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Research Article

The Investigation of Tropospheric Changes with GNSS: A study on 6 February 2023 Kahramanmaraş Earthquake Sequence

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Abstract

The earthquakes that occurred in Kahramanmaraş on February 6, 2023, are among the significant seismic events in Türkiye. Recorded at moment magnitudes of 7.8 and 7.6 in ten hours on East Anatolian Fault Zone (EAFZ), these earthquakes resulted in extensive destruction and loss of lives in the region. The effects of these earthquakes have been actively studied following the events, utilizing geodetic measurement techniques, particularly GNSS measurements, which are commonly employed in earthquake studies for determining tectonic movements and crustal deformations. As known, GNSS signals pass through significant atmospheric layers, namely the ionosphere and troposphere, before reaching the Earth's surface, and the influence of these atmospheric layers is evident in the results due to various error sources within these layers. One of the main limiting factors in studies such as determining crustal movements is the influence of the troposphere, as surface velocities are on the order of a few mm/yr and require high accuracy (at the mm level). In this study, changes in the troposphere during the earthquakes on February 6, 2023, were investigated using tropospheric zenith delays (Zenith Total Delay - ZTD) computed from GNSS observations. The results indicate the presence of zenith tropospheric delay anomalies at stations close to the fault rupture during and after the main shock, while no such anomalies were observed at distant stations from the fault rupture zone. This finding indicates a relationship between earthquakes and changes occurring in the troposphere.

Keywords: GNSS, Zenith Troposferic Delay, 6 Şubat 2023 Kahramanmaraş Earthquake Sequence, GNSS Meteorology

Introduction

The Arabian, Nubian and the European plate interactions in Eastern Mediterranean cause the tectonic structures of Türkiye such as strike slip faults North Anatolian Fault (NAF) and East Anatolian Fault (EAF) (McClusky et al., 2000; Reilinger et al., 2006). During the 20. century, many Mw>7 earthquakes occurred on the right lateral, strike-slip NAF (Gazioğlu et al., 2002). On the other hand, left lateral strike- slip EAF has broken its silence in this century, proving significant seismic potential of Türkiye. Especially the last two earthquakes happened on February 6, 2023, called as Kahramanmaraş earthquake sequence with the 7.8 and 7.6 moment magnitudes, had ruptured ~300 km and ~150 km along the EAF, respectively (Barbot et al., 2023; Karabulut et al., 2023; Sevgi Birincioğlu et al., 2024).

To be able to understand the fault behavior, main and aftershocks (Okuwaki et al., 2023; Petersen et al., 2023; Karabulut et al., 2023; Güvercin 2024), also combination of aftershocks with GNSS data (Melgar et al., 2023) are studied with rupture analysis. GNSS data is also used to calculate the coseismic and early postseismic deformation analysis of the earthqukes (Özarpacı et al., 2023; Özkan et al., 2023). According to the GNSS analysis, the largest displacement is in the EKZ1, which is the nearest station to the epicenter of Mw7.6 Elbistan earthquake. The total coseismic displacement calculated at EKZ1 GNSS station for the two earthquakes are 467.1 cm and 49.7 cm in the west and north direction, respectively.

Since the late 20th century, GNSS has found extensive use not only in geodetic applications but also in estimating atmospheric parameters. As a GNSS signal traverses through the atmosphere, it encounters errors within atmospheric layers known as the ionosphere and the troposphere. Employing two distinct phase or code measurements enables the removal of the primary component of ionospheric error, termed first order. Nevertheless, the secondary and tertiary orders of ionospheric error are typically disregarded in research studies (Yuan et al., 2014, Gurbuz et.al., 2017). Within the troposphere, GNSS signals encounter a phenomenon known as tropospheric delay, which cannot be eliminated but can be modeled. This delay comprises two components: dry and wet delays. The dry component correlates with atmospheric gas concentrations, whereas the wet delay is influenced by atmospheric conditions such as temperature, pressure, and humidity (Xia et al., 2023, Gratton et al., 2021).

