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Original scientific paper

Integration of GPS Data and Seismic Events using Lomb-Scargle Spectral Analysis: a Study of GPS Station SPLT

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Abstract: This study analyzes the long-term and seasonal variations in the GPS time series of the SPLT station, located in a seismically active region. By integrating data on seismic events with a time series of GPS coordinates, we identify coseismic displacements, especially emphasizing the variability of the vertical component. In the analysis, the Lomb-Scargle spectral method was used to estimate the spectral indices after the detection of seismic events, and to obtain detailed information about the changes in the spectral characteristics of the series. The results show significant changes in vertical motion, with the largest coseismic displacement recorded on January 13, 2005, during the seismic swarm. Seasonal oscillations significantly affect the vertical components, which suggests the need for precise modelling to reduce inaccuracies. We also find that seismic activity introduces higher frequency energy into GPS signals, changing the values of the spectral indices, especially in the vertical axis. These studies highlight the effectiveness of integrating geodetic and seismic data for monitoring crustal deformations and their contribution to a more detailed understanding of seismic dynamics in the Adriatic basin.

Keywords: coseismic displacements; earthquakes; GPS continuous time series; Lomb-Scargle model; spectral analysis

1 INTRODUCTION

The surface parts of the Earth's crust are in constant motion and can move significantly horizontally and vertically. Sometimes changes in the Earth's state happen instantly, but most changes occur gradually and slowly so that they are not noticed at all. Modelling of tectonic movements and quantification of deformations of the Earth's crust using GNSS (Global Navigation Satellite System) technology represents an important approach in the study of geodynamics and seismic activity [5]. Analysis of time series taken from GNSS stations, especially those located near tectonic boundaries, provide valuable data for monitoring deformations of the Earth's crust [3]. These time series are often analyzed to identify periodic changes (such as seasonal variations) and temporary events such as earthquakes [5]. Time series of GNSS coordinates are sensitive to real-time seismic motions during moderate to strong earthquakes [9].

The influence of tectonic processes on seismic activity can be better understood by integrating seismic parameters and geodetic data [9]. Spectral indices are derived using the Lomb-Scargle periodogram method. It enables the identification of periodic components in GNSS data and their connection with seismic activity [19]. This is the key to understanding how ground motions are linked to tectonic stress and earthquakes [5]. Integrating seismic and geodetic data enables precise monitoring of deformations of the Earth's crust at both global and regional levels. Tong et al. [24] calculated interseismic deformation rates along the San Andreas fault by integrating high-resolution GPS and InSAR data, enabling a more precise assessment of potential seismic risks. The study by Mavrommatis et al. [14] emphasises the importance of long-term geodetic observation in deciphering pre-earthquake deformation processes, as seen in the analysis before the 2011 Tohoku-Oki earthquake. Shen and Liu [23] use GPS and InSAR data to quantify strain rates in seismically active southern California, highlighting the association of strain patterns with upcoming earthquakes. ElGharbawi and Tamura [7] compare strain data from a single GPS station and an InSAR source in the context of the 2011 Tohoku-Oki earthquake, demonstrating the importance of multiple methods for a more comprehensive analysis of coseismic displacements.

Kai Liu et al. [10] analyze the post-seismic displacements of the 2010 Maule earthquake through high temporal resolution GPS data, which enables a precise separation of co-seismic and post-seismic deformation components. Murray and Segall [16] investigate the spatiotemporal evolution of transient slip on the San Andreas fault through a detailed analysis of time series GNSS data. Cheloni et al. [4] analyzes earthquake mechanisms in Friuli using the integration of geodetic and seismic data and provides significant insight into seismic activity and tectonic processes along the Adriatic microplate boundaries.

One of the main goals of this research is the integration of time series of GPS data from one station and multiple seismic events that contain information about the time, location and magnitude of the earthquake. GPS time series are crucial for the analysis of crustal deformations, where spectral analysis is used to identify discontinuities caused by earthquakes. These time series often contain noise, which is reduced by various techniques to obtain more accurate measures of tectonic and earthquake movements. This research aims to lay the foundations for a deeper understanding of the interaction between tectonic and seismic processes in the area of the Adriatic basin.

2 MATERIALS AND METHODS

2.1 Study of the Area

The territory of Croatia, as part of the Balkan Peninsula, belongs to a seismically active area due to its geological and tectonic position. The active tectonics of the Balkans is conditioned by the continuous movement of the Adriatic microplate towards the northeast. This movement is a consequence of the pushing of Africa towards Eurasia, which creates intense deformation and mutual interactions between local tectonic units [2]. In the global geodynamic context, the Adriatic microplate is surrounded by major mountain ranges: the Dinarides in the northeast, the Alps in the north and west, the Apennines in the west and southwest, and the Hellenides in the south. The Dinarides play a significant role in absorbing and modulating the movement of the Adriatic microplate, creating complex tectonic conditions that contribute to the increased seismicity of the area. The island of Sveti Andrija and the volcanic island of Jabuka, which are located south of Split in the Adriatic Sea, represent complex tectonic structures. The island of Jabuka, with its volcanic origin, results from magmatic processes shaped by tectonic activities on the border between the African and Eurasian plates.

