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Ionospheric Anomaly Related to a Deep (>200km) Earthquake on 17 April 2012, M=6.8 Papua New Guinea Using Two-Dimensional Principal Component Analysis: A Case Study

Jyh-Woei, Lin

Dept. of Earth Science, National Cheng Kung University, No.1 University Road, Tainan City, Taiwan,

E-mail: pgjwl1966@gmail.com

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Abstract

*Ionospheric total electron content (TEC) data during the time period from 00:00 on 12 April to 23:00 on 18 April, 2012, which was 5 days before to 2 days after a deep earthquake at 07:13:50 on 17 April, 2012 UT (M_w=6.8) with a depth about 200km in Papua New Guinea, were examined by two-dimensional principal component analysis (2DPCA) to detect TEC anomaly related to this earthquake, because such TEC anomalies usually have shown up in earlier time periods (*Liu et al*. 2006). An earthquake-related TEC anomaly was highly localized around the epicenter during the time period from* ***07:15*** *to 07:30 on 17 April, where its duration time was at least 15 minutes. Radon gas release should be a possible reason to cause the anomalous TEC gradients or fluctuations.*

Keywords: Ionospheric total electron content, Papua New Guinea, TEC anomaly, Two-dimensional Principal Component Analysis, Anomaly TEC gradients or fluctuations

1 Introduction

Recent studies have shown that using principal component analysis (PCA), which is a technique for mapping multidimensional data into lower dimensions with minimal loss of information (*Kramer*, 1991), the earthquake-associated TEC anomalies can be distinguished from other possible causes of TEC disturbance such as TEC long term variance, solar flare and geomagnetic storm activity (*Lin,* 2010; 2011). PCA applied to earthquake-related TEC anomalies has been able to detect and even describe the physical shape of earthquake-associated TEC anomalies (*Lin,* 2010; 2011). TEC is an important descriptive quantity for the ionosphere of the Earth. TEC is the total number of electrons present along a path between two spatial points, with the units of electrons per square meter, where 10^{16} electrons/m² = 1 TEC unit (TECU) at a time point. Lin's work (2010) used the one-dimensional TEC data at the ground-based receiving stations near the epicenters of the earthquakes to detect the earthquake-associated TEC anomalies. Global ionospheric maps (GIMs) were decoded by image processing and then the earthquake-associated TEC anomalies were found by PCA in Lin's work (2011).

In this study, two-dimensional principal component analysis (2DPCA) is used to detect the ionospheric TEC anomaly related to an earthquake at 07: 13:50 on 17 April, 2012 (UT) (M_w=6.8) with the epicenter of 5.474° S, 147.097° E in Papua New Guinea. The interesting aspect about this earthquake is its depth at **about 200 km.**

The time period of the investigated global Ionospheric TEC data is from 00:00 on 12 April to 23:00 on 18 April, 2012 UT, which starts 5 days before this earthquake, giving time for any earthquake-related TEC anomaly to develop because such earthquake-related TEC anomaly usually revealed in such mentioned time period (*Liu et al*. 2006).

GPS users with single-frequency receivers need ionospheric electron content information in order to achieve positioning accuracy similar to dual-frequency receivers. The GDGPS System provides a global real-time map of ionospheric electron content (currently producing a map each 5 minutes). These maps are also of value in monitoring the effect of the ionosphere on radio signals, power grids, and on space weather. The maps are derived using data from the ~100 real-time GDGPS tracking sites. The integrated electron density data along each receiver-GPS satellite link is processed through a Kalman filter to produce the global maps of TEC each 5 minutes. The maps are available from multiple GDGPS Operations Centers (GOCs) as images, as text files containing the gridded TEC values, or as a binary data stream containing the gridded TEC values (http://www.gdgps.net/products/tec-maps.html). TEC measured errors (biases), and their correction using the Kalman filter, are described in the following references: *Mannucci et al.* (1998, 1999); *Wu and Bar-Sever* (2005); *Kechine et al.* (2004); *Muellerschoen et al.* (2004); *Ouyang et al.* (2008).

The TEC data have been corrected for biases during measurements of dual-frequency (L1 = 1575.42 MHz and L2 = 1227.60 MHz) delays of GPS signals e.g. carrier phase biases, satellite state (orbit) corrections, ionospheric delay and troposphere, which need to be removed using ground-based post-processing software (*Raman and Garin*, 2005; *Wu and Bar-Sever*, 2005).

