Tectonic plates under Japan. Author: Pimvantend. Source: https://commons.wikimedia.org/wiki/File:Bosotriplejunction.svg (Wikimedia Commons)

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Vladan Janković
University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, vladan.jankovic@student.aggf.unibl.org

Tanja Đukanović
University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, tanja.djukanovic@aggf.unibl.org

Sanja Tucikešić
University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, sanja.tucikesic@aggf.unibl.org

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* corresponding author

Vladan Janković

University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, vladan.jankovic@student.aggf.unibl.org

Tanja Đukanović *

University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, tanja.djukanovic@aggf.unibl.org

Sanja Tucikešić

University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Bosnia and Herzegovina, sanja.tucikesic@aggf.unibl.org

MODELING TECTONIC MOVEMENTS USING THE KALMAN FILTER ON GNSS COORDINATE TIME SERIES

ABSTRACT

The paper is dedicated to the modeling of tectonic movements based on GNSS coordinate time series, which were analyzed using the Kalman filter. The research area includes the territory of Japan, which is one of the most seismically active regions on Earth. The devastating Tohoku earthquake of 2011 was the result of subduction between the Pacific and North American plates. Different offsets were observed by analyzing the time series of GNSS coordinates. The intensity of the offset caused by the Tohoku earthquake is proportional to the distance of the observed station from the epicentre of the earthquake. The horizontal and vertical movements of Honshu Island are not homogeneous, which results from the fact that the GNSS stations are located on different tectonic plates.

Keywords: *Tectonic movements, seismology, GNSS coordinate time series, Kalman filter.*

1. INTRODUCTION

Earthquakes are one of the most dangerous natural disasters, claiming a large number of human lives every year around the world [1]. The first step toward earthquake prediction is to accurately observe what happens during an earthquake to use the information obtained for geophysical models. Geodynamic research is based on the monitoring of GNSS (Global Navigation Satellite Systems) coordinate time series, from which information is obtained about the movements and velocities of GNSS stations over time. Based on GNSS measurements, the three-dimensional positions of the stations can be estimated with a precision ranging from several millimetres to several centimetres. If station observations are conducted over a long period, conclusions can be drawn about the processes occurring before, during and after the earthquake. It often happens that the movement starts days or weeks before the earthquake itself. Additionally, after strong earthquakes, slight movements can be observed for months, leading to continued deformation of the affected area and often to a return to its original state. If the network of GNSS stations is densely distributed in the vicinity of an earthquake, data on the spread and course of the earthquake can be obtained from dense temporal resolution measurements [1].

The first regional continuous GNSS networks for geodynamics have been developed since 1990. A small regional continuous GNSS network for geodynamics with a spacing of about 1,000 km was established in Japan in 1991. Such networks were developed primarily to measure deformations related to tectonic processes. The Geospatial Information Authority of Japan (GSI) operates GNSS CORSs that cover the Japanese archipelago with over 1,300 stations at an average interval of about 20 km for crustal deformation monitoring and GNSS surveys in Japan [2].

The paper focuses on the modelling of tectonic movements based on GNSS measurement technology. The result of continuous GNSS measurements is represented by a time series of GNSS coordinates over which the Kalman filter was applied.

Kalman filtering is an algorithm that uses a series of measurements observed over time, including statistical noise and other inaccuracies, and makes estimates of unknown variables [3]. It is a recursive method used to estimate the random state of a dynamic system in a way that minimizes the mean square prediction error. The recursive method refers to solving the problem by breaking it down into smaller instances of the same problem, which are then solved in the same way. The algorithm enables optimal evaluation of time-varying parameters of a dynamic system. The Kalman filter is particularly suitable for processing satellite measurements because the station coordinates and their velocities, phase uncertainties, atmospheric influences or clock conditions can be viewed as parameters that change as a function of time. The extended Kalman filter is a nonlinear version of the Kalman filter that linearizes the estimation of the current mean and covariance and is used in the theory of nonlinear state estimation of navigation systems and GPS (Global Positioning System).

It is necessary to point out that the implementation of the Kalman filter is most effective for linear systems and that its use is limited in cases where the system is not strictly linear. In such cases, variations of the Kalman filter, such as the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF), can be applied.

The Extended Kalman Filter (EKF) is a generalization of the Kalman filter that is well-suited for most nonlinear systems. In the EKF, the state of the nonlinear system is approximated by its linearization, using the first term of the partial derivatives of the Taylor series around the current estimated mean value of the state and covariance. For the linear approximation to converge properly, the system should not be extremely nonlinear, and the initial state and variance values should be accurate. If the system is linear, the EKF would give the same results as the standard Kalman filter [4].

The UKF represents a newer version of the Kalman filter for nonlinear systems in which the so-called "unscented" transformation overcomes the shortcomings of the EKF linearization, where the state covariance expansion is assumed to be linear [4], [5]. In UKF, the unknown state probability distribution is approximated by a discretized version using several sampled state values called “sigma points”. The probability distribution of the newly estimated state is obtained from the sigma point propagation directly through the nonlinear model.

The Kalman filter represents a precise method by which the velocities of GNSS stations can be derived from epochal geodetic measurements [6]. By applying the Kalman filter, during the analysis of the time series of the positions of the GNSS stations, deformations of the Earth's crust can be estimated.

