Ionospheric Anomaly associated with Xiaolin Mudslide following Typhoon Morakot in Taiwan: Two-Dimensional Principal Component Analysis (2DPCA)

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Abstract
This paper reports on the application of two-dimensional Principal Component Analysis (2DPCA) to characterize the two dimensional total electron content (TEC) in the ionosphere associated with the Xiaolin mudslide at 10:09 August, 8, 2009 (UTC) in the aftermath of Typhoon Morakot. Our results revealed a five minute TEC anomaly over the location of the Xiaolin mudslide (23.162°N and 120.644°E) from 10:15 to 10:20 (UTC). This paper tries to address the cause of the TEC anomaly, in particular considering high-speed shock waves in the form of an impulse wave produced by mudslide, more dense TEC data are still necessary to confirm this hypothesis.

Keywords: Two-Dimensional Principal Component Analysis (2DPCA), Total Electron Content (TEC), Xiaolin mudslide, typhoon Morakot, shock wave, impulse wave.

Introduction
Landslides involve the movement of masses of rock, earth, or debris down a slope. Debris flows, also known as mudslides, are a common type of fast-moving landslide [Bhattacharya, 2013], which tends to travel along channels. Landslides and mudslides commonly occur as a consequence of heavy rainfall associated with Typhoons. On 03 July 2014, heavy rains marked the onset of the rainy season in China. The Landslide Blog reported (http://blogs.agu.org/landslideblog) an increase in the frequency of landslides in China, particularly in Yunnan Province. One especially massive landslide occurred at Tuohe village in Daguan County, Zhaotong City in Yunnan. On August 8, 2009, the record-breaking rainfall associated with typhoon Morakot caused wide scale flooding over nearly the entire southern region of Taiwan. Rainfall in Painting County exceeded 2,600 millimeters (100 in), which smashed all previous records of rainfall in a single place in Taiwan. Airlines managed a number of flights; however, the seaports were closed. Approximately 25,000 homes were cut off from electricity and no fewer than 600 people were reported missing in southern Taiwan alone. Most of those were residents of Xiaolin village (23.162°N and 120.644°E),
a mountain village with 1,300 residents in Jiaxian Township. Monitoring deformations, due to the effects of flooding, using topographical methods represents. Aarons [1978] included ionospheric predictions among the host of geophysical methods available for the prediction of changes on the surface of the earth, such as landslides, earthquakes, volcanoes, hurricanes, tornadoes, floods, and tsunamis. This depends on by the coupling between the troposphere and thermosphere/ionosphere [Richter, 1998; Pulinets, 2004; Artru et al., 2005; Bishop, 2012]. Multi-sensor satellites have the ability to monitor the land, the oceans, the atmosphere, and even the ionosphere at a global level at all times of the day and night and under all environmental conditions. The last decade in particular has seen the application of data from multi-sensor satellites in the monitoring and mapping of damage caused by a variety of natural hazards, including earthquakes, landslides, floods, volcanoes, hurricanes, algae blooms, oil spills, dust storms, and droughts with the strong coupling between land-ocean-atmosphere-ionosphere [Singh, 2005]. Numerous technologies have been devised for monitoring rain-induced landslides [Scaioni et. al., 2014], including remote sensing methods as in Hong et al. [2006] evaluated NASA multi-satellite precipitation analysis in the global assessment of landslide hazards. Hong et al. [2007] also monitored landslide on a global basis using satellite remote sensing methods. Lytvyn et al. [2012] applied a Precise Point Positioning (PPP) approach to reduce the costs associated with GPS-based landslide monitoring systems, particularly in mountainous regions. Wang and Soler [2012] applied a novel approach based on the Online Positioning User Service (OPUS) provided by the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA) for the processing of Global Positioning System (GPS) data. They then demonstrated the effectiveness of this approach in the long-term monitoring of landslides in Puerto Rico and Virgin Islands. Tronin [2004] used an InSAR (Satellite Interferometric Synthetic Aperture Radar) technique to record information related to the deformation of the earth due to geological events, such as volcanoes, earthquakes, and landslides, for use as an early warning system.