Areas like this, located along key tectonic boundaries, are often affected by seismic events due to the continuous movement of tectonic plates.

In this paper, a GPS station located in Split, localized in the research area under the influence of the Adriatic microplate, is used. Regional tectonic activity, accentuated by the movement of the Adriatic microplate, makes this area ideal for studying the relationship between GPS data and seismic events.

2.2 Input Data

In this paper, the data of the GPS time series of coordinates of the SPLT station were used, downloaded from the Nevada Geodetic Laboratory (NGL) internet service [11], which is known for the collection and analysis of geodetic data. NGL provides access to a wide database of GPS data through its MAGNET + Global GPS Network Map service. The data was collected via a high-precision GPS receiver that is part of a global network that continuously records time series data. The technology enables the monitoring of the surface movement of the soil with millimetre precision, which is of key importance for geodetic and seismological studies.

The data used is a time series of GPS coordinates referring to the IGS14 reference frame established by the International GNSS Service (IGS) in 2014. Although the analyzed data refers to the period from May 5, 2004, to April 2, 2012, all coordinates are expressed in the modern IGS14 reference frame projected to the 2010.0 epoch, following IGS reprocessing standards. The use of this reference frame ensures homogeneity, accuracy, and the ability to directly compare with other contemporary geodetic and seismic data, as IGS14 is compatible with ITRF2014 and includes velocity models that allow coordinate transformation to the defined epoch.

Earthquake data was taken from the U.S. Earthquake Catalog Geological Survey (USGS) [25]. The USGS collects and stores earthquake data around the world, providing open access to scientists and experts for research purposes. In this case, the "Search Earthquake Catalog" was used to obtain the relevant data [25]. The downloaded data includes all earthquakes with a magnitude greater than 2.5 Mw in the period from May 5, 2004, to April 2, 2012. These earthquakes were localized in the area of the islands of Sveti Andrija and Jabuka, as well as in their immediate surroundings (Fig. 1).

In the period from the end of 2004 to the middle of 2005, an earthquake swarm was recorded. An earthquake swarm is a series of smaller earthquakes that occur in a short period in the same region and can significantly affect the spectral analysis of a GPS station, introducing increased seismic noise and a series of smaller changes that can accumulate over time.

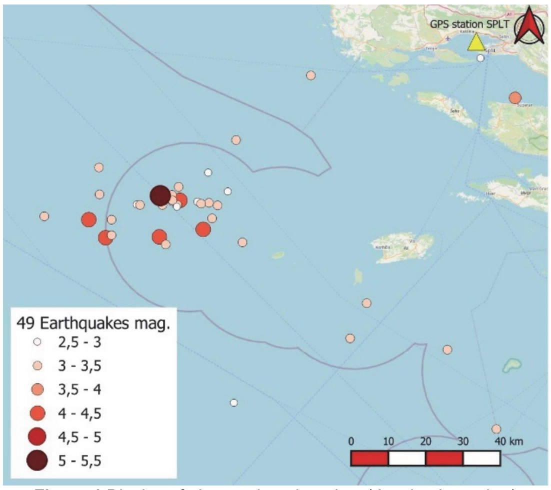

Figure 1 Display of observed earthquakes (drawing by author)

These fluctuations can affect the slope of the spectral indices and signal changes in seismic activity. To facilitate data analysis and integration, all seismic events are stored in JSON (JavaScript Object Notation) format. This data format is easy to read and interpret and provides easy data transfer between different systems and analysis tools. Each recorded earthquake in the USGS catalogues corresponds to data recorded in the time series of the GPS station SPLT.

2.3 Methods

Fig. 2 presents a flowchart showing the steps of the GPS and seismic data processing and analysis model. GPS data goes through a time series cleaning process, then long-term trends are modelled. After that, the GPS data is analyzed to identify periodic variations.

