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Seasonal Variations of GNSS Zenith Tropospheric Delay at the VARA Station in the Rivne NPP Region

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SUMMARY

ZZenith tropospheric delay is one of the main atmospheric effects influencing high-precision GNSS positioning and the interpretation of geodetic time series. This study investigates seasonal variations of GNSS zenith tropospheric delay at the VARA station located in the Rivne Nuclear Power Plant region. The research is based on time series of zenith total delay, zenith hydrostatic delay, and zenith wet delay obtained from GNSS observations of the GeoTerrace network for the 2019–2025 period. The GNSS observations were processed using PRIDE PPP-AR software. To support meteorological interpretation, ERA5 reanalysis data were used, including air temperature and surface pressure obtained from the Copernicus Climate Data Store. ERA5 gridded hourly values were spatially interpolated to the VARA station values. The analysis included comparison of daily time series, monthly mean seasonal variations, and relationships between GNSS delay components and ERA5 meteorological parameters. The results show that the zenith total delay has a pronounced seasonal pattern, with increased values during the warm period of the year. The wet component demonstrates the strongest seasonal variability and generally follows the annual behaviour of ERA5 2 m air temperature. The hydrostatic component is more stable and shows an almost linear relationship with ERA5 surface pressure. The obtained results confirm the importance of accounting for seasonal tropospheric effects in GNSS data processing and geodetic monitoring near critical infrastructure.

Keywords: GNSS; Zenith tropospheric delay; ZHD; ZWD; ERA5; Seasonal variations; VARA station; Rivne NPP.

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Introduction

Zenith tropospheric delay (ZTD) is one of the main atmospheric effects influencing the accuracy of Global Navigation Satellite System (GNSS) observations. Since GNSS signals propagate through the neutral atmosphere, they are delayed depending on the physical state of the troposphere, primarily atmospheric pressure, temperature, and water vapor content. This effect is especially important in high-precision geodetic applications, where unmodelled or incorrectly estimated tropospheric delay may affect station coordinate estimates.

ZTD is usually represented as the sum of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The hydrostatic component constitutes the major part of the absolute delay and is primarily related to atmospheric pressure, whereas the wet component is associated with atmospheric water vapor and exhibits stronger temporal variability. Previous studies have shown that seasonal changes in hydrostatic and wet components of ZTD can be effectively analysed using GNSS and meteorological data (Kladochnyi, Zablotskyi, & Serant, 2022; Tekin Ünlütürk & Doğan, 2024).

The GeoTerrace GNSS network provides an important basis for geodynamic and atmospheric studies in Ukraine. The reliability of GeoTerrace stations for further monitoring applications has been previously investigated using specialized time-series analysis software (Doskich & Serant, 2024). In this study, the analysis is focused on one permanent GNSS station, VARA, located in the Rivne Nuclear Power Plant region. The aim of the study is to investigate seasonal variations of GNSS ZTD, ZHD, and ZWD at the VARA station during 2019–2025 and to compare these variations with selected ERA5 meteorological parameters.

Method and Theory

The study was carried out for one permanent GNSS station, VARA, located in the Rivne Nuclear Power Plant region in north-western Ukraine. The station was selected because it provides a continuous time series of tropospheric delay parameters for the analysed period and is located in an area where geodetic monitoring is important for critical infrastructure applications.

