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Ionospheric anomaly after a deep earthquake on 17 April 2012, M=6.8 Papua New Guinea using two-dimensional principal component analysis (2DPCA)

Abstract

Global ionospheric total electron content (TEC) map (GIM) data at the time 07:15:00UT-07:30:00UT on 17 April, 2012 (UT) is examined by Two-dimensional Principal Component Analysis (2DPCA) in order to detect TEC anomaly related to a deep earthquake at 07: 13:50 UT on 17 April, 2012 (UT) (M_W=6.8) with the depth of 208.2km in Papua New Guinea. The TEC anomaly is highly localized around the epicenter and its duration time is at least 10 minutes.

Key Words

Global ionospheric total electron content (TEC) map (GIM); Two-dimensional principal component analysis (2DPCA); Papua New Guinea.

INTRODUCTION

Recent studies have shown that earthquake-associated TEC anomalies are detectable using principal component analysis (PCA) regardless of other possible causes of TEC disturbance such as TEC long term variance, solar flare and geomagnetic storm activity. PCA is an alternative pure mathematical method for the measuring TEC anomalies[5,6]. PCA applied to both pre-earthquake and post earthquake TEC has been able to detect and even describe the physical shape of earthquake associated TEC anomalies[5,6].

In this paper, two-dimensional principal component analysis (2DPCA) is used to detect an ionospheric TEC anomaly relating to an earthquake at 07: 13:50 on 17 April, 2012 (UT) (M_W=6.8) (the epicenter is 5.474° S, 147.097) in Papua New Guinea. The interesting aspect about this earthquake was its depth at 208.2 km. The time for the investigation Global Ionospheric TEC map (GIM) data is 07:15UT-07-30UT approximately 70 second after the earthquake giving time for any earthquake related TEC anomaly to develop. Data source is from NASA Global Differential GPS system (GDGPS), and the maps are derived using data from ~100 real-time GDGPS tracking sites, augmented with additional sites that are available on 5 minutes basis, probing the ionosphere with high spatial and temporal resolution. The integrated electron density data along each receiver-GPS satellite link is processed through a Kalman filter in a sun-fixed frame to produce the global gridded TEC maps.

METHOD

2DPCA

2DPCA performing is essentially PCA on the rows of the data if each row is viewed as a computational unit. For 2DPCA, let data be represented by a matrix B with the dimension of n x m. Linear projection of the form is considered as followed[4,9],

$$\mathbf{y} = \mathbf{Bx} \tag{1}$$

Here x is an n dimensional project axis and y is the projected feature of this data on x called principal component vector. E is mean.

$$\mathbf{W_x} = \mathbf{E(y-Ey)(y-Ey)^T} \tag{2}$$

Here W is the covariance matrix of the project feature vector.

The trace of W is defined;

$$\mathbf{J(x) = tr(W_x)} \quad (3)$$

$$\mathbf{tr(W_x) = tr\{x^T Sx\}}, \text{ where } \mathbf{S = E[(B - EB)^T (B - EB)]} \quad (4)$$

The matrix W is called covariance matrix. The alternation criterion is expressed by $\mathbf{J(x) = tr(x^T Wx)}$, where the data inner-scatter matrix W_x is computed in a straightforward manner by

$$\mathbf{w} = \frac{\mathbf{1}}{\mathbf{m}}\sum_{k=1}^{m}(\mathbf{B}_k - \overline{\mathbf{B}})^T(\mathbf{B}_k - \overline{\mathbf{B}}), \text{ where } \overline{\mathbf{B}} = \frac{\mathbf{1}}{\mathbf{m}}\sum_{1}^{m}\mathbf{B}_k \quad (5)$$