$$STD = SHD + SWD \tag{1}$$

where STD is the slant total delay, SHD is the slant hydrostatic delay and SWD is the slant wet delay (Solheim et al., 1999, Hajj et al., 2002). The STD can be expressed by projecting ZTD in the zenith direction of a station along the signal direction.

$$STD = f(ele, azi) * ZTD \qquad (2)$$

where f refers to the mapping function while ele and azi represent the elevation angle and azimuth angle respectively. NMF, GMF and VMF1 mapping functions can be used to obtain the accurate STD when neglecting the influence of satellite ray-bending (Hopfield, 1969, Marini, 1975, Herring, 1992). ZTD is the average delay value of the signals derived from the same receiver and can be expressed by:

$$ZTD = ZHD + ZWD \qquad (3)$$

where ZHD is the zenith hydrostatic delay, about 90% of ZTD, mainly affected by the latitude of the station and the surface pressure. ZWD is the zenith wet delay, about 2% to 20% of ZTD, which affects the propagation of satellite signals by the movements of the poles of water vapor molecules and is largely related to the water vapor concentration (Saastamoinen, 1972).

The tropospheric parameters can be estimated by processing the GNSS observation by un-differenced or double-differenced methods. For processing the GNSS observations, GNSS processing software such as GAMIT/GLOBK, Bernese, GIPSY can be used, as well as online PPP services and software like CSRS-PPP.

In (Akgul et al., 2020), tropospheric delay and gradients in Türkiye are investigated. GNSS observations from CORS-TR stations were processed using GAMIT/GLOBK software, and the ZTD values for the stations were obtained with an RMS of <1mm. (Selbesoglu, 2019) processed the GNSS observations from 40 stations in the EPOSA GNSS network and calculated the ZTD values using the PPP module of Bernese 5.0 software with an average 5.2 mm RMSE. In a study conducted by (Astudillo et al. 2018), a comparison of online PPP services and PPP processing software for zenith tropospheric delay calculation was conducted. The study found that the RMSE values for zenith tropospheric delays obtained from APPS, CSRS-PPP, and MagicGNSS services were below 1cm. In (Zhao et al., 2023), CSRS-PPP online PPP service was used for real-time estimation of tropospheric parameters, and results were obtained with a standard deviation of 3mm. (Lu et al., 2018) tested the multi-GNSS PPP-AR method for obtaining real-time zenith tropospheric delay values and suggested that the method could be used in meteorological studies where the timing of tropospheric parameter estimation is crucial.

In recent years, there has been an increase in studies focusing on determining tropospheric parameters using online GNSS PPP services and other processing software, with some of these studies specifically concentrating on establishing the relationship between earthquakes occurring in different regions of the world and the troposphere.

In the study conducted by (Gurbuz and Kocyigit in 2020), changes occurring in the troposphere during earthquakes of magnitudes Mw8.8 and Mw8.3 in Chile in 2010 and 2015, respectively, were investigated using zenith tropospheric delay values calculated from GNSS observations. The results indicate significant tropospheric anomalies at GNSS stations closest to the epicenter of the earthquakes, both during and after the main shock. Similarly, (Akılan et al., 2021) investigated zenith tropospheric delays during the 2015 Nepal earthquake (Mw 7.8). The study revealed a sharp decrease in ZTD values during and after the main shock. (Yao et al., 2014) examined anomalies in zenith tropospheric delay following the Mw 7.8 Haida Gwaii earthquake, detecting anomalies in ZTD changes on the 302nd GPS day after the earthquake occurred.

This study examines the correlation between the earthquakes centered in Kahramanmaraş on February 6, 2023, with magnitudes of Mw7.8 and Mw7.6, and the troposphere. To investigate this relation, zenith tropospheric delay (ZTD) values were calculated using GNSS observations from a total of 10 TUSAGA-Aktif (Turkish National Permanent GNSS Network- Active) stations, spanning both affected and unaffected regions. The GNSS observations was processed using the CSRS-PPP online service, followed by an analysis of the earthquake's impact on ZTD values.