The GIMs contain vertical (VTEC), which has been converted from the slant (STEC) at the ionospheric pierce points as STEC=VTEC. ME + b + r, where ME = 1/cos(Θ) is the mapping function, Θ is the zenith angle of GPS satellite at the single layer height of the ionosphere, b and r are the instrument biases of the satellites and receivers, respectively. Then VTEC and the instrument biases b and r are obtained by combining interpolation and least-square fitting procedure. For details of the method used to derive the VTEC from GPS measurements, please refer to *Mao* (2007) and *Mao et al.* (2008) and *Lin* (2012).

2 Method

2.1 2DPCA

2DPCA is a procedure which can detect anomalies for two-dimensional data (e.g. a map of pixels' gray intensity). Let the data be represented by a matrix B with the dimension of m x n, where m, n>1 (for a map with m x n pixels' gray intensity). The linear projection of the matrix B is considered as follows (*Sanguansat,* 2012),

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

Here x is projection axis with the dimension of *n x 1* and y is the projected feature with dimension of *m x 1* of this data on x called principal component vector. E is ensemble average of the elements of a vector. The covariance matrix for 2DPCA is defined as follows;

$$W = (y - Ey)(y - Ey)^T \tag{2}$$

The trace of W is defined;

$$tr(W) = x^T Sx \text{ where } S = (B - EB)^{\mathrm{T}}(B - EB) \tag{3}$$

The vector x maximizing Eq. 3 corresponds to the largest (principal) eigenvalue of W which represented the main characteristics of the data.

The PCA converts the measurements into one-dimensional data before covariance matrix calculation (*Yang et al.* 2004). The covariance matrix of PCA is based on an input matrix with the dimension of *m x n*, which is reshaped from one-dimensional data (m multiplied by n). The spatial structure information can not be well preserved due to some original information loss when inverting to original dimension (*Kramer*, 1991) under the condition of the matrix being small sample size (SSS). Such loss is called SSS problem. However, the covariance matrix in 2DPCA is full rank for a matrix of low dimension. Therefore the curse of dimensionality and SSS problem can be avoided (*Kong et al*. 2005; *Sanguansat*, 2012).

2.2 Data Processing using 2DPCA

The TEC data for the mentioned time period is examined by 2DPCA; however after the data processing, only a TEC anomaly related to this earthquake is detectable during the time period from 07:15 to 07:30 on 17 April 2012. TEC anomalies related to other earthquakes in the world in the same time period are also not detectable. Therefore the processed TEC data during this time period are represented in the figures of the paper. The TEC data in other examined time period are done with the mentioned same data analysis by 2DPCA but not shown in this study because earthquake-related anomaly is not detectable. Figure 1(a) shows the GIMs in the mentioned time period. Red spot indicates the epicenter of this earthquake. This global region is divided into 600 smaller areas, 12° in longitude and 9° in latitude to detect more detailed TEC information because the resolution of the original TEC data for this GPS system is 5.0 and 2.5 degrees in longitude and latitude, respectively (*Hernández-Pajares et al.* 2009), and therefore in each area 4 TEC data points are taken (12/5=2.4, 9/2.5=3.6, the 2 and 2 TEC data are taken in longitude and latitude, respectively. If 6 points are taken, which are 2 and 3 points in longitude and latitude, then more computing time is needed, however the results are the same as using 4 TEC points). These 4 TEC points form the input matrix B (it belongs to SSS data) of dimensions 2 x 2 for Eq. (1) using 2DPCA to avoid SSS data problem and detect a clear TEC anomaly related to the earthquake. This allows for principal eigenvalues to be computed for each of the 600 smaller areas.