Like PCA, the vector x maximizing Eq.4 corresponds to largest (principal) eigenvalue of W which represented the main characteristics of data. Principal Eigenvector is one of all bases in 2DPCA domain and doesn't be used in this study. PCA assigns large principal eigenvalues i.e., principal eigenvalues > 0.5 in a normalized set to the earthquake related TEC anomalies[5]. 2DPCA is a accurate version of PCA, which can be removed small sample data size problem that will be explained later. Therefore large principal eigenvalues of 2DPCA (> 0.5 in a normalized set) are also earthquake-related TEC anomalies. The explanations of the advantages of 2DPCA over PCA are briefly given. First, when the row vector dimension in an data in much smaller than those of the long vector from the entire data and then the dilemma of course of dimensionality diminishes. Secondly, when the input feature vectors to be analyzed are actually the row vectors of the training data and then the feature set is significantly enlarged. Therefore, the Small Sample data Size (SSS) problem[1] does not exist when performing 2DPCA. Such SSS problem causes larger data reconstruction error when data in PCA domain is transformed back to its original domain and principal eigenvalue is not very close to represent he main characteristics of data. More detailed contents can be referred to the studies of Fukunnaga[1] and Kong et al.[4]

TEC data should be estimated TEC values. If TEC values are estimated, and then some biases during restore of TEC values from measurements of dual-frequency delays of GPS signals e.g. resolving of carrier phase ambiguity, determination hardware delays for phase, tropospheric and multipath problems, are necessary to be reduced. The Kalman filter was performed to estimate the TEC values with less bias (error). However the temporal and spatial discrimination has a little influence for compensation and such influences could be endured. The estimated TEC data can be optimized to represent true TEC situation[3,8].

Data processing using 2DPCA

The global ionospheric map (GIM) data of Figure 1 (a) in the time period 07:15-07:30 UT on 17 April 2012 are examined. Two equatorial ionization anomaly (EIA) crests of dense GPS TEC bands at low latitudes centered about 30°N and 15°S geographic latitudes straddle the geomagnetic equator and range from about 60°E to 170°E. This GIM is divided into 600 smaller grids (small map) 12° in longitude and 9° in latitude, respectively. The resolution of the original TEC data for this GPS system is 5 and 2.5 degrees in latitude and longitude, respectively[2], and therefore each grid has 6 TEC data (small sample data size). These 6 TEC data form the input matrix B of dimensions 2 x 3 of Eq. (1) using 2DPCA to remove SSS problem and detect clear TEC anomaly related to the earthquake. This allows for principal eigenvalues to be computed for each of the 600 smaller grids.