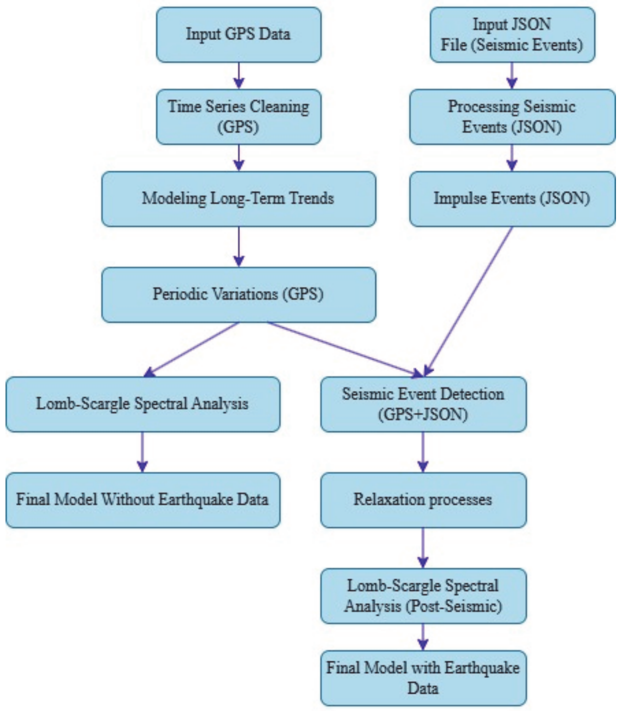

Figure 2 Flow diagram for seismic and GPS data modelling and analysis

There are two parallel branches after periodic variations. The first branch leads to the Lomb-Scargle spectral analysis and gives the final model without earthquake data, and the second branch leads to the post-seismic Lomb-Scargle spectral analysis and the final model with earthquake data. A model structured in this way enables analysis with and without earthquakes, providing two different interpretations of the data at the end of the analytical process.

2.4 Mathematical Model of the Time Series of GPS Coordinates of the Station SPLT

The mathematical model of the time series of GPS coordinates consists of a deterministic and a functional part. The deterministic part of the model refers to long-term trends and seasonal changes in the data. These changes can be caused by factors such as annual temperature variations, atmospheric pressure or other natural phenomena that systematically affect changes in the position of the GPS station. The functional part of the model refers to stochastic components, that is, to random and unpredictable changes in the data, which remain present even after the deterministic part is removed.

Before applying the mathematical model, it is necessary to eliminate outliers, which may arise due to measurement errors or temporary anomalies in the environment. Outliers can significantly degrade model accuracy, especially if they remain unidentified and not removed from the data set. For this reason, the application of algorithms for the detection and removal of outliers is a key step in data preprocessing. The outlier identification process in this paper includes the application of the SIGSEG (SIGnal SEGmentation) algorithm, which is a tool for detecting discontinuities in the GPS time series of coordinates, originally developed in 1987 by Blake and Zisserman for image processing [27]. Removal of outliers in the GPS time series of SPLT station coordinates was realized using a robust algorithm based on IQR (Interquartile Range) for identification and rejection decision level $\mathrm{n}=3$ [17]:

$$\left|\hat{v}_i - median\left(\hat{v}_{i-w/2}, \hat{v}_{i+w/2}\right)\right| > 3 \cdot IQR\left(\hat{v}_{i-w/2}, \hat{v}_{i+w/2}\right) \quad (1)$$

where: $\hat{v}_i$ - the GPS coordinate value at epoch *i*, i.e., the observed point in the time series, $\hat{v}_{i-w/2}, \hat{v}_{i+w/2}$ - neighbouring values around epoch *i*, within a sliding window of width w, and $3 \cdot IQR$ - the outlier detection threshold: if the deviation from the median exceeds three times the *IQR*, the value is considered an outlier.

To mathematically model a time series of GPS coordinates, it is necessary to take into account several different factors that contribute to the overall variation in the data. A complete mathematical model for a GPS time series of coordinates for a single position component is presented [30]:

$$\begin{aligned} y(t_i) = & \left[a + \sum_{i=1}^{n} b_i (t_i - t_0)^i\right] + \\ & + \left[\sum_{i=1}^{n_p} \left(c_i \sin(2\pi t_i / p_i) + d_i \cos(2\pi t_i / p_i)\right)\right] + \\ & + \left[\sum_{i=1}^{n_g} g_j H\left(t_i - t_{g_j}\right)\right] + \\ & + \sum_{i=1}^{n_A}\left[\left(c_{A_i} + AH \ln\left(1 + \frac{t_i - t_{eq}}{\tau}\right)\right)\right] + \left[\sum_{i=1}^{n_e}\left(t_{e_i}\right)\right] \end{aligned} \quad (2)$$

This term describes a complex mathematical model of a GPS time series of coordinates that includes various components that model both smooth variations of coordinates over time (trends) and periodic variations and impulsive events such as earthquakes. The first part of the model is a polynomial model used to describe the long-term trend and non-linear variations in time series data where: $y(t_i)$ - the value of the time series at the time t_i, a - constant that represents the initial value or average value, b_i - polynomial coefficients that represent unknown parameters that define the shape of this trend and t_0 - reference moment (eg the beginning of observations).

The second part models seasonal (periodic) variations, such as seasonal oscillations or other periodic phenomena that often occur in GPS data, usually due to atmospheric effects. The periodic components are expressed through sine and cosine functions with periods p_i, while c_i and d_i are the amplitudes of the sine and cosine components of these oscillations for the corresponding period.