A time series is used to monitor some statistical phenomenon and represents an ordered series of measurements, which were realized in different epochs, usually in equal time intervals. Although they provide three-dimensional displacements, the vertical component is less precise than the horizontal one. By extracting geophysical signals from a time series of GNSS coordinates, clear insights into Earth deformation patterns are obtained. In combination with seismological data, time series of GNSS coordinates are used to develop algorithms for earthquake modelling. Seismological data includes data from seismographs, which measure earthquake waves as they pass through the Earth. GNSS data provide information about long-term ground motions, such as slow deformation before and after an earthquake, while seismological data provide fast information about the waves moving through the Earth during an earthquake. The correlation between the dynamics of the recorded seismic waves and the time series of GNSS data leads to an understanding of which parts of the ground deformations are associated with certain types of waves (P-waves, S-waves, etc.) [20], [21].

High-frequency GNSS data can be used to model the rupture process during strong earthquakes, providing useful information on the correlation between GNSS and seismic data [22].

To understand the dynamics that cause deformations, interseismic models of surface deformation and seismic hazard analyses are most important [7], [4], [9], [8].

Time series models represent different stochastic processes. A stochastic process is a function of the outcome of a statistical experiment and time. Accordingly, the time series represents one realization of the stochastic process [10]. In the analysis of time series, this mutual dependence is used to form a time series model, after which it is used to make a forecast of future observations based on past observations [10].

2. MATERIALS AND METHODS

2.1. THE STUDY AREA

The area of study includes the territory of Japan, which is one of the most seismically active regions on Earth. Japan is an island country in East Asia, comprising 6,852 islands, the largest of which are Hokkaido, Honshu, Shikoku and Kyushu. The Japanese islands are part of a geologically very unstable region known as the Pacific Ring of Fire. This area is characterized by a large number of seismic and volcanic activities. Most earthquakes are the result of tectonic movements, which lead to the interaction of the Pacific, Philippine, North American and Eurasian plates (Figure 1). The most famous volcano is Fuji, which is also the highest peak in Japan, with a height of 3776 m. Some of the many earthquakes are highly destructive, such as the Tohoku earthquake in 2011. Therefore, the Japanese have invested significant effort and funding into geodynamic research, leading to the establishment of a network of 1,200 GPS stations in 2000.

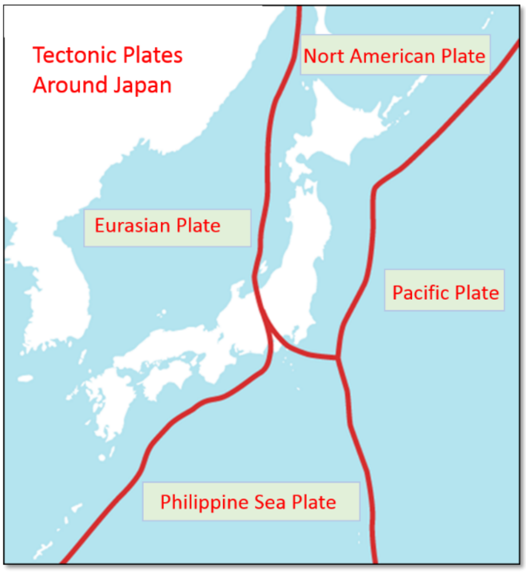

Figure 1. *Layout of tectonic plates in the research area* [11]

2.1. INPUT DATA

The Nevada Geodetic Laboratory (NGL) conducts research in the field of satellite geodesy to study scientific problems of both regional and global significance [12]. The Global Positioning System is used to study tectonic and geothermal activity. The main research objective of this laboratory is the Earth's deformation in different time trends and different areas. These deformations are mostly caused by the movement of tectonic plates. Seismic activities occur at the boundary zones of the plates. It is precisely by quantifying the deformation at the boundary zones of the plates that we want to understand as much as possible the complex force of interaction that leads to seismic processes [12].

The GPS station network data, which is updated weekly, daily, and even at five-minute intervals, can be accessed via the NGL web service. NGL publishes metadata, station lists, coordinate position charts, and data tables. In addition to station locations, time series data are available in various formats: tenv3, tenv, xyz, kenv, trop, and QA files. Furthermore, information about equipment changes or earthquakes in the vicinity of each station, as published by the USGS (United States Geological Survey), is available for each station.

NGL collects raw GPS data from more than 17,000 stations around the world and then processes it. The region of Japan is densely covered by a network of GPS stations with time series lasting about 14 years. The final NGL products can be used for various research, such as tectonic plate motion or the improvement of the global reference frame for studying global sea level change [12].

To model tectonic movements, the time series of four GPS stations shown in Figure 2 were analyzed. All stations are located on the Japanese island of Honshu.

Figure 2. Station positions (source: author)

The reference frame for all stations is IGS14 (International GNSS Service 2014), which, for most practical tasks, is equivalent to the international terrestrial reference frame ITRF14 (International Terrestrial Reference Frame 2014). The coordinates of the stations are shown in Table 1. The observation period ranges from the beginning of 2009 to August 2023.

Table 1. *Coordinates of stations*

Point mark	J549	J191	I053	J645
Latitude	38.425˚	39.206˚	34.751˚	35.621˚
Longitude	141.213˚	139.908˚	138.990˚	134.677˚
Height	49.081 m	47.294 m	52.721 m	70. 208 m

2.2. MATHEMATICAL MODEL OF GNSS COORDINATE TIME SERIES

The mathematical model of GNSS coordinate time series can be represented as the sum of deterministic (functional) and stochastic parts (noise). The deterministic part refers to long-term trends and seasonal changes, while the stochastic part remains after removing the deterministic model from the data [7].