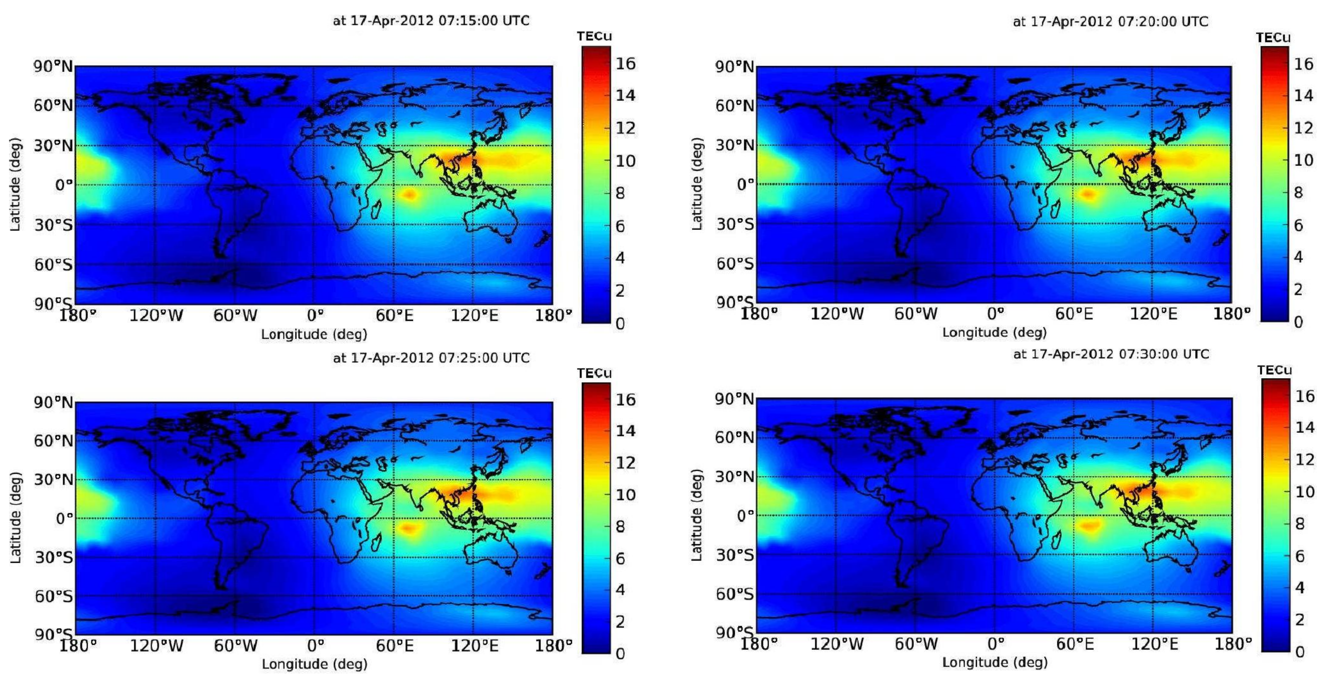

Figure 1(a) : This figure shows the GIMs at 07:15-07:30 UT on 17 April 2012. Two equatorial ionization anomaly (EIA) crests of dense GPS TEC bands at low latitudes centered about 30°N and 15°S geographic latitudes straddle the geomagnetic equator and range from about 60°E to 170°E.

