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Research paper

ANALYSIS OF GNSS STATION SRJV00BIH AND SEISMIC ACTIVITY

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Abstract

This paper deals with the analysis of the time series of GNSS coordinates from station SRJV00BIH and their connection with seismic activity along key faults in Bosnia and Herzegovina. By using data on a time series of GNSS coordinates, the possibility of detecting tectonic movements in the context of specific earthquakes that occurred on a certain day was investigated. This seismic activity is linked to the data collected from the GNSS station. This involves the interaction of GNSS data with seismic events of intermediate magnitudes to identify potential deformations accompanying an earthquake. By monitoring these data, it is revealed whether there was a movement of the ground or deformations during the period of the earthquake. The methodology includes using the TSAnalyzer tool to analyse long-term trends and use of the Heaviside function, thereby identifying fluctuations potentially related to seismic activity. The results showed the existence of certain patterns in coordinate changes that coincide with seismic events on faults in the region, which suggests that GNSS stations can serve as an additional tool for monitoring geodynamic phenomena and improving the precision of seismic monitoring. Further research is proposed to improve the detection accuracy and integration of GNSS networks into regional early warning systems. The study aims to determine to what extent terrain deformations that precede significant seismic events can be detected and how GNSS data can help better understand fault activity.

Key words: *Global navigation satellite systems, Seismic activity, Time series, Ground deformation, Bosnia and Herzegovina, TSAnalyzer*

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1. INTRODUCTION

The advancement of geodetic measurement techniques and GNSS technology facilitates the recording of displacements and the precise determination of persistent movements of GNSS stations. Geodetic measurements in seismology are very demanding and of great importance for understanding processes at plate boundaries, because data on surface deformations help find new slip redistributions that can cause surface displacements. Tectonic geodesy is a branch of geodesy and geophysics that has significant applications in geoscience. It is an interdisciplinary field that studies the tectonic activity of the crust and its basic kinematics using geodetic measurement methods such as Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR).

Time series of GNSS coordinates allow a quantitative description of the movement of the GNSS station SRJV00BIH. By extracting geophysical signals from the time series of GNSS coordinates, clear insights into the movement of the GNSS station SRJV00BIH are obtained. In combination with seismological data, time series of GNSS coordinates are used to develop algorithms for earthquake modelling [1].

Time series of GNSS coordinates are most commonly used for geophysical research and have proven useful in investigating cycles of seismic deformations that relate to the entire seismic cycle.

The tectonic structure of Bosnia and Herzegovina is characterised by a complex geological structure that includes different tectonic units. Bosnia and Herzegovina is located within the Dinaric system, which is the result of the collision of the African and Eurasian tectonic plates. There are numerous faults in the territory of BiH as a result of tectonic processes. Faults are a factor that affects seismic activity in the country. In some areas, there is a folding of the lithosphere, that is, the deformation of the Earth's crust due to the action of tectonic forces, which leads to specific geomorphological characteristics of that area [2].

Seismic activity in Bosnia and Herzegovina is not evenly distributed throughout the country, but is concentrated in certain zones that are known for their greater activity. The southern part of BiH is known for its significant seismic activity. The area of Mostar, Čapljina and the surrounding areas are often affected by earthquakes. The fault that runs through the southern and northwestern part of BiH is known for its numerous earthquakes that have occurred in the past. The area around Sarajevo has often registered significant seismic events. The area around Banja Luka is also known for its registered seismic activity [2].

Based on data on the seismicity of BiH, it can be concluded that the highest frequency of earthquakes is in the area of Herzegovina, the border with Croatia, and the area of Banja Luka. In Banja Luka, Derventa and Tuzla, in recent years, there has been an increase in seismic activity. Earthquakes with the smallest depth were recorded in the Drina area (Prača, Višegrad, Srebrenica, Zvornik), and with the largest in the northwest and west of BiH [2].

Real-time global navigation systems and fault analysis play a key role in understanding geodynamic processes. The paper analyses the GNSS station SRJV00BIH and seismic activity on faults. The result of continuous GNSS measurements is a time series of GNSS coordinates. A connection has been established between the GNSS coordinates of the SRJV00BIH station and seismic activity on faults, with a special focus on the narrow area around the SRJV00BIH GNSS station.