The following form represents a complete linear model for a GNSS coordinate time series related to a single position component [13]:

$$y(t_i) = a + bt_i + c\sin(2\pi t_i) + d\cos(2\pi t_i) + e\sin(4\pi t_i) + f\cos(4\pi t_i) + \sum_{j=1}^{n_j} g_j H\left(t_i - T_{gj}\right) + \varepsilon(t_i) \quad (1)$$

where t_i represents the daily solutions of the GNSS coordinate time series, t_i denotes the series of n elements, where $i = 1, \dots, n$, a is the position of the station, and b is the linear velocity of the station. The coefficients c and d in the model describe the annual motion, while e and f describe the semi-annual motion. The following terms in the model describe the sudden occurrences caused by equipment or seismic events for any number of deviations n_g of size g and epoch t_{g_j}, using the Heaviside function (a single jump function used in signal processing to represent the signal that changes state). In addition, t_{eq} is the time of the earthquake (represents the time of the main shock), c represents the coseismic displacement after the earthquake (modeled with a logarithmic or exponential function), A is the amplitude of the simplified Omori's law, τ is the time delay of the occurrence of post-seismic deformation after the main shock. The remaining term in the model t_{e_i} denotes measurement errors, i.e. any remaining changes attributable to other random or systematic instabilities.

The Heaviside function corresponds to shifts in the time series, which are most often the result of seismic events or changes in instruments, software, or reference frames. The linear expression is analogous to the position and rate of change of the GNSS antenna, while the harmonic components are included to model annual, seasonal and high-frequency dependent phenomena present in the time series [7].

2.3. GNSS TIME SERIES ANALYSIS METHODS

GNSS networks for geodynamic research are based on permanent stations that continuously collect data. The obtained positions that make up the time series are originally expressed in geocentric coordinates (X, Y, Z). To make the concept of moving a specific location more intuitive, geocentric coordinates are transformed into topocentric ones, and thus, three components (N, E, U) are obtained, which represent north, east, and elevation. Based on the analysis of the time series, we arrive at the movement speed vector as well as the anomalies that could have occurred in the period covered by the time series.

Topocentric GNSS time series are burdened with errors originating from various sources. Therefore, the precision of the ephemeris, correction of the satellite oscillator, parameters of the Earth's rotation, tropospheric and ionospheric influence, station stability, multiple reflections, etc., decisively influence the quality of the calculated time series. The existence of observations with errors, loss of observations due to obstacles, noises originating from other signals, and others make necessary a preliminary descriptive analysis of the measured time series. By analyzing the raw series, outliers, gross errors, and especially the noise level can be detected [14].

Given the differences in terms of horizontal components and vertical components, as well as the linear and nonlinear behaviour of a time series and the like, there is no single method for analyzing each time series. Therefore, different time series analysis procedures have been developed, which are shown in Figure 3.