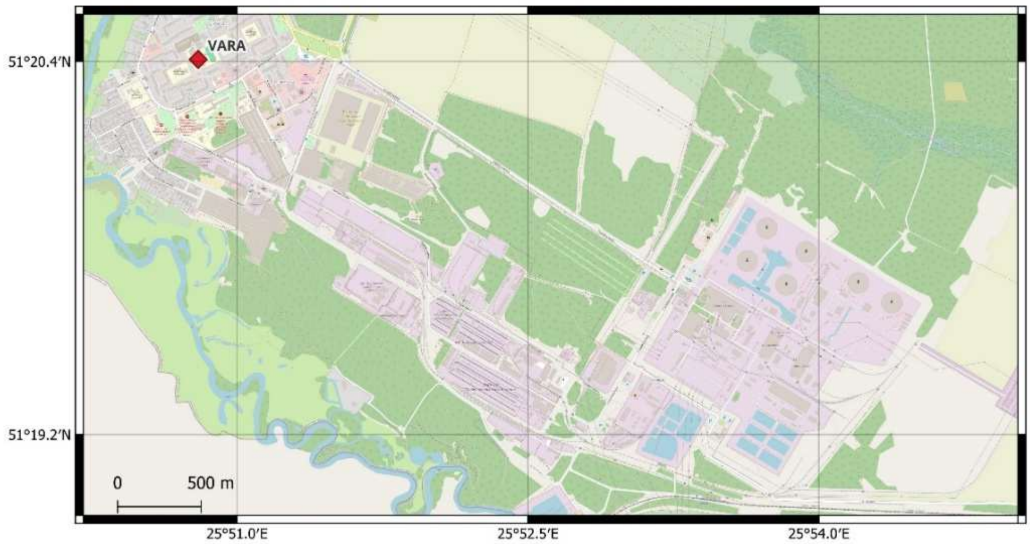

Figure 1. *Location of the VARA GNSS station in the Rivne NPP region*

The GNSS data used in this study were obtained from observations at the permanent VARA station, which is part of the GeoTerrace GNSS network of Lviv Polytechnic National University. The input GNSS observations were processed using PRIDE PPP-AR software. As a result, time series of zenith total delay (ZTD), zenith hydrostatic delay (ZHD), and zenith wet delay (ZWD) were obtained for the 2019–2025 period. All tropospheric delay values were expressed in millimetres for further analysis.

To support the meteorological interpretation of GNSS tropospheric delay variations, ERA5 reanalysis data were used. ERA5 is the fifth-generation atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). The ERA5 data used in this study were obtained from the Copernicus Climate Data Store and included hourly gridded meteorological parameters for the 2019–2025 period.

Two ERA5 parameters were used: 2 m air temperature and surface pressure. The 2 m air temperature was used to interpret seasonal changes in ZTD and ZWD, as it reflects the annual thermal regime and is indirectly related to atmospheric moisture conditions. Surface pressure was used to analyse ZHD because the hydrostatic component of tropospheric delay is physically controlled by the mass of the dry atmosphere above the station. ERA5 temperature values were converted from Kelvin to degrees Celsius, and surface pressure values were converted from pascals to hectopascals.

Since ERA5 data are provided on a regular spatial grid, the meteorological parameters were spatially interpolated to the coordinates of the VARA station. After spatial interpolation, hourly ERA5 values were averaged into daily values. The GNSS ZTD, ZHD, and ZWD estimates were also averaged into daily values. Finally, the GNSS and ERA5 daily time series were merged by date.

The analysis was performed at two temporal levels. First, daily time series were compared to identify the general agreement between GNSS tropospheric delay components and ERA5 meteorological parameters. Second, monthly mean values were calculated to better reveal the seasonal cycle and reduce the influence of short-term atmospheric fluctuations. In addition, scatter plots were used to evaluate the relationships between ZWD and air temperature, and between ZHD and surface pressure.

Results

The combined GNSS and ERA5 daily time series covered the period from 2019 to 2024. Several gaps are present in the GNSS time series; therefore, the analysis was focused on common daily epochs for which both GNSS tropospheric delay parameters and ERA5 meteorological data were available. Despite these gaps, the obtained results clearly demonstrate the seasonal behaviour of zenith tropospheric delay components at the VARA station.

Daily variations of GNSS tropospheric delay components and ERA5 meteorological parameters are presented in Figure 2. The ZTD time series shows a clear annual pattern, with higher values during the warm period and lower values during the cold period. This behaviour indicates that the total zenith tropospheric delay is strongly influenced by seasonal atmospheric conditions. The comparison between ZWD and ERA5 2 m air temperature shows that the wet component has the strongest seasonal variability. ZWD increases during warmer months and decreases during colder months, which is physically consistent with the seasonal increase of atmospheric water vapour. In contrast, ZHD is more stable and follows pressure-related variability rather than temperature-related seasonal changes.

