Ionospheric Anomaly due to the volcanic eruption in Colima, Mexico, 06 January 2013: Two-Dimensional Principal Component Analysis

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Abstract
The ionospheric total electron content (TEC) data from 05 to 10 January 2013 (UT) were examined by two-dimensional principal component analysis (2DPCA) and revealed a TEC anomaly related to the volcanic eruption in Colima, Mexico on 06 January, 2013. A TEC anomaly was detected above the volcano from 21:00 to 21:05 on 06 January 2013 (UT). The anomaly occurred for at least 5 minutes, during this time period we could identify the equatorial ionization anomaly (EIA). The shock acoustic wave produced by eruption-induced seismic activity may be the cause of the observed TEC anomaly. We show that it is possible to monitor or predict volcanic eruptions and their associated seismic activity through the use of two-dimensional principal component analysis of the resulting TEC anomalies.

Keywords: Equatorial Ionization Anomaly (EIA), Total Electron Content (TEC), Two-Dimensional Principal Component Analysis (2DPCA), volcanic eruption.

Introduction
The effect of large earthquakes, on the ionosphere has been well researched [Liu et al., 2006; Shirke and Narayana Rao, 2012; Qin et al., 2013]. However, our study focuses on the ionospheric response due to volcanic eruptions [Argelia et al., 2004; Dautermann et al., 2009a, 2009b; Zlotnicki et al., 2010; Komjathy et al., 2012]. Similar ionospheric disturbances caused by volcanic eruptions have been documented in North and South America. Argelia et al. [2004] reported on effects on the ionosphere of the Mount Pinatubo volcanic eruption, June, 1991. They used 1-minute interval soundings made by stations north of Mount Pinatubo. A decrease in $f_0F_2$ and an increase in the F layer virtual height data ($h'F$) for the Mount Pinatubo eruption were detected the day before and after the eruption. Such an ionospheric response might be associated with the upwelling of molecule-rich thermospheric gas from lower altitudes propagated through the volcanic eruption. Dautermann et al. [2009a] has described oscillatory perturbations...
observed by volumetric borehole strainmeter data and GPS-derived ionospheric total electron content following the 2003 July 13, Soufrière Hills volcanic eruption. They stated that the volcanic eruptions or shallow earthquakes can trigger acoustic and gravity waves that propagate into the atmosphere at infrasonic speeds. At ionospheric heights, coupling between neutral particles and free electrons induces variations of electron density detectable with dual-frequency Global Positioning System (GPS). They have identified an ionospheric perturbation after a major volcanic explosion at the Soufrière Hills Volcano (Montserrat, Lesser Antilles) on 13 July 2003. Zlotnicki et al. [2010] performed the DEMETER mission to observe ionospheric disturbances related to 74 active volcanoes over the time period 2004 August–2007 December. They have shown that three types of electric and/or magnetic anomalies can be observed in the time window of 30 d preceding an eruption to 15 d after. The 74 eruptions occurred on 50 volcanoes. From this, 48 anomalies were recognized belonging to 30 of those eruptions. 41% of the eruptions were accompanied by electromagnetic (EM) signals detected by the satellite. 81% of the anomalies were observed prior to the eruptions for the period (−30 d, +15 d) and 69% for the period (−15 d, +15 d). The second study by Zlotnicki et al. [2010], analyzed anomalies above three nearby volcanoes (Lopevi, Ambrym and Aoba), systematically searching all orbits from August 2004 to December 2006. Most volcanic eruptions can be predicted by the integration of continuous real-time observations, data processing and analysis. In the EM field, a long history of ground observations shows that electric, magnetic and electromagnetic signals may precede and accompany volcanic eruptions. Sharma and Sharma [2009] have shown that F2 layer anomalies could be caused by phenomena occurring below the ionosphere such as thunderstorms, light sprites, volcanic eruptions and earthquakes. They suggested that thermal fluctuations resulting from volcanic eruptions may cause the observed ionospheric fluctuations. However, determining a method of predicting volcanic eruptions remains a largely unsolved problem. Komjathy et al. [2012] has mentioned that volcanic eruptions generate acoustic and gravitational waves that can cause TEC perturbations. At ionospheric heights, the coupling between neutral particles and free electrons induces electron density fluctuations.

In this paper, we present a two-dimensional principal component analysis (2DPCA) used to detect the ionospheric TEC anomaly related to Mexico’s Colima volcanic eruption, 06 January, 2013. The Colima Volcano is 12,533 feet, located 430 miles northwest of Mexico City at 19.514°N, 103.62°W. The eruption led to the ejection of a massive column of black ash and was preceded by a day of increasing seismic activity (Smithsonian Intuition, National Museum of Natural History, Global Volcanism Program).