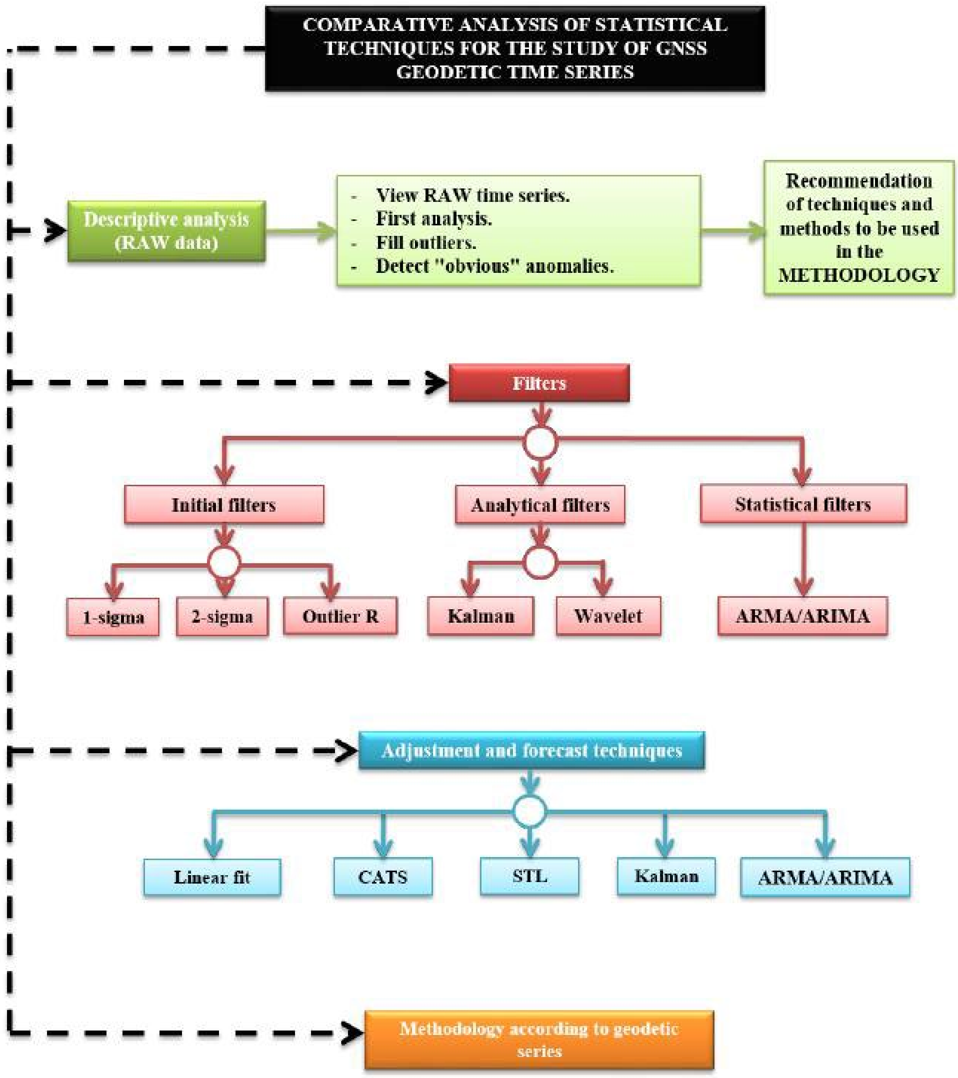

Figure 3. *Methods of analysis of GNSS time series* [14]

The essence of the initial filtering applied to the GNSS series is reflected in the elimination of data that deviate greatly from the rest of the series in terms of values. 1-sigma and 2-sigma filters eliminate data depending on the distance of the series points from the linear regression line. However, in the case of nonlinear series, this process takes place along linear sections within the series.

In the paper, the Kalman filter was applied to GNSS coordinate time series.

The estimation process of the Kalman filter can be divided into continuous and discrete, where they can be represented by the following equations that describe the dynamic system and the measurement system [15]:

$$\dot{X} = F(t).X(t) + G(t).w(t), \text{ dynamic system} \quad (2)$$

$$\tilde{Z} = H(t).X(t) + v(t), \text{ measurement system} \quad (3)$$

$$X_k = \Phi_{k-1}X_{k-1} + \Gamma_{k-1}\omega_{k-1}, \text{ dynamic system} \quad (4)$$

$$\tilde{Z}_k = H_k \cdot X_k + v_k, \text{ measurement system} \quad (5)$$

where $F(t)$ dynamic matrix, $X(t)$ system state vector, $G(t)$ disturbance configuration matrix, $w(t)$ disturbance function (system noise), $\tilde{Z}$ observation vector, $H(t)$ observation configuration matrix, $v(t)$ measurement noise, Φ transition matrix, Γ configuration matrix of system disturbance. Equations under (4) refer to continuous time, while under (5) refer to discrete time, where both X_k and $\tilde{Z}_k$ contain position components (N, E, U).

3. RESULTS OF NUMERICAL RESEARCH

3.1. APPLICATION OF SARI SOFTWARE FOR ANALYSIS OF TIME SERIES

The time series of GNSS coordinates contain signals caused by the deformation of the Earth but also by systematic errors at different moments, from daily to seasonal and annual variations [4]. With the help of the SARI software (French: Señales y Análisis de Ruido Interactivo), it is possible to visualize GNSS position time series, remove outliers and discontinuities, fit the model and save the results. There are additional options that enable the extraction of adequate information from the time series, including spectral analysis with the Lomb-Scargle periodogram and wavelet transform, signal filtering using the Kalman filter, and estimating the time correlation of the stochastic residual noise. The program is oriented toward daily/weekly time series of GPS positions in NEU format, but it is possible to analyze other data series as well.

First of all, it is necessary to download the data from the NGL website and prepare it in the appropriate format. After loading the data, it is necessary to set the time resolution of the series, as well as the linear dimensions. It is then possible to visualize the time series by components in the form of points, points and lines, or only lines, as can be seen in Figure 4.

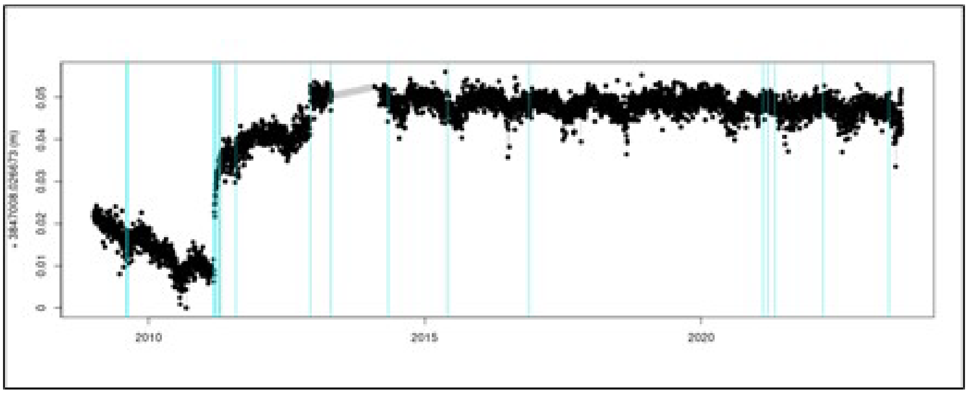

Figure 4. *The northern component of the time series from the station I053 (source: author)*

Vertical cyan lines represent offsets downloaded from the Nevada Geodetic Laboratory web service. The displayed offsets are a consequence of seismic activity, as well as changes in equipment at the stations themselves. After visualizing the time series, we get information about the number of points, that is, observations in the series, the length of the series, its range, the sampling period and the completeness of the series. The above time series data for station I053 are presented in Table 2.

