CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 5, ISSUE 1, 2025, 18 - 26
DOI: https://doi.org/10.15282/construction.v5i1.11419

RESEARCH ARTICLE

Crustal Deformation in Peninsular Malaysia in Year 2020

N. M. L. Supparamaniyan[1], W. A. Wan Aris*, T. A. Musa, A. H. Omar, and M. A. Alim Shah

Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81210 UTM Johor Bahru, Johor, Malaysia

ABSTRACT - Peninsular Malaysia is situated on Sunda Plate, that moves 2-3 cm/year, causing coordinate change in national datum. Maintenance of the national datum is necessary by considering the crustal deformation rate of Sunda plate, also known as site velocity. The site velocity can be quantified by using space-based technique which can be facilitated by Global Positioning System Continuously Operating Reference Station (GPS CORS) networks. This study aims at investigating crustal deformation in Peninsular Malaysia. The objectives include generating precise geodetic baseline vectors between Malaysian Real Time Kinematic GPS Network (MyRTKnet) and International GNSS Service (IGS) stations, providing trend of crustal deformation via International Terrestrial Reference Frame (ITRF) coordinate time series at MyRTKnet station and analysing the magnitude and direction of tectonic plate movement in Peninsular Malaysia. Raw GPS and ephemerides data at MyRTKnet and IGS stations has been utilized to generate the baseline vectors using Bernese GNSS Software 5.2. The precision of coordinate time series has been achieved at 1.393cm. Network adjustment has been performed by using these baseline vector network to generate high precision coordinate time series in ITRF. The changes of coordinate in horizontal and vertical components have been estimated based on site velocity with precision 0.5172cm. From the site velocity, each station moved to south-eastward at 1-2cm/year according to the 6 months processing. This study also attempted to calculate Sunda plate rotation from the estimated site velocities. The angular momentum of Sunda plate rotation was found at 45°26'06" N, 125°32'56" E with rotation at ± 355.3586°. The output of the study can be used as time dependency model for maintaining national datum of Malaysia.

ARTICLE HISTORY

Received	:	15th Oct. 2024
Revised	:	11th Nov. 2024
Accepted	:	05th Dec. 2024
Published	:	02nd May 2025

KEYWORDS

Sunda land
Earth Centered Earth Fixed
Coordinate time series
Plate motion
Euler pole

1. INTRODUCTION

A national reference frame is essential for achieving precision, consistency, and traceability in surveying and mapping, forming the backbone of spatial data infrastructure and supporting applications critical to sustainable development and decision-making [1]. It has components of coordinate systems for Cartesian and Geographical positioning which depends on the mobility of the plates [2]. Those are the important aspects of plate tectonics where the knowledge about the plate motion and its temporal changes is the key for maintaining the uniformity of the Terrestrial Reference System (TRS). Earlier works in the Sunda land region concerning the countries such as Malaysia, Thailand and Indonesia have assumed the tectonic coupling and surface uplift [3]. This is supported by continuous Global Positioning System (GPS) velocities that assist in improving site velocities and therefore improve the understanding of crustal movements in the region.

Keeping a national reference frame is required to accurately measure the Earth's steady motion caused by plate tectonics [4]. This maintenance involves correcting coordinates obtained at the time of plate movements, and thus it entails crustal deformation modeling to enable the use of space positioning methods such as GPS. Ongoing site velocity estimation improves the plate motion modeling using site velocity as a measure of current crustal deformation trends. While the Southeast Asia's Global Positioning System Continuously Operating Reference Station (GPS CORS) network has often been employed in the research for site velocity estimation, there are relatively few studies on Sunda land [5, 6, 7]. Therefore, it is necessary to estimate site velocity using the most recent data to enhance the knowledge of tectonics of the area.

High-precision GPS technology has improved various industries by providing precise and up-to-date positioning data. To obtain high precision GPS derived Coordinate Time Series (CTS), a few prerequisites must be considered: 1) GPS data analysis that addresses the challenges in analyzing GPS observation and suggests solutions; and 2) Terrestrial reference frame [8]. Deformation quantification on earthquakes requires careful observation and analysis [9]. High precision GPS applications typically require accurate and reliable data to achieve precise positioning. The application of the GPS techniques in structural integrity monitoring have been addressed frequently. The International Terrestrial Reference Frame (ITRF) is the system that creates the reference frame that will be suitable to use for measurement on Earth's surface [10]. ITRF was developed by International Earth Rotation and Reference Systems Service (IERS) that covers all areas on the Earth's surface.