The Global Navigation Satellite System (GNSS) has been used to monitor landslides in the Dolomites in Italy, the Eastern Pyrenees in Spain, and San Juan Mountains in Colorado, USA (GNSS for Global Environmental Earth Observation, 2013). One benefit of using GNSS geodetic measurements is the ability to measure the Total Electron Content (TEC) in the ionosphere according to phase and code delays between satellites and receivers. Continued development of dense ground-receiver networks has also made it possible to perform 2D and 3D imaging of dynamic changes in ionospheric plasma. One potential application for this technology is in the study of typhoon-related TEC anomalies. The relationship between typhoon activity and TEC anomalies dates back to the work of Bauer [1958] who noticed that the FoF2 region of the ionosphere would extend to its maximum height immediately prior to the arrival of a typhoon at the observation station. In more recent research, fluctuations in the FoF2 layer have also been observed during the approach of typhoons [Shen, 1982; Liu et al., 2006 a, b]. Huang et al. [1985] researched 15 typhoons throughout 1982 and 1983 in the vicinity of Taiwan using a real-time HF Doppler frequency-shift sounding array for the detection of typhoon-induced Doppler Frequency Shifts (DFS) in the ionospheric. Two typhoons in particular, Wayne and Andy, produced significant ionospheric variations, which have been attributed to typhoon-generated acoustic gravity waves. In theory, the upward propagation of internal atmospheric disturbances such as planetary waves, tides
and gravity waves into the troposphere and stratosphere should create the momentum necessary to influence the thermosphere/ionosphere [Kazimirovsky et al., 2003; Kim, 2011; Lin, 2012]. A number of studies have demonstrated a coupling between the troposphere and thermosphere/ionosphere associated with mudslides. It has been proposed by Fritz et al. [2003], Heller et al. [2008], Ataie-Ashtiani and Nik-Khah [2008] that impulse waves (shock waves) would result in ionospheric anomalies similar to those caused by earthquakes [Kazimirovsky et al., 2003; Sun, 2007; Liu, 2011]. It would follow that relatively large mudslides should cause impulse waves of high speed. However it is an argument because triggering mechanism is different from earthquakes. Sumantyo [2014] reported progress on the development of CP-SAR (Circularly Polarized Synthetic Aperture Radar) onboard UAV JX-1/JX-2 (Josaphat Laboratory Unmanned Aerial Vehicle) (http://www2.cr.chiba-u.jp/jmrsl/?p=3037) and microsatellites for the monitoring of earthquake prone areas, volcanic activity, and landslides. He also developed sub-mission sensors (GPS Radio Occultation, GPS-RO) as well as electron density-temperature probes (EDTP) for the monitoring of ionospheric phenomena. Ionospheric observation sensors can also be implemented in conjunction with CP-SAR to monitor terrestrial surface deformations from the ionosphere. Therefore it proclaims large landslide should induce corresponding ionospheric anomaly. However, ionospheric anomalies can also be induced by gravity waves created by tsunamis associated with submarine landslides. The objective of this study was the application of two-dimensional principal component analysis (2DPCA) in the examination of the spatial distribution of TEC anomalies in the ionosphere. Specifically, we examined data associated with the Xiaolin village mudslide, in the aftermath of Typhoon Morakot at 10:09 on 08 August 2009 (UTC). Stations Kau001 and Kau047 near Xiaolin village reported intensity 1 degrees according to the earthquake intensity scale of the Central Weather Bureau (CWB), Taiwan). The TEC data covering the period from 00:00 (UTC) on 06 to 00:00(UTC) on 09 August 2009 (UTC) were examined. One mudslide-related TEC anomaly was observed from 10:15 to 10:20 on 08 August 2009, No other TEC anomalies related to this mudslide were detected at any other times.

