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ANALYSIS OF ANNUAL SEASONAL SIGNAL IN GNSS TIME SERIES FROM GNSS STATION IN THE WESTERN PART OF ROMANIA

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ABSTRACT:

Earth's surface deformation can be measured at millimeter level using continuous Global Positioning System (GPS) data. Periodic signals, mostly annual and semiannual, originating from geophysical, environmental, and instrumental processes can be determined in these time series. Improving geodetic products, fine-tuning tectonic velocity estimates and expanding knowledge of Earth's system mass redistribution all rely on the accurate identification and interpretation of these seasonal signals. This article analyzes the annual seasonal signal amplitude of GNSS stations located in the Western part of Romania from two different CORS networks, one of which is for monitoring the tectonic movement. The results show that the annual seasonal signal of the East component exhibits an increase of three to four times the amplitude compared to the North component, whereas the Up component shows an increase between three to four times higher than the East component.

1. INTRODUCTION

The Global Positioning System (GPS), which now is a part of the Global Navigation Satellite Systems (GNSS), has transformed geodesy during the last thirty years by making it possible to continuously monitor the Earth's surface with high precision. Thus, with the help of GNSS, the research of tectonic plate motions, postseismic deformation, volcanic activity, glacial isostatic adjustment, and infrastructure stability is at the level of centimeter to millimeter level accuracy in station positioning (G Blewitt, Hammond, and Kreemer 2018; Larson 2009). GNSS time series has the capability of offering an increasingly solid basis for analyzing long-term geodynamic processes as they get longer – at this moment there are stations that have more than 20–30 years in well-instrumented areas (Altamimi et al. 2016).
However, secular (linear) tectonic trends do not predominate in GNSS position time series. Seasonal changes are one of the most noticeable and prominent features among the many transient and periodic signals that are superimposed on long-term motion (Dong et al. 2002; Williams et al. 2004). Strong annual and, in many areas, semiannual components are characteristic of these seasonal signals. In hydrologically active areas, seasonal amplitudes in the vertical component typically range from a few millimeters to more than one centimeter (van Dam et al. 2001; Argus, Fu, and Landerer 2014). Although they often have smaller amplitudes, horizontal components also show discernible seasonal variations (Dong et al. 2002).
Seasonal changes in GNSS time series were first considered as colored noise or nuisance characteristics that masked tectonic velocities (Langbein 2004; Williams et al. 2004). It is now evident that these periodic signals contain important geophysical information due to the development of GNSS networks and the growing availability of independent environmental data (Geoffrey Blewitt and Lavallée 2002; Dong et al. 2002; Williams et al. 2004). The Earth's elastic response to time-varying surface mass loads brought on by variations in atmospheric pressure (Koulali et al. 2022; Peidou et al. 2024), hydrology (Sorin Nistor et al. 2021; White et al. 2022), ocean circulation (Peidou et al. 2024), and cryospheric processes is reflected in seasonal deformation (Liu and Larson 2018). Thus, the GPS has become a potent sensor of the global water cycle and climate-driven mass redistribution in addition to being a geodetic instrument (Jiang et al. 2021; Anne et al. 2019).
However, not every seasonal signal that has been determined is solely geophysical. Some signals can also be introduced into GNSS time series solutions represented by non-geophysical contributions, such as thermoelastic expansion of monuments and structures (Yan et al. 2009), mismodeling of tropospheric

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delays (S. Nistor and Buda 2015), antenna phase center fluctuations, multipath (King and Watson 2010), and reference frame inconsistencies (Bogusz, Rebischung, and Klos 2025). Physical interpretation may be made more difficult by these effects, which could result in station-dependent seasonal signals that are able to mimic true surface deformation. One of the key problems in seasonal GNSS research is still separating environmental loading signals from local instrumental or monument-related influences (Santamaría-Gómez and Ray 2021).

