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Dependence of seasonal phenomena in coordinate time series on GNSS antenna mounting height

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Abstract: The purpose of this paper is analysing the correlation between the magnitude of the annual amplitude of seasonal changes in the coordinate components of GNSS reference stations and the height of the antenna mounting above the ground. For this purpose, the daily coordinate solutions of more than 500 GNSS reference stations that are part of the IGS (International GNSS Service) network were studied due to their distribution across the globe and long operating time, for some stations dating back to the 1990s. To minimize the impact of the tectonic plate movements authors adopted coordinates of reference stations inside each of the 21 tectonic plates. The coordinates in a topocentric reference frame were detrended in accordance with a linear model, with the objective of removing first-order trends. Subsequently, the seasonal yearly functions were calculated for each North, East and Up component. Finally, the amplitude of the seasonal factor for each station was determined. As a result of the analysis, the existence of annual amplitudes of coordinate changes was demonstrated for some of the stations, but no significant correlation between this phenomenon and the height of the GNSS antenna mounting was shown. In the case of the horizontal components, the majority of the station's time series is characterized by the amplitude of seasonal function does not exceed 2.5–3 mm, and 5 mm for the vertical component.

Keywords: GNSS, IGS, time series, seasonality, height

1. Introduction

Satellite methods and, above all, the reference stations that make up GNSS (Global Navigation Satellite System) networks are the most widely used for measurements worldwide (Magiera et al., 2022). Among other things, GNSS is used in surveys aimed at detecting land surface displacements (Tiwari et al., 2018). Points established based on reference stations form the control points for TLS (Terrestrial Laser Scanning) and RTS (Robotic Total Station) (Figurski et al., 2010). Local GNSS networks can realise a stable reference for various surveying measurements, especially in construction. However, Savčuk and Tadęęv (2020) studies have pointed out that reference systems, due to the influence of various factors, are subject to changes over time in terms of violation of their basic geometrical and physical conditions. Among these, the most affected is the Earth's tectonic activity. Violation of such conditions causes deformation of the reference system, which further affects the geodetic control network (Fazilova, 2022). Reference systems such as the International Terrestrial Reference System (ITRS) or the European Terrestrial Reference System (ETRS) are created based on continuous monitoring of the Earth by satellite techniques. They provide stability of the datum, primarily taking into account the influence of tectonic processes at the local level (Savčuk and Tadęęv, 2020). Any point on the Earth's surface can have seasonal changes in its position, and this type of phenomenon can be studied using geodetic methods, such as analysing time series of GNSS coordinates based on observations at reference stations (Vārna et al., 2019), as well as a model is implemented for time series prediction patterns (Fazilova et al., 2018). This type of research confirms the existence of seasonal changes on an annual, semi-annual, or daily basis.

The annual amplitude of seasonal changes in the coordinate components of GNSS reference stations is influenced by various environmental and geophysical factors. Thermal expansion of the ground and GNSS mounts, for example, causes slight expansions and contractions due to temperature variations throughout the year, leading to shifts in coordinates, especially in the vertical component. Soil moisture changes from seasonal rainfall cycles affect the density and stability of the ground near the station, causing minor subsidence or uplift, while frost heaves in colder regions introduces upward displacements during freeze-thaw cycles. Atmospheric pressure changes lead to vertical ground deformation through atmospheric loading, as higher pressure compresses the Earth's crust, creating seasonal variations in elevation. Additionally, hydrological loading from water sources such as groundwater levels, rivers, or snowpack adds or relieves weight on the Earth's crust seasonally, which can cause periodic vertical shifts. Vegetation growth and decay near the GNSS station can also influence coordinate measurements due to increased signal multipath errors as plants grow and reflect signals differently. Together, these sources introduce periodic variations in GNSS coordinates, resulting in seasonal amplitudes that are particularly pronounced in specific environments and locations. Numerous studies have investigated the seasonal variations of GNSS station coordinates. Research in Poland has revealed notable variations of 2–4 mm for certain stations (Maciuk, 2016). Another study indicates permanent station velocities of 1–2 mm/year and 2–4 mm/year for the horizontal and vertical components, respectively (Hefty et al., 2005). In addition, regional trends have also been identified. A 2021 study

(Michel et al., 2021) found that the largest amplitudes and maximum displacements occurred in areas with heavy snowfall and were linked to the season of a year. In Asia, velocities for stations in the seismic zone in the Himalayas were observed to be as high as 52.42 mm/year (Nagale et al., 2022). Higher seasonal effects were noted for the E and N components, whereas in the Sichuan-Yunnan area (Liu et al., 2022), the vertical component showed greater seasonality. However, recent studies in central Europe found coefficient values of less than 1 mm, confirming the lack of seasonality in the long-term coordinate time series (Savchuk et al., 2023).