*CORRESPONDING AUTHOR | Wan Anom Wan Aris | ✉ wananom@utm.my
© 2025 The Author(s). Published by Universiti Malaysia Pahang Al-Sultan Abdullah Publishing. This is an open access article under the CC BY-NC 4.0 license

This research study aims at investigating crustal deformation in Peninsular Malaysia. To achieve the aim of the research, there are several objectives that need to be achieved. The objectives include (1) To generate coordinate time series at MyRTKnet station by using high precision coordinate software [11]; (2) To estimate site velocity at MyRTKnet station [12]; (3) To evaluate the magnitude and direction of tectonic plate movement in Peninsular Malaysia [13]. This paper is divided into four (4) sections. Section 1 is the introduction which covers the background of study, problem statement, literature review and aim and objectives. Section 2 is the methodology that covers the 3 phases in this study which are GPS-derived CTS, Site Velocity Estimation and Euler pole Parameter Estimation. Section 3 contains the result and analysis fulfilling the 3 objectives stated in this study and followed by Section 4, the conclusion and recommendations.

1.1 GPS-derived Coordinate Time Series

In this phase, baselines have been processed and CTS for each station has been derived. GPS coordinate time series for MyRTKnet stations is obtained in this work using GPS raw RINEX data comprising L1 and L2 signals from 6 months of weekly observation from DoY 001/2020 to DoY 176/2020 at ten (10) MyRTKnet stations and thirteen (13) IGS stations. Figure 1 shows the distribution of selected IGS and MyRTKnet stations respectively [14].

