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Analysis of ionosphere changes due to earthquakes (case study: Regency of Lombok and Donggala)

M N Cahyadi and M T A Prasetyo

Geomatics Engineering Department, Faculty of Civil, Environmental, and Geo Engineering Sepuluh Nopember Institut of Technology, Surabaya 60111 Indonesia

Abstract. Earthquakes will form and propagate atmospheric waves, rayleigh waves, acoustic waves and gravity waves. When acoustic waves reach the ionosphere, this affects the ionospheric electron density that can be known from GNSS signals, this disorder is commonly called CID. Electromagnetic waves transmitted by GPS satellite signals that pass through the ionosphere will cause a delay in time, from this data can be used to detect the presence of ionospheric variations through TEC values. In this study an analysis of ionospheric changes due to the earthquake that occurred in Lombok Regency and Donggala Regency. The result of the analysis show that the value of ionospheric disturbance from 5 August – 28 September 2018 was around 0.19 TECU – 0.56 TECU.

1. Introduction
Indonesia is a country that has a mountainous topography and frequent earthquakes and volcanoes. This is because Indonesia is a meeting place for four of the world's main plates, the Eurasian Plate, the Indo-Australian Plate, the Philippine Sea Plate and the Pacific Plate [1]. In 2018 Indonesia experienced several earthquakes that claimed many lives, the first of which occurred in Lombok Regency and the second occurred in Donggala which resulted in a tsunami [2]. Earthquakes will form and propagate wave energy, namely Rayleigh Wave, Acoustic Wave and Gravity Wave. Rayleigh waves propagate away from the epicenter horizontally on the surface of the earth. While Acoustic and Gravity Waves will propagate vertically through troposphere and ionosphere. when it reaches the ionosphere, these Acoustic waves will make electron density deviations in the ionosphere called CIDs (Coseismic Ionosphere Disturbances). This CIDs phenomenon occurs several minutes to 1 hour after the earthquake occurred [3].

The discussion about tropospheric biases has been carried out by Cahyadi MN, et all [4]. In this study an analysis of how earthquakes that have more than Mw 6 in Lombok and Donggala Regency affects the ionosphere layer which is seen through a quantity called the TEC (Total Electron Content) using data of GNSS station around the epicenter. Electromagnetic waves transmitted by GNSS satellite signals delay when the signal passes through the ionosphere. This time delay or delay can be used to detect ionospheric variations through a quantity called TEC (Total Electron Content). TEC is the number of electrons along the satellite signal path that passes through the ionosphere expressed in TECU (TEC Unit) with a value of 1 TECU is $10^{16}$ electrons/ m$^2$ [5]. Among others, many studies have done for
Coseismic ionospheric disturbances (CID), the use of CID for possibility of early warning system during West Sumatra earthquake 2016 [6]. And earthquake precursor detection from ionospheric TEC data [7].

2. Methodology

2.1. Study area

The location of earthquake for the first study is Lombok Regency. In order to observe ionospheric fluctuations, some GNSS stations owned by Geospatial Information Agency (BIG) were used, these stations were spread in Kalimantan, Sulawesi, East Java and Bali Island (CMAT, CDNP, CNYU, CPES, CLBJ, CSIT, PALP, CTOL, CAMP, CBAL, CMLI, CPAL, CKEN, CMAK, CBIT, CRAU, CNAU, CPUT, CKTP, CPON and CBAS stations) with detailed positions described in Figure 1 and Table 1. The observation data on August 5, 2018 - August 19, 2018 were used.

Figure 1. Location of research and distribution of CORS in Lombok District

The location of earthquake for the second study is Donagala Regency. The GNSS stations were used are PALP, CTOL, CAMP, CBAL, CMLI, CPAL, CKEN, CMAK, CBIT, CRAU, CNAU, CPUT, CKTP, CPON and CBAS stations with detailed positions described in Figure 2 and Table 1. The observation data on September 28, 2018 - October 8, 2018 were used.
Figure 2. Research location and distribution of CORS in Donggala Regency.