Observations from GNSS stations are actively used for many surveys and geodetic measurements including monitoring geodynamic processes, (Bos et al., 2010) points out the trend error depends on the estimation of the noise properties for short time series (Bock and Melgar, 2016) and (He et al., 2017) review GPS infrastructure, surveys and analysing of daily position time series in 30 years consequently. The basics of time series analysis shows by (Montillet and Bos, 2020). Savchyn (2022) reaches to the correlation between the change of absolute rotation poles of major tectonic plates depending on GNSS stations data. Currently, it is possible to determine the coordinates and velocities of GNSS stations at the level of a few millimeters (Krawczyk, 2023). However, additional research is needed for increasing the accuracy of coordinate definitions in order to obtain more reliable data. One of the main sources of error is systematic measurement errors (Table 1). To date, the procedure for their removal is still incomplete and imperfect. The accuracy of coordinate determination in satellite systems is significantly affected by perturbations caused by inhomogeneities in electron density in the ionosphere and troposphere. The number of electrons in the ionosphere along the satellite-observer path depends on many factors:

- solar activity,
- the number of spots on the sun,
- the time of year,
- time of day,
- the geographic location of the observation,
- direction to the satellite.

Table 1. The main factors affecting the accuracy of GNSS measurements

	Sources of error	Error rate
Satellite	orbit satellite clock S/A	5–10 m 10 m 5–80 m
Wave path	ionosphere troposphere	2–50 m 2–30 m
Receiver	code multitasking code noise multitracking of the carrier wave carrier wave noise	0.2–3 m 0.1–3 m 1–50 mm 0.2–2 mm

The ionospheric carrier wave delays caused by them are the largest, as they reach 1/3 of the total error. The impact of ionospheric delay affects the calculation of the unknown receiver time correction more than the horizontal coordinates, while it is as much as 6 times larger when determining the vertical component (Lamparski, 2020). Also according to the study (Krasucki at al., 2019), the signal running from the satellite to the receiver undergoes deflection and refraction when passing through the center of the atmosphere. Therefore, in scientific research on the state of the world's atmosphere, it was decided to use the concept of tropospheric refraction index and ionospheric and tropospheric delay. Among other things, the value of this index is influenced by the temperature at the height of the sensor and thus the reference station, atmospheric pressure or water vapor pressure.

Also in the research (Amos et al. 2014; Argus et al. 2014) have shown significant and consistent seasonal changes in the plate boundary zone in California. The largest inter-peak changes occur in northern California, where the largest vertical displacements occur. Vertical seasonal shifts have been shown to largely reflect hydrological loading, which is also explained by interannual vertical shifts (Borsa et al., 2014; Argus et al., 2017). It was observed, horizontal shrinkage under surface loading has been observed in northern California and Nevada. It has also been found that each general anomaly is reliable from the point of view of the repeatability of each year, which show differences in details that depend on whether it is a normal, drought or heavy rainfall year (Wahr et al., 2013; Liu et al., 2017). Local height maxima occur each winter or early spring. Significant subsidence is exacerbated during drought. Anthropogenic influences on surface loading, such as groundwater pumping (Amos et al., 2014), precisely cause seasonal transient deformation. Analysis reveals that only seasonal changes in horizontal deformation due to loading can vary significantly in space and time from year to year, depending on the amount of rainfall (Kim et al., 2021).

In addition, during the processing of long-term GNSS measurements, it was found that the coordinate time series, after removing trend effects, are also characterised by seasonal variations, mainly in annual and semi-annual periods (Savchyn, 2022). The largest amplitude is characterized by annual and semi-annual changes, respectively, with values up to several millimeters (Deng et al., 2017; Li et al., 2019). These analyses are important because understanding how antenna height influences seasonal variations can improve the accuracy of long-term GNSS data interpretation, especially for applications requiring high precision like tectonic studies and geodetic reference systems. By clarifying the relationship between mounting height and seasonal variation amplitude, researchers can better correct environmental factors, leading to more reliable GNSS-based measurements globally. Therefore, one of the needed studies is precisely to analyse the correlation between the magnitude of the annual amplitude of the seasonal variations in the coordinate components of GNSS reference stations and the height of the antenna mounting above the ground.