GNSS time series analysis refers to the examination of data collected from GNSS stations that allow monitoring of changes in position in space over time [1]. The analysis is often used for geodetic, engineering and geophysical research. These researches also include monitoring of the movement of the Earth's crust, landslides, seismic activity and similar phenomena.

GNSS time series represent the position of a GNSS station in certain time intervals and are made up of a series of coordinates (most often in three dimensions: east-west, north-south and vertical). Time series analysis aims to understand movement patterns, long-term trends, short-term events and seasonal changes. The analysis includes statistical and mathematical techniques for data processing, modelling, and interpretation of results to obtain the necessary information about geodynamic processes [1].

2. MATERIALS AND METHODOLOGY

2.1. Study of the area

Compared to other stations, the GNSS station SRJV00BIH, located at the Faculty of Civil Engineering building in Sarajevo, has the longest time series in the region, lasting about 24 years. Stronger earthquakes are rare for the area around Sarajevo, although the territory of Bosnia and Herzegovina falls into a seismically active zone. The hypocenter depth in this area ranges from 4 km to 30 km. Figure 1 shows the antenna of the GNSS station SRJV00BIH, while Figure 2 shows its location.

Figure 1. Antenna TRM57971 on the chimney of the Faculty of Civil Engineering in Sarajevo [3]

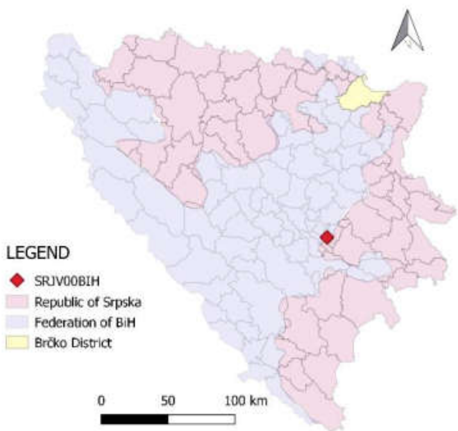

Figure 2. Location of GNSS station SRJV00BIH (drawing by author)

2.2. Input data

This work uses data downloaded from the Nevada Geodetic Laboratory (NGL) [4] website. NGL, through its MAGNET + Global GPS Network Map [4] service, provides access to a wide range of geodetic data and is known for its collection and analysis of geodetic data. These data were collected using a highly accurate GPS (Global Positioning System) receiver that is part of a global network that continuously records time series of data. The technology provides the ability to track surface ground motion with millimetre-level accuracy, which is important for geodetic and seismological studies. The data used are time series of GPS coordinates that refer to the IGS14 reference frame, which was established by the International GNSS Service (IGS) in 2014. The required earthquake data were retrieved from the U.S. Geological Survey (USGS) database [5], which collects and stores earthquake data worldwide. Access to the data and tools is open to researchers and scientists for research purposes. In this case, the Search Earthquake Catalog [6] was used to obtain the relevant data.

2.3. Time series analysis from GNSS station SRJV00BIH

Before applying a mathematical model, it is necessary to eliminate outliers, that is, it is necessary to carry out data cleaning. Outliers can arise due to various factors, such as temporary environmental anomalies or measurement errors and can significantly impair the accuracy of the model, especially if they are not removed from the data set or remain unidentified. For this reason, the application of algorithms for detecting and eliminating outliers is a key step in data preprocessing.

Using a robust algorithm based on the IQR (Interquartile Range) for identification and a rejection decision level of n = 3, outlier removal was implemented in a GPS time series of SPLT station coordinates [7].

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

For long-term trend analysis in GNSS time series, a linear model is most commonly applied, which is expressed as [8]:

$$y(t) = a + bt + \epsilon(t) \quad (2)$$

Where: $y\ (t)$ – GNSS station position at time t, a – initial value, b – trend coefficient (slope) showing the average change in position per unit time and $\epsilon\ (t)$ – residual component (error or noise) containing variability not explained by the linear model.

The coefficient b is a key parameter that indicates the existence of a long-term trend in the data. If b is positive, this indicates the existence of an upward trend (position increases over time), while a negative value of b indicates a downward trend (position decreases over time). When b is close to zero, which suggests that there is no significant long-term trend.

The Least Squares Method is most often used to estimate the parameters a and b. This method minimises the sum of the squares of the differences between the actual values of $y(t)$ and the estimated values from the model [8].