The third part models jumps in the time series. Jumps can be the result of geophysical events such as earthquakes, changes in GPS instrumentation or some other discontinuities where: $H\left(t_i - t_{g_j}\right)$ – Heaviside's function that includes the signal at the time t_{g_j}. This part models impulsive changes in the time series, such as sudden jumps caused by earthquakes or other sudden changes and g_j - amplitude of the jumps at the time t_{g_j}.

The fourth part models the slow, gradual change that can occur after an event such as an earthquake. The coefficient c_{A_i} determines the base value after the change, AH is the amplitude of the change. The logarithmic function describes the slow recovery or stabilization over time after the change occurs, t_{eq} is the moment when the change started and τ represents a time constant that determines the speed of system adaptation, i.e. the speed with which the effect of the earthquake decreases or "dies" over time. A higher value τ indicates a slower recovery process after an earthquake.

The fifth part presents noise or measurement errors that are not modelled by the previous parts. Noise is usually random and may be due to atmospheric disturbances, instrumental errors, or other sources of variability in the data, describing residual random or nonlinear effects.

Defining a periodogram or spectral analysis of a time series is used to detect dominant frequencies within a series of data. Spectral density estimation is very important in seismology, especially before and during seismic events, because it provides insight into ground movements and internal mechanisms of tectonic activities. Time series of GPS coordinates are often unevenly sampled, which is a challenge in analysis. In the paper, the Lomb-Scargle model was used to estimate unevenly sampled data and it represents the basis for estimating the power spectral density $P_x(\omega)$ as a function of frequency ω [12]:

$$P_x(\omega)=\frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{j=1}^{N}\left(y_j-\bar{y}\right)\cos\omega\left(t_j-\tau\right)\right]^2}{\sum_{j=1}^{N}\cos^2\omega\left(t_j-\tau\right)}+\frac{\left[\sum_{j=1}^{N}\left(y_j-\bar{y}\right)\sin\omega\left(t_j-\tau\right)\right]^2}{\sum_{j=1}^{N}\sin^2\omega\left(t_j-\tau\right)}\right\} \tag{3}$$

where: $P_x(\omega)$ - power spectral density as a function of frequency ω and measures how much variation there is in the data at different frequencies, y_i - observed value of the time series at the moment t_j, $\bar{y}$ - mean value of the time series, ω - the frequency for which the power spectral density is calculated, N - total number of observations in the time series, τ - time phase shifting the cosine and sine functions, to achieve an optimal fit between the periodic data components and the cosine and sine functions.

The spectral index α is used to describe how the spectral power decreases with frequency in the time series:

$$\alpha=\frac{d\log P(\omega)}{d\log\omega} \tag{4}$$

The spectral index α can indicate the nature of the process that generates these data and is divided into Fractal Brownian motion $(-3<\alpha<-1)$ and Fractal Gaussian motion $(-1<\alpha<+1)$, which are usually geophysical phenomena in the range $-3<\alpha<-1$ [1]. Special cases of spectral indices are the special cases of uncorrelated white noise ($\alpha=0$), flicker noise ($\alpha=-1$) and random walk noise ($\alpha=-2$).

3 RESULTS OF NUMERICAL RESEARCH

3.1 Time series of GPS coordinates of SPLT station

The original GPS-contaminated time series of SPLT station coordinates (Fig. 3) illustrates position changes in the E, N and Up components in the period from May 2004 to February 2012. The total number of epochs (daily resolution) is 2839, with gaps of 1.7%. As can be seen, there are no significant anomalies except for a few outliers that may be the result of interference or technical problems. The northern and eastern components show a linear trend of constant movement towards the north and east through the culvert. The up component shows significantly less stability compared to the horizontal components.