**TEC Data Correction**

The examined time period is from 05 to 10 January 2013. The TEC data, is vertical TEC, were acquired from The NASA Global Differential GPS System (GDGPS). GPS users with single-frequency receivers need ionospheric electron content information in order to achieve positioning accuracy, similar to that of dual-frequency receivers. The GDGPS provides a global real-time map of ionospheric electron content. These maps are also of value in monitoring the effect of the ionosphere on radio signals, power grids, and space weather. The maps are derived using data from more than 100 real-time GDGPS tracking
sites. The integrated electron density data collected along each receiver-GPS satellite link is processed through a Kalman filter to produce the global maps of TEC every 5 minutes. The maps are available from multiple GDGPS Operations Centers (GOCs) as images, 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.htm). Descriptions of measured TEC errors (biases), which are corrected using the Kalman filter, are included in the following references [Mannucci et al., 1998; Mannucci et al., 1999; Wu and Bar-Sever, 2005; Kechine et al., 2004]. The TEC data were corrected for biases during measurements of dual-frequency (L1 = 1575.42 MHz and L2 = 1227.60 MHz) delays of GPS signals, such as carrier phase biases, satellite state (orbit) corrections, ionospheric and tropospheric delays, which were then removed using ground-based post-processing software [Raman and Garin, 2005; Wu and Bar-Sever, 2005]. The GIMs contain vertical TEC (VTEC), which have been converted from the slant TEC (STEC) at the ionospheric pierce points as: STEC = VTEC, \( \frac{1}{\cos(\Theta)} \) the mapping function, \( \Theta \) is the zenith angle of the GPS satellite at the single layer height of the ionosphere, b and r are the instrument errors 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].

**Background Technology**

**Theory of Two-Dimensional Principal Component Analysis (2DPCA)**

2DPCA is a procedure by which anomalies in two-dimensional data can be detected e.g. a map of pixels’ gray intensity. Let the data be represented by a matrix \( B \) with the dimension of \( m \times n \), where \( m, n > 1 \) (for a map with \( m \times n \) pixels’ gray intensity). The linear projection of the matrix \( B \) is considered as follows [Sanguansat, 2012; Lin, 2013]:

\[
y = Bx \quad [1]
\]

Here, \( x \) is projection axis with the dimension of \( n \times 1 \) and \( y \) is the projected feature with a dimension of \( m \times 1 \) of this data onto \( x \), the principal component vector. \( E \) is the ensemble average of the elements of a vector. The covariance matrix for 2DPCA is defined as follows:

\[
W = (y - Ey)(y - Ey)^T \quad [2]
\]

The trace of \( W \) is defined;

\[
tr(W) = x^T Sx, \text{ where } S = (B - EB)(B - EB)^T \quad [3]
\]

The vector \( x \) maximizing equation [3] corresponds to the largest (principal) eigenvalue of
$W$ which represents the main characteristics of the data. The PCA converts the measurements into one-dimensional data before being entered into the covariance matrix calculation [Yang et al., 2004]. The covariance matrix of PCA is based on an input matrix with the dimension of $m \times n$, which is reshaped from one-dimensional data (length of $m$ multiplying $n$). The spatial structure information can not be well preserved due to some original information loss when inverting to original dimension under the conditions of the matrix being of small sample size (SSS) [Kramer, 1991]. Such loss is called SSS problem. However, the covariance matrix in 2DPCA is effective for matrices of low size, thereby avoiding the SSS problem.

**TEC Data Processing using 2DPCA: Methodology**

The corrected TEC data, using the Kalman filter (VTEC), collected from 05 - 10 January, 2013, during the Colima volcanic eruption, were examined. No TEC anomaly related to this eruption was found using 2DPCA, only the Equatorial Ionization Anomaly (EIA) was detected. However, A TEC anomaly related to this eruption, represented by large principal eigenvalues was found during the time period 20:55 to 21:10 UT on 06 January, 2013. Therefore the procedure of the TEC data processing of 2DPCA for this time period is shown in this study.

