

# Determination of Zenith Tropospheric Delay (ZTD) Using CORS GNSS Data, 2016 -2020 in Lampung

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## ABSTRACT (10 PT)

GNSS satellites transmit signals in the form of electromagnetic waves to ground-based observation stations (receivers). As these signals pass through the atmosphere - particularly the troposphere - they undergo delays and bending due to differences in atmospheric properties. This results in deviations in signal path length, known as *Zenith Tropospheric Delay* (ZTD). In positioning applications, ZTD is considered an error that must be minimized. However, in meteorological studies, ZTD serves as valuable information representing atmospheric water vapor content. This study aims to estimate ZTD values using GNSS observation data from CORS stations in the Lampung region. Data was processed using the *Precise Point Positioning* (PPP) method via an online platform. The results show that the highest ZTD value in 2016 was recorded at the CSBK station on DOY 182 with 2682.8 mm. In 2017, the highest value occurred at the CTCN station on DOY 274 with 2650.2 mm. From 2018 to 2020, the highest ZTD values were recorded at the CKRI station, with 2655.8 mm (DOY 001.18), 2676.4 mm (DOY 001.19), and 2691.0 mm (DOY 091.20), respectively. These findings indicate that ZTD data derived from GNSS observations hold significant potential for supporting local atmospheric studies.

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## I. Introduction

The utilization of technology in the fields of geodesy and geomatics continues to evolve in line with advancements in information and communication technology. One of the most widely applied technologies across various scientific disciplines is the *Global Navigation Satellite System* (GNSS). GNSS is a global satellite navigation system that provides continuous position and time information across the Earth's surface [1][2][3]. Initially, GNSS was extensively applied in geodesy and navigation for precise positioning purposes [3][4]. However, in its development, GNSS data have also been employed in meteorology [5], particularly for monitoring atmospheric dynamics [5][6].

GNSS signals are transmitted by satellites in the form of electromagnetic waves toward receiving stations (receivers) located on the Earth's surface [1][4]. As these signals pass through the atmosphere especially the tropospheric layer, they experience disturbances in the form of delays and bending due to variations in the refractive index of the atmospheric layers they traverse [6][7]. The primary contributors to these disturbances are water vapor and other atmospheric gases (wet and dry components) in the troposphere, which cause changes in the travel time of the signals from satellite to receiver [8].

This propagation delay is referred to as *Tropospheric Delay*, while the delay component measured along the signal's path is known as *Slant Tropospheric Delay* (STD) [6][8]. The STD is then converted using a mapping function into *Zenith Tropospheric Delay* (ZTD), which refers to the signal delay measured vertically from the zenith to the Earth's surface. ZTD is an important parameter for correcting GNSS data in high-precision positioning applications [9]. However, in meteorological



contexts, ZTD is considered an indicator reflecting atmospheric conditions, particularly the distribution of water vapor in the troposphere [6][5][10].

The main challenge addressed in this study is the limitation of conventional meteorological methods in capturing detailed variations of atmospheric water vapor, particularly in tropical regions with highly dynamic weather conditions. To overcome this, the estimation of Zenith Tropospheric Delay (ZTD) from CORS GNSS observations is proposed as a precise and continuous approach, capable of representing atmospheric changes both spatially and temporally. Therefore, this research focuses on estimating ZTD values from several CORS stations in Lampung during the 2016–2020 period to support atmospheric analysis and the development of GNSS-based climatological applications.

This study aims to estimate ZTD values based on observational data from *Continuously Operating Reference Stations* (CORS) of GNSS located in the Lampung region. CORS stations were selected due to their capability to provide continuous GNSS data over 24 hours, enabling accurate daily time series analyses for ZTD estimation. The estimation was conducted for several CORS stations with four observation epochs per year over a five-year period. Observation intervals were determined at three-month intervals to represent differences in atmospheric conditions based on seasonal variation. The findings of this study are expected to contribute to the utilization of GNSS data for atmospheric studies and to support the development of geospatial-based meteorological applications.