The model can be extended with sinusoidal components, if necessary, to include seasonal effects in the analysis [8]:

$$y(t) = a + bt + ccos\ (\omega t) + d\ sin(\omega t) + \epsilon(t) \quad (3)$$

Where c and d are the coefficients for the sinusoidal components, and ω is the frequency of seasonal oscillations.

These expressions allow for precise analysis of long-term trends and periodic variations in GNSS time series. The long-term trend is analysed without including seasonal variations that occur at specific time points t_0.

The Heaviside function can be useful when we want to include jumps in the time series. This function is used to model such discontinuities.

The Heaviside function, $H(t - t_0)$, is defined as [8]:

$$H(t - t_0) = \begin{cases} 0, t < t_0 \\ 1, t \geq t_0 \end{cases} \tag{4}$$

The Heaviside function can be integrated into a time series model to simulate sudden changes or jumps in the series, such as earthquakes or other sudden changes in the position of GNSS stations.

The modified time series model with this function can be written as [8]:

$$y(t) = a + bt + \sum_{i=1}^{N} k_i H(t - t_i) + \epsilon(t) \tag{5}$$

Where: $y(t)$ – position of the GNSS station at time t, a – initial value (intercept), b – trend coefficient (slope), k_i – amplitude of the jump at time t_i, $\mathrm{H}(\mathrm{t} - \mathrm{t}_i)$ – Heaviside function that activates the jump at time t_i and $\epsilon(\mathrm{t})$ – residual component (error or noise).

The Heaviside function ensures that the jump becomes active only from time t_i onwards, while k_i determines the size of the jump in this model. This method allows for precise modelling of discontinuities that arise due to specific events such as earthquakes or technical changes in GNSS stations.

The weighted root mean square (WRMS) error is used to estimate the precision of a time series, which takes into account the different weights that may be assigned to different points in the series (e.g. due to different measurement reliability).

WRMS is defined as: $\hat{y}$

$$WRMS = \sqrt{\frac{\sum_{i=1}^{N} \omega_i (y_i - \hat{y}_i)^2}{\sum i = 1^N \omega_i}} \tag{6}$$

Where: y_i – actual value of the time series at time *i*, $\hat{y}_i$ – predicted value at time *i* from the model, ω_i – weight assigned to the data at time i, and N – total number of points in the time series.

Implementation procedure:

1. Weight assignment: Based on the reliability of the data, weights ω_i are usually assigned (Points with higher measurement precision receive higher weights).
2. Calculation of residual error: The square of the difference between the actual value y_i and the predicted value $\hat{y}_i$ is calculated for each point i.
3. Summarisation with weights: Each square of the error is multiplied by the corresponding weight ω_i and summed for all points in the time series.
4. Normalisation: The sum of the weighted squared errors is divided by the sum of all weights $\sum_{i=1}^{N} \omega_i$.
5. Calculating WRMS: The square root of the expression gives WRMS.

WRMS takes into account the inhomogeneities in the precision of the measurements and allows a better understanding of the variability of the time series. For example, if some measurements are more precise than others, WRMS will take them into account more when estimating the total error of the series. WRMS can help assess the quality of the model used to analyse trends and spikes in GNSS time series, allowing a more precise quantification of the remaining errors in the series.

3. RESULTS

In this paper, earthquakes in the vicinity of the GNSS station SRJV00BIH were analysed. TSAnalyzer was used for time series analysis. Figure 3 shows the location of the GNSS station SRJV00BIH, as well as earthquakes in its vicinity.