Table 2. *Time series data for the station I053*

Time series data	Values
Number of points	4978
Series length	14.6256 years
Series range	2009.0048 - 2023.6304
Series sampling	0.0027 years
Series completeness	91.9 %

After that, it is necessary to fit the model using the least squares method. In this procedure, linear and sinusoidal functions were used. A linear function is used to model the trend of a time series, while a sinusoidal function is used to model periodic variations that occur due to different seasonal changes. The period of the sinus function itself can be estimated based on the Lomb-Scargle periodogram, where the amplitudes are shown as a function of the period of the year (Figure 5). In the figure, we can see a pronounced amplitude between the five-year and one-year periods, and therefore, in the modeling of the northern component, it is necessary to include a sine function.

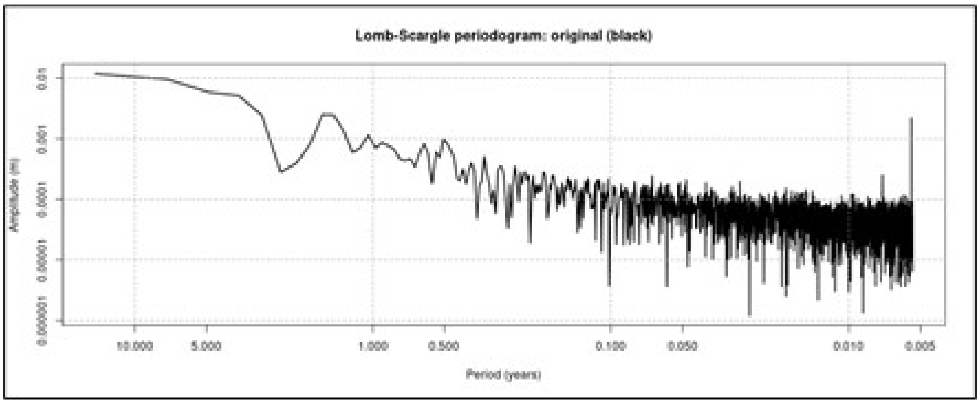

Figure 5. *Periodogram of the northern component of the time series I053 (source: author)*

After modelling using the least squares method, the Kalman filter is applied to model the time series as accurately as possible and estimate the velocity of the station with the greatest possible precision. When using the Kalman filter, it is necessary to define the measurement noise and the a priori state of all parameters that are evaluated. The quality of the Kalman filter depends precisely on the assumed a priori values, which are derived from the time series data. If modeling was performed using the least squares method, estimates of certain parameters would serve as a priori values of the state parameters of the Kalman filter system. After running the filter, the result shown in Figure 6 is obtained. Figure 6 shows the actual modelling of the data using the Kalman filter, that is, the time series of the northern component data with the modelled data overlaid to show how well the Kalman filter fits the observed data.

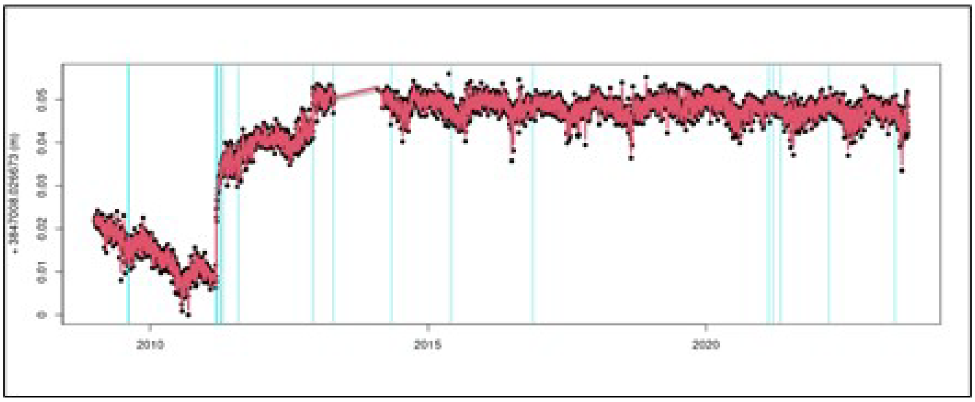

Figure 6. *Modelling of the northern component of station I053 using the Kalman filter (source: author)*

Also, it is useful to show the residuals of the performed modeling (Figure 7), as well as the histogram of the residuals (Figure 8). Based on them, it can be seen whether the residuals follow a normal distribution, that is, whether the modeling was performed adequately.

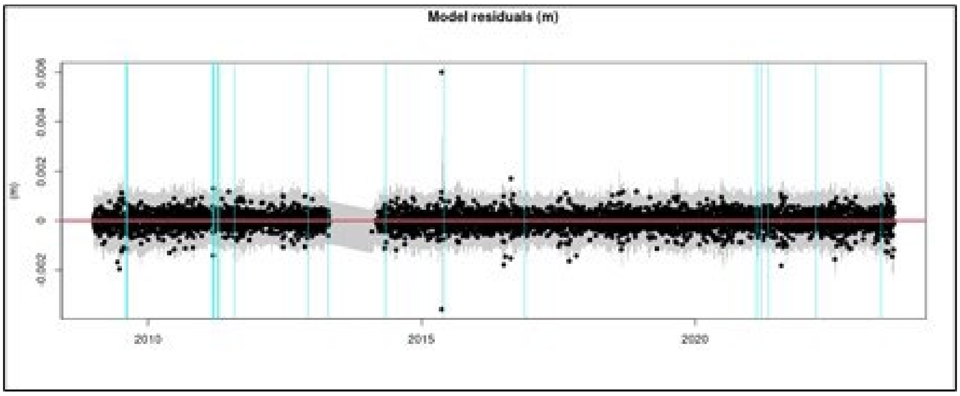

Figure 7. Residual model for the northern component of the station I053 (source: author)