## II. Theoretical Basis

### A. Global Navigation Satellite System (GNSS)

The *Global Navigation Satellite System* (GNSS) is a satellite-based system designed to provide three-dimensional positional information, velocity, and time in real time and on a continuous basis across the Earth's surface. The system operates independently of time and weather conditions, allowing simultaneous use by a large number of users [2][4]. GNSS functions by transmitting signals from satellites to users on Earth, carrying data such as satellite position, transmission time, and other parameters [4] required for position computation.

GNSS signals are transmitted from satellite antennas toward the Earth's surface in the form of electromagnetic waves [2]. Along their path, these signals pass through various atmospheric layers—primarily the ionosphere and the troposphere—which can cause disturbances such as refraction, scintillation, and atmospheric attenuation [2]. Additionally, GNSS signals may be affected by the multipath phenomenon, in which the received signal is a combination of the direct signal and reflected signals from surfaces or objects near the receiver [1]. The coverage of GNSS signals extends beyond the Earth's surface to include the airspace above it up to a certain altitude, enabling its application not only in navigation but also in atmospheric monitoring [2][8].

### B. Continuously Operating Reference Station (CORS)

The *Continuously Operating Reference Station* (CORS) is a network of permanent geodetic reference stations based on the Global Navigation Satellite System (GNSS) that operates continuously to record and transmit satellite observation data [4]. CORS provides datasets that can be utilized for both post-processed and real-time positioning applications [11]. In Indonesia, this system is known as *Ina-CORS* and is managed by the Geospatial Information Agency (*Badan Informasi Geospasial*, BIG). As of 2022, Ina-CORS consists of 397 active stations [12] distributed across the entire Indonesian territory. All data collected from these stations are transmitted to BIG's central servers for processing and subsequently made available to users to support geospatial applications and high-precision surveying.

### C. Zenith Tropospheric Delay (ZTD)

In the process of position determination using the Global Navigation Satellite System (GNSS), atmospheric disturbances such as signal delays in the ionospheric and tropospheric layers [2] can introduce significant systematic errors in measurement results [6]. Therefore, systematic and appropriate correction methods are required to minimize these impacts. To mitigate tropospheric effects, users may apply standard atmospheric models or directly estimate tropospheric errors as part of the positioning solution [2][13]. In practice, the total signal propagation delay caused by the

troposphere is referred to as the Zenith Total Delay (ZTD). ZTD represents the total GNSS signal delay in the vertical (zenith) direction and consists of two main components: Zenith Hydrostatic Delay (ZHD), a relatively stable component caused by dry atmospheric pressure, and Zenith Wet Delay (ZWD), a more variable component caused by water vapor content in the troposphere [6][14]. These two components were first classified in [15], and form the basis for various atmospheric estimation approaches using GNSS data, both for geodetic and meteorological applications [2][6].

The ZTD can be expressed as:

$$ZTD = ZWD + ZHD \tag{1}$$

The ZHD can be calculated using the formula:

$$ZHD = \frac{(0.002277 \times P)}{1 - 0.00266 \times \cos 2\varphi - 0.00028 \times H} \tag{2}$$

where:

$P$  = surface pressure (hPa), obtained from a meteorological sensor installed in the field;

$\varphi$  = latitude of the station

$H$  = geodetic height of the station

### III. Methodology

#### A. Data and Study Area

This study utilized Global Navigation Satellite System (GNSS) observation data obtained from the Continuously Operating Reference Stations (CORS) managed by the Geospatial Information Agency of Indonesia (Badan Informasi Geospasial/BIG) through the Ina-CORS network. The dataset was derived from Receiver Independent Exchange Format (RINEX) files collected from four CORS stations located in Lampung Province, namely: CKRI - Pesisir Barat; CTCN - Tanggamus; CLGI - Pesawaran; dan CSBK - Kepulauan Sibesi, Kalianda. The spatial distribution of the selected Ina-CORS stations is presented in Figure 1.