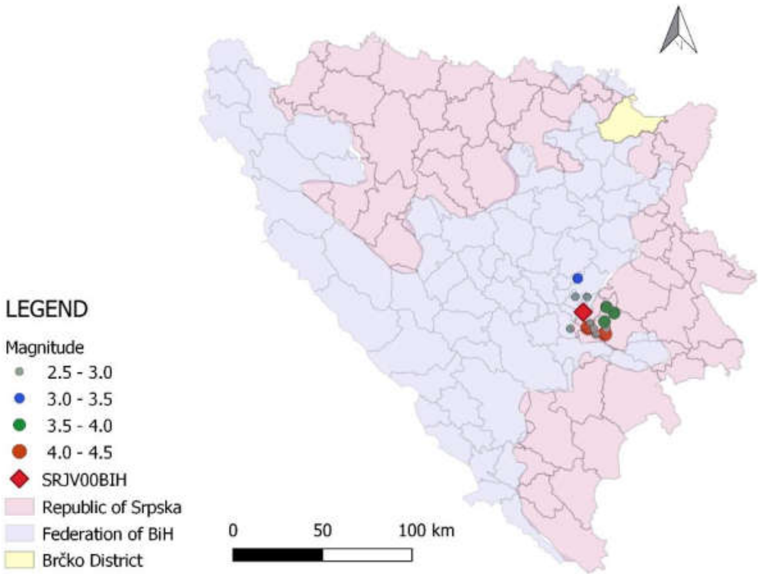

Figure 3. Earthquake report in the vicinity of the SRJV00BIH station (drawing by author)

Table 1 presents earthquakes in the vicinity of GNSS station SRJV00BIH. This table contains information on the depth, magnitude and distance from GNSS station SRJV00BIH for the listed seismic events. The earthquakes range in magnitude from 2.6 to 5.5 on the Richter scale. The depths of earthquakes range from 2 km to 13 km, indicating relatively shallow earthquakes. The distance from the station varies, with some earthquakes being more than 19 km away, while others are closer, e.g. SRJ8 (9,2 km).

Table 1. Depth, magnitude and distance from GNSS station SRJV00BIH for different seismic events

Seismic event	Date	N [°]	E [°]	Deep [km]	Magnitute	Distance from SRJV00BIH [km]
SRJ1	11.06.2000.	43.896	18.582	10.0	3.7	16.6
SRJ2	14.10.2000.	44.041	18.383	10.0	3.4	7.6
SRJ3	11.08.2001.	43.788	18.492	13.3	2.5	11.7
SRJ4	09.05.2003.	43.788	18.330	4.7	2.9	10.9

SRJ5	24.06.2003.	43.814	18.471	10.0	2.7	19.2
SRJ6	31.03.2004.	43.823	18.567	10.0	3.9	13.4
SRJ7	18.08.2005.	43.758	18.508	11.0	2.7	17.2
SRJ8	29.12.2007.	43.947	18.448	5.5	2.6	9.5
SRJ9	31.12.2007.	43.949	18.361	3.2	2.9	17.5
SRJ10	19.07.2008.	43.790	18.580	11.0	2.7	15.7
SRJ11	30.03.2009.	43.866	18.635	2.0	3.9	8.7
SRJ12	31.03.2009.	43.792	18.452	5.0	4.1	14.5
SRJ13	12.04.2015.	43.761	18.569	3.6	4.1	13.0
SRJ14	22.02.2019.	43.760	18.558	10.0	2.7	9.6

Table 2 shows the time intervals of the GNSS series, the number of epochs and WRMS before and after data cleaning. It can be seen that data cleaning reduces the WRMS values in all N (North), E (East) and Up (vertical) components, indicating an improvement in the measurement quality. There are gaps in series SRJ6 and SRJ10. Gaps in time series occur for several reasons and can significantly affect data analysis and modelling. One of the main causes is technical problems. If data is collected using sensors, power outages, equipment failures, or sensor calibration can lead to interruptions in data collection. Errors can occur during the transfer of data from the sensor to the database. If the connection is unstable or the data is stored incorrectly, this can lead to missing values. Sometimes data is intentionally filtered or deleted if it is considered invalid, which also creates gaps.

Gaps in time series can have a significant and often negative impact on data analysis and modelling. They have an important influence on statistical measures such as the mean, variance, and standard deviation. If data from periods with extreme values (peaks or troughs) are missing, these statistics will be incorrectly estimated. This can lead to incorrect conclusions about the underlying characteristics of the series. Understanding gaps is a key step in preparing data for analysis. Ignoring gaps can lead to wrong conclusions and ineffective models.