Thus, it is essential to accurately classify the seasonal signal. First, estimates of station velocities can be strongly biased by unmodeled seasonal effects, especially in short time series, leading to incorrect interpretations of tectonic strain accumulation (Dong et al. 2002; Geoffrey Blewitt and Lavallée 2002). Second, the timing and character of seismic and magmatic activity may be affected by seasonal loading, which modifies the stress on faults and volcanic systems (Amos et al. 2014; Bettinelli et al. 2008). Third, seasonal deformation complements satellite gravimetry missions such as GRACE and GRACE-FO by providing an independent geodetic constraint for regional and global hydrological models (Velicogna and Wahr 2013). Lastly, a variety of Earth research and engineering applications rely on the long-term stability and precision of terrestrial reference frames, which are impacted by seasonal signals (Altamimi et al. 2016).

In this regard, both geophysical interpretation and geodetic practice require a comprehensive understanding of seasonal signals that can be found in GNSS time series. This article aims to provide a comprehensive scientific overview of the seasonal signal in GNSS time series. The objectives of this article are to: (1) identify the seasonal signal in the GNSS time series of the stations that are located in the Western part of Romania; and (2) discuss the implications of these findings. The results show that the annual seasonal signal of the East component exhibits an increase of three to four times the amplitude compared to the North component, whereas the Up component shows an increase between three to four times higher than the East component.

2. MATERIALS AND METHODS

Long-term geological motion, seasonal environmental loading effects, transient deformation resulted from earthquakes and volcanic activity, instrumental offsets, and stochastic noise are all present in GNSS coordinate time series. Therefore, to accurately extract seasonal signals and to prevent bias in velocity estimation, a robust mathematical model is needed.

The general functional model of GNSS position time series is expressed by:

$$X(t) = X_0 + Vt + \sum[A_i \cos(2\pi f_i t) + B_i \sin(2\pi f_i t)] + \sum C_k H(t - t_k) + \varepsilon(t) \quad (1)$$

$X(t)$ – coordinate component (East, North, or Up)
X_0 – reference position
V – linear velocity
f_i – seasonal frequencies (annual, semiannual)
A_i, B_i – harmonic coefficients
C_k – offset amplitudes
$H(t - t_k)$ – Heaviside step function
$\varepsilon(t)$ – stochastic noise

The harmonic representation of the seasonal signal for annual and semiannual displacement is modeled by:

$$X_s(t) = A_1 cos(2\pi t) + B_1 sin(2\pi t) + A_2 cos(4\pi t) + B_2 sin(4\pi t) \quad (2)$$

The amplitude of each harmonic component is:

$$C_n = \sqrt{(A_n^2 + B_n^2)} \quad (3)$$

The phase is computed as:

$$\Phi_n = tan^{-1}(-B_n / A_n) \quad (4)$$

Latest research in seasonal signals is based on time-Varying Seasonal Models, in which to model non-stationary seasonal signals, amplitudes and phases are allowed to vary with time:

$$X_s(t) = C(t) \cos(2\pi t + \Phi(t)) \quad (5)$$

3. RESULTS

The conducted study is done based on GNSS stations that are located in the Western part of Romania. There is a total of 13 analyzed stations, of which four are from the National Institute for Earth Physics (NIEP) CORS network, two are from the EUREF GNSS network and the other seven GNSS stations are from the Romanian position determination system (ROMPOS). The data was downloaded from Nevada Geodetic Laboratory (G Blewitt, Hammond, and Kreemer 2018). The processing strategy of the GNSS data is based on the JPL software called GipsyX using version 2.3. using the reference frame IGS2020. The processed data were obtained using the Precise Point Positioning technique. The daily time series were pre-processed not only for outliers but also for offsets and gaps and it was analyzed with the help of maximum likelihood estimation (MLE) implemented in Hector software package (Bos et al. 2013).

The annual seasonal amplitude for the North component is presented in Figure 1.