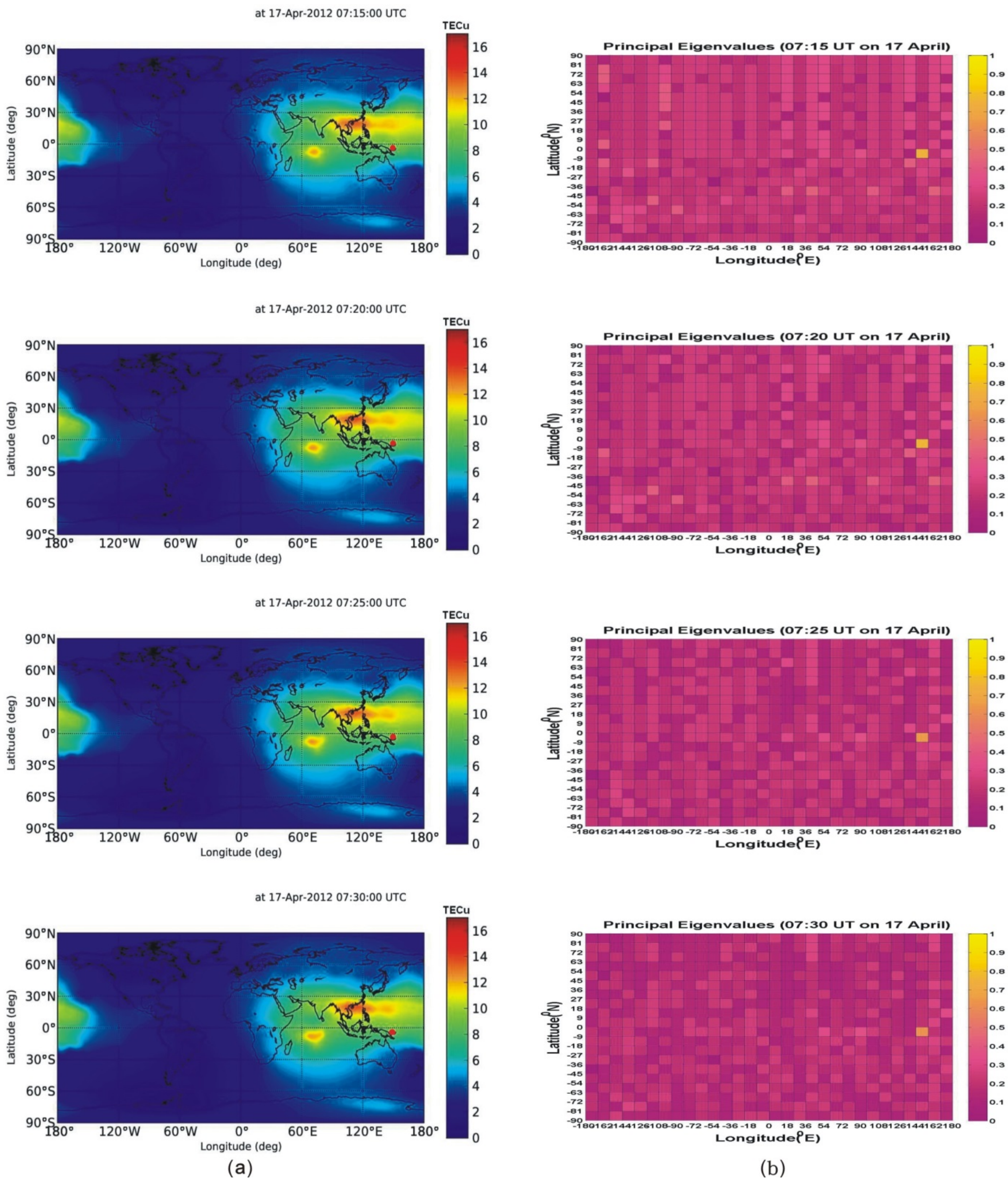

Fig. 1. **The figure (a)** shows the GIMs during the time period from 07:15 to 07:30 UT on 17 April 2012. The red spots indicate the epicenter of this earthquake. **Figure (b)**. The figures give a color-coded scale of the magnitudes of principal eigenvalues corresponding to Figure 1(a) with 2DPCA. The earthquake-related TEC anomalies are represented with large principal eigenvalues.

3 *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. Each principal eigenvalue represents the TEC characteristic or situation for each area**.** High 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 during the time period from 07:15 to 07:30 (UT). This indicates strong spatial gradients within the 4 TEC values during this time period. 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.