Table 2. Time series intervals, number of epochs and WRMS before and after data cleaning

Time series	Time series interval		No. of epochs	WRMS (contaminated)			No. of epochs after cleaning	WRMS (after cleaning)		
	From	To		N [mm]	E [mm]	Up [mm]		N [mm]	E [mm]	Up [mm]
SRJ1	15.06.1999.	11.06.2002.	620	2.7	3.2	20.5	599	2.3	2.9	7.7
SRJ2	15.06.1999.	14.10.2002.	743	2.6	2.7	18.9	727	2.4	2.5	6.8
SRJ3	16.02.2000.	19.07.2003.	921	2.5	2.6	7.2	893	2.4	2.5	5.9
SRJ4	08.12.2001.	27.09.2005.	840	1.6	1.8	6.8	811	1.5	1.6	5.5
SRJ5	08.12.2001.	27.09.2005.	840	1.6	1.8	6.8	810	1.5	1.6	5.5
SRJ7	22.02.2002.	29.03.2008.	1109	1.7	2.0	10.0	1078	1.5	1.8	5.7
SRJ8	20.05.2005.	28.04.2009.	625	1.6	2.0	12.1	605	1.4	1.8	6.3
SRJ9	20.05.2005	28.04.2009.	625	1.6	2.0	12.1	605	1.4	1.8	6.3
SR11	26.08.2005.	02.07.2010.	852	1.6	1.9	11.1	826	1.4	1.7	6.5
SR12	26.08.2005.	02.07.2010.	852	1.6	1.9	11.1	826	1.4	1.7	6.5
SR13	26.12.2013.	16.03.2020.	2178	1.6	1.9	12.3	2092	1.3	1.6	5.8
SR14	29.08.2017.	02.03.2021.	2178	1.6	1.9	12.3	1205	1.3	1.5	6.1

Table 3 presents the time series velocity by component N, E, Up and the component coseismic displacement (i.e., ground movement caused by earthquakes) for different time series. The velocity shows the changes in millimetres per year for each component. The coseismic displacement values represent sudden movements due to seismic events.

Table 3. Presentation of time series velocity by component and coseismic displacement by component

Time series	Velocity displacement by component			Coseismic displacement by component		
	N [mm/god]	E [mm/god]	Up [mm/god]	N [mm]	E [mm]	Up [mm]
SRJ1	27.4±0.4	12.0±0.5	4.2±1.4	16.1±0.9	-24.5±1.1	13.9±3.0
SRJ2	24.9±0.4	12.9±0.4	1.4±1.0	-1.8±0.8	-4.0±0.9	0.2±2.3
SRJ3	19.6±0.2	19.7±0.3	-3.6±0.6	-6.9±0.7	9.9±0.7	-1.1±1.7
SRJ4	22.9±0.2	16.3±0.2	-3.1±0.6	-1.9±0.6	-4.1±0.6	1.7±2.2
SRJ5	22.9±0.1	16.4±0.2	-3.0±0.5	-0.9±0.4	-3.0±0.4	2.2±1.5
SRJ7	23.4±0.1	16.1±0.1	-1.8±0.2	0.8±0.4	5.7±0.5	-9.3±1.7
SRJ8	22.8±0.1	15.2±0.2	1.0±0.6	-0.1±0.4	-3.2±0.5	-1.1±1.8
SRJ9	22.9±0.1	15.2±0.2	1.0±0.6	-0.1±0.4	-3.6±0.5	-0.8±1.9
SR11	22.9±0.1	14.9±0.1	2.1±0.2	1.8±0.4	0.4±0.5	4.2±2.0
SR12	22.9±0.0	14.9±0.1	2.1±0.2	1.9±0.4	0.2±0.5	4.5±2.0
SR13	22.2±0.0	14.9±0.0	0.0±0.2	-1.9±0.3	-2.1±0.4	-5.5±1.4
SR14	22.4±0.1	14.1±0.1	-0.6±0.5	-1.9±0.4	-3.2±0.4	1.3±1.6

The data indicate continuous motion, with significant horizontal and vertical displacements evident over long-term time series. Earthquakes in this area are relatively shallow but strong enough to cause coseismic displacements. GNSS data from the stations allow for precise tracking of these changes, which can help in better understanding seismic activity and its impact on the ground.

The correlation between the coseismic vertical displacement (Up) of the GNSS station and the earthquake magnitude (left graph in Figure 4) was performed, and it is -0.12, which indicates a very weak negative correlation. This means that there is no clear relationship in the data between the earthquake strength (magnitude) and the vertical ground displacement. It can be seen that earthquakes of smaller magnitude (below 4.0) as well as those of larger magnitude (above 4.0) can cause ground displacements that vary from positive to negative values. This indicates that the magnitude factor itself is not decisive for determining the vertical displacement. The correlation between the distance from the GNSS station and the coseismic vertical displacement (Up) is 0.23 (right graph in Figure 4), which also indicates a very weak positive correlation. The graph shows that vertical displacements are present in both earthquakes, closer to the station and those further away, but there is no clear trend indicating a significant effect of distance on ground motion.