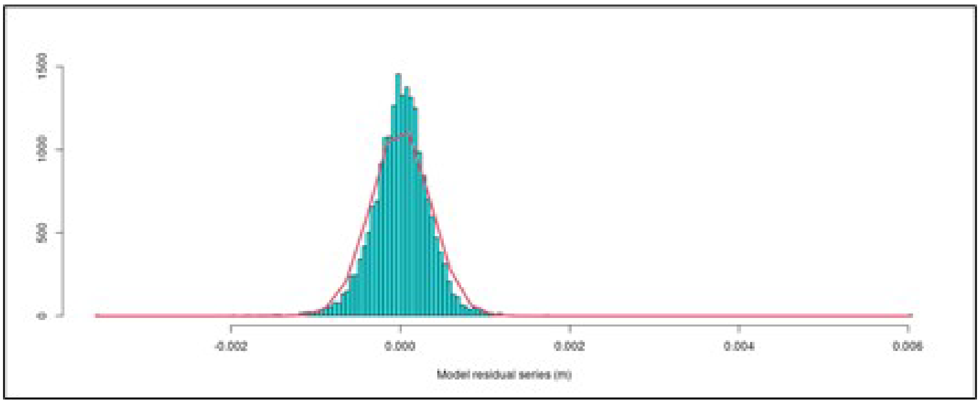

Figure 8. Histogram of residuals of the northern component of the station I053 (source: author)

Using the described procedure, a time series analysis was performed with the four mentioned GNSS stations. The obtained values of horizontal and vertical velocities are presented in Table 3. The table shows the estimated annual displacement values for GNSS stations in three dimensions: north (N), east (E) and vertical (Up). These values are expressed in millimetres per year (mm/year). For example, for station J549, the displacement in the north is -111.41 mm/year, in the east 317.13 mm/year, and vertically 12.49 mm/year. This indicates that the station has moved south and east and has risen.

Table 3. Estimated speed values of GNSS stations

Stations	Station position velocities		
	N [mm/year]	E [mm/year]	Up [mm/year]
J549	-111.41	317.13	12.49
J191	-70.74	165.61	-1.84
I053	1.49	4.26	1.57
J645	-5.94	33.12	-4.65

The intensity of the resultant vector of displacement of GNSS stations is shown in Table 4, the graphic display of horizontal velocities is shown in Figure 9, and the vertical velocities are presented in Figure 10.

Table 4 presents the intensity of the resultant displacement vector for the same GNSS stations, also expressed in millimetres per year. The intensity of the resultant vector provides an overall measure of the station's displacement regardless of direction, by combining both horizontal and vertical components.

Table 4. *The intensity of the resultant displacement vector*

Stations	The intensity of the resultant displacement vector [mm/year]
J549	336.13
J191	180.08
I053	4.51
J645	33.65

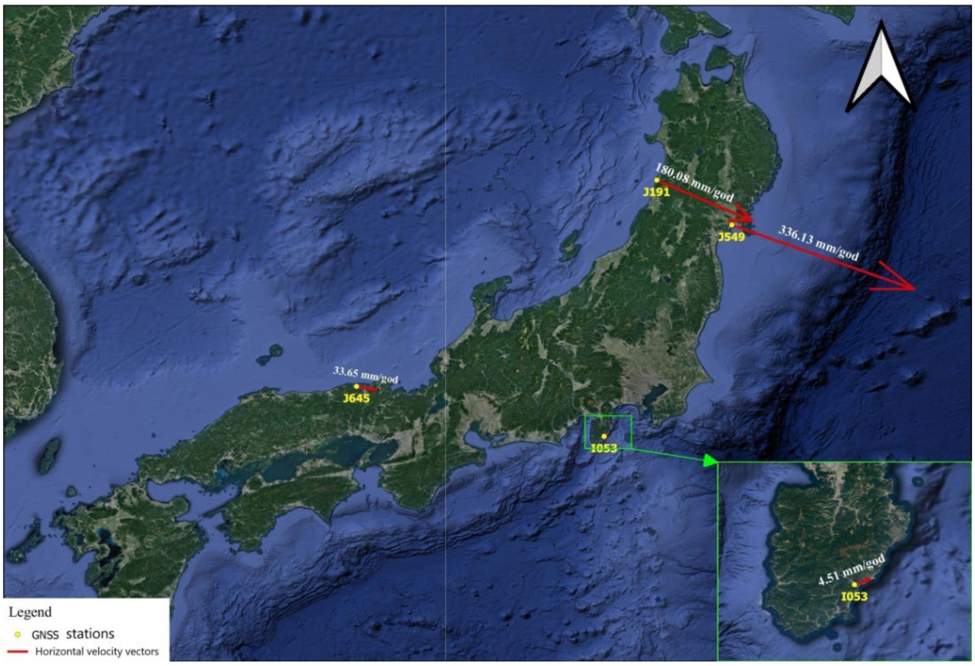

Figure 9. *Horizontal velocities of GNSS stations (source: author)*

Figure 10. *Vertical velocities of GNSS stations (source: author)*

Figure 9 shows the horizontal velocities of the GPS stations. The arrows show the direction and velocity of horizontal movement in millimetres per year (mm/year). Each marked point on the map represents a GPS station, and the speeds are indicated next to the arrows. In northern Japan, the velocity of movement is 180.08 mm/year in the southeast direction. The large red arrows on the map highlight the higher movement speeds in northeastern Japan and its eastern coastal region. The figure also shows the location in the southern part, marked as IO53, with a movement velocity of 4.51 mm/year.