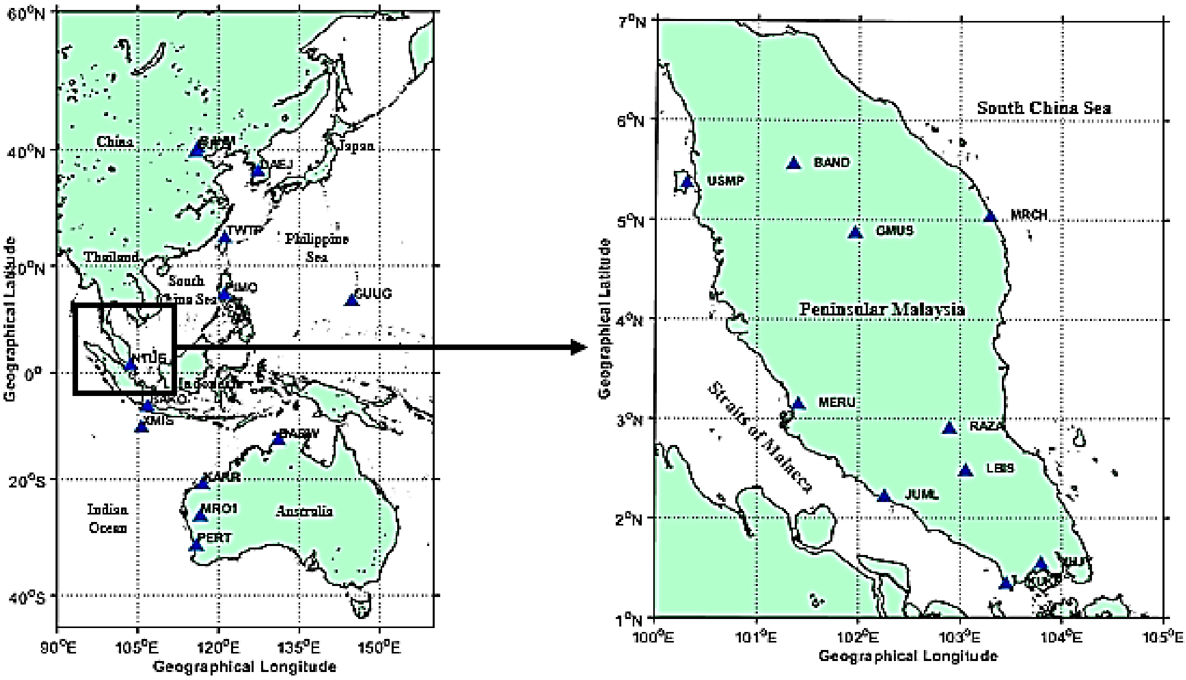

Figure 1. Distribution of selected IGS and MyRTKnet Stations

A highly precise scientific processing software, Bernese GNSS Software 5.2, was used to process the GPS data. To minimize the errors, the precise orbit, ionosphere, and Earth Orientation Parameters (EOP) parameters were used. The baseline between stations was established using obs-max processing strategy to ascertain the measurements that were being taken. In phase pre-processing, cycle slip cleaning and repair were performed and saastamoinen model is applied for correcting tropospheric delay. Ambiguity resolution is carried out based on distance of baseline such as sigma is used for baseline less than 20km and Quasi Ionosphere-Free (QIF) used for baseline more than 20km [15].

The ambiguity resolved measurements are then used to estimate the weekly coordinate. Finally, a coordinate time series is obtained, and this series depicts the variation in coordinates at each GPS site at a given period. This data relates to the relative motion of the earth's crust at locations which are important for estimating site velocity.

1.2 Site Velocity

The output of this phase is the velocity in the local topocentric coordinate system. Coordinate conversion from Earth-Centered Earth-Fixed (ECEF) Coordinate System to Geographical Coordinate System has been performed, followed by the Local Topocentric Coordinate System in Northing, Easting and Up components using MATLAB.

The statistical method is used to estimate the velocity of each site. By applying linear regression to the coordinate time series data, the rate of change in the north (V_N) and east (V_E) directions can be determined. Linear regression is particularly effective for GNSS data because it minimizes random errors by fitting a line through noisy observations, providing a stable estimate of the movement trend in each component [16,17]. The slope of the regression line in each direction directly reflects the site's velocity, giving insight into both the rate and direction of tectonic or structural displacement. These estimated velocities in the north and east directions are essential for understanding the movement patterns of the tectonic plates in the study area [18].

Linear regression is performed using a general equation as shown in Equation (1). On the other hand, Equation (2) and (3) indicate the mathematical representation for the linear fitting model for Northing and Easting components respectively.

$$P = vt + c \tag{1}$$

$$PN_{t_A} + \varepsilon P_N = v\Delta t_N + c_N \tag{2}$$

$$PE_{t_A} + \varepsilon P_E = v\Delta t_E + c_E \tag{3}$$

where t is time in day of year and P are the position of a point, ε is the residual, v is the slope of a line and c is the y-intercept at t=0.

As the measurement contain errors, the equations for the four points A, B, C, and D are written as:

$$\begin{aligned} PNt_A + \varepsilon_{PA} &= vt_A + b \\ PNt_B + \varepsilon_{PB} &= vt_B + b \\ PNt_C + \varepsilon_{PC} &= vt_C + b \\ PNt_D + \varepsilon_{PD} &= vt_D + b \end{aligned} \tag{4}$$

Equation 4 contains two unknowns, v and c, with four observations. Their matrix representation is:

$$AX = L + V \tag{5}$$

where:

$$A = \begin{bmatrix} t_A & 1 \\ t_B & 1 \\ t_C & 1 \\ t_D & 1 \end{bmatrix} \quad X = \begin{bmatrix} v \\ c \end{bmatrix} \quad L = \begin{bmatrix} PNt_A \\ PNt_B \\ PNt_C \\ PNt_D \end{bmatrix} \quad V = \begin{bmatrix} \varepsilon_{PA} \\ \varepsilon_{PB} \\ \varepsilon_{PC} \\ \varepsilon_{PD} \end{bmatrix} \tag{6}$$

The X-matrix can be computed with the equation written as:

$$X = (A^T W A)^{-1} A^T W L \tag{7}$$

where W is the weight matrix.