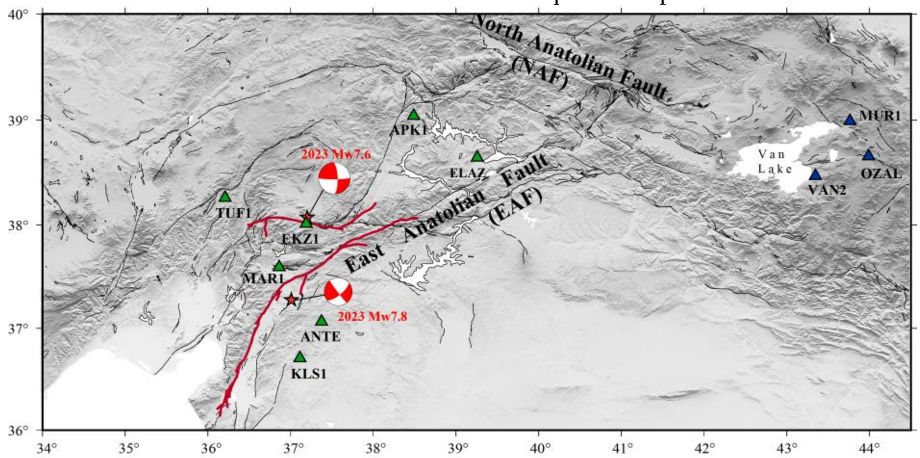

Fig. 1. GNSS stations used in the study. Green triangles show the close GNSS stations to the surface rupture, blue triangles illustrate the far GNSS stations to the earthquake epicenters. Red stars and the focal mechanisms show the Mw7.8 and the Mw7.6 earthquake sequence epicenters. Black lines are the active faults of Türkiye (Emre et al., 2013). Red lines are the surface rupture of these earthquakes (Reitman et al., 2023).

Materials and Methods

In order to examine the relation between the troposphere and the earthquakes that occurred in Kahramanmaraş on February 6, 2023, GNSS data from a total of 10 stations, consisting of 7 TUSAGA-Aktif stations located in the earthquake surface rupture zone and 3 unaffected TUSAGA-Aktif stations located at a distance from the earthquake epicenter, were obtained for a period of 7 days, including 3 days before and after the earthquake day, as well as the earthquake day itself (from 34th to 40th GPS days). These data were collected and evaluated using the CSRS-PPP online service to calculate the Zenith Total Delay (ZTD) values.

In the analysis, data from the stations ANTE, APK1, EKZ1, ELAZ, KLS1, MAR1, and TUF1 located near the earthquake zone, as well as from the stations MUR1, OZAL, and VAN2 situated at a distance, were utilized (Figure 1). CSRS-PPP stands as an online tool designed for post-processing GNSS data, enabling users to derive more accurate positions from their raw observation data. Leveraging precise GNSS satellite orbit ephemerides, CSRS-PPP calculates the corrected coordinates for a user's location, irrespective of their proximity to available base stations. This versatile software can handle RINEX observation data from both single and dual-frequency receivers, whether in static or kinematic mode. The latest version of CSRS-PPP integrates PPP with ambiguity resolution (PPP-AR) for data collected on or after January 1, 2018. Following processing, the software delivers the output to users in a compressed folder format. Notably, it generates a tropospheric zenith delay file (with a .tro extension), which includes hydrostatic and wet zenith path delays along with tropospheric gradients for each processed epoch. In this study, data for a total of 7 days, from the 34th GPS day to the 40th GPS day, were obtained for the ANTE, APK1, EKZ1, ELAZ, KLS1, MAR1, and TUF1 TUSAGA-Aktif stations, which are located close to the epicenter of the earthquakes and depicted in Figure 1. However, data for the 37th day, corresponding to the day of the earthquake, could not be retrieved for the MAR1 station. Because it was determined that the MAR1 station in Kahramanmaraş was inoperable after the first earthquake. Initially, data from the seven stations for the seven days were analysed using the CSRS-PPP service, and based on the hydrostatic and wet zenith path delay values obtained from the .tro extension file, the ZTD values were calculated. In the second stage, data from stations MUR1, OZAL, and VAN2, located farther away from the epicenters and in areas unaffected by the earthquake, were similarly processed using the CSRS-PPP service to calculate ZTD values. This enabled the direct correlation between the earthquake and tropospheric changes to be examined, and aimed to determine the dimensions of these tropospheric changes at points close to the epicenter of the earthquake.