This region is divided into 600 smaller areas, $12^\circ$ in longitude and $9^\circ$ in latitude to detect more detailed TEC information (Fig. 1a). This is because the resolution of the original TEC data for this GPS system is $5^\circ$ and $2.5^\circ$ in longitude and latitude, respectively [Hernández-Pajares et al., 2009]. Therefore in each area 4 TEC data points are taken ($12/5=2.4$, $9/2.5=3.6$), the 2 TEC and 2 TEC data are taken in longitude and latitude, respectively. If 6 TEC data are taken, which are 2 TEC and 3 TEC data in longitude and latitude, then more computing time is needed, however the results are the same as using 4 TEC data). These 4 TEC data points form the input matrix $B$ (it belongs to SSS data) of dimensions $2 \times 2$ for equation [1] using 2DPCA to avoid the 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.

**Results**

Figure 1b has a color-coded scale of the magnitudes of principal eigenvalues corresponding to 2DPCA in Figure 1a. From the figures, 600 principal eigenvalues were assigned, i.e. each area in the bottom figures represents a principal eigenvalue. The same TEC data processing was performed from 21:00 - 21:10 UT on 06 January, 2013. The results of 2DPCA are shown in the bottom three images of Figure 1b. Representative of more large principal eigenvalues, this shows a TEC anomaly over the eruption region during the time period 21:00 to 21:05 on 06 January, 2013 (UT). These large principal eigenvalues are likely to be a TEC anomaly related to this eruption. The other large principal eigenvalues in Figure 1b around the eruption region should mainly indicate the equatorial ionization anomaly (EIA) referred to Figure 1a. Other ionospheric anomalies unrelated to volcanic eruptions were suppressed due to their small principal eigenvalues in the examined time period.
Figure 1a - These figures show the GIMs during the time period from 20:55 to 21:10 (UT) on 06 January 2013.
Figure 1b - These figures give a color-coded scale of the magnitudes of principal eigenvalues corresponding to Figure 1(a) with 2DPCA. The color within an area denotes the magnitude of a principal eigenvalue corresponding to Figure 1(a), so that there are 600 principal eigenvalues assigned for 600 areas in each small map, respectively.
Discussion

Figure 2 shows the Kp indices from 05 - 10 January, 2013, and on 06 January, 2013. The indices are relatively small indicating that geomagnetic activity can not be responsible for the TEC anomaly. In other examined time periods, the magnitude of principal eigenvalues of the TEC is similar to that in Figure 1b at the time of 20:55 - 21:10 on 06 January, 2013. Only the (EIA) could be identified. Therefore, it has been shown that the TEC anomaly from 21:00 - 21:05 (UT) over the volcano is related to the eruption. However, the physical cause of this anomaly must also be considered. According to the statements in the section one, studies of TEC disturbance suggest some possible explanations for eruption-related TEC anomalies.

![Figure 2 - This figure shows the Kp indices from 05 to 10 January 2013 (UT) (NOAA Space Weather Prediction Center).](image)

The effect of shock acoustic wave is a possible cause from the work of Komjathy et al [2012]. To confirm this, Afraimovich et al. [2001] researched how shock acoustic waves produced by earthquakes affect the ionosphere. They studied these effects in seismic events produced in Turkey on 17 August and 12 November 1999 and in Southern Sumatra on 04...
June, 2000. They found the ionospheric response time due to the seismic production of acoustic shock waves is 180 - 390 s. Such an ionospheric response also fits the TEC anomaly time period determined in this study. This technique could be useful for understanding of the physical coupling between the ionosphere and terrestrial processes. The large principal eigenvalue shown here has a physical meaning and may not be only a mathematical index. If eruption-related ionospheric anomalies are not easily observed or monitored (Fig. 1a), then at least the form of the anomaly can predicted by a mathematical index. Monitoring or predicting volcanic eruptions and coseismic activity through ionospheric response has been successfully exemplified by Castagnetti et al. [2013], using a multi-sensor integrated system for landslide monitoring. Bhattacharya et al. [2013] used a similar system to automatically assess vulnerability due to landslides on the socio-economy of a region by categorizing landslide hazards using spatial as well as temporal causative factors. Pons et al. [2012] lead a ten-year project where a high number of medium resolution satellite images (MODIS and Landsat) were integrated to assess the daily water management and improve decision making.

**Conclusion**

A TEC anomaly was discovered over the Colima volcanic eruption region during the time period from 21:00 - 21:05 on 06 January, 2013 (UT). The anomaly lasted for at least 5 minutes during which the EIA could simultaneously be identified. A possible reason for the TEC is the production of acoustic shock waves by seismic activity. Therefore, we conclude that the monitoring or prediction of volcanic eruptions via coseismic activity could be performed by TEC Data Processing of ionospheric anomalies using 2DPCA.

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