Table 1. CORS GNSS station data.

| Station | Distance from Lombok Epicentre (km) | Distance from Donggala Epicentre (km) |
|---------|-------------------------------------|-------------------------------------|
| CMAT    | 52.40197733                         | 1000.467201                         |
| CDNP    | 156.9130734                          | 1071.538411                         |
| CPES    | 261.1568779                          | 1105.891449                         |
| CNYU    | 229.900074                           | 1059.618609                         |
| CSIT    | 277.2074521                          | 1038.245236                         |
| CLBJ    | 384.4107797                          | 901.5551996                         |
| PALP    | 904.0233004                          | 58.33251974                         |
| CBAL    | 780.9516241                          | 344.4763033                         |
| CTOL    | 1144.451172                          | 195.6109222                         |
| CAMP    | 1001.947814                          | 203.5002884                         |
| CMLI    | 813.2616979                          | 286.9304206                         |
| CPAL    | 718.6439523                          | 293.2715519                         |
| CKEN    | 831.058809                           | 499.7555146                         |
| CMAK    | 479.7962056                          | 529.0154088                         |
| CBIT    | 1454.260596                          | 632.3908701                         |
| CRAU    | 1164.750158                          | 383.4510126                         |
| CNAU    | 1318.879132                          | 568.5334923                         |
| CPUT    | 1089.928536                          | 780.13649                           |
| CBAS    | 1333.652054                          | 1186.55199                          |
| CPON    | 1213.019522                          | 1167.965914                         |
| CKTP    | 1014.943318                          | 1106.426521                         |
2.2. Data
The data used in this study is earthquake data that has a strength greater than 6 Mw in the two regions used for the study. Earthquake data in Lombok Regency can be seen in Table 2.

| Date/DOY             | Time (UT Hour) | Strength (Mw) | Location                  |
|----------------------|----------------|---------------|----------------------------|
| August 5, 2018/217   | 11.46          | 6.9           | 8° 15' 36" S ; 116° 26' 24" E |
| August 19, 2018/231  | 04.10          | 6.3           | 8° 20' 24" S ; 116° 36' E  |
| August 19, 2018/231  | 14.56          | 6.9           | 8° 19' 12" S ; 116° 37' 48" E |

Whereas for earthquake data in Donggala Regency can be seen in Table 3.

| Date/DOY             | Time (UT Hour) | Strength (Mw) | Location                  |
|----------------------|----------------|---------------|----------------------------|
| September 28, 2018/271| 06.59          | 6.1           | 0° 24' S ; 119° 48' 48" E  |
| September 28, 2018/271| 10.02          | 7.5           | 0° 15' 36" S ; 119° 51' E  |

2.3. Research methodology
The processing stages carried out in this study include:

- **Data Inventory**
The GNSS observation and navigation data are obtained from BIG in the form of RINEX on the date of the study in both earthquake locations. This observation data will be used to calculate the TEC value. While the navigation data will be used to determine the position of the satellite orbit.

- **Processing of RINEX Data**
At this stage, processing RINEX data is observed and navigated. Observation data is processed using the rdrnx.f program to obtain the time and STEC value, while the navigation data is processed using the rdeph.f program to obtain time data and satellite orbit coordinates in cartesian. Both data processing programs are run with Fortran software.

- **Calculation of Anomalies**
After the observation data has been processed, then the processed results are plotted using Matlab together with its 8th polynomial, to analyze and determine which satellites have fluctuations due to the earthquake. Then the calculation is done to determine the VTEC value by subtracting the STEC value from the polynomial. After calculation, VTEC data is plotted with Matlab to display the graphical visualization of the TEC changes.

- **Determination of IPP Position**
The satellite orbit position determines the position of Ionospheric Pierce Point (IPP) to determine the position of the satellite orbit that records fluctuations after an earthquake occurs. This processing is done using the Matlab application, which results in plotting the position of the IPP on the surface of the earth.
3. Result and discussion

3.1. RINEX data processing results
Observation data and navigation data obtained from BIG in the form of RINEX are processed using the rdrnx.f and rdeph.f programs that are run using Fortran software. The results of processing observational data are time data in the form of UT and STEC values (TECU) with a time interval of 30 seconds on each satellite recorded by each station. While the results of processing navigation data are time in UT and satellite orbit position coordinates in the cartesian coordinate system with a time interval of 3 minutes.