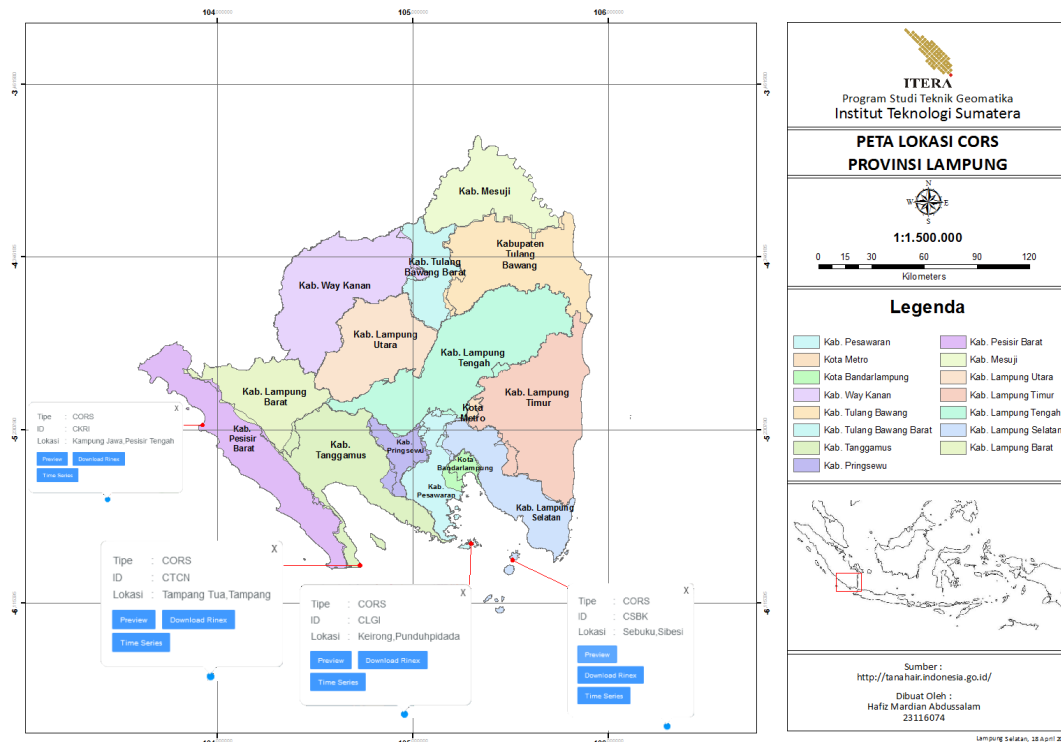


Fig. 1. Research Location

These stations were selected due to their continuous GNSS observation records since 2016. The analyzed dataset spans a five-year period, from 2016 to 2020. For each station, four observation epochs were selected annually, corresponding to specific Days of Year (DoY): DoY001 (January 1), DoY091 (April 1), DoY182 (July 1), and DoY274 (October 1). The DoYs were chosen at three-month intervals to represent atmospheric conditions across different seasonal variations. In total, the dataset comprises **80 observation days**, calculated as: 4 stations×4 DOY/year×5 years=80 days.

*B. Zenith Tropospheric Delay (ZTD) Estimation Method*

The estimation of Zenith Tropospheric Delay (ZTD) was performed through Global Navigation Satellite System (GNSS) data processing using the Precise Point Positioning (PPP) method. The processing was conducted via the Canadian Spatial Reference System – Precise Point Positioning (CSRS-PPP) online platform provided by Natural Resources Canada (NRC), accessible at <https://webapp.csrscs-nrcan-rncan.gc.ca> [16]. The PPP method was selected because it enables absolute parameter estimation without inter-station dependency [17][18]. Unlike the differential (relative) positioning method, which requires a pair of reference stations, PPP offers the advantage of observation independence, as each station is processed individually [19]. The ZTD estimates obtained from this approach are derived from high-precision satellite orbit and clock corrections [20][21], enabling the extraction of atmospheric parameters suitable for further analysis [19].

**IV. Results and Discussion**

This study produced **Zenith Tropospheric Delay (ZTD)** estimates from the processing of GNSS observation data in RINEX format obtained from four CORS stations — CKRI, CTCN, CLGI, and CSBK — covering the period from 2016 to 2020. The data processing was carried out using the Canadian Spatial Reference System – Precise Point Positioning (CSRS-PPP) online platform, which not only generates precise station coordinate information but also provides ZTD estimates as part of its output.