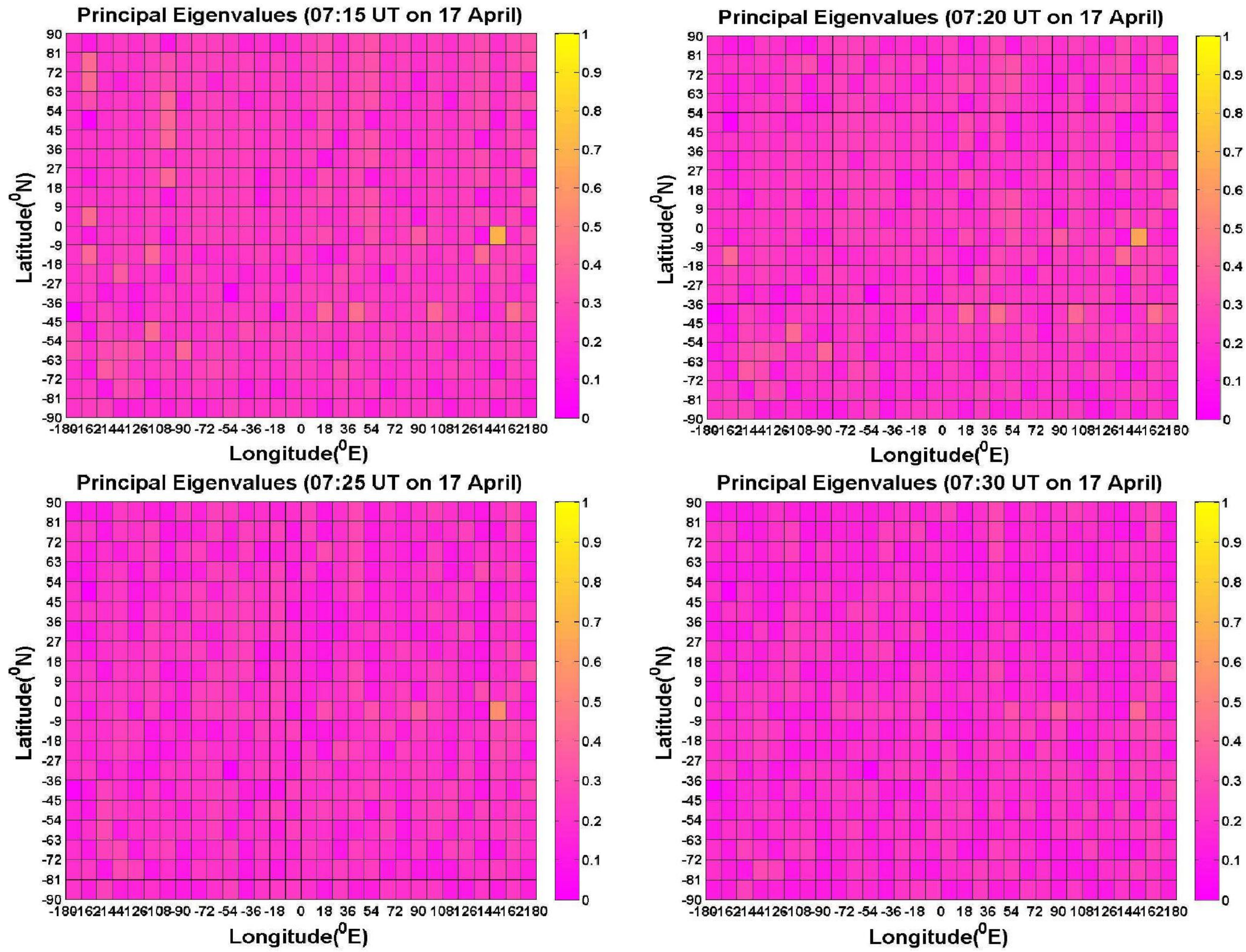

Figure 1(b) : The figures give a color-coded scale of the magnitudes of principal eigenvalues corresponding to Figure 1(a) with 2DPCA. The color within a grid denotes the magnitude of a principal eigenvalue corresponding to Figure 1(a), so that there are 600 principal eigenvalues assigned for 600 grids in each small map, respectively. The earthquake-related TEC anomalies are represented using large principal eigenvalues except at 07:30 UT (i.e., principal eigenvalues > 0.5 in a normalized set)[5].

RESULTS

Figure 1(b) gives a color-coded scale of the magnitudes of principal eigenvalues corresponding to Figure 1 (a). Color intensity denotes magnitude. From the figure it can be seen that 600 principal eigenvalues are assigned (i.e., each grid in the bottom figures represents a principal eigenvalue). Varying color intensity, representative of large principal eigenvalues in this shows the existence of a TEC anomaly with a large principal eigenvalue given over the region of this large earthquake (i.e., principal eigenvalues > 0.5 in a normalized set)[5]. The principal eigenvalue magnitudes of EIA and other non-earthquake background noises are suppressed by a large principal eigenvalue magnitude caused by the earthquake-associated TEC anomaly, and thereby earthquake-associated TEC anomaly releases except at 07:30 UT. Figure 2 shows the Kp indices from 16 to 18 April 2012 were relatively small indicating that geomagnetic activity could not have been responsible for the TEC anomaly.

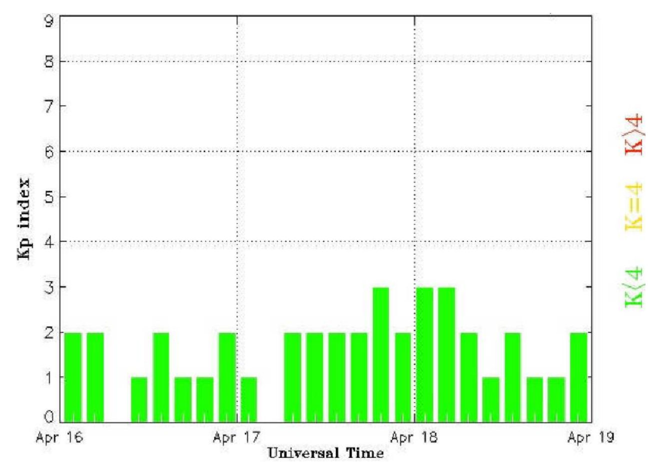

Figure 2 : This figure shows the Kp indices from 16 to 18 April 2012 (NOAA Space Weather Prediction Center).

ANALYSIS OF GIMS BEFORE AND AFTER THE EARTHQUAKE

2DPCA is applied to the GIMs in Figure 3(a) at 07:15-

07:30 UT on 16 April, 2012 for comparison with the previous results. The same analysis method described in Section 2.2 was used due the same data source. The analysis results of 2DPCA are shown in Figure 3(b). Figure 4(a) shows the GIMs at 07:15-07:30 UT on 18 April, 2012, and the analysis results of 2DPCA are shown in Figure 4(b). The three days (16-18 April) are geomagnetic quiet days according to Figure 2. Similar TEC phenomena to that found just before and after the earthquake were not observed. This result supports earthquake association between the TEC anomaly and the 17 April 2012 earthquake.