In this paper, authors analysed the correlation between the magnitude of seasonal effect in the coordinates time series from GNSS measurements and the height of antenna mounting over the ground level. The reasons of this type of research are related to a few environmental and physical effects such as atmospheric refraction variability (Tekin Ünlütürk and Doğan, 2024), surface loading (Usifoh et al., 2024), and thermal expansion and soil properties (Romagnoli et al., 2003). Through the results of the mentioned papers, all of them are based on local station/stations. Narrowed analyses confirm that in this field of research they are still in their infancy and are yet to be fully explored.

2. Materials and methods

Coordinate time series of IGS network (https://network.igs.org) stations, which currently consist of 515 points (Fig. 1), were used in this paper. The choice of points of the IGS network was dictated primarily by the very long time series of coordinates (some stations have been in continuous operation since 1994) with very good quality of solutions, as well as the available images of the stations allowing verification of their location.

Fig. 1. Map of IGS reference stations used in the analysis (https://igs.org/station-resources/)

For each permanent station, based on the daily PPP (Precise Point Positioning) solutions obtained from the NGL (Nevada Geodetic Laboratory, http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html) in topocentric coordinates, the yearly seasonal amplitude factor for each North, East, and Up component was determined. NGL uses the PPP technique for data processing, which is based on multiple frequencies and GNSS systems. The data is most often collected from dual-frequency observations (L1 and L2 for GPS, with corresponding frequencies for other systems such as GLONASS, Galileo, and BeiDou). The EGM2008 geoid model was used, which is a high-resolution gravitational model commonly applied in global navigation satellite systems (GNSS) due to its high precision and accuracy in modeling the Earth's global gravitational field (Blewitt et al., 2018).

The seasonal amplitude factor for each North, East, and Up component was determined using a fitting function according to an equation that combines a linear and sinusoidal part:

$$x(t_i) = a + b \cdot t_i + A \cdot \sin\left(\varphi + \frac{2\pi}{365.2422} t_i\right), \tag{1}$$

where $x(t_i)$ are one of N, E or U component, a is an independent factor, b slope of the function, A is an amplitude and φ is a phase shift. Moreover, in a preprocessing outliers in each time series was deleted using median absolute deviation. Abovementioned function components for each station's coordinate component were determined using least squares method. Moreover each antenna mounting height was determined based geodetic height, global geoid model calculator provided by UNAVCO (Hanagan and Mershon, 2024) and terrain elevation. The elevation of the terrain was determined using the Google Elevation API (GoogleMapsPlatform, 2024). This elevation model provides data based on a global terrain model, allowing for precise elevation determination in almost any place on Earth. However, the accuracy of this data is not uniform and may vary depending on the location. It can be assumed that the vertical accuracy is about 1 meter for developed areas and up to several meters in less accessible regions of the world. For such analyses, the assumed vertical accuracy was deemed satisfactory due to the purpose and scale of the study, where small discrepancies in height measurements have a minimal impact on overall results. Since GNSS antenna heights are calculated using globally available data sources, slight variations in elevation accuracy – particularly in remote areas – are within acceptable limits for interpreting general spatial trends. Additionally, the chosen accuracy range accounts for known data limitations, balancing precision with practicality for global applications.

3. Results and discussion

For each station's coordinate component was determined seasonal amplitude and height of the antenna mounting over the ground. Based on that we determined cumulative relation between seasonality and height of the antenna. Figure 2 shows relationship between height of the reference station antenna over the ground and the amplitude of seasonal variations for each component: N (North), E (East) and U (Up) respectively. Each dot represents one of more than 500 IGS station, horizontal axis shows a mounting height above the ground (in meters), and vertical magnitude of amplitude (in millimetres). Graphs also contain a line, which shows a directly proportional increase of amplitude to height at the angle 45°. The vast majority of stations don't reach the amplitude over 2.5 mm for components N and E. From component U can be observed raised average amplitude of seasonal variations, getting to 5 mm for some of the chosen stations. It is connected mostly with a quality of the determination height component, which has up to 3 times less accuracy than horizontal components. In contrast to the two first charts, points in the last one don't spread symmetrically to the line of directly proportional increase, but most of them are located above it. For chart N the biggest amplitude is 6.4 mm for the station located 1.1 m above the ground, whereas for the three stations placed higher than 50 m above the ground the average amplitude is 1–2 mm. A similar situation is for graph E, whose greatest amplitude (9.5 mm) is for a station located at 0.8 m. The stations located more than 50 m above the ground has small amplitudes around 0.6 mm. For U component the largest seasonal amplitude is 15.2 mm for the station situated 22.1 m above the ground. The highest placed stations' (> 50 m) amplitude is bigger around 8–9 mm. The result does not indicate the relationship between the mounting above the ground height and the amplitude of seasonal variations, but part of the stations has a very big seasonal component.