The final computed value of v in X-matrix shows the site velocity of the station. The horizontal displacement of the station and its direction can be computed with equation written as:

$$Horizontal\ displacement = \sqrt{Vn^2 + Ve^2} \tag{8}$$

$$Direction\ of\ displacement = \tan^{-1}\left(\frac{V_e}{V_n}\right) + \alpha \tag{9}$$

where Vn is the velocity in north component, Ve is velocity in east component and α is constant in quadrant I (0˚), II (180˚), III (180˚), and IV (360˚).

1.3 Euler Pole Parameter Estimation

In this phase, a localized plate motion model is developed or refined based on the estimated site velocities. MORVEL-2010 is used to predict the movement of the tectonic plates over time. The estimated velocities from the GPS data are compared with the velocities predicted by the plate motion model. This comparison helps in validating the accuracy of the local model. The differences between the estimated and predicted velocities are calculated to obtain the residuals. These residuals (ΔV_N for the north direction and ΔV_E for the east direction) indicate the discrepancies between MORVEL-2010 and regional model [19].

2. METHODOLOGY

The methodology of this study has been illustrated in Figure 2. The methodology comprises of three (3) phases. Phase 1 provides the methodology for preparing GPS-derived CTS. Next, the estimation and assessment of site velocities is described in phase 2. Finally, phase 3 focuses on Sunda plate rotation parameter estimation.

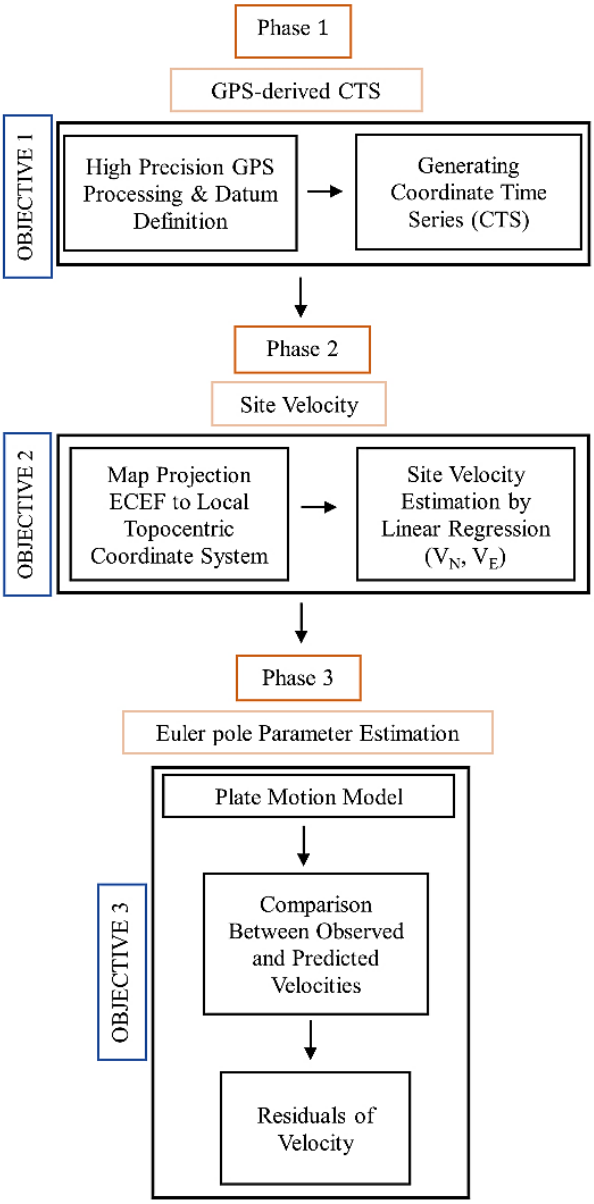

Figure 2. Flowchart of methodology

3. RESULTS AND DISCUSSION

Results and analysis divided into three (3) sections, which are (i) result and analysis of GPS-derived CTS, (ii) result and analysis of site velocity and (iii) Euler pole parameter estimation.