DISCUSSION

2DPCA is able to detect a TEC anomaly over the epicenter after the 07: 13:50 UT 17 April 2012 earthquake in Papua New Guinea. The anomaly was detected at 07:15-07:25 UT with duration time of at least 10 minutes. Another earthquake-associated TEC anomaly after China's Wenchuan earthquake of 12 May, 2008 (UT) (M_W=7.9) has been identified using PCA (Lin 2011). However, unlike this earthquake, the Wenchuan earthquake was not a deep earthquake. 2DPCA has the ability to detect nascent anomalies.

Regardless of the specific cause 2DPCA was able to detect a TEC anomaly in the ionosphere above and shortly after the earthquake. The results of this study show that 2DPCA is better at detecting TEC anomalies. Past studies have shown that detection of earthquake associated TEC anomalies is independent of long term variance in TEC[5] and the method is also not affected by the geomagnetic storm[7].

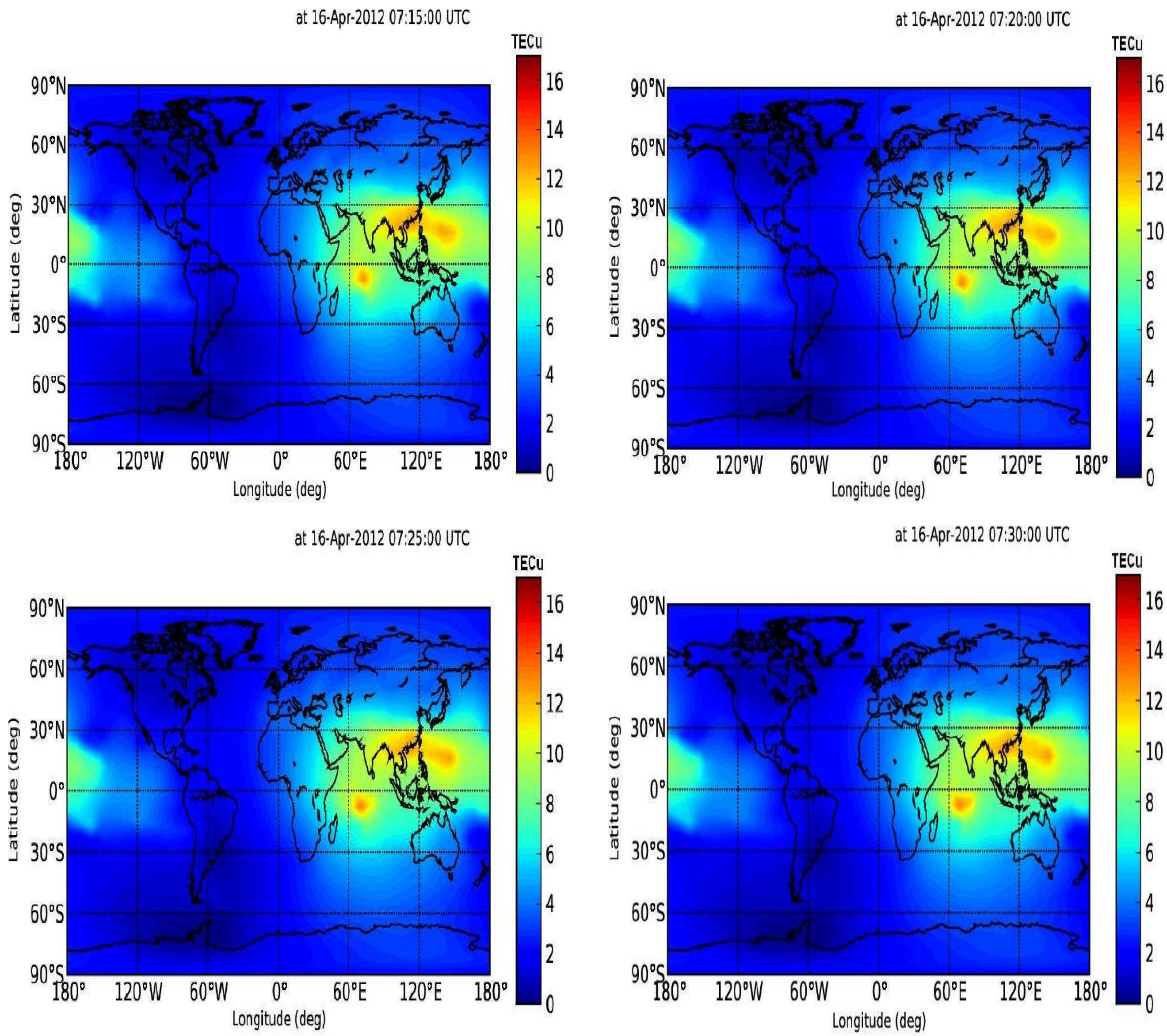

Figure 3(a) : These figures show the GIM at 07:15-07:30 UT on 16 April 2012. Two equatorial ionization anomaly (EIA) crests of dense GPS TEC bands at low latitudes centered about 30°N and 15°S geographic latitudes straddle the geomagnetic equator and range from about 60°E to 150°E.