The results of the analysis of horizontal displacement and the correlation between earthquake magnitude and horizontal coseismic displacement (N and E components) are -0.07, indicating a very weak negative correlation (left graph in Figure 5). This means that there is no clear relationship between earthquake strength (magnitude) and horizontal ground motion. Earthquakes of different magnitudes cause similar levels of horizontal displacement. The correlation between distance from the GNSS station and horizontal coseismic displacement is 0.31, indicating a slightly positive correlation (right graph in Figure 5). Although not strong, this correlation is a little bit more pronounced compared to vertical displacements, suggesting that distance from the station may have a slightly greater impact on horizontal ground displacement.

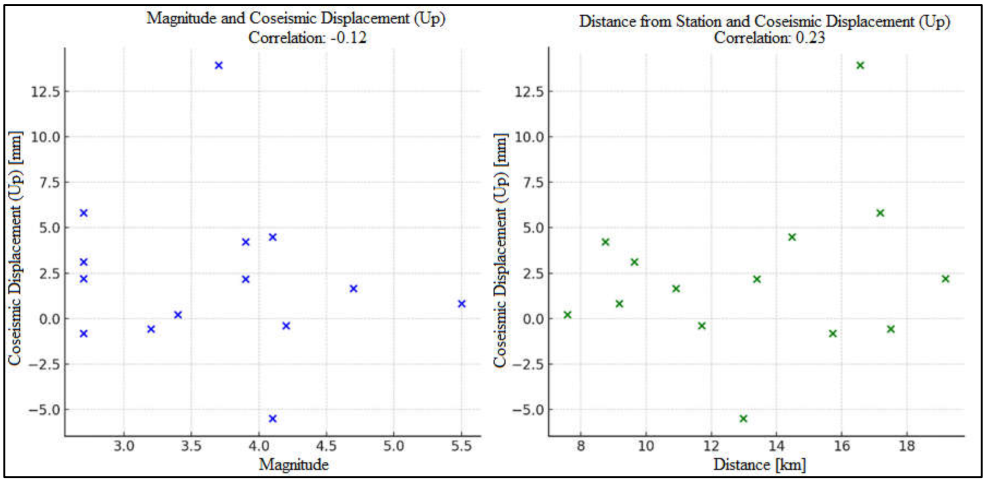

Figure 4. Display of weak correlation between the coseismic vertical displacement of the GNSS station and the earthquake magnitude, as well as the distance from the station (drawing by author)

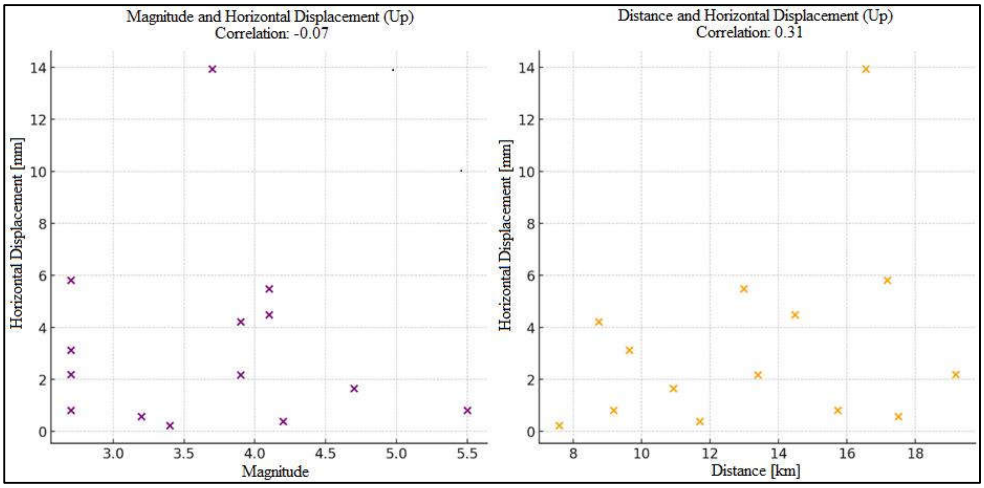

Figure 5. Display of the analysis of the relationship between the horizontal coseismic displacement of the GNSS station and the earthquake magnitude, as well as the distance from the station (drawing by author)