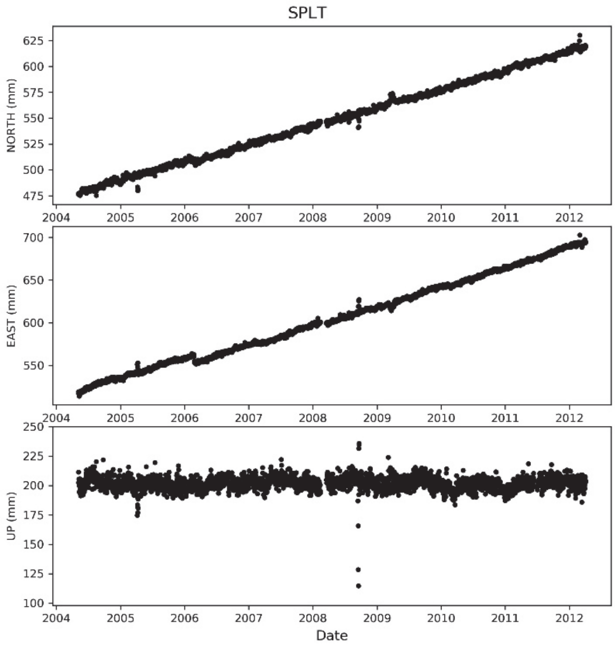

Figure 3 GPS time series coordinates for station SPLT

3.2 Detection and Removal of Offsets and Outliers from GPS Coordinate Time Series

The displacements identified in the SPLT time series, as shown in Fig. 4, show different amplitudes. Using the SIGSEG algorithm allows us to identify and remove irregularities in the data. It can be particularly useful in the context of earthquake or post-seismic displacement detection, where sudden changes in GPS data are crucial.

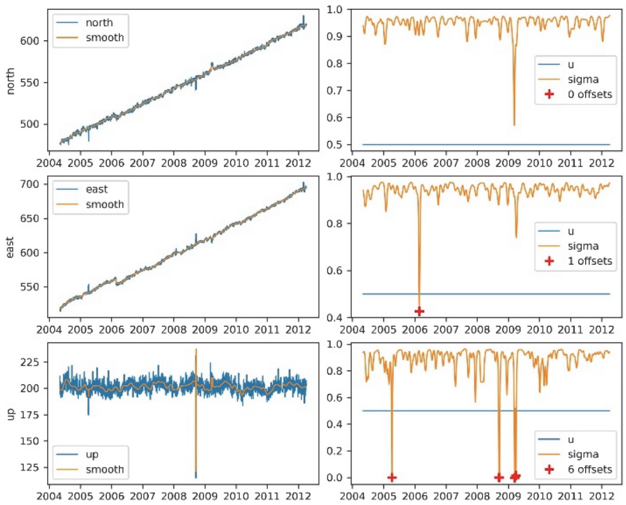

Figure 4 Offset detection for station SPLT using the SIGSEG algorithm

Tab. 1 shows the data before and after discarding gross errors, that is, all data in the SPLT time series whose deviation was three times higher than the value of the standard deviation on the entire time series sample according to (Eq. 1).

The process of removing gross errors improved the quality of the data. The percentage of gaps in the time series increased, but anomalies that could distort long-term trends, especially in the vertical component, were removed.

Table 1 Data availability and gaps in time series before and after cleaning

	GPS time series coordinates for station SPLT	
	Contaminated time series	Cleaned time series
Epoch	2839	2740
Gaps / %	1.7	5.2

3.3 Modeling the Basic Long-Term Trend and Seasonal Changes in GPS Time Series

Fig. 5 shows the time series of coordinates of GPS station SPLT for all three components N (North), E (East) and Up, and their movement during the period from 2004 to 2012. The North and East components clearly show a linear trend towards the north and east. This suggests continuous tectonic activity. The vertical component shows much greater variability and does not follow a linear trend as the horizontal component.

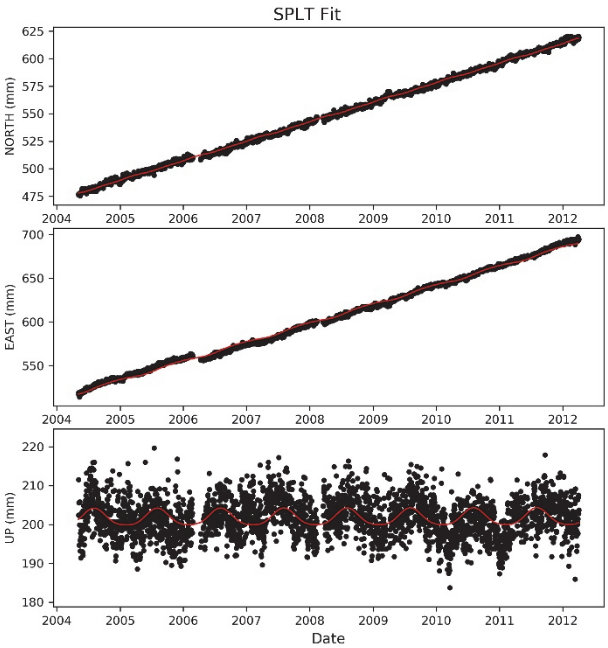

Figure 5 GPS station SPLT: long-term trends and seasonal variations

Tab. 2 shows the results of GPS station SPLT, including WRMS (Weighted Root Mean Square), semi-annual and annual variations, as well as estimated velocities in the IGS14 frame. WRMS represents the average deviation between observed and predicted values, using weights for each value.