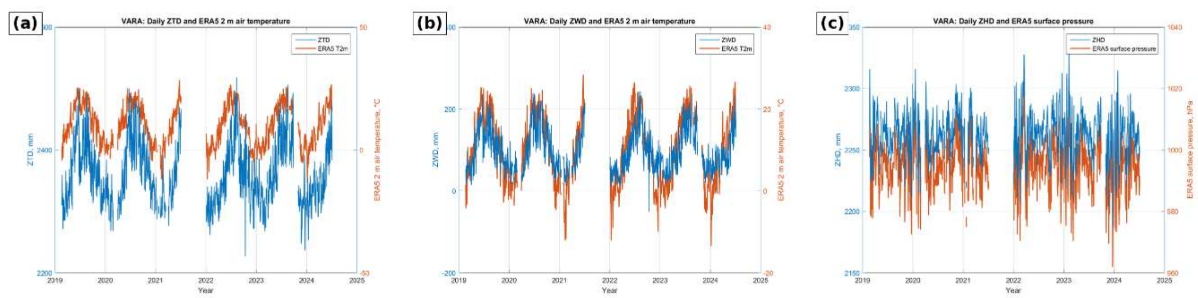

Figure 2. *Daily variations of GNSS tropospheric delay components and ERA5 meteorological parameters at the VARA station during 2019–2025: (a) ZTD and ERA5 2 m air temperature; (b) ZWD and ERA5 2 m air temperature; (c) ZHD and ERA5 surface pressure*

To better reveal the annual seasonal cycle, monthly mean values were calculated for the 2019–2025 period. Figure 3a shows the monthly mean seasonal variations of standardized ZTD, ZWD, and ERA5 2 m air temperature. The curves demonstrate a consistent annual pattern: the lowest values are observed in winter and early spring, followed by an increase in spring and maximum values during the summer months. This confirms that the seasonal behaviour of ZTD at the VARA station is mainly controlled by the wet component.

Figure 3b presents the monthly mean seasonal variations of ZHD and ERA5 surface pressure. The close agreement between these two parameters confirms that the hydrostatic component is mainly controlled by atmospheric pressure. Unlike ZWD, the hydrostatic component does not exhibit a strong temperature-related seasonal cycle; instead, it reflects pressure-related atmospheric variability.

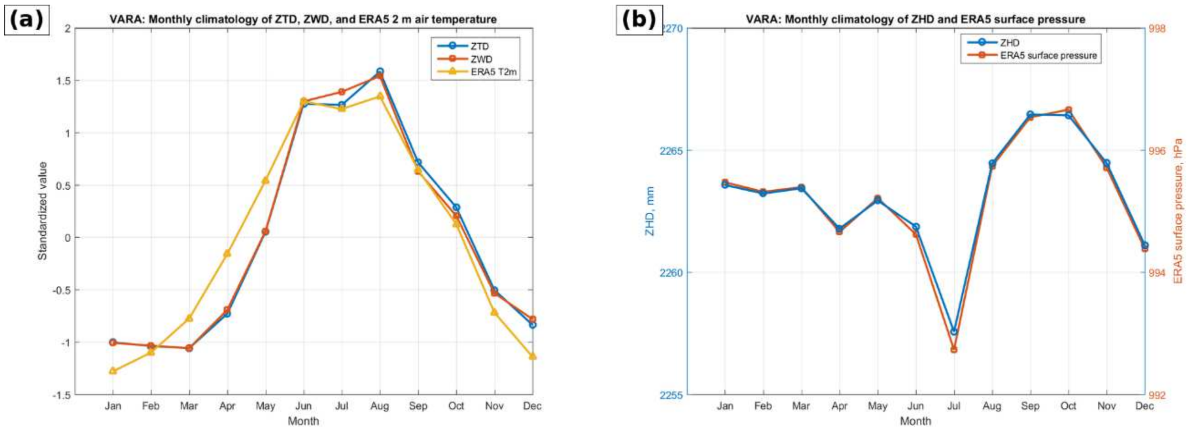

Figure 3. *Monthly mean seasonal variations of GNSS tropospheric delay components and ERA5 meteorological parameters at the VARA station:*
(a) standardized ZTD, ZWD, and ERA5 2 m air temperature; (b) ZHD and ERA5 surface pressure

The relationships between GNSS delay components and ERA5 meteorological parameters were additionally analysed using scatter plots (Figure 4). The relationship between ZWD and ERA5 2 m air temperature is positive, but relatively dispersed. This indicates that air temperature explains the general seasonal behaviour of the wet component, although it is not the only factor controlling ZWD. The wet component is directly related to atmospheric water vapor, and therefore, additional meteorological parameters would be useful for a more complete interpretation. In contrast, the relationship between ZHD and ERA5 surface pressure is much stronger and almost linear. This is expected because the hydrostatic delay is physically related to the dry atmospheric mass above the station and, consequently, to surface pressure.