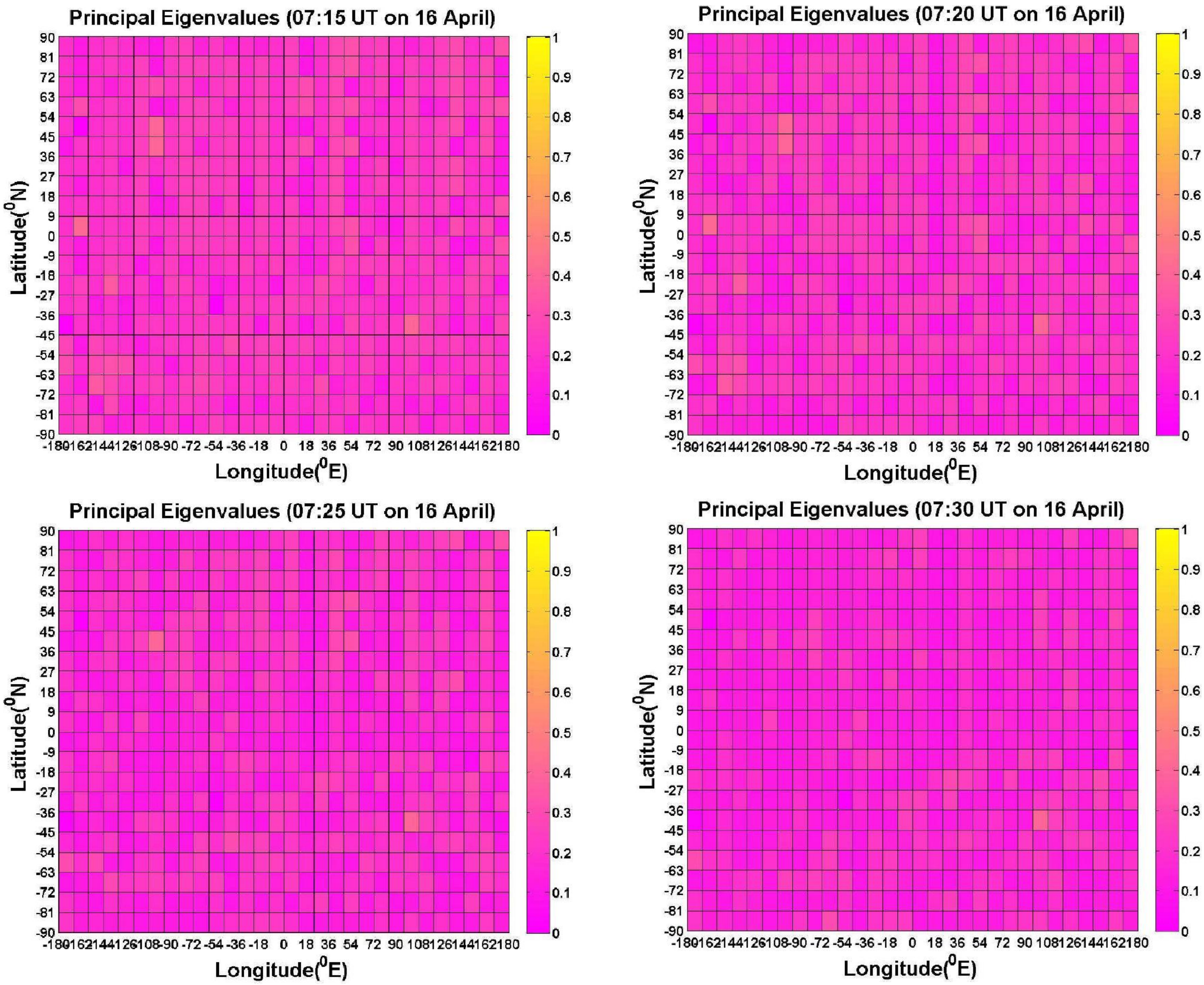

Figure 3(b) : These figures give a color-coded scale of the magnitudes of principal eigenvalues related to Figure 3(a).

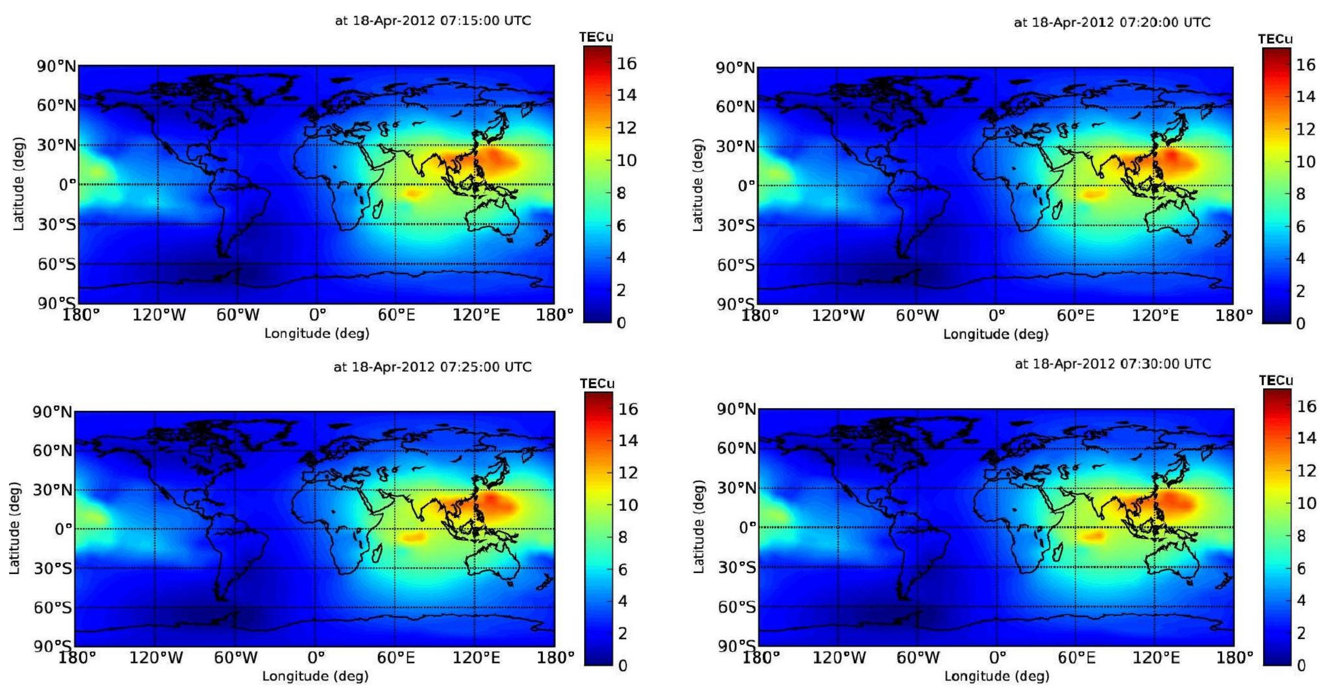

Figure 4(a) : These figures show the GIMs at 07:15-07:30 UT on 18 April 2012. Two equatorial ionization anomaly (EIA) crests of dense GPS TEC bands at low latitudes centered about 30°N and 10°S geographic latitudes straddle the geomagnetic equator and range from about 60°E to 130°E.