The ZTD estimates were generated for each observation epoch (one-second intervals) and accompanied by standard deviation (STDDEV) values, representing uncertainty at a 95% confidence level ( $\sigma = 2$ ). Subsequently, all one-second ZTD values for each day were averaged to obtain a daily mean ZTD for each Day of Year (DoY), resulting in a single representative ZTD value per observation day. The daily average ZTD values served as the basis for analyzing spatial and temporal variations at each observation station. Differences between DOY values as well as among stations were examined to assess potential seasonal influences on tropospheric water vapor fluctuations. The complete processed dataset is presented in Table 1, which lists the daily ZTD estimates for each DOY across all observation stations over the five-year study period.

Table 1. Estimated ZTD values from four GNSS CORS observation stations for the 2016–2020 observation period

DoY	Year	CORS GNSS			
		CKRI	CLGI	CSBK	CTCN
001	2016	-	2586,8	2663,0	2667,0
	2017	2614,6	2546,3	2616,7	2625,7
	2018	2655,8	2545,6	2619,7	2634,2
	2019	2676,4	2593,8	2665,3	2674,8
	2020	2684,4	2591,6	2667,2	2673,4
091	2016	-	2610,3	2679,9	2680,8
	2017	2660,1	2564,5	2642,4	2644,6
	2018	2654,9	2564,7	2637,0	2636,6
	2019	2620,7	2551,7	2631,5	2604,0
	2020	2691,0	2591,7	2661,1	2678,6
182	2016	-	2592,7	2682,8	2668,2
	2017	2645,2	2563,1	2633,2	2637,0
	2018	2608,7	2510,2	2585,2	2582,4

DoY	Year	CORS GNSS			
		CKRI	CLGI	CSBK	CTCN
	2019	2627,4	2525,0	2590,3	2592,0
	2020	2546,4	2477,8	2549,8	2570,2
	2016	-	2578,4	2667,8	2652,6
	2017	2641,8	2560,1	2631,5	2650,2
<b>274</b>	2018	2603,3	2486,9	2559,1	2562,3
	2019	2561,8	2468,3	2545,9	2534,7
	2020	2619,9	2526,5	2590,3	2613,2

Table 1 presents the estimated Zenith Tropospheric Delay (ZTD) values obtained from four GNSS CORS observation stations — CKRI, CLGI, CSBK, and CTCN — for the observation period 2016–2020. The results show significant variations in ZTD values both between stations (spatial variability) and across observation days (DoY, temporal variability). These variations reflect atmospheric dynamics in the study area, particularly the influence of water vapor content, which is the primary factor in ZTD formation.

At CKRI, the highest ZTD value was recorded on DoY 091 in 2020 (early April) at 2691.0 mm, while the lowest occurred on DoY 182 in 2020 (early July) at 2546.4 mm. This fluctuation indicates differences in atmospheric conditions between seasons, where early April (rainy season) tends to have higher humidity compared to early July (dry season onset).

For CLGI, the maximum ZTD value was 2610.3 mm on DoY 091 in 2016 (early April), while the minimum was 2468.3 mm on DoY 274 in 2019 (early October). The low ZTD in early October suggests reduced atmospheric water vapor, typically occurring before the onset of an extended dry season in the region.

At CSBK, the highest ZTD was recorded on DOY 182 in 2016 (early July) at 2682.8 mm, whereas the lowest was 2545.9 mm on DoY 274 in 2019 (early October). This trend reinforces the influence of seasonal and weather variability on ZTD values, particularly in coastal and island areas.

For CTCN, the maximum ZTD reached 2680.8 mm on DoY 091 in 2016, while the minimum was 2534.7 mm on DoY 274 in 2019. The recurring pattern of minimum values in early October during low-rainfall years is evident. Notably, three of the four stations — CLGI, CSBK, and CTCN — recorded their lowest ZTD values on the same date, DOY 274 in 2019. This indicates the possibility of a regional atmospheric anomaly or a simultaneous drop in humidity across Lampung during that period.