The analysis also indicates that the regions with significant hydrological loading, such as South America, exhibit higher vertical seasonal amplitudes. For instance, the station in Porto Velho (POVE), Brazil, located 22.1 m above the ground, has the largest vertical amplitude (15.2 mm). This result highlights the potential influence of hydrological loading

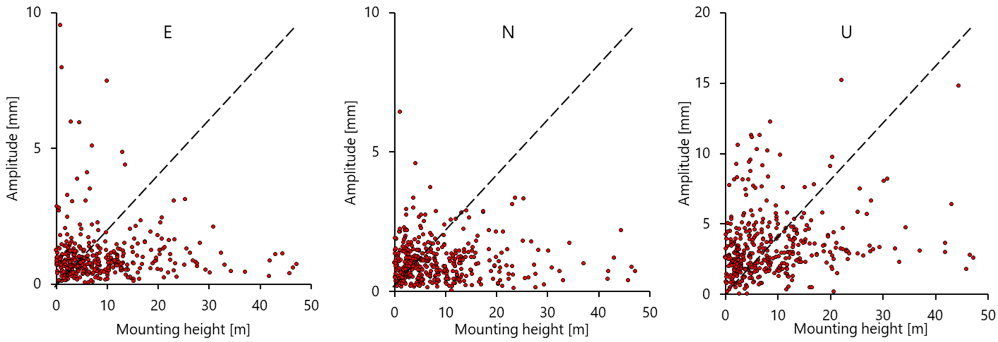
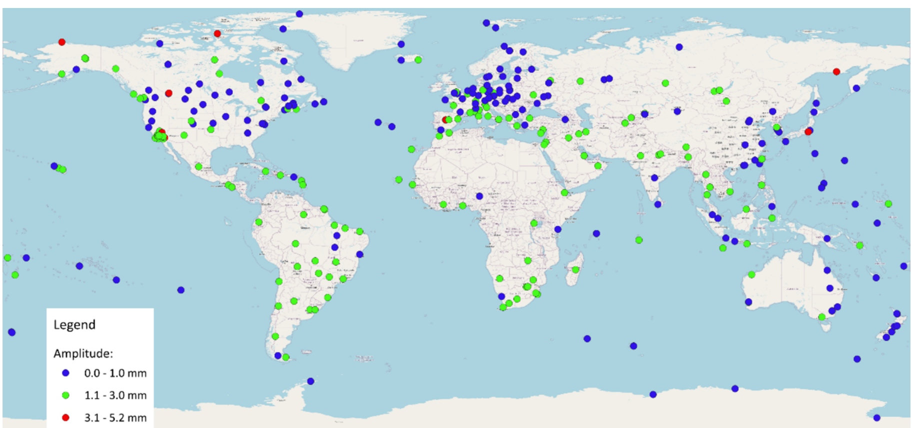


Fig. 2. Amplitude vs mounting above the ground height

in areas where seasonal changes in water mass are substantial. In such cases, the amplitude of the hydrological signal may interact with the antenna height, potentially enhancing the vertical seasonal component. The higher placement of antennas can lead to reduced damping of local hydrological effects by the immediate surroundings, emphasizing the importance of environmental context in interpreting seasonal variations. However, the lack of a consistent relationship between mounting height and seasonal amplitude across the dataset suggests that local environmental and loading conditions are dominant factors, rather than the height of the installation alone.

Figure 3 represents the distribution of each component's amplitude magnitude, but also the mounting heights of stations. The maps show that in most cases, every component of each station is in the same class. The area of North America and Europe (especially northern and central region) are representing the same tendency in relations between the components. However, it should be noted that the mounting height does not affect these results. Additionally, the biggest values in every map do not cover with each other and do not allow to draw any bonded relationship and conclusions.