Table 2 The results of station velocity SPLT including WRMS, semi-annual and annual variation and estimated velocity in the IGS14 frame

Solution	SPLT		
	North component	East component	Up component
WRMS /mm	1.61	2.82	4.72
Velocity-IGS14 / mm/yr	17.76 ± 0.01	21.73 ± 0.02	0.02 ± 0.04
Semi-ann. / sin mm	0.13 ± 0.04	0.21 ± 0.08	0.34 ± 0.13
Semi-ann. / cos mm	−0.27 ± 0.04	−0.06 ± 0.08	0.18 ± 0.13
Ann. / sin mm	0.29 ± 0.04	−0.93 ± 0.08	−1.17 ± 0.13
Ann. / cos mm	0.25 ± 0.04	1.03 ± 0.07	−1.82 ± 0.13

The northern component has the smallest WRMS value of 1.61 mm, while the vertical component shows the largest uncertainty with a value of 4.72 mm. WRMS provides useful information about the stability of measurement results over time and helps to assess the reliability of the measurement system. Low WRMS values show more consistent and reproducible measurement results, indicating higher precision of the measurement system. The SPLT station moves towards the northeast, while the vertical component is almost unchanged. Semi-annual and annual oscillations are present in all components but are most pronounced in the vertical component. Seasonal oscillations are most pronounced in the annual components and show significant changes in position during different seasons, especially in the vertical component (−1.82 ± 0.13 mm for the cosine term).

3.4 Identification and Quantification of Coseismic Movements of the GPS Station SPLT

By applying a complex mathematical model and parts related to the Heaviside function and the gradual change model for $w = 1$, the coseismic displacements of the GPS station SPLT were quantified (Fig. 6).

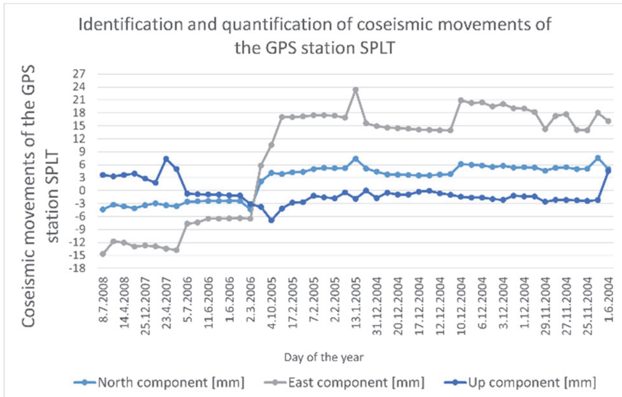

Figure 6 Coseismic movements of the GPS station SPLT (North component, East component and Up component)

The maximum coseismic displacement was identified on January 13, 2005, and represents the largest seismic event within the seismic swarm. All three components are stable until the moment of increased seismic activity when there is a clear jump in displacement values. The largest displacement was recorded in the East component (approximately 25 mm). Such data enable precise analysis of earthquake dynamics and risk assessment of future events, which is of crucial importance for the protection of infrastructure and human lives.

3.5 Coefficients of Spectral Indices of Time Series of GPS Coordinates

The importance of spectral indices is reflected in the detection and characterization of crustal movements and seismic activity. It is particularly useful for analyzing how a GPS station reacts to tectonic stress and how these changes are manifested in the frequency domain. Using the Lomb-Scargle periodogram, the periodograms for all three components of the SPLT station position were calculated and displayed (Fig. 7). Spectral indices, without including data on earthquakes, contain key information about energy distribution in different frequencies. The spectral index for the northern component is −1.62±0.02, for the eastern component 1.64±0.02 and the vertical component −1.53±0.03. These indices indicate how the energy of the time series is distributed depending on the frequency. Negative slopes indicate that energy decreases with increasing frequency, which is common for natural processes, where lower frequencies contain more energy, while higher frequencies refer to faster oscillations and smaller displacements.

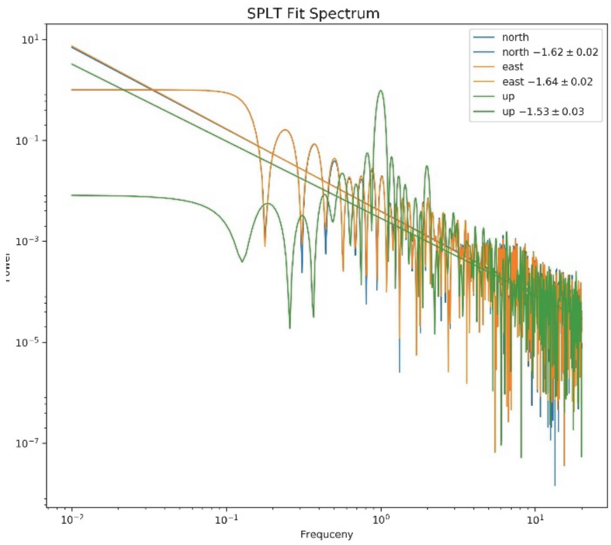

Figure 7 Spectral indices of the GPS station SPLT.