Overall, the observed temporal variations in ZTD across different DOYs highlight seasonal influences on tropospheric conditions, while the spatial differences between stations reveal local atmospheric variability. These findings provide a basis for further analysis of atmospheric behavior in the Lampung region. To illustrate the daily variation patterns, Figure 2 presents time series plots of ZTD values for the CLGI and CSBK stations.

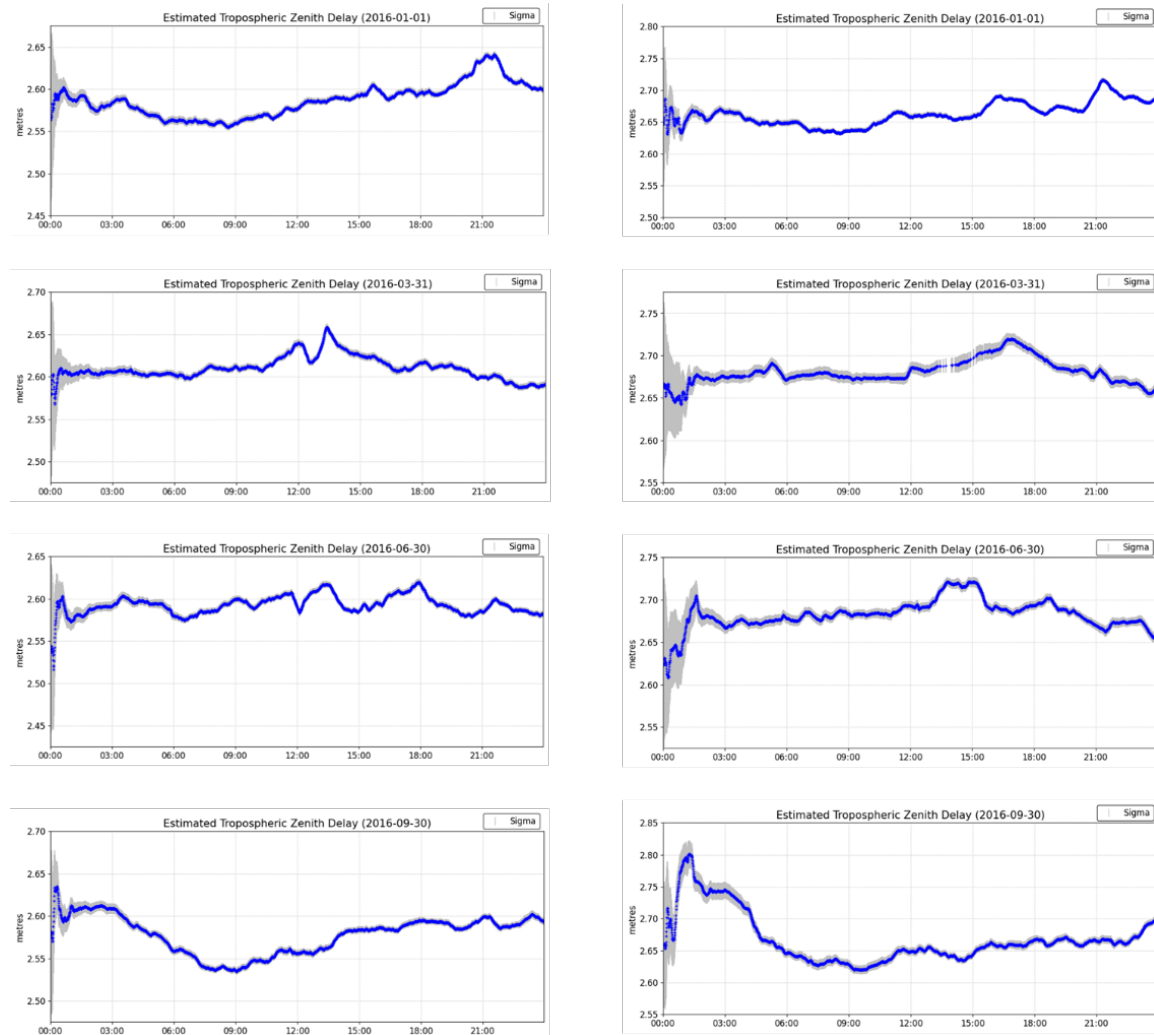


Fig. 2. ZTD graph for 2016 at CLGI station (left side) and CSBK station (right side)