3.2. Earthquake analysis August 5, 2018 (DOY 217) At 11.46 in Lombok Regency
The results of processing observational data and navigation data are then visualized using Matlab. The results of processing the observation data, namely STEC, are plotted together with the polynomial to analyze which satellites detect fluctuations caused by earthquakes. While the results of navigation data, namely satellite orbit coordinates are processed first to get the IPP position coordinates when fluctuations are detected by satellites, then the results are plotted and obtained maps of IPP position and satellite orbit.

3.2.1. Analysis VTEC.
From the results of the analysis it was found that on satellite No. 15 at the CAMP and CNAU stations there were fluctuations due to the earthquake. After determining which satellites have fluctuations, then VTEC calculations are performed to determine the value of the fluctuation, namely by reducing the STEC value of the polynomial. The VTEC value is then visualized using Matlab, the results of the visualization can be seen in Figure 3 below.

![Figure 3. VTEC Satellite No. 15 in All Stations Detected for Earthquake Disorders on August 5, 2018](image1)

From Figure 3 above it can be seen that the earthquake occurred at 11.46 UT (vertical black line). Based on the graph above, it can be seen that the TEC value of each observation station, namely CAMP: 0.19 TECU was detected after 13 minutes of the earthquake and CNAU: 0.19 TECU was detected after 19 minutes of the earthquake.
3.2.2. Analysis IPP

From the results of navigation data processing that produces satellite orbit coordinates, then the data is calculated to determine the position of the IPP at the time of detection of fluctuations. Then plotting the Matlab is done and the results are as follows.

![Figure 4](image)

**Figure 4.** Satellite Flow No. 15 Mapped Through SIP from All Stations Detected The Disruption of Earthquakes on August 5, 2018 11.46

From Figure 4 above the colored line is the no. 15 satellite flow projection at each station. The black dot is the epicenter of the earthquake / epicenter of the earthquake. The red dot is the position of the IPP when fluctuations are detected. From the figure, it can be seen that the number 15 satellite of all the main flow stations is north of the epicenter. This is caused by the position of the epicenter located south of the equator which results in the resulting acoustic waves moving towards the south of the earth. This movement is affected by the presence of geomagnetic earth.

3.3. Earthquake Analysis August 19, 2018 (DOY 231) At 4:10 in Lombok Regency

The results of processing observational data and navigation data are then visualized using Matlab. The results of processing the observation data, namely STEC, are plotted together with the polynomial to analyze which satellites detect fluctuations caused by earthquakes. While the results of navigation data, namely satellite orbit coordinates are processed first to get the IPP position coordinates when fluctuations are detected by satellites, then the results are plotted and obtained maps of IPP position and satellite orbit.

3.3.1. Analysis VTEC

From the results of the analysis it was found that the number 5 satellites at CBAL, CMLI, CNAU and CPAL stations had fluctuations due to the earthquake. After determining which satellites have fluctuations, then VTEC calculations are performed to determine the value of the fluctuation, namely by reducing the STEC value of the polynomial. The VTEC value is then visualized using Matlab, the results of the visualization can be seen in Figure 5 below.
Figure 5. VTEC Satellite No. 5 at All Stations Detected by the Earthquake Disruption on August 19, 2018 At 4:10 a.m.

From Figure 5 above, it can be seen that the earthquake occurred at 04.10 UT (vertical black line). Based on the graph above, it can be seen the TEC value of each observation station, namely CBAL: 0.56 TECU detected after 4 minutes of earthquake, CMLI: 0.18 TECU detected after 10 minutes earthquake, CNAU: 0.19 TECU detected after 10 minutes earthquake and CPAL: 0.36 TECU detected after 12 minutes of an earthquake.

3.3.2. Analysis IPP
From the results of navigation data processing that produces satellite orbit coordinates, then the data is calculated to determine the position of the IPP at the time of detection of fluctuations. Then plotting the Matlab is done and the results are as follows.