3.1 GPS-derived CTS

GPS-derived CTS has been processed for all selected local stations. Figure 3 shows the CTS data for station JHJY in 2020 reveals notable trends in three components Northing, Easting, and Up. The Northing component shows a slight southward movement with a velocity of -1.695cm/year and a low standard deviation of 0.424cm, indicating stable and precise measurements in this direction. In contrast, the Easting component exhibits a more pronounced eastward movement at a velocity of 2.894cm/year with a standard deviation of 0.705cm, suggesting that the station shifting significantly in the east direction, potentially due to tectonic activity or structural influences. The Up component indicates a minor downward trend with a velocity of -0.370cm/year, though it has a higher standard deviation of 1.203cm, reflecting more variability and sensitivity to external factors, such as atmospheric or tidal effects. Overall, the data suggest that the station is primarily moving eastward, with a slight southward and downward trend offering insights into the structural or geographical factors affecting its position.

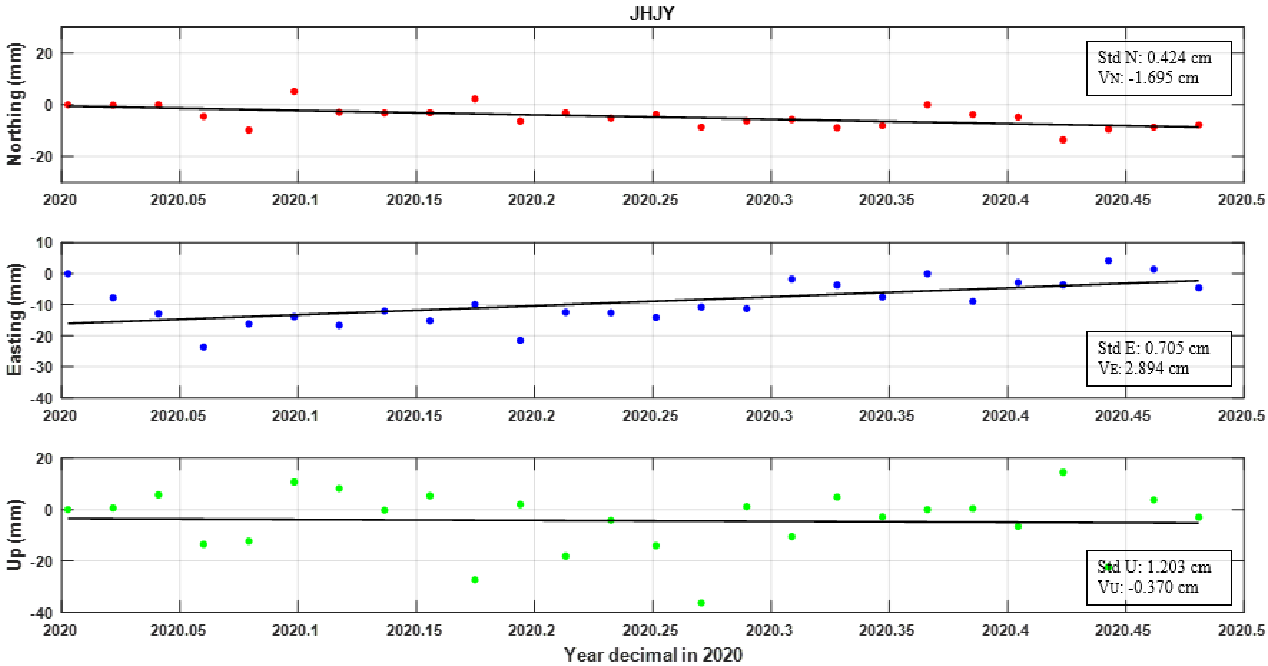

Figure 3. CTS of JHJY in 2020 after outlier removal

Figure 4 illustrates the standard deviation of GPS-derived CTS for all the MyRTKnet stations, which are represented by colours red, purple and orange for Northing, Easting and Up components respectively. The Up component consistently exhibits the highest standard deviations across most stations [20], suggesting more variability in the vertical positions of the GPS stations. On the other hand, the East component generally has higher standard deviation than the North where it indicates more variability in the eastward positions while the North component has the lowest standard deviation, suggesting the most stability in the northward positions. The precision of coordinate time series has been achieved at 1.393 cm [21].