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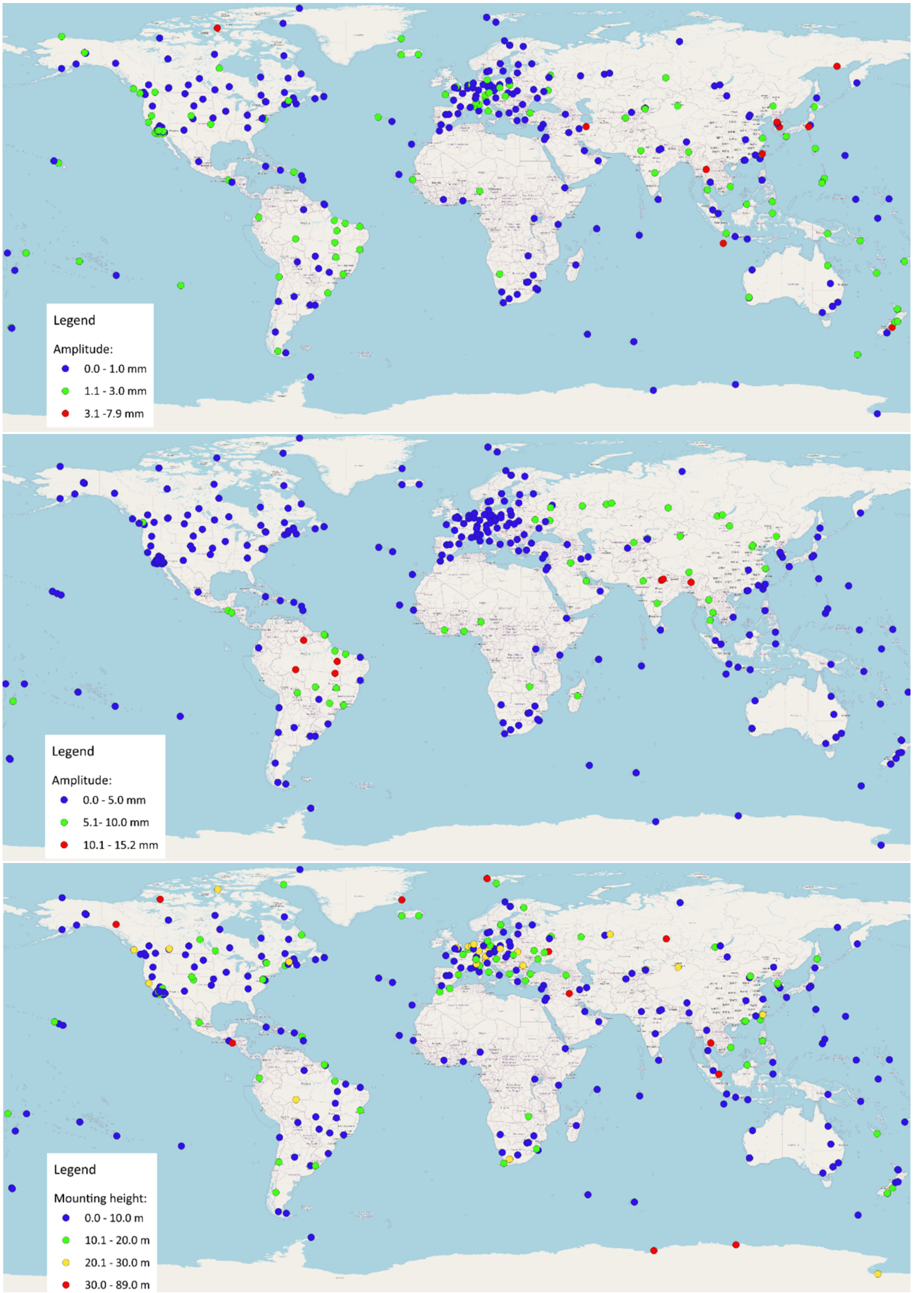

Fig. 3. The distribution of amplitude magnitude for N, E, U components and the distribution of mounting heights (from top to bottom)

Figure 4, 5 and 6 illustrates daily coordinates (blue dots) for components N, E and U for selected stations: UTQI (Utqiagvik, Alaska, 7 m about the ground, amplitude of seasonal effect 3.7 mm), CMUM (Chiang Mai, Thailand, 7 m and 5.1 mm) and POVE

(Porto Velho, Brazil, 22 m and 15.2 mm), respectively. By using the least squares method, the curves of the sinus function on the plots were estimated and marked in red colour. Time series, which had removed outlying positions, were applied for the analysis. Each of the graphs consists of vertical cm and horizontal axes in years.