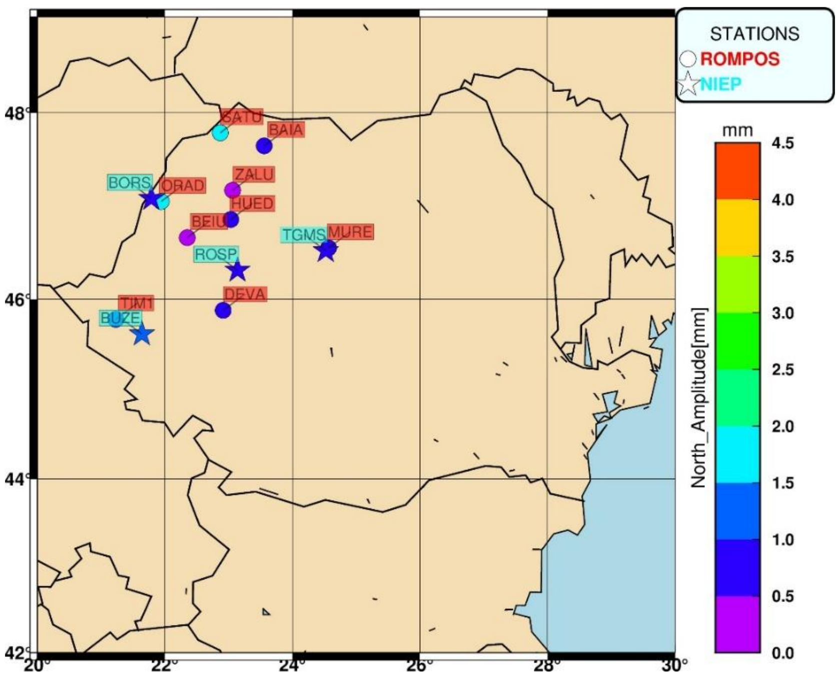

Figure 1. The annual seasonal amplitude for the North component.

The stations with a circle and red writing are from ROMPOS and EUREF networks, whereas the stations with a star and cyan writing represent the stations from NIEP network. The minimum and maximum of the annual seasonal amplitudes for the North component vary between 0.5777 mm for the station BORS and 1.762 mm for the ORAD GNSS station. Although the stations are relatively close together, being separated by a distance of approximately 12 km. Another group of stations that are relatively close together are the GNSS stations TGMS-MURE, which shows an annual seasonal amplitude of 0.702 mm and 0.671 mm, respectively.

The annual seasonal amplitude for the East component is presented in Figure 2.

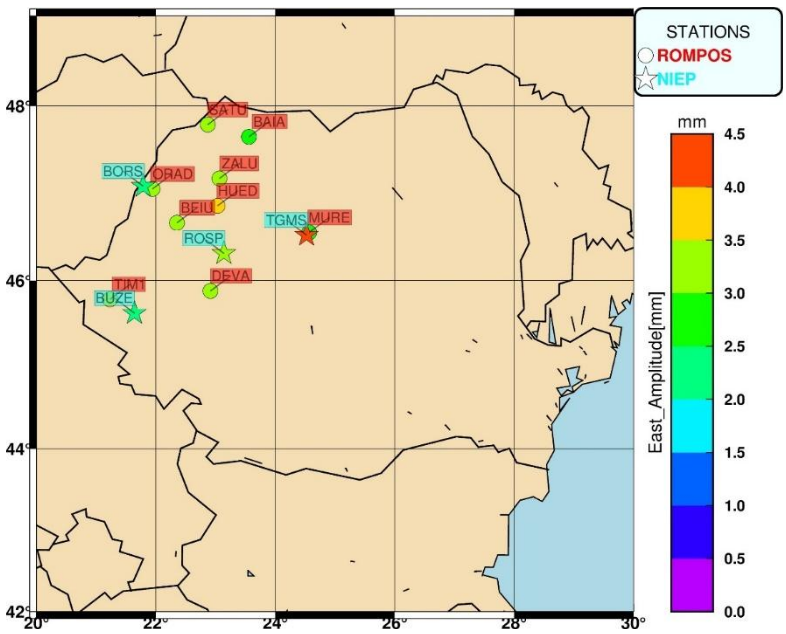

Figure 2. The annual seasonal amplitude for the East component.