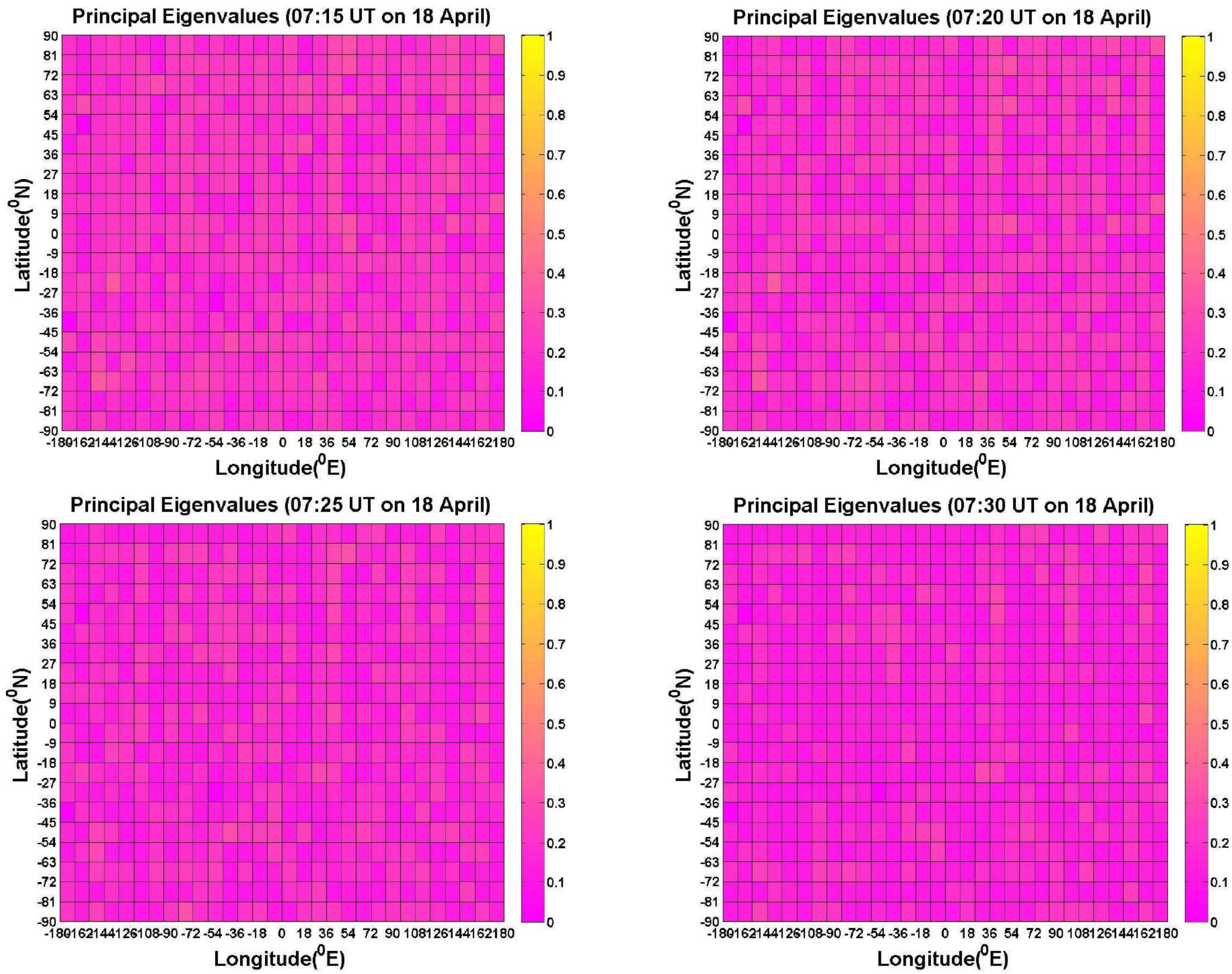

Figure 4(b) : These figures give a color-coded scale of the magnitudes of principal eigenvalues related to Figure 4 (a).

CONCLUSION

In this study, 2DPCA is used to detect a highly localized TEC anomaly that occurred shortly after the mainshock of the April 17, 2012 Papua New Guinea earthquake with the duration time is at least 10 minutes.

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