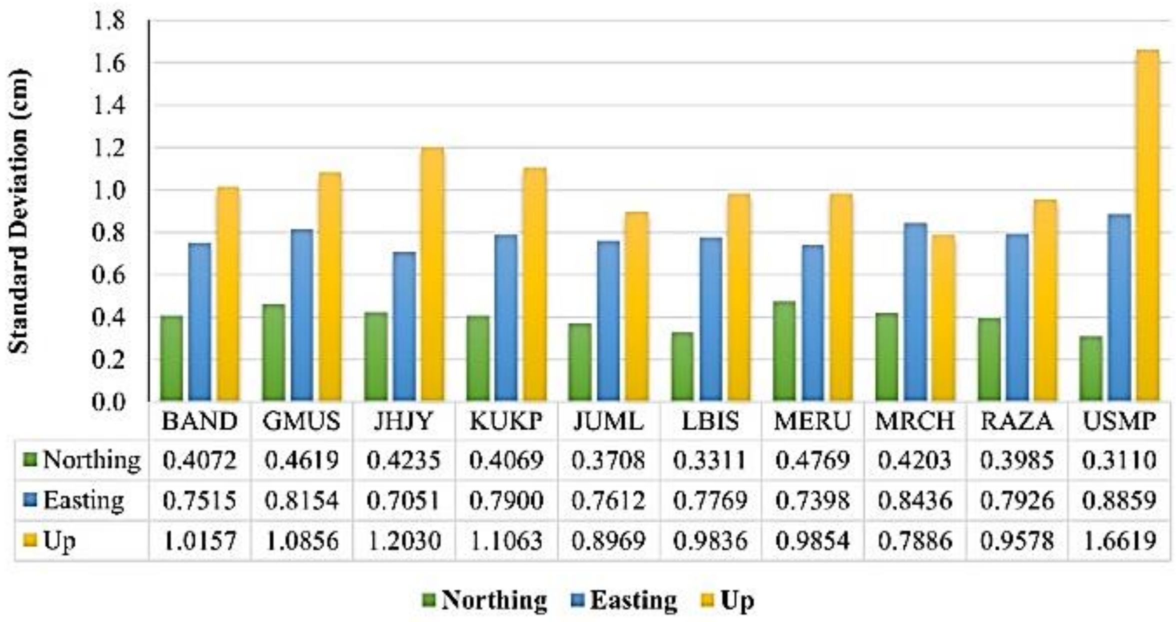

Figure 4. Standard deviation of GPS-derived CTS

3.2 Site Velocity

Figure 5 illustrates data from ten (10) MyRTKnet stations from the year 2020, focusing on site velocities. Significant velocities were observed during this year, highlighting a general movement trend in the region. The velocity vectors from the map indicate that the site velocities predominantly move towards the southeast. This south eastward movement aligns with regional tectonic activities.