Fig. 8 shows the estimated spectral indices for the north, east and elevation components for each earthquake for which the coseismic movements of GPS station SPLT were identified and quantified. Negative values of spectral indices indicate the dominance of low-frequency components in the spectrum, which is often associated with long-term or post-seismic ground movement. Spectral indices of seismic activity and earthquake magnitude are related, but not directly. The magnitude of the earthquake measures the total amount of energy released, while the spectral analysis provides insight into the distribution of that energy by frequency.

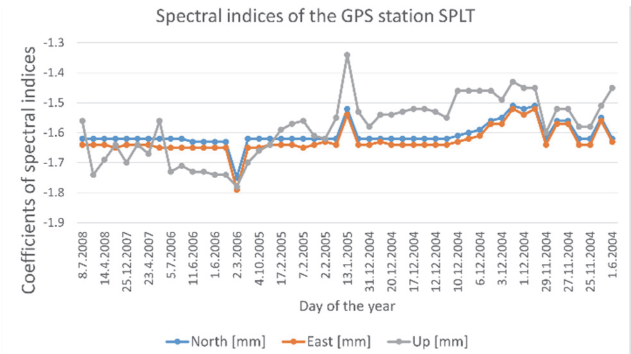

Figure 8 Spectral indices of GPS station SPLT for days of the year

Fig. 9 presents one of the spectral indices with included data on the earthquake (January 13, 2005) and shows changes in the time series of GPS coordinates due to the seismic event. Spectral analysis with included earthquake data shows clear differences compared to values without seismic data. The introduction of earthquake data changes the energy distribution at higher frequencies, especially in the vertical component, which indicates significant coseismic effects and changes in station position due to the seismic event.

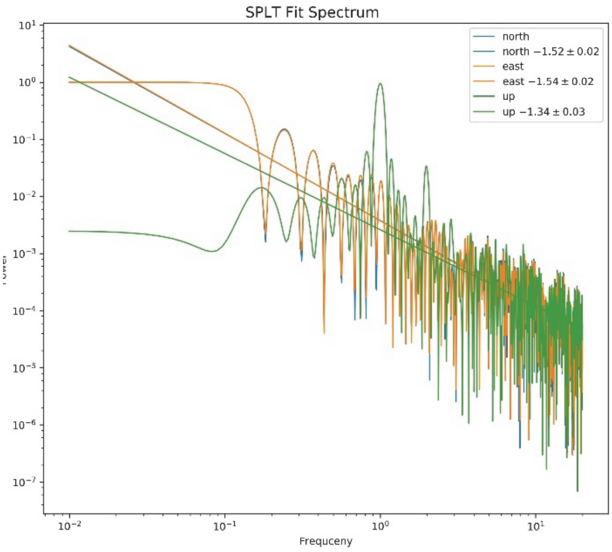

Figure 9 Spectral indices on 13.01.2005. year

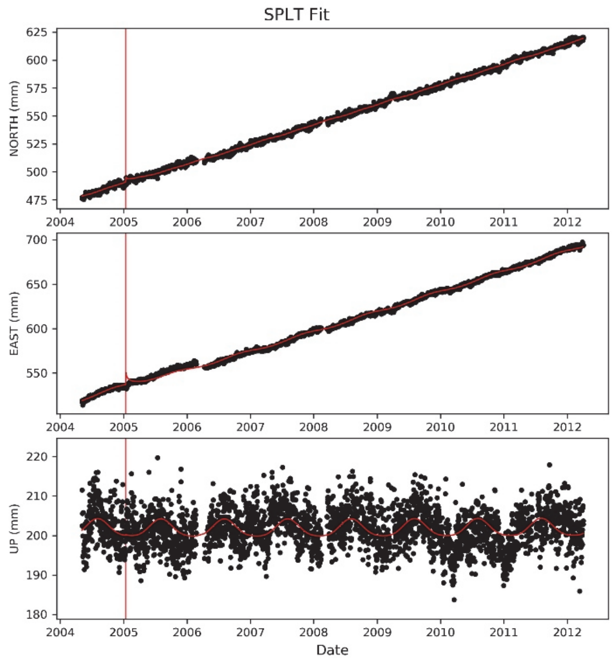

Figure 10 Changes in the time series of GPS coordinates due to the seismic event (13.01.2005. year)

4 DISCUSSION

The advanced development of modern geodetic techniques, GNSS, has a significant contribution to the evaluation of temporal and spatial changes in the Earth's surface. Today, GNSS has reached the necessary accuracy and precision for monitoring surface deformations at the local and global levels. The great contribution of the time series of GNSS coordinates is reflected in the detection of geophysical phenomena, especially seismic ones. The interaction of seismology and geodesy provides access to the dynamic study of the Earth's interior and the measurement of global deformations at different levels.