**Figure 2** presents the ZTD observation graphs from the CLGI station (left) and the CSBK station (right), both based on observational data from 2016. The figure shows that, for the same DOY, both stations display a somewhat similar time-series pattern. This similarity can be attributed to the geographical proximity of the two stations, which likely results in comparable atmospheric conditions and weather patterns at both sites. Temporally, within the span of a single day, variations in ZTD values indicate that atmospheric conditions fluctuate over short periods, as well as across the year. The annual ZTD time-series visualization for each station provides a clearer depiction of seasonal influences on the pattern of ZTD fluctuations over time.

The time-series variations of ZTD across different DOYs reveal the highest and lowest ZTD values, reflecting atmospheric conditions during the propagation of satellite signals to the receiver. These variations are primarily driven by changes in atmospheric water vapor content at each CORS observation station [7]. Such changes are the result of the inherently dynamic nature of the atmosphere, which can alter rapidly due to weather phenomena, including temperature fluctuations, humidity variations, sunlight penetration through the atmosphere, and changes in wind speed and direction [22].

Overall, fluctuations in ZTD values are strongly correlated with seasonal cycles and local weather dynamics around each observation site. As widely recognized, atmospheric water vapor content is the dominant factor influencing the increase in ZTD values [6][23]. During the rainy season, elevated water vapor levels tend to increase ZTD values, while during the dry season, ZTD values typically decrease in line with reduced atmospheric humidity [24].