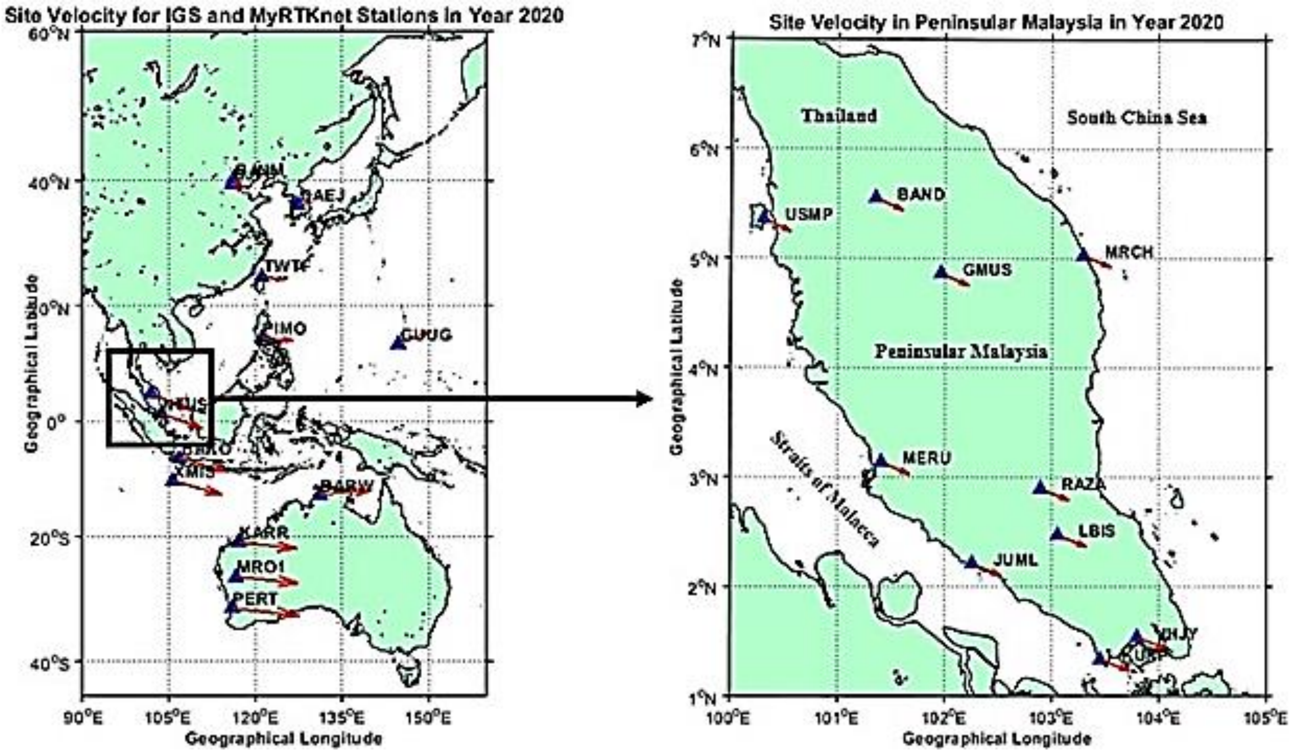

Figure 5. Horizontal site velocity of all stations

3.3 Euler Pole Parameter Estimation

Table 1 indicates that the Euler pole parameter model is generally effective in predicting the velocities at the MyRTKnet stations, with most residuals being very small. Some stations exhibit slightly larger residuals, particularly in the East component, suggesting areas where the model could be refined. Overall, the close match between estimated and predicted velocities supports the reliability of the Euler pole parameters in modelling tectonic movement in Peninsular Malaysia. The changes of coordinate in horizontal and vertical components have been estimated based on site velocity with precision of 0.5172 cm.

Table 1. Comparison on the estimated and predicted velocities between selected MyRTKnet stations

Stations	Estimated Velocities		Predicted Velocities		Difference		Direction	Azimuth
	V_N (cm)	V_E (cm)	V_N (cm)	V_E (cm)	dV_N (cm)	dV_E (cm)	V_{NE} (cm)	N (°)
BAND	-1.733	1.911	-1.138	2.560	-0.596	-0.650	1.963	358.847
JHJY	-1.695	2.894	-1.029	2.748	-0.666	0.146	1.951	358.787
MRCH	-1.291	2.825	-1.051	2.582	-0.239	0.243	1.920	358.816

Figure 6 shows the Euler pole calculator as a tool for calculating the rotation pole of tectonic plates where it shows the output data of corrected velocity components V_N and V_E for each station, along with residuals dV_N and dV_E, which indicates the differences between estimated and predicted velocities. The Euler pole is located at a latitude of 45°26’06” N, 125°32’56” E with a rotation rate of ±355.3586°. The precision of the Euler pole parameter for Latitude, Longitude and Rotation has been computed as 1.021cm, 0.687cm and 6.460cm respectively. The azimuth values are very close, ranging from 358.791° for KUKP to 358.861° for USMP. These small differences indicate very similar directional alignments among the stations.

During the research period, the crustal deformation trend changed at a steady rate because there were no earthquakes that occurred. Moving forward, the six months data that has been processed is insufficient to derive a reliable trend due to the influence of yearly tidal motions, and other seasonal variations. Processing weekly data, causing gap between data increase difