The determination of earthquake parameters such as location (longitude, latitude, and depth) and magnitude are important in the development of reliable Earthquake Early Warning (EEWS) and Tsunami Early Warning System (TEWS), and for many projects in earthquake and tsunami mitigation. In the traditional method, these parameters are determined using recording seismic waveform from strong-motion accelerometers or broadband seismometers [1]. Those methods use several seconds of P-wave data to quickly estimate the magnitude, hypocenter, and origin time (OT) of earthquakes [2, 3]. However, the saturation of magnitude is a common problem in the magnitude determination from seismic data for large earthquakes (M > 7) [3–5]. To avoid this saturation problem, several studies [5, 6] have used the Global Positioning Satellite System (GNSS) for the EEWS application over the last 15 years.
Several applications that have used GNSS data for EEWS are ShakeAlert system (developed by the United State Geological Survey (USGS)) [7], Geodetic Alarm System (GARMs) [8], Bayesian Evidence-based Fault Orientation and Real-Time Earthquake Slip (BEFORE) [9], and Geodetic First Approximation of Size and Timing (G-FAST) [10], and Real-Time on the GNSS Earth Observation Network (GEONET) Analysis System for Rapid Deformation monitoring ( REGARD) [11].

On the period of July to August 2018, there were several earthquakes occurred in the North of Lombok Island 1 with a magnitude greater than 6. The first earthquake occurred on July 28th, 2018 (28J) with a magnitude M6.4 continuously with the second earthquake on August 05th, 2018 (05A) with M6.9, and the two last earthquakes occurred on August 19th, 2018, with magnitude M6.3 (19A-1) and M6.9 (19A-2). The magnitude of this event has been modeling using Interferometric Synthetic Aperture Radar (InSAR) data and seismic data [12] and using local seismographic networks [13].

In this research, we use the high-rate data of the CMAT GNSS station to estimate the magnitude of the August 05, 2021 event. We use the Peak Ground Displacement (PGD) formula from GFAST modules to estimate the earthquake magnitude [10]. This event has the biggest coseismic displacement at the CMAT GNSS station than other events [14]. The event has the most significant impact on near volcano [12]. Due to the limitation of GNSS station distribution, we only have one GNSS station which operating continuously in Lombok Island (Figure 1). Furthermore, we investigate the estimated magnitude parameter starting from OT to 240 seconds after OT, and to give a comparison of our findings, we used the official magnitude released by Indonesia’s Meteorological, Climatological, and Geophysical Agency (Badan Meteorologi, Klimatologi, dan Geofisika / BMKG).

2. Data and method

In this research, we use GNSS data obtained from the Geospatial Information Agency (Badan Informasi Geospasial/BIG) as a part of the Indonesian Continuous Operating Reference System (Ina-CORS). The CMAT GNSS station is located at Mataram city which is ± 51.89 km from the epicentral location from August, 5th, 2018 event. Figure 1 shows the location of the CMAT GNSS station. The GNSS data for this research was focusing only on the August, 5th event with Mw 6.9. The GNSS data for another events (28J, 19A-1, 19A-2) were not included in this research because the waveform did not show clearly coseismic displacement.

We use the GPS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) version 6.3 from the Jet Propulsion Laboratory (JPL) [15] to generate the kinematic time-series positions of CMAT station at 1 Hz (Figure 2). We apply the final precise satellite orbit and clock from JPL 15 and use the IGS14 absolute phase center variations [16]. The FES2004 model from the Onsala Space Observatory (http://holt.oso.chalmers.se/loading/) uses to modeled and corrected the tidal effects (solid earth tide, pole tide, and ocean tide) [17]. The tropospheric wet zenith delays
and horizontal gradients were estimated as random-walk parameters [18] and mapped into the tropospheric slant delays down to elevation angle 7 using the Global Pressure and Temperature 2 (GPT2) mapping functions [19]. We apply single-receiver ambiguity resolution to resolve phase ambiguities [20]. We rotate the global coordinates solution (the International Terrestrial Reference Frame (ITRF) 2014) [21] into local coordinates (north, east, up). We produce the displacements waveform in the local reference frame by removing the mean of 10-samples pre-event [1].

