the satellite are in the region of 5°S-15°N and 80°E-120°E. In this region, a significant decrease in *GIM-TEC** was detected, as shown in Fig. 2 (b), which shows the electron density profiles obtained by FORMOSAT-3/C. The F2 peak density on September 9 was found to be decreased significantly (by approximately 25%) compared to the median density. The hmf2 is approximately the same in both cases and at 340 km. The tendency of this profile is consistent with that derived using the RMTNN method (Fig. 2 (a)). However, the estimations by the RMTNN tomography and by FORMOSAT-3/C below 200 km are different, and the RMTNN estimation provides lower values. This tendency is also in agreement with the results of previous studies [6, 7].

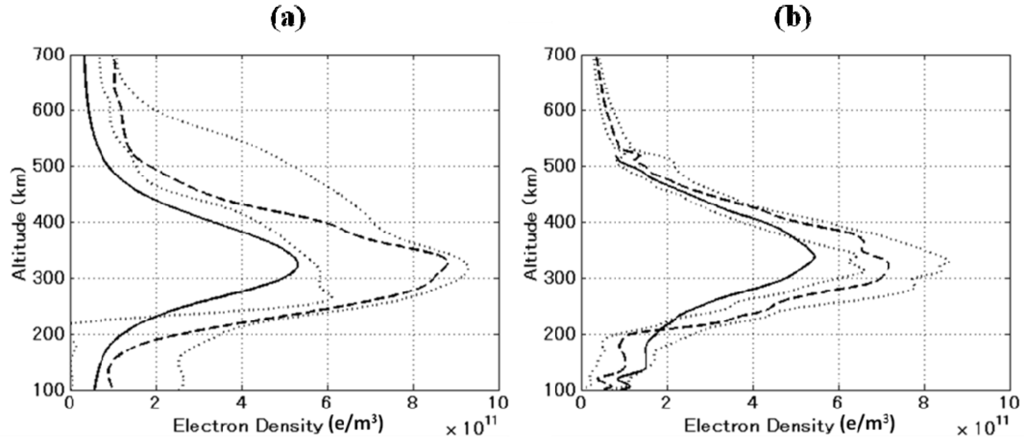

Fig. 2. Ionospheric electron density profiles.
The solid line indicates the profile observed on September 9. The dashed and dotted lines indicate the median and first and third quartile values calculated during the period from August 25 to September 8, respectively.
(a) RMTNN tomography, (b) FORMOSAT-3/C

3. Conclusion

In this paper, we applied the RMTNN method to estimate the electron density distribution of the ionosphere using GPS and ionosonde data. The analyzed day is three days before the 2007 Southern Sumatra earthquake. Regions of significantly reduced 15-day backward median values of electron density at the same local time are recognized in the IEC and profile analyses using reconstructed tomographic data. The characteristic of the reduction for the TEC (IEC) analysis is consistent with the characteristics of the *GIM-TEC*. The results for the IEC indicate that significant decreases occur at altitudes of 250 to 400 km, especially at 330 km. However, the height that yields the maximum electron density remains the same. The obtained structure is such that a region of significantly reduced 15-day backward median values of electron density exists in the southern side of the IEC (altitude: 250 to 400 km). The global tendency is that this region expands to the east with increasing altitude and concentrated in the Southern hemisphere over the epicenter.

The profile obtained from the tomographic reconstruction is compared with that obtained from FORMOSAT-3/C in order to evaluate the performance of the proposed RMTNN method. The results indicate good agreement, with the exception of altitudes in the range from 100 to 200 km. The tendency of the decrease in electron density at approximately 300 km before the occurrence of large earthquakes has been reported [6, 7], which suggests the high applicability of the RMTNN method to the estimation of the ionospheric electron density. Differences between the results of the present study and the results of previous studies are also found. Hsiao et al. [6] reported the three-dimensional ionospheric structures obtained prior to the 2006 Pingtung earthquake using FORMOSAT-3/C. They found decreases in the F2 peak height, significant decreases in the electron density at altitudes of from 300 to 350 km, and increases in the lower altitudes within five days prior to the earthquakes. Similar results have been reported for the 2008

Wenchuan earthquake [7, 8]. On the other hand, the RMTNN results of the present study indicate no enhancement at lower altitudes. The numerical simulation results also revealed that the IEC at altitudes of 100 to 250 km are slightly underestimated compared to the model (within ±1 TECU). This might arise from the lack of information on the lower ionosphere. Additional information on the bottom sounding and/or lower height data using satellite occultation may be required. With respect to the peak height, no obvious reduction was found from the profiles derived from the RMTNN and FORMOSAT-3/C data. This indicates that no remarkable reduction in hmF2 occurred for the 2007 Southern Sumatra earthquake.

Continuous tomographic images can provide dynamic variations of the electron density, which reveal the transport of energy from the lithosphere. In other words, the tomographic approach has the advantage of providing a fine spatial distribution and is important for clarifying the coupling mechanism between earthquake preparation processes and ionospheric anomalies.

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