Figure 10 shows the vertical velocities of the GPS stations and indicates the vertical movement of the ground, where the values are given in millimetres per year. Positive values (e.g. 12.49 mm/year) indicate soil elevation, while negative values (e.g. -4.65 mm/year) indicate soil subsidence. In northeastern Japan, the GNSS station, which is marked as 3549, recorded the highest ground uplift of 12.49 mm/year. In contrast, station 3645 in central Japan shows ground subsidence of -4.65 mm/year.

3.2. ANALYSIS OF THE RESULTS OBTAINED

Based on the obtained results, an analysis of horizontal and vertical velocities was performed, as well as the most noticeable offset, which is noticeable in the all-time series and occurred as a result of the devastating Tohoku earthquake on March 11, 2011.

The earthquake occurred near the northeastern coast of the island of Honshu, at a depth of about 25 km, with a magnitude of 9.1 Mw [16]. The earthquake resulted from a shallow subduction fault at the boundary between the Pacific and North American plates. In this area, the Pacific Plate is moving approximately westward relative to the North American Plate at a speed of 83 mm/year and is subducting under the mainland of Japan in the Japan Trench. Earthquake rupture modelling showed that the fault moved as much as 50-60 m

[16]. The Tohoku earthquake was preceded by a series of earthquakes two days before the main shock, starting on March 9 with a magnitude 7.4 Mw earthquake. Also, since 1973, nine earthquakes of magnitude over 7 Mw have been recorded in this area [16]. The distance values are shown in Table 5.

Table 5. *Distance of GNSS stations from the epicentre of the Tohoku earthquake*

Stations	Distance [km]
J549	102.1
J191	236.5
I053	496.7
J645	745.4

Observing the time series of GNSS stations, it can be seen that the largest offsets are represented in the time series of GNSS station J549, which is the closest to the epicentre of the earthquake. During the period of the earthquake, displacements in the northern component of approximately 1.3 m were recorded, while in the eastern component, the intensity of the displacement was as much as 4.5 m. Also, an offset with a value of almost 0.5 m was observed in the vertical component. In the time series of station J191, the offsets are also significant but still smaller compared to station J549. Based on the assumed expectations, the offsets at GNSS stations I053 and J645 are much smaller than those at the previous two stations, where there were almost no significant movements in the vertical components.

By analyzing the horizontal velocities of the observed stations, it can be seen that the resultant vectors of stations J549 and J191 are higher in intensity compared to the other two stations. Also, the directions of these vectors approximately coincide and indicate the movements of the North American part of the tectonic plate towards the southeast. The horizontal velocity of station J645 is rather less intense compared to the previous two velocities, while the direction of the vector also indicates movement in the southeast direction. The largest differences were observed during the analysis of the resultant vectors of horizontal displacement at station I053. The intensity of the vector indicates significantly smaller movements in this area, while the direction also differs compared to the previous three stations. Looking at Figure 12, it can be assumed that these differences arose from the fact that the GNSS station is located on Izu Island, which belongs to the Philippine tectonic plate. In addition, it can be observed that station J645 is located on the Eurasian plate, which, in addition to the distance from the epicentre of the Tohoku earthquake, is probably another reason for the slower horizontal movement compared to stations J549 and J191 located on the North American tectonic plate.

Differences in intensity and direction can also be observed in vertical velocities. By observing the vertical velocities, a lowering of the west coast of the island of Honshu, where GNSS stations J191 and J645 are located, was observed, while stations J549 and I053 indicate an uplift of the east coast of this island. The obtained results are in agreement with the detected subduction of the Pacific Plate under the mainland of Japan, which was precisely the cause of the Tohoku earthquake.

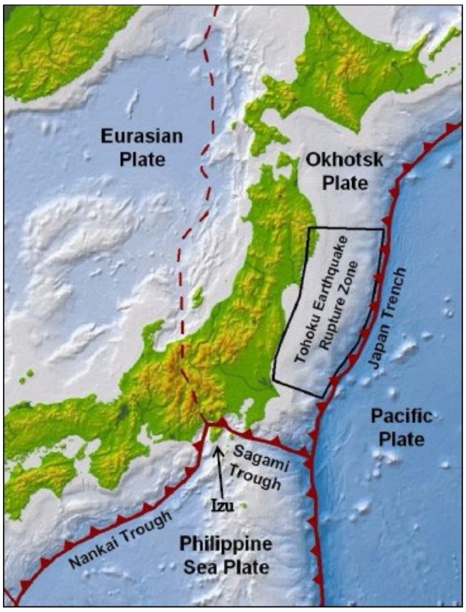

Figure 11. *The position of the Izu peninsula in the arrangement of tectonic plates [14]*

In addition to the above, in most components of the analyzed time series of GNSS stations in the post-seismic phase, movements similar to those before the earthquake were observed. Also, in certain components of the time series, a movement was observed that returns the stations to their pre-earthquake condition, for example, in the case of the vertical component of station J549.

4. CONCLUSION

GNSS technology is a powerful tool for monitoring and quantifying deformations on the surface of the Earth's crust. The progress of the aforementioned technology, i.e. the development of other global navigation satellite systems in addition to GPS, has made it possible to monitor deformations on a global level. Based on continuous GNSS measurements, three-dimensional station coordinates are estimated daily over a long period.