**Figure 1.** Location of CMAT GNSS station. The focal mechanism and earthquake location were taken from USGS with 28J is event on July 28, 2018; 05A is event on August 5, 2021; 19A-1 is first event on August 19, 2021 and 19A-2 is the second event on August 19 2018. The light blue circles are aftershock of the event taken from [22]; The fault delineation from Pusat Studi Gempa Nasional (PUSGEN) [23]. The topography data were taken from SRTM15+V2 [24]. Inset shows the position of the study area (red rectangular) area concerning the Indonesian region.

We modeled the GNSS displacements using the G-FAST earthquake early warning packages [10]. We compute the earthquake moment magnitude using PGD scaling. Due to the limitation of station number, we did not apply all the PGD modules of
GFAST. We estimated the earthquake magnitude using epoch-by-epoch of displacement waveform and analyzed the evolution of the earthquake magnitude results.

3. Result and discussion

The displacement waveforms for each component (north, east, up) show in Figure 2. The coseismic displacement clearly shows in the North-South (NS) and East-West (EW) components, respectively, while the Up-Down (UD) component did not show any coseismic displacement. The NS and EW components have a maximum coseismic displacement of about 11.25 cm to the North and 6.61 cm to the East directions.

![Figure 2](image.png)

**Figure 2.** The waveform displacements for each component. (a) is the displacement waveform in the north-south component. (b) is the displacement waveform in the east-west component. (c) is the displacement waveform in the vertical component.

Figure 3 shows the total displacement in two dimensions (2D), three dimensions (3D), the PGD magnitude evolution starting from OT (2018-08-05 11:46:56 GPS time). The 2D displacement was calculated using two components displacement waveform (NS and EW), while the 3D component was calculated using three components of the displacement waveform (Figure 2). The 2D and 3D displacements have a similar pattern. This results indicate that the coseismic displacement from vertical component (UD) did not affected to the 3D displacement because there is no significant coseismic displacement in the UD component as saw in the time series 2(c). The total displacement waveform changes quite bigger at 10 seconds after OT. The displacements show the surface wave pattern starting from 10 - 60 seconds after OT.

The PGD magnitude evolution shows in Figure 3 (c) and Figure 3 (d) for 2D and 3D displacements. In the PGD magnitude calculation, to investigate the evolution
of the magnitude, we used all the coseismic displacement to estimate the magnitude. There were two PGD magnitudes in the result which calculates using epicentral distance (Me) and hypocentral distance (Mh), respectively. Our suggestion the vertical coseismic displacement will give a contribution to the PGD magnitude determination. **Figure 3 (c) and (d)** show Mh is relatively higher than Me. The first 10s from OT, the PGD magnitude (2D and 3D) have a value below Mw 6.2 and reach Mw 6.6 - 6.8 at 30s after OT. Overall, from 30 to 240 seconds after OT, the average PGD magnitude has a value between Mw 6.7 - 6.9.

We compare our PGD magnitude results with the evolution of magnitude from BMKG database. The August, 5th, 2018 event has been detected by the BMKG seismic stations at 90 seconds after OT, and the first magnitude was estimated (FE) at 118 - 119 minutes after OT (green square with red circle in **Figure 3 (c,d)**), and first announcement at 150 - 178 seconds after OT (FA).

**Figure 3.** The total displacements and PGD magnitude; Me is the PGD magnitude using epicentral distance; Mh is the PGD magnitude using hypocentral distance; MBKMG is magnitude from BMKG; FE is first magnitude estimation; FA is first magnitude announcement. (a) the 2D total displacement; (b) the 3D displacement; (c) the PGD magnitude from 2D total displacement; (d) The PGD magnitude from 3D total displacement; green squares at (c) (d) are magnitude from BMKG.

### 4. Conclusions

This research demonstrates the ability to use a high-rate GNSS waveform to determine the earthquake magnitude rapidly. From this research, using GNSS post-processing, the PGD magnitude of the August 05th, 2018 Lombok earthquake with the value Mw 6.6 -
6.8 was reached at 30 seconds after OT, while the seismic magnitude needs about 188 - 119 s after OT for the first magnitude estimation. The first time seismic magnitude estimation depends on the nearest distance of the seismic stations to the earthquake source location. How fast PGD GNSS has estimated depends on several factors, such as the reliable communication data to transfer GNSS high-rate data to the processing center, the quality of the real-time kinematic positioning, the distance GNSS network stations to the earthquake source location, and the modeling method to estimate PGD magnitude.

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