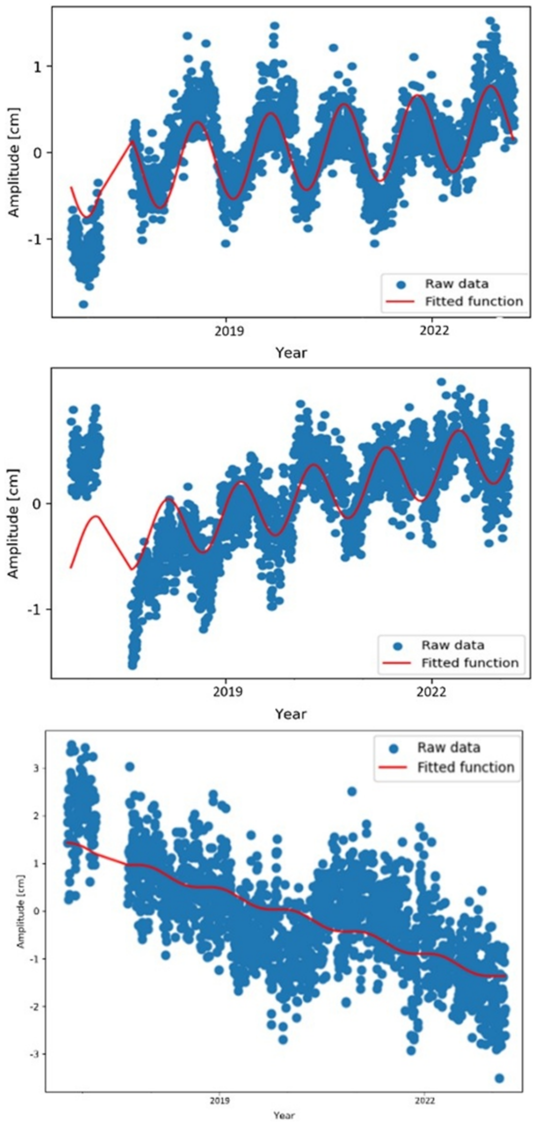

Fig. 4. Samples station with big amplitude for each component NEU UTQI station
(N – top, E – middle, U – bottom)

Amplitude of the estimated sinus function informs about seasonal variations. For those three stations, it is sequentially: 3.7 mm for N, 5.1 mm for E and 15.2 mm for Up component. For the first two referenced stations, while periodic seasonal variations are evident, progressive movements in the curves remain visible. These residual movements may be indicative of nonlinear trends or physical processes that have not been fully addressed by linear detrending. For POVE station, throughout the entire period of observation, can be recognized as constant amplitude, however it is the biggest one of all three components.

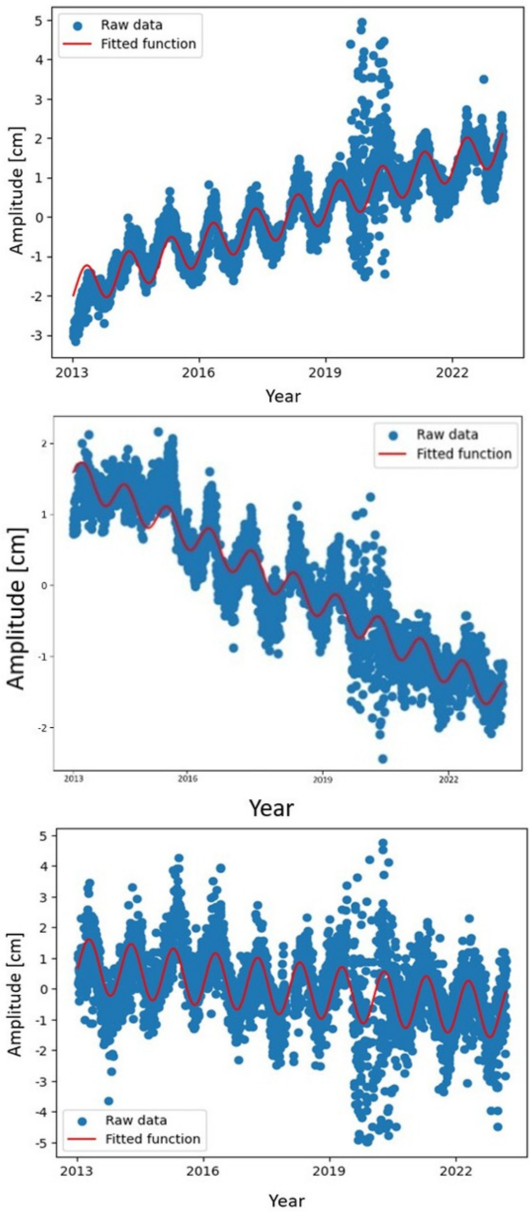

Fig. 5. Samples station with big amplitude for each component NEU CMUM station
(N – top, E – middle, U – bottom)