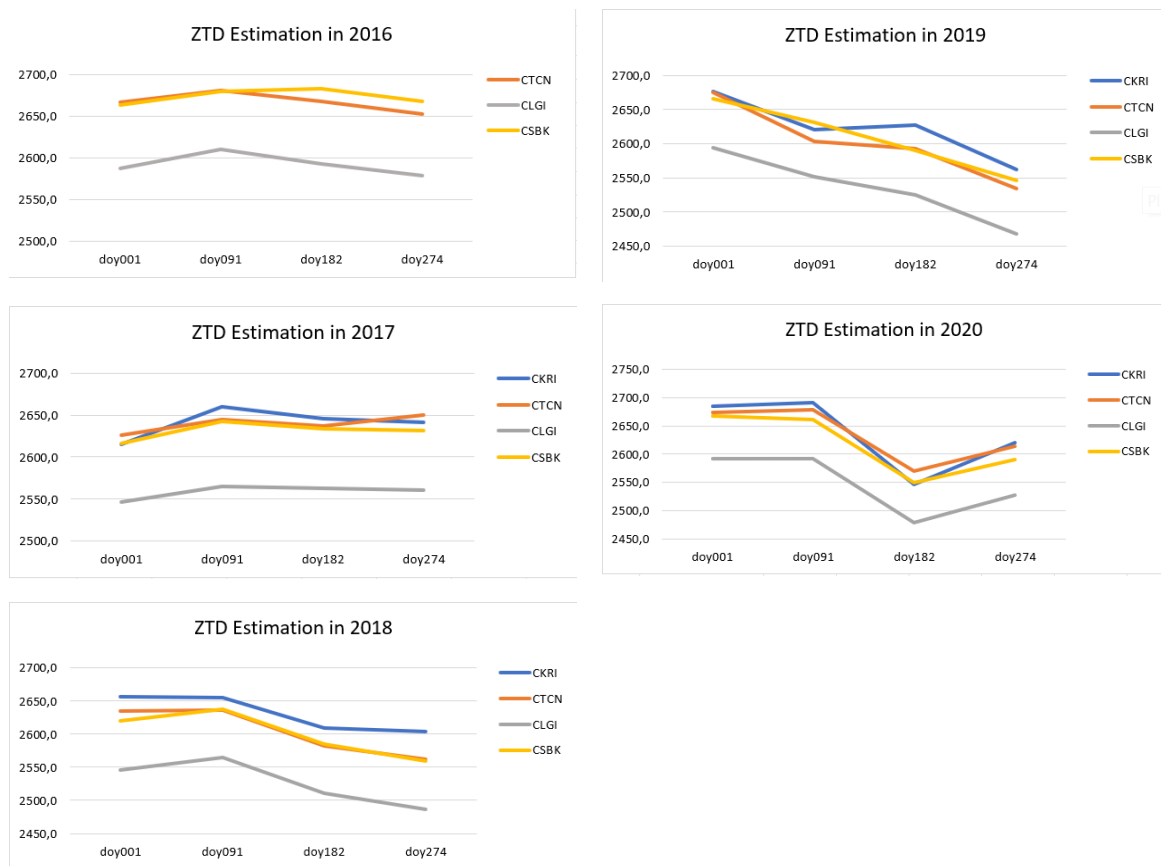


Fig. 3. Graph of ZTD estimation value variations based on seasonal changes for each year during the 2016–2020 observation period

**Figure 3** illustrates the seasonal trends of average Zenith Tropospheric Delay (ZTD) values derived from four CORS observation stations over a one-year cycle during the 2016–2020 period. Overall, the annual ZTD pattern is strongly influenced by seasonal changes, which are directly correlated with the water vapor content in the troposphere.

At the beginning of the year, approximately between DOY 001 and DOY 091 (January to early April), ZTD values tend to remain relatively high. This condition aligns with Indonesia's rainy season, during which increased atmospheric humidity raises the atmospheric refractive index, thereby amplifying ZTD values [24]. The high water vapor content during this period causes more significant delays in GNSS signal propagation. Entering the period from DoY 091 to DoY 274 (around April to early October), a general decrease in average ZTD values is observed for almost all observation years. This decline reflects the transition to the dry season, during which atmospheric water vapor content gradually decreases [24], resulting in reduced ZTD values. This time frame represents a period of lower humidity, producing smaller tropospheric biases.

However, an exception is evident in 2020, when the ZTD trend displayed a distinct pattern. In that year, ZTD values decreased from early April (DOY 091) to early July (DOY 182), consistent with the typical dry-season pattern. Yet, from DOY 182 to DOY 274, ZTD values increased again, suggesting an anomaly in the seasonal cycle for that year. This rise in ZTD from July to October 2020 indicates increased atmospheric humidity, likely signaling an earlier onset of the rainy season in the study area.

These findings suggest that beyond the influence of regular seasonal cycles, ZTD values are highly responsive to regional climate anomalies and variations in annual weather patterns. Consequently, GNSS-based ZTD analysis from CORS observations can serve as a reliable indicator for detecting atmospheric water vapor dynamics both spatially and temporally, with strong potential applications in climatological studies and local weather forecasting.

## V. Conclusion

The processing of CORS GNSS data has proven to be valuable not only for providing precise positional coordinates but also for generating Zenith Tropospheric Delay (ZTD) estimates that can be utilized for atmospheric analysis. Based on the estimation results, the variation patterns of ZTD values at the CKRI, CLGI, CSBK, and CTCN stations during the 2016–2020 period show a consistent relationship with the seasonal cycle in the study area. ZTD values tend to be higher during the rainy season (January to early April), characterized by increased atmospheric water vapor content, and decrease during the dry season (April to October) in line with reduced atmospheric humidity.

The range between the highest and lowest ZTD values detected at each station indicates the influence of local factors such as topography, station elevation, and the spatial distribution of rainfall around the observation site. For instance, the highest ZTD value at CKRI station was recorded on DOY 091.20 at 2691.0 mm, while the lowest was on DOY 182.20 at 2546.4 mm. Similar patterns were found at other stations, with magnitude variations corresponding to their respective local characteristics.

Overall, ZTD estimation from CORS GNSS data processing is beneficial not only for tropospheric correction in precise positioning but also holds significant potential for monitoring atmospheric dynamics and conducting regional climatological analyses. Integrating this method with conventional meteorological data could enhance the accuracy of climate models and contribute to more comprehensive weather studies in Indonesia.

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