In this analysis, we used data from the GPS station SPLT for the analysis of long-term and seasonal variations, as well as for the evaluation of spectral indices before and after the inclusion of earthquake data. The results show a clear difference in the spectral distribution of energy, especially in the vertical component, when earthquakes are included in the analysis.

When we analyze time series without earthquake data, long-term trends and seasonal variations dominate. The linear growth of the northern and eastern components indicates a stable horizontal movement of the station, which is expected considering the tectonic activities in the region. The northern, eastern and vertical components are stable over the years until the moment of increased seismic activity when there is a clear jump in displacement values. The largest displacement is observed in the East component because the vector of the coseismic ground movement was predominantly directed eastward, which is typically directly related to the orientation and type of the fault.

When earthquake data are included, the energy spectrum shows significant changes, especially in the vertical component. Seismic activity causes an increase in energy at higher frequencies, indicating rapid ground oscillations caused by co-seismic movements. Also, the spectral slopes of all components become less negative, which indicates a redistribution of energy in higher frequencies. Negative spectral indices indicate the dominance of low−frequency components, especially in scenarios without earthquakes. This is expected because long-term trends and seasonal changes usually dominate in the absence of seismic activity. However, when earthquakes are triggered, the spectral slopes become less negative, indicating a redistribution of energy towards higher frequencies, which is characteristic of seismic events.

5 CONCLUSION

The biggest challenge in the analysis is seasonal variations, where the most pronounced oscillations are in the annual components and show the most significant changes in the vertical component of −1.82 ±0.13 mm for the cosine term, which is why it is necessary to carefully model these effects to eliminate possible inaccuracies. Given that the SPLT GPS station is installed in the coastal area, there are several factors associated with this phenomenon. Changes in sea level, and tides, are often rhythmic effects and can create seasonal or semi-annual oscillations. The increase in water mass during high tide can cause local deformations of the soil, which can result in a temporary vertical movement of the GPS station. Stations close to the coast may be more susceptible to seismic and geological processes, such as micro-soil movements or tectonic changes associated with soil movement in coastal zones. Proximity to the sea can significantly affect the vertical component of the SPLT station due to a combination of hydrographic and geophysical effects.

After modelling seasonal variations, data on long-term position changes were obtained. The estimated velocities show that the SPLT station, in the IGS14 reference frame system, is moving at a rate of 17.76 mm/yr to the north and 21.73 mm/yr to the east. In comparison, the vertical component showed a near-stationarity of 0.02 mm/yr.

Spectral indices with included data on earthquakes indicate changes in the GPS time series due to the seismic event. The introduction of earthquake data changes the distribution of energy at higher frequencies, especially in the vertical component, which indicates significant co-seismic effects and changes in the position of the station due to the seismic event. Spectral indices with included data on the earthquake on January 13. 2005, show the spectral slope of the northern component of −1.52 compared to the spectral slope without including earthquakes of −1.62. The spectral index of the eastern component also shows a slope of −1.54 compared to the spectral slope without including earthquakes of −1.64. The vertical component has a slope of −1.34 and shows a significant increase in energy in higher frequencies compared to the spectral slope without including earthquakes of −1.53. This suggests the presence of an earthquake that causes ground movements and increases activity at higher frequencies. Earthquakes often cause sudden changes in the vertical position of GPS stations, which explains the significant drop in the spectral index in the vertical component.

Although spectral indices are useful for the identification of seismic events, analysis alone is not sufficient for precise quantification of earthquake magnitude. The magnitude of the earthquake does not speak directly about the spectral composition of the signal, so additional methods should be introduced for a better assessment of the magnitude and intensity of seismic activity. Additional care is needed when analyzing vertical components in coastal areas because seasonal changes can mask real tectonic signals. The inclusion of additional methods, such as the analysis of atmospheric effects and tides, is suggested to improve the understanding of seasonal variations in the vertical components.

Unlike a single large earthquake, an earthquake swarm creates a series of smaller fluctuations, which can add up to an accumulated effect on ground motion. The earthquake swarm produced seismic noise, which is seen as increased activity in the indices, especially in the vertical components. The noise caused by the swarm has fractal characteristics, which are described by fractal Brownian motion indicating complex geophysical processes. An earthquake swarm can signal the accumulation of stress in the crust, which can precede a larger earthquake, and changes in spectral indices can help predict seismic events. To improve future analysis, it is recommended to improve the time resolution of the data, including external data from other stations, continuous monitoring of seismic activity, and additional research of local geological factors can help in better understanding of variations in spectral indices.

This analysis shows that GPS stations can provide significant insight into tectonic and seismic processes. In this analysis, a complex mathematical model of the GPS time series of coordinates was used, which models long-term trends, seasonal variations, and jumps in the time series that are the result of geophysical events - earthquakes. Although atmospheric and geophysical models are not included in this study, their inclusion in future research could improve the accuracy of seismic effects estimation.

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