4. DISCUSSION

The WRMS values for the N, E and Up components were reduced after data cleaning in almost all time series. This shows that the data cleaning process significantly improves the measurement accuracy by reducing noise and eliminating contaminated data. Some series, such as SRJ1 and SRJ2, have a significant reduction in WRMS values, especially in the vertical component (Up), indicating that these series were significantly affected by noise or irregularities before cleaning. For example, for SRJ1, the WRMS in the vertical component (Up) was reduced from 20,5 mm to 7,7 mm, which is a significant improvement. The vertical component (Up) generally shows higher WRMS values compared to the horizontal components (N and E). This is expected because GNSS measurements usually have higher imprecision in the vertical axis. After cleaning, the improvements in the N and E components are less pronounced than in the Up component, indicating that the vertical component was more affected by noise. Time series such as SRJ3, SRJ4 and SRJ5 show relatively small WRMS values even before cleaning, indicating a more stable measurement during that period. These series had less noise, which means that the GNSS data in those periods were less contaminated. Time series such as SRJ6 and SR10 have gaps, which can further affect the accuracy of the WRMS values. Gaps in the data can lead to larger errors in coordinate interpretation, especially during periods of increased seismic activity.

The movement speeds are expressed in mm/yr and represent the mean annual movement speed for each component (N-north, E-east, Up-vertical). The highest movement rates in the northern component were recorded for the SRJ1 series (27.4 mm/yr), while the lowest rates were recorded for the SRJ3 series (22.2 mm/yr). In the eastern component, the SRJ3 series shows a relatively high rate of 19.7 mm/yr, while the SRJ1 series has the lowest rate of 12.0 mm/yr. The vertical component (Up) shows significant deviations, with the SRJ1 series recording the highest movement rate of 4.2 mm/yr, while the SRJ3 series has a negative rate, indicating ground subsidence in that area. The coseismic displacement shows the total displacement by component in mm during the monitoring period. The SRJ1 series shows the highest coseismic displacement in the eastern component (24.5 mm), indicating a significant eastward shift. Also, the SRJ1 series shows relatively high coseismic displacement in the vertical component (13.9±3.0 mm), which indicates ground uplift in this area during the measurement period.

Negative values of coseismic displacement, such as those recorded in the SRJ7 series for the Up component (-9.3 mm), indicate ground subsidence during that period. Series with gaps in the time series (SRJ6 and SRJ10) may show larger fluctuations due to a lack of continuity in the data. The SRJ13 series shows more stable movement rates in all three components, which may indicate a more stable tectonic regime during the monitoring period. The vertical component shows larger oscillations compared to the horizontal components (N and E), which is expected because GNSS measurements are traditionally less precise in the vertical axis. Series with positive vertical displacement (e.g. SRJ1) indicate ground uplift, while series with negative displacement (e.g. SRJ7) indicate ground subsidence.

This analysis of velocities and coseismic displacement by component allows a deeper understanding of tectonic movements and ground deformations in the area monitored by GNSS stations. The data indicate significant changes in the horizontal and vertical components, which can be associated with tectonic activities and seismic events in the region.

5. CONCLUSION

Based on the conducted research and analysis of time series of coordinates from the GNSS station SRJV00BIH, it can be concluded that there is a significant potential for using GNSS data for monitoring seismic activity and detecting tectonic movements in Bosnia and Herzegovina. The analysis showed that changes in GNSS coordinates often coincide with periods of increased seismic activity, especially near key faults in the region. This shows that GNSS stations have an important role in predicting seismic events and improving early warning of earthquakes.

Based on the WRMS analysis, it can be concluded that the cleaning process significantly contributes to improving the accuracy of GNSS data, especially in the vertical component. Data cleaning is crucial for ensuring reliability in monitoring tectonic movements and accurate monitoring of seismic activity. Based on the results, it can be concluded that neither earthquake magnitude nor distance from the GNSS station shows a significant relationship with horizontal or vertical coseismic displacements. However, distance from the station may have a slightly greater impact on horizontal displacements compared to vertical displacements. This indicates that for a deeper understanding of these displacements, other factors should be included, such as local geology, earthquake depth, tectonic faults and soil types, which can significantly affect the patterns of ground displacement during seismic events.