Results

The GNSS data from the stations ANTE, APK1, EKZ1, ELAZ, KLS1, MAR1, and TUF1, located in the region affected by the Kahramanmaraş earthquakes on February 6, 2023, were processed using the CSRS-PPP service, resulting in the calculation of ZTD values for a total of 7 days. Upon examination of the ZTD variations (ZTD value - daily average) for the 37th day, corresponding to the day of the earthquake, anomalies were identified in the ZTD values for all stations. However, when examining the ZTD variation graphs for other days for all stations, no anomalies or fluctuations were observed. Figures 2 to 8 depict the daily ZTD variation graphs for the stations ANTE, APK1, EKZ1, ELAZ, KLS1, MAR1, and TUF1, respectively.

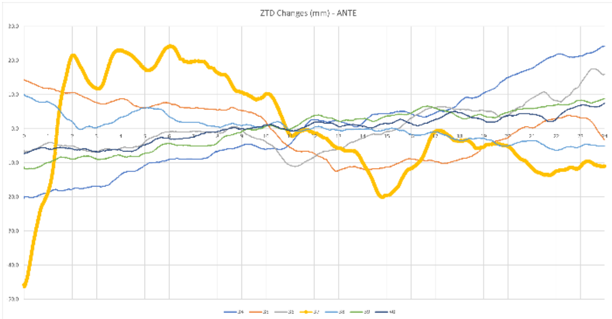

Fig. 2. Daily ZTD variations for the ANTE station

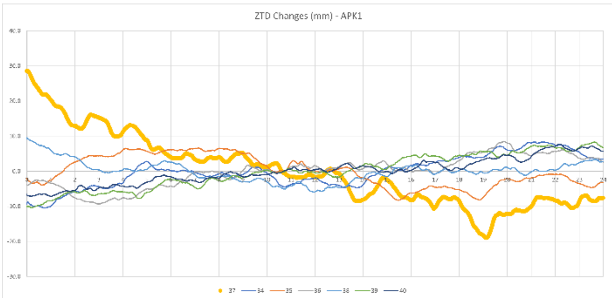

Fig. 3. Daily ZTD variations for the APK1 station

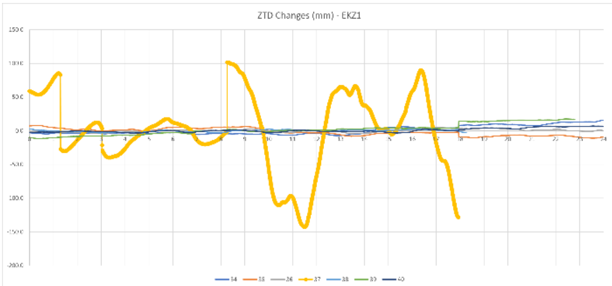

Fig. 4. Daily ZTD variations for the EKZ1 station

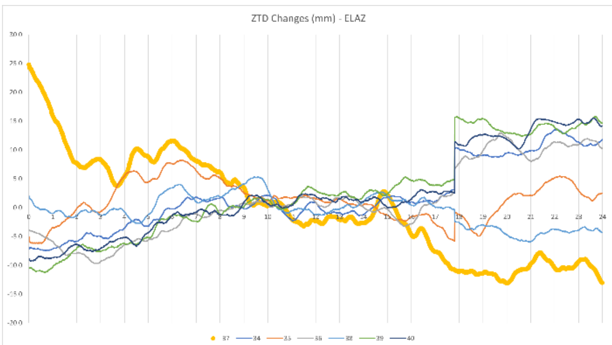

Fig. 5. Daily ZTD variations for the ELAZ station

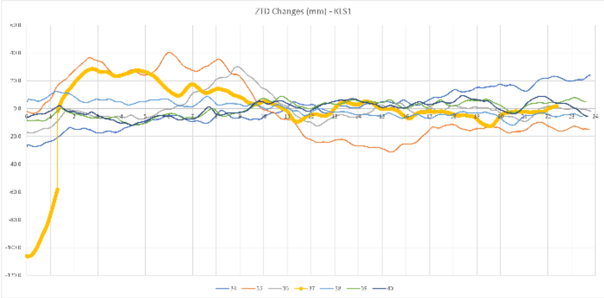

Fig. 6. Daily ZTD variations for the KLS1 station

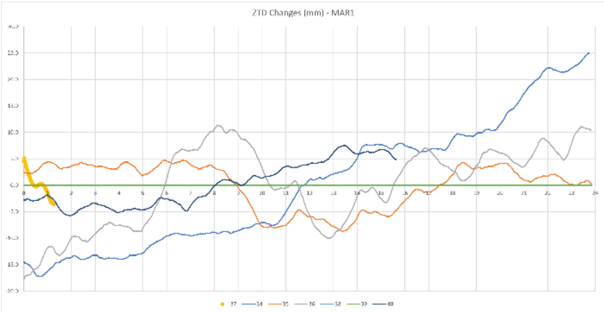

Fig. 7. Daily ZTD variations for the MAR1 station

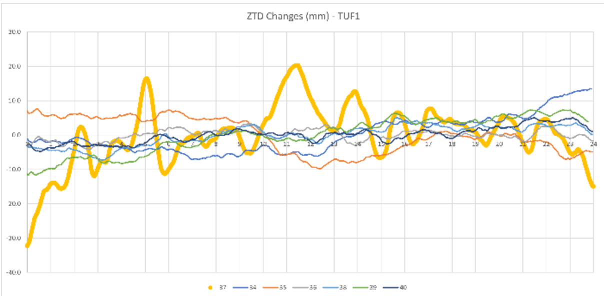

Fig. 8. Daily ZTD variations for the TUF1 station

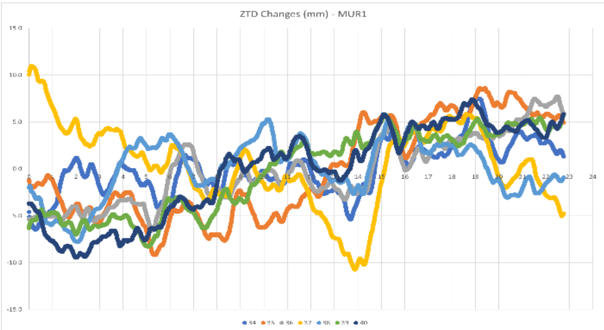

Fig. 9. Daily ZTD variations for the MUR1 station

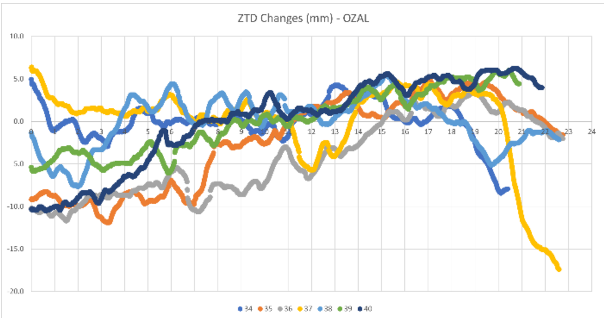

Fig. 10. Daily ZTD variations for the OZAL station

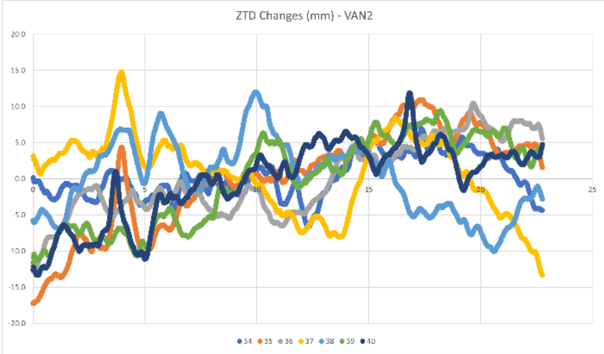

Fig. 11. Daily ZTD variations for the VAN2 station