The minimum and maximum annual seasonal amplitudes for the East component vary between 2.155 mm for the station BORS and 4.161 mm for the TGMS GNSS station. In the case of the ORAD GNSS station, the annual seasonal signal is 3.087 mm, whereas the MURE GNSS station, which is relatively close to the TGMS GNSS station, exhibits an annual seasonal signal of 2.939.

The annual seasonal amplitude for the Up component is presented in Figure 2.

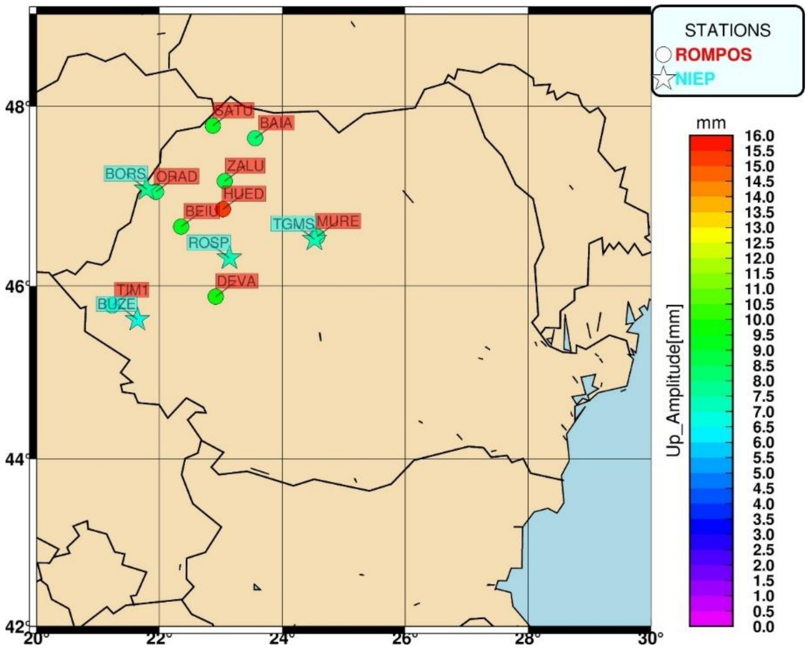

Figure 3. The annual seasonal amplitude for the Up component.

Figure 3 reveals that the annual seasonal amplitude of the Up component ranges from 6.984 mm at station BUZE to 15.013 mm at station HUED. Regarding the group of stations that are relatively close together such as BORS-ORAD and TGMS-MURE, they present 7.950 mm-8.499 mm and 7.002 mm-7.663 mm respectively, for the annual seasonal signal.

In Figure 4, the daily time series is presented for the DEVA station which has an approximately 20-year time period.