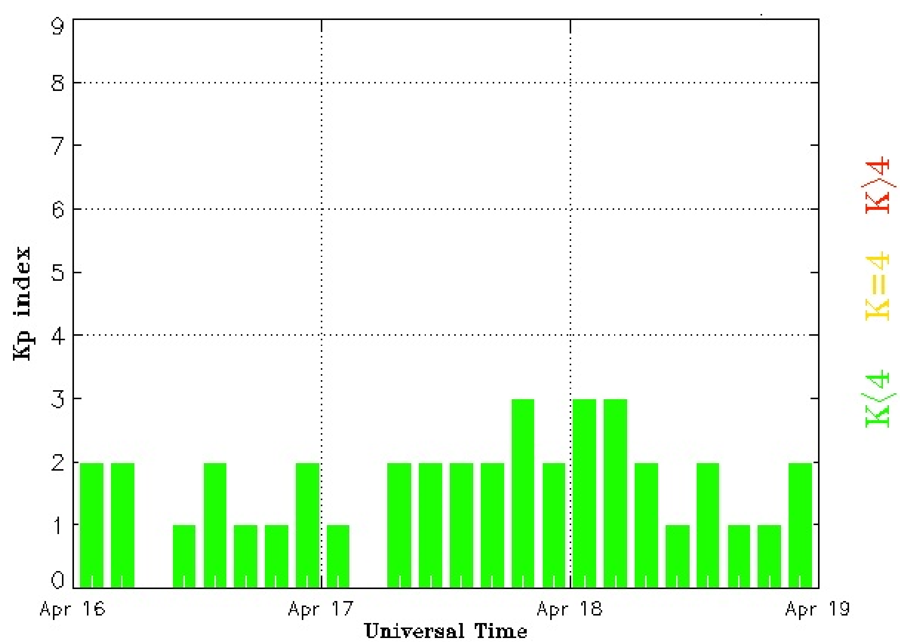

Fig. 2. This figure shows the Kp indices during the time period from 16 to 18 April 2012 (NOAA Space Weather Prediction Center).

4 *Discussion*

2DPCA was able to detect a TEC anomaly over the epicenter related to this earthquake. The anomaly was detected from 07:15 to 07:30 UT with the duration time of at least 15 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 and image processing (*Lin*, 2011). However, unlike this earthquake, the Wenchuan earthquake was not a deep earthquake. 2DPCA had the ability to detect the TEC anomalies related to such deep earthquake.

2DPCA has detected and located a TEC anomaly apparently related to the earthquake. The physical cause of this relation will now be considered. Accordingly, studies of TEC disturbance suggest three possible explanations for earthquake associated anomalies. One is shock waves (*Jin et al*., 2010). Since the earthquake was very deep, it is not likely those acoustic shock waves from topside vibrations would be responsible for the TEC anomaly. The other possibility is the presence of an electric field creating large scale ionospheric density irregularities either from radon gas release or P-type semiconductor effects due to stress variance in rocks near the focus of the earthquake (*Pulinets and Legen'ka*, 2003; *Pulinets*, 2004; *Freund*, 2003; *Bošková et al*. 1994; *Rothkaehl et al*. 2006). A possible electric field being generated by radon release in the lower atmosphere rather than P-type semiconductor effects would seem to be more likely. P-type semiconductor effects would not be able to travel through the heterogeneous rocks that exist between the surface and about 200 km down, while P and S type waves would have attenuated so greatly as to not create adequate rock compression at the surface to generate the P-type semiconductor effect. Radon gas release, on the other hand, could occur through micro-cracks formed in the crust and the Earth surface. Radon gas can lead to lower-atmosphere electric fields, and these can travel unimpeded into the ionosphere along geomagnetic lines (Pulinets, 2004). This seems like the most reasonable explanation for the earthquake-related TEC anomaly. It implies that Radon gas release might cause the anomaly TEC gradients or fluctuations.

5 Conclusion

2DPCA has been used to detect a highly localized TEC anomaly that occurred shortly after the mainshock of the April 17, 2012 Papua New Guinea earthquake, where the duration time of the TEC anomaly was at least 15 minutes. Radon gas release was a possible reason. If this is true, then this technique could be useful for understanding of the physical coupling between the ionosphere and processes on the ground and at lower altitudes due to Radon gas release, and the large principal eigenvalue has a physical meaning and is not only a mathematical index.

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