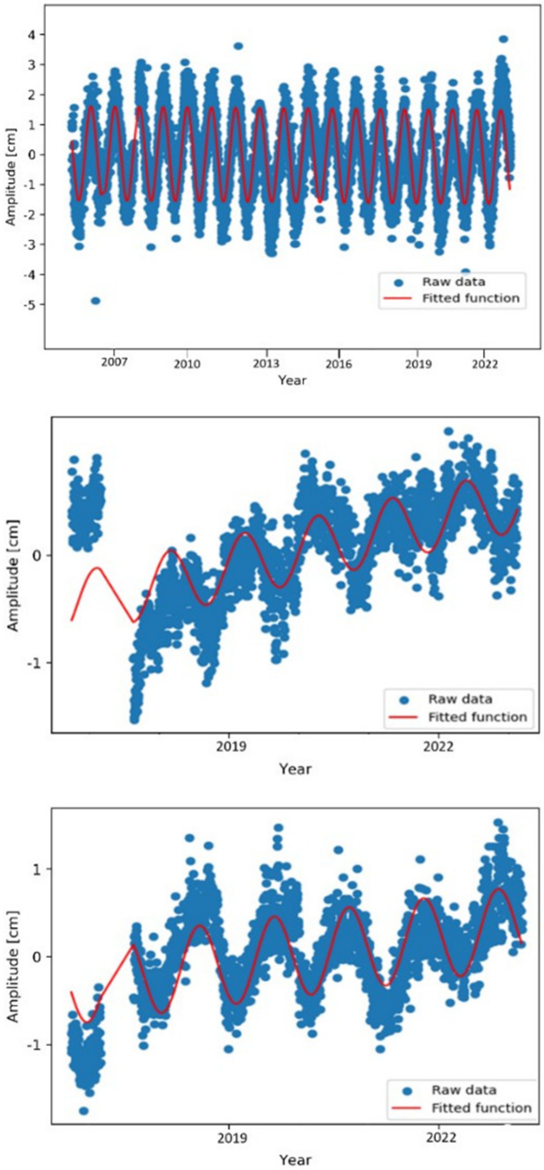

Fig. 6. Samples station with big amplitude for each component NEU POVE station (N – top, E – middle, U – bottom)

4. Conclusion

The International GNSS Service (IGS) has conducted its mission to provide high-precision GNSS data and products freely and openly. Depending on the data provided by the IGS high-precision positioning and navigation tasks can be calculated. For the mentioned importance of IGS and as a part of its network, five hundred GNSS reference stations' coordinates were studied trying to detect the correlation between the annual amplitudes of seasonal changes in its East, North, and Up components respectively and the height of the GNSS antenna mounting above the ground. Antenna mounting height was determined based on the digital terrain model (DTM).

Regarding the relation between the height of the reference station antenna and the amplitude of seasonal variation after analyzing around 500 stations, it's shown that most of them haven't exceeded 2.5 mm for both North and East components in addition to 5 mm for Up component which is evidence that this component is three time less accurate than horizontal ones. Concerning some selected stations e.g. in Alaska (UTQI), Thailand (CMUM) Brazil (POVE) and others after applying the least square method to estimate the curves of sinus function on the relation between the amplitude of seasonal variation it is found but with no correlation with the height of the antenna mount over the ground.

Author contributions

Conceptualization and methodology: K.M., G.O., M.A., A.B., K.K., P.P., A.M.; formal analysis and investigation: K.M., G.O., M.A., A.B., K.K., P.P., A.M.; writing original draft preparation: K.M., G.O., M.A., A.B., K.K., P.P., A.M.; writing – review and editing: K.M., G.O., M.A., A.B., K.K., P.P., A.M.; supervision: K.M.

Data availability statement

The data might be available form the authors upon email request.

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