Coseismic displacements derived from the time series of the GNSS station SRJV00BIH indicate that vertical and horizontal ground changes are closely related to activities on local faults. Different values of movement velocities and coseismic displacements reflect how seismic activities affect deformations in certain periods.

The coverage of seismic sensors is poor. One century-old analogue and a few recently installed seismometers are insufficient for a region that exhibits mild to high seismic activity. Significant investments are needed to establish or improve GNSS, seismic and other sensor networks.

It is important to properly expand GNSS networks and integrate them with seismic sensors to obtain accurate and reliable data for seismic surveys and early warning systems. The combination of these two technologies allows for the measurement of both fast dynamic movements (seismic sensors) and slow, long-term ground movements (GNSS).

It is crucial to carefully select the locations of the stations to maximize coverage and accuracy. The stations should be placed on geologically stable ground (e.g. on rocks or stable foundations) to reduce the impact of noise from surface waves and human activities. A denser network is required for monitoring local seismic activity, while a sparser one can be used for regional studies. It is recommended to place the stations at 30-40 km for optimal monitoring, and this distance can be smaller in areas with high earthquake risk [9].

GNSS receivers and seismic sensors (accelerometers) must be installed at the same location, preferably on the same stable ground, to ensure accurate data correlation. Precise time synchronization between the GNSS receiver and the seismic sensors is essential. This is usually achieved by using the PPS (Pulse Per Second) signal from the GNSS receiver as a reference for the seismic sensors [10].

Complex algorithms, such as the Kalman filter, are used to process data, which combine dynamic data from the accelerometers (high frequency) with absolute displacements from the GNSS (lower frequency). This results in a wideband signal with high accuracy and no drift [11].

Improved methods of GNSS data analysis could significantly contribute to reducing the risk of natural disasters, especially in seismically active areas. In this way, GNSS technology can provide additional security and improve the ability to detect potentially destructive seismic events early.

REFERENCES

[1] Tucikešić Sanja: **Modeling tectonic movements and quantification deformations of the Earth's crust using GNSS technology.** *Faculty od Civil Engineering in Belgrade,* Belgrade, 2020.

[2] Omerbašić Mensur, Sijarić Galiba: **Seismotectonics of Bosnia – Overview**. *Acta Geodynamica et Geomaterialia* 2, Vol. 3, No. 2, 17-29, 2006, https://doi.org/10.48550/arXiv.physics/0611279

[3] https://epncb.oma.be/_networkdata/siteinfo4onestation.php?station=SRJV00BIH (24.04.2025.)

[4] https://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html (24.04.2025.)

[5] https://www.usgs.gov/ (24.04.2025.)

[6] https://earthquake.usgs.gov/earthquakes/search/ (24.04.2025.)

[7] Nikolaidis M. Rosanne: **Observation of Geodetic and Seismic Deformation with the Global Positioning System.** *University of California,* San Diego, 2002.

[8] Montillet Jean-Philippe, Bos S. Machiel: **Geodetic Time Series Analysis in Earth Sciences**. *Springer*, 2020.

[9] Solaric, N., Solaric, M., Marjanovic, M., Bogdanovski, Z., & Dimeski, S.: **Reference GNSS stations for warning on possibility of upcoming earthquake in Zagreb**. *Earth Science*, *9*(3), 100-107, 2020, https://doi: 10.11648/j.earth.20200903.12

[10] Valls, O. P., Panahi, S. S., del Río Fernández, J., & Lázaro, A. M.: **Time synchronization of a commercial seismometer through IEEE-1588**. *Instrumentation ViewPoint*, (11), 12, 2011.

[11] Zhang, Y., Nie, Z., Wang, Z., Zhang, G., & Shan, X.: **Integration of High-Rate GNSS and Strong Motion Record Based on Sage–Husa Kalman Filter with Adaptive Estimation of Strong Motion Acceleration Noise Uncertainty**. *Remote Sensing*, *16*(11), 2000, 2024, https://doi.org/10.3390/rs16112000