**TEC Data Source**

The Global Differential GPS (GDGPS) system is a highly accurate and extremely robust real-time GPS monitoring and augmentation system. A large ground network of real-time reference receivers in conjunction with an innovative network architecture and real-time data processing software enables the GDGPS system to provide positioning accuracy at the decimetre (10 cm)-scale as well as time transfer accuracy at the sub-nanosecond scale on the ground, in the air, and in space, independent of local infrastructure. Comprehensive real-time information related to the GPS state, environmental data, and ancillary products are also available to support even the most demanding GPS augmentation operations; i.e., Assisted GPS (A-GPS) services aimed at facilitating situational assessments and environmental monitoring. Real-time measurements of global TEC data can be obtained in real-time using sensors (receivers) onboard GPS satellites and routed back to this network. The spatial resolution of TEC data in the GDGPS system is based on real-time dual frequency measurements from a vast global tracking network (real-time tracking network on the ground). The GDGPS system produces two dimensional total electron content (TEC) values within a 2°×2° global grid every 5 minutes [Yoaz and Byron, 2014]. TEC estimates
are corrected for bias induced during the measurement of dual-frequency delays in the GPS signals, including carrier phase biases, satellite state corrections, and ionospheric and tropospheric delays, which must be removed using post-processing software on the ground [Raman and Garin, 2005; Wu and Bar-Sever, 2005].

Processing of 2DPCA and TEC data

2DPCA

For 2DPCA, two-dimensional TEC data in an area (an area is 12° in longitude and 9° in latitude in this study) is represented by matrix $A$ (the dimension of $n \times m$). Linear projection of the form is defined as follows [Sanguansat, 2012]:

$$y = Ax$$  \[1\]

Mathematically, $x$ is called an n-dimensional projection axis that transforms $A$ with high-dimensional space to a low-dimensional space. $y$ is the projected feature of $A$ on $x$ after dimensionality reduction without losing of TEC data information by 2DPCA. However, a commensurately small amount of TEC data information after dimensionality reduction will be lost by using Principal Component Analysis (PCA) [Zhang et al., 2009].

$$S_x = E(y - Ey)(y - Ey)^T$$  \[2\]

where $S_x$ is the covariance matrix of the project feature vector.

The trace of $S_x$ is defined as follows:

$$J(x) = tr(S_x)$$  \[3\]

where:

$$tr(S_x) = tr\{ x^T G x \}$$

$$G = E \left[ (A - EA)^T (A - EA) \right]$$  \[4\]

Matrix $G$ is called the covariance matrix. Vector $x$ maximizing Equation 4 corresponds to the largest eigenvalue of $G$, which is referred to as the principle eigenvalue of the two-dimensional TEC data in a given area, representing the most dominant component of the TEC data in this area. The principal eigenvalue indicates the most important spatial characteristics, patterns, and conditions associated with TEC data in this area. 2DPCA is able to overcome the small sample size data (SSS data) [Sanguansat, 2012]. The PCA converts the measurements into one-dimensional data prior to the calculation of the covariance matrix, which is based on an input matrix with the dimensions of $n \times m$ and reshaped from...
one-dimensional data. The reshaping of data can cause computational errors because PCA was designed to deal only with one-dimensional data. This makes it exceedingly difficult to preserve the spatial structure and related information due to the loss of some of the original information when undergoing inversion to the original dimensions when the matrix is limited to the SSS data. This loss of information is a low dimensional data problem referred to as the SSS problem. However, the covariance matrix in 2DPCA is full rank for a matrix of low dimension, which enables it to overcome the SSS problem. This study employed 2DPCA for the detection of TEC anomalies associated with the Xiaolin mudslide through the adoption of non-dense two dimensional TEC data from the GDGPS network System.