The data for the 37th day of February 6, 2023, for the MAR1 station located in Kahramanmaraş, as provided in Figure 7, could not be accessed due to the station being out of operation following the Mw7.8 Pazarcık earthquake. Upon examining the data from other stations except for MAR1, anomalies and differences in ZTD variations for the 37th day compared to other days were observed for all stations. To determine whether the tropospheric changes were related to the earthquake, data from the stations MUR1, OZAL, and VAN2 located in unaffected regions were also evaluated using the CSRS-PPP service to calculate ZTD variations. Figures 9 to 11 depict the ZTD variation graphs for the stations MUR1, OZAL, and VAN2, respectively.

When examining the daily ZTD variation graphs for the region unaffected by the earthquake, it was observed that the ZTD variations for the 37th day, the day of the earthquake, were similar to the other days and ZTD changes for these stations and all days are approximately 20mm. On the other hand, when graphs for other stations are examined, changes range from 40mm to 250mm. This indicates that no significant changes were observed for the stations MUR1, OZAL, and VAN2.

Discussion and Conclusion

The study investigated the tropospheric changes following the earthquakes in Kahramanmaraş on February 6, 2023, utilizing ZTD values derived from GNSS data. It encompassed a seven-day data analysis, spanning both pre- and post-earthquake periods. Examination of three days of data before and three days after the earthquake unveiled consistent ZTD variations throughout each day, with notable anomalies evident on the day of the earthquake.