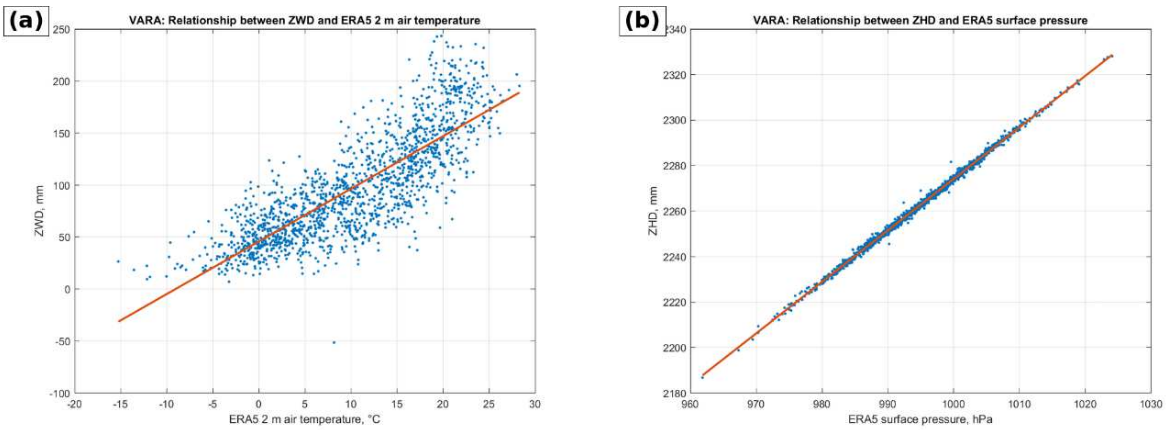

Figure 4. *Relationships between GNSS tropospheric delay components and ERA5 meteorological parameters at the VARA station:*
(a) ZWD and ERA5 2 m air temperature; (b) ZHD and ERA5 surface pressure

Overall, the results confirm that seasonal variations in ZTD at the VARA station are primarily driven by ZWD, whereas ZHD reflects pressure-related atmospheric variability. ERA5 2 m air temperature provides a useful meteorological explanation for the seasonal behaviour of the wet component, whereas ERA5 surface pressure explains the variability of the hydrostatic component. Thus, the combination of GNSS-derived tropospheric delay estimates and ERA5 reanalysis data provide a consistent basis for interpreting atmospheric effects in GNSS monitoring near critical infrastructure.

Conclusions

The study confirmed clear seasonal variations of GNSS zenith tropospheric delay at the VARA station during 2019–2025. ZTD increases during the warm season and decreases during the cold season, which indicates the influence of seasonal atmospheric conditions on GNSS observations. The seasonal behaviour of ZTD is mainly controlled by the wet component. ZWD shows the strongest temporal variability and generally follows the annual pattern of ERA5 2 m air temperature. This confirms that warmer periods are associated with increased wet tropospheric delay. The hydrostatic component behaves differently. ZHD is more stable than ZWD and mainly reflects pressure-related atmospheric variability. Its close relationship with ERA5 surface pressure confirms the physical consistency of the hydrostatic delay estimates obtained from GNSS processing. ERA5 reanalysis data provided useful meteorological support for interpreting GNSS tropospheric delay variations. ERA5 2 m air temperature helped to explain the seasonal behaviour of ZTD and ZWD, while ERA5 surface pressure explained the variability of ZHD. The obtained results demonstrate the importance of considering seasonal tropospheric effects in GNSS data processing and monitoring near critical infrastructure. Further research should include additional meteorological parameters, especially total column water vapor, for a more complete interpretation of the wet component.

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