Figure 6. Satellite Flow No. 5 Mapped Through SIP from All Stations Detected The Earthquake Disruption August 19 2018 At 4:10

From Figure 6 above the colored line is the no. 5 satellite flow projection at each station. The black dot is the epicenter of the earthquake / epicenter of the earthquake. The red dot is the position of the IPP when fluctuations are detected. From the figure, it can be seen that the No. 5 satellite of all the main flow stations is north of the epicenter. This is caused by the position of the epicenter located south of the equator which results in the resulting acoustic waves moving towards the south of the earth. This
movement is affected by the presence of geomagnetic earth.

3.4. Earthquake Analysis August 19, 2018 (DOY 231) At 14:55 in Lombok Regency
The results of processing observational data and navigation data are then visualized using Matlab. The results of processing the observation data, namely STEC, are plotted together with the polynomial to analyze which satellites detect fluctuations caused by earthquakes. While the results of navigation data, namely satellite orbit coordinates are processed first to get the IPP position coordinates when fluctuations are detected by satellites, then the results are plotted and obtained maps of IPP position and satellite orbit.

3.4.1. Analysis VTEC
From the results of the analysis it was found that on satellite no. 21 at CAMP, CBAL, CNYU, CPES, and CSIT stations there were fluctuations due to the earthquake. After determining which satellites have fluctuations, then VTEC calculations are performed to determine the value of the fluctuation, namely by reducing the STEC value of the polynomial. The VTEC value is then visualized using Matlab, the results of the visualization can be seen in Figure 7 below.

![Figure 7. VTEC Satellite No. 21 at all stations detected for earthquake disruption on August 19, 2018 At 14.56](image)

From Figure 7 above it can be seen that the earthquake occurred at 14.56 UT (vertical black line). Based on the graph above, it can be seen the TEC value of each observation station, namely CAMP: 0.19 TECU detected after 27 minutes of earthquake, CBAL: 0.2 TECU detected after 50 minutes earthquake, CNYU: 0.45 TECU detected after 35 minutes of earthquake, CPES: 0.43 TECU detected after 35 minutes the earthquake and CSIT: 0.3 TECU were detected after 41 minutes of the earthquake.

3.4.2. Analysis IPP
From the results of navigation data processing that produces satellite orbit coordinates, then the data is calculated to determine the position of the IPP at the time of detection of fluctuations. Then plotting the Matlab is done and the results are as follows.
From Figure 8 above the colored line is the satellite plot projection 21 at each station. The black dot is the epicenter of the earthquake / epicenter of the earthquake. The red dot is the position of the IPP when fluctuations are detected. From the figure, it can be seen that satellite number 21 of all the main flow stations is located in the north of the epicenter and also in the south of the epicenter. This is caused by the position of the epicenter in the south of the equator which results in the acoustic waves produced moving towards the south of the earth and the magnitude of the earthquake strength also influencing it. This movement is affected by the presence of geomagnetic earth.

3.5. Earthquake Analysis September 28, 2018 (DOY 271) At 6:59 in Donggala Regency
The results of processing observational data and navigation data are then visualized using Matlab. The results of processing the observation data, namely STEC, are plotted together with the polynomial to analyze which satellites detect fluctuations caused by earthquakes. While the results of navigation data, namely satellite orbit coordinates are processed first to get the IPP position coordinates when fluctuations are detected by satellites, then the results are plotted and obtained maps of IPP position and satellite orbit.

3.5.1. Analysis VTEC
From the results of the analysis it was found that on satellite no. 24 at CBAL, CBIT, CKEN, and CKTP stations there were fluctuations due to the earthquake. After determining which satellites have fluctuations, then VTEC calculations are performed to determine the value of the fluctuation, namely by reducing the STEC value of the polynomial. The VTEC value is then visualized using Matlab, the results of the visualization can be seen in Figure 9 below.