In the paper, an analysis of the time series of GNSS coordinates, which are publicly available on the Nevada Geodetic Laboratory website, was performed. During the analysis, the time series that contained daily estimates of coordinates were used. The Kalman filter was used to estimate the velocities of the observed GNSS stations, based on which tectonic movements were modeled in the area of Japan.

Japan is located at the junction of several important tectonic plates: the Pacific, Philippine, North Pacific, and Amur plates. The movements of these plates cause seismic activity, volcanism, and tectonic deformations in the Earth. The horizontal velocities of the GPS stations, the arrows showing the directions and the movement velocities, indicate how different parts of Japan are moving due to tectonic forces. The larger arrows in northeastern Japan may indicate an area where the Pacific Plate is subducting beneath the North Pacific Plate, which is responsible for intense tectonic activity. The different speeds and directions of movement indicate the complexity of the interactions between the different plates. The northern part of Japan shows significant movements, which is consistent with the region where the Pacific Plate is subducting, while the central and southern parts of Japan exhibit less movement.

These differences in horizontal and vertical velocities may be the result of different geological and tectonic processes in the region. Japan is known for its complex tectonic situation, where multiple plates meet and move, causing varying rates of ground motion. Areas with higher vertical velocities may be particularly susceptible to seismic activity, such as earthquakes and volcanic eruptions. This information is important for understanding tectonic activity, earthquake risk, and long-term monitoring of relief change in Japan.

The Tohoku earthquake, which occurred on March 11, 2011, was one of the strongest earthquakes on record, with a magnitude of 9.0. This earthquake caused massive ground movements and changed the geological structure of a large part of Japan. The ground movements, both horizontal and vertical, which are shown in this paper, can be directly related to the long-term effects of that earthquake. During the Tohoku earthquake, horizontal ground movements were extremely significant. Some parts of Japan's east coast moved up to 2.4 meters eastward. GPS stations display different horizontal drift rates. These changes are a continuation of post-seismic processes, where the ground under stress during the earthquake recover and adapt to new tectonic conditions.

The large horizontal velocity shown in northeast Japan may be part of the recovery process after the large movement during the earthquake. During the Tohoku earthquake, there were significant vertical movements in addition to horizontal movements. Some parts of Japan fell as much as 1 meter, increasing the risk of a tsunami, while other parts rose. After the earthquake, the vertical movements currently underway may be related to post-earthquake ground adjustment processes.

A link between tectonic movements and seismic activity can be established. It is assumed that in the future, a lot of effort will be invested in understanding seismic processes, as well as phenomena that indicate the possible occurrence of earthquakes. In proportion to the development of technology and scientific achievements, progress can be expected in improving the reliability of early warning systems for earthquakes, which would undoubtedly reduce the number of victims of this natural disaster.

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AUTHORS' BIOGRAPHIES

Vladan Janković

Vladan Janković was born in Banja Luka on August 5, 1999. He obtained the title of Bachelor of Science in Geodesy in 2022. During his undergraduate studies, he was a recipient of the "Dr. Milan Jelić" Fund scholarship and received the award as the best graduate student in Geodesy. In May 2023, he began an internship at the Republic Administration for Geodetic and Property-Legal Affairs.

Tanja Đukanović

Tanja Đukanović was born on February 22, 1994, in Nevesinje. She completed her bachelor's studies in Geodesy in 2017 at the Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka. She obtained her Master's degree from the same faculty in 2021. She is currently a PhD student at the Faculty of Civil Engineering, University of Belgrade. Since 2019, she has been employed at the Faculty of Architecture, Civil Engineering and Geodesy, where she works as a teaching assistant in a group of course units within the scientific field of geodetic surveying.

Sanja Tucikešić

She was born in Banja Luka on May 13 1981. She graduated in 2008 from the Faculty of Civil Engineering at the University of Belgrade. She obtained her PhD from the Faculty of Civil Engineering of the University of Belgrade in 2020. In her scientific research, she deals with the analysis and modeling of tectonic movements and Earth's crust deformations using GNSS technology, as well as with the calibration and quality control of geodetic instruments and the laboratory testing of scales used in geodesy, civil engineering, and other related fields, including volumetric scales. She is employed at the Faculty of Architecture, Civil Engineering and Geodesy as an assistant professor.

МОДЕЛОВАЊЕ ТЕКТОНСКИХ ПОМЈЕРАЊА ПРИМЈЕНОМ КАЛМАН ФИЛТЕРА НА ВРЕМЕНСКЕ СЕРИЈЕ GNSS КООРДИНАТА

Сажетак: Рад се односи на моделовање тектонских помјерања на основу временских серија GNSS координата које су анализиране примјеном Калман филтера. Подручје истраживања обухвата територију Јапана која представља једно од сеизмички најактивнијих подручја на Земљи. Резултат субдукције Пацифичке и Сјеверноамеричке плоче је разорни земљотрес Тохоку 2011. године. Посматрањем анализираних временских серија GNSS координата уочени су различити офсети. Интензитет офсета који је изазван земљотресом Тохоку је сразмјеран растојању посматране станице од епицентра земљотреса. Хоризонтална и вертикална помјерања острва Хоншу нису хомогена, што проистиче из чињенице да се GNSS станице налазе на различитим тектонским плочама.

Кључне ријечи: *тектонска помјерања, сеизмологија, временске серије GNSS координата, Калман филтерзоне.*