Especially at stations close to the earthquake epicenter, significant tropospheric anomalies, reaching up to 25 cm, were observed, particularly at the EKZ1 station, on the day of the earthquake. EKZ1 is the GNSS station where the maximum coseismic displacement is observed as a result of the two earthquakes. However, as the distance from the epicenter increased, ZTD variations on the earthquake day and other days exhibited similar characteristics and magnitudes, indicating that the earthquake's impact was not observed in the troposphere as it moved away from the epicenter. This result is also a clear evidence of a positive correlation between tropospheric changes and earthquakes.

The findings of this study are similar to those of Gurbuz and Kocyigit (2020), Akılan et al. (2021), and Yao et al. (2014), indicating that ZTD anomalies occurring during and after earthquakes are directly related to the proximity of the GNSS stations used in the evaluation to the earthquake epicenter. Unlike the ionosphere, tropospheric anomalies were observed to affect a smaller area.

Gurbuz and Kocyigit (2020), Yao et al. (2014), and Akılan et al. (2021) investigated changes in the troposphere during the earthquakes in Chile, Haida Gwaii, and Nepal respectively. In order to establish a relationship between these changes in the troposphere and atmospheric parameters, data from meteorological stations near the earthquake epicenters were also examined, and significant changes, especially in pressure values in the troposphere during the earthquakes, were identified. It is observed that these pressure changes in the troposphere cause anomalies in ZTD values. In this study, it is also considered that the anomalies in ZTD that occur particularly on the day of the earthquake can be correlated with changes in pressure in the troposphere.

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