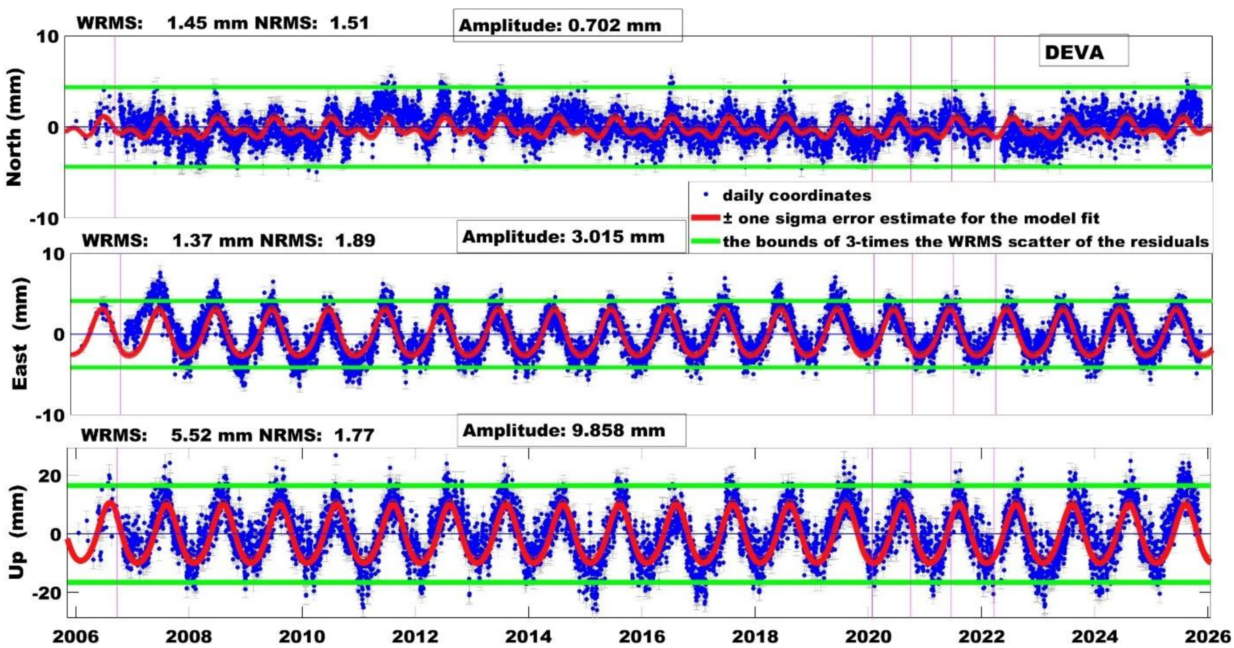

Figure 4. Daily time series for station DEVA

The data from Figure 4 unveils the fact that for the horizontal annual seasonal amplitude, the East component has a value 4 times higher than the North component. Thus, the sinusoidal shape of the annual seasonal signal for the East component can be clearly seen in Figure 4, whereas the annual seasonal signal for the North component cannot be precisely defined. As expected, the annual seasonal signal for the Up component shows three times higher amplitude values compared to the East component.

4. CONCLUSION AND DISCUSSIONS

The annual seasonal amplitude for the horizontal part, namely for the North component, is presented in Figure 1, whereas for the East component is presented in Figure 2. As shown, the stations analyzed are located on the mainland, at least 400 km from the

Black Sea. Although there are two pairs of stations that are relatively close one to another – 12 km away, the stations BORS-ORAD and TGMS-MURE, in which the first stations from the pairs are from the NIEP network, the first pair BORS-ORAD shows a discrepancy between the annual seasonal signal in the North component, in which BORS has an amplitude of 0.577 mm, whereas ORAD has 1.762 mm. Thus, ORAD has a three-time higher annual seasonal signal compared to the BORS station, although TGMS presents an annual seasonal signal of 0.702 mm and MURE has an amplitude of 0.671mm, which are very close to each other as comparative values. As a consequence, the difference between BORS and ORAD can be attributed to possible unmodelled local effects, monument problems or instrument issues.

In the case of the East component, compared to the North component, all stations show an increase in annual seasonal signal of three to four times higher. For the pair of stations that are relatively close to each other, BORS-ORAD and TGMS-MURE, BORS has an amplitude of 2.155 mm and ORAD 3.087 mm, representing an increase in the annual signal amplitude of approximately 70%. For the TGMS the amplitude is 4.161 mm and for MURE 2.939 mm, thus the increase in amplitude is almost 70%. Consequently, we see that the North component for the stations BORS-ORAD is more affected by the undetermined effect.

As expected, for the Up component, the annual seasonal signal presents higher values compared to the horizontal component. The increase is between three to four times and in some cases such as station HUED, the increase is five times higher. For the pair of stations BORS-ORAD, the difference is 0.549 mm, which represents approximately a difference of less than 7%. In the case of stations TGMS-MURE the difference is 0.661 mm, which represents less than 9%. The annual seasonal signal for the Up component is quite compact comparing the results between all stations, showing values between 7 to 9 mm amplitude, except station HUED.

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