From Figure 9 above, it can be seen that the earthquake occurred at 6:59 UT (vertical black line).
Based on the graph above, it can be seen the TEC value of each observation station, namely CBAL: 0.13 TECU detected after 19 minutes of earthquake, CBIT: 0.16 TECU detected after 15 minutes of earthquake, CKEN: 0.19 TECU detected after 22 minutes earthquake and CKTP: 0.14 TECU detected after 27 minutes of the earthquake.

3.5.2. Analysis IPP
From the results of navigation data processing that produces satellite orbit coordinates, then the data is calculated to determine the position of the IPP at the time of detection of fluctuations. Then plotting the Matlab is done and the results are as follows.

![Ionospheric Pierce Point by Satellite no. 24](image)

**Figure 10.** Satellite Flow No. 24 Mapped Through SIP from All Stations Detected for Earthquake Disorders September 28 2018 At 6:59

From Figure 10 above the colorful line is the No. 24 satellite track at each station. The black dot is the epicenter of the earthquake / epicenter of the earthquake. The red dot is the position of the IPP when the fluctuation is detected. From the figure, it can be seen that satellite No. 24 of all the main flow stations is south of the epicenter. This is due to the position of the epicenter located north of the equator which results in the resulting acoustic wave moving towards the south of the earth. This movement is affected by geomagnetic earth.

3.6. Earthquake Analysis September 28, 2018 (DOY 271) At 10:02 in Donggala District
The results of processing observational data and navigation data are then visualized using Matlab. The results of processing the observation data, namely STEC, are plotted together with the polynomial to analyze which satellites detect fluctuations caused by earthquakes. While the results of navigation data, namely satellite orbit coordinates are processed first to get the IPP position coordinates when fluctuations are detected by satellites, then the results are plotted and obtained maps of IPP position and satellite orbit.

3.6.1. Analysis VTEC
From the results it was found that on satellite No. 21 at CAMP, CKEN, CMAK, CPAL and CTOL stations there were fluctuations due to the earthquake. After determining which satellites have fluctuations, then VTEC calculations are performed to determine the value of the fluctuation, namely by reducing the STEC value of the polynomial. The VTEC value is then visualized using Matlab, the results of the visualization can be seen in Figure 11 below.
From Figure 11 above, it can be seen that the earthquake occurred at 10.02 UT (vertical black line). Based on the graph above, it can be seen the TEC value of each observation station, namely CAMP: 0.2 TECU detected after 16 minutes of earthquake, CKEN: 0.09 TECU detected after 15 minutes earthquake, CMAK: 0.13 TECU detected after 18 minutes earthquake, CPAL: 0.2 TECU detected after 11 minutes the earthquake and CTOL: 0.15 TECU were detected after 15 minutes of the earthquake.

3.6.2. Analysis IPP
From the results of navigation data processing that produces satellite orbit coordinates, then the data is calculated to determine the position of the IPP at the time of detection of fluctuations. Then plotting the Matlab is done and the results are as follows.

From Figure 12 above the colorful line is the number 21 satellite track at each station. The black dot is the epicenter of the earthquake / epicenter of the earthquake. The red dot is the position of the IPP when the fluctuation is detected. From the picture, it can be seen that the number 21 satellite paths are just above the epicenter and some of them are in the southern epicenter. This is caused by the position of the epicenter near the equator which results in the resulting acoustic wave moving towards...
the south of the earth. This movement is affected by geomagnetic earth.

4. Conclusion
From this study, it can be concluded that earthquakes that occur in North Lombok Regency, there are several satellites that detect fluctuations in the ionosphere as a result of the earthquake. namely satellite 15 in the August 5 earthquake at 11.46 with a TEC value of 0.19 TECU; satellite 5 in the August 19 earthquake at 04.10 with a value of TEC 0.18-0.56 TECU; satellite 21 in the August 19 earthquake at 14.56 with a value of TEC 0.19-0.45 TECU. While earthquakes in Palu and Donggala districts also have satellites that detect fluctuations, namely satellite 24 in the September 28 earthquake at 6:59 with a value of TEC 0.13-0.19 TECU and satellite 21 in the September 28 earthquake at 10.02 with a value of TEC 0.09-0.2 TECU.

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