**Processing of TEC data**

Figure 1 presents the GIMs covering the period from 10:10 to 10:20 on 08 August 2009. In Figure 1, Global TEC data are uniformly divided into 600 smaller grids measuring 12° in longitude and 9° in latitude. For the sake of convenience, this study used a terminology grid instead of area. Please refer to “TEC Data Source” concerning the spatial resolution of the TEC data for the GDGPS system. Each grid includes approximately 24 TEC data points; i.e., 6 longitudinal and 4 latitudinal. Performing 2DPCA with 24 TEC data points per grid (higher dimensional data) requires a substantial amount of computing resources; however, the effectiveness is nearly undiminished when using just 4 TEC data points (low dimensional data). This allows that when performing 2DPCA, the accuracy is enough by with 4 TEC data points per grid. We therefore adopted 4 TEC data points for processing in each grid. As shown in Figure 1, quantitative analysis involved 4 TEC data points (2 x 2) in each grid to form a matrix A for use as an input for Equation 1. Equations 2, 3 and 4 were used to estimate the principal eigenvalue G. The largest principal eigenvalue of G in each grid during the period of interest was over Xiaolin village. We then computed the principal eigenvalues for each of the 600 smaller grids around the globe. Therefore, the meaning of Figure 2 is necessary to explain, it resulted in a principal eigenvalue in each grid represented the TEC principal spatial characteristics of this grid. For convenience in illustration, each grid was filled with a uniform color. During this time period, the wind of this typhoon is no starker, and therefore Xiaolin mudslide-related TEC anomaly should reveal. That proclaims the typhoon-related TEC anomaly, other TEC anomalies (e.g. non-earthquake-associated TEC anomalies, and other earthquake-associated TEC anomalies in the meantime and the Equatorial Ionization Anomaly (EIA), non-Landslide (mudslide)-associated TEC anomalies in the examined time period) were already suppressed that resulted in smaller principal eigenvalues and thus a largest principal eigenvalue of 2DPCA should be a pattern of mudslide-related TEC anomaly. The time when the mudslide occurred was close to time at which the TEC anomaly was observed. Clearly, 2DPCA was able to differentiate this mudslide-related TEC anomaly from other TEC anomalies and during the period under investigation.
Figure 1 - These figures present GIMs for the period from 10:10 to 10:20 on 08 August 2009 (UT). The equatorial ionization anomaly (EIA), a trough in the ionization in the F2 layer, lies within approximately ± 30 degrees of the magnetic equator. The anomaly associated with the Xiaolin mudslide cannot be observed in this figure; however, it was revealed by 2DPCA analysis.
Figure 2 - Color-coded scale related to the magnitudes of principal eigenvalues corresponding to the 600 principal eigenvalues assigned Figure 1. The largest principal eigenvalue in any of the grids covers the location of Xiaolin village. During this time period, the wind of this typhoon is no starker, so that Xiaolin mudslide-related TEC anomaly should be enlarged.
Results
As shown in Figure 2, the largest principal eigenvalues from 10:15 to 10:20 on 08 August 2009 indicate the TEC anomaly associated with the Xiaolin mudslide. This Xiaolin mudslide was in the aftermath of Typhoon, and at this time of 10:10 (UTC) the effects of Typhoon did not cause TEC anomalies shown on the top in Figure 2. By examining the Kp indices [Bartels, 1957; Elliott et al., 2013], we were able to eliminate the possibility of other factors such as solar flares or geomagnetic effects affecting our results. The K_p index in Figure 3 was calculated as a weighted average of K-indices from a network of geomagnetic observatories, wherein disturbances in the horizontal component of earth’s magnetic field can be represented on a scale of 0-9, with 1 indicating calmness and 5 or more indicating a geomagnetic storm. Clearly, August, 8 was a geomagnetic quiet day with K_p<4.

Discussion
2DPCA proved effective in the detection of a TEC anomaly related to the Xiaolin mudslide in 2009. In the Xiaolin mudslide, the most evident physical mechanism was ground motion, which is similar to the effects of an earthquake, with co-seismic ionospheric and deformation...
signals as well as fine surface vibrations. These effects produced shock waves (impulse waves) in the lower atmosphere, which then traveled up into the ionosphere resulting in large-scale irregularities in ionospheric density [Jin et al., 2010]. However, researching more detailed propagating of the anomalous fluctuation as a shock wave by 2DPCA is a weakness in this study due to non-dense TEC data (a limited number of TEC data points in each area). Afraimovich et al. [2001] researched shock waves due to the earthquakes with a focus on the seismic activity in Turkey (17 August and 12 November 1999) as well as in Southern Sumatra (04 June 2000). They found that the ionospheric response to shock waves caused by earthquakes is 180-390 s. In this study, 2DPCA was shown to provide a credible estimation with regard to the duration of the TEC anomaly associated with the Xiaolin mudslide.

Conclusion
This study demonstrated the efficacy of 2DPCA in the detection of TEC anomalies associated with a shock wave (impulse wave) of high speed produced by the Xiaolin mudslide. The TEC anomaly is indicative of a shock wave, which probable caused anomalous fluctuations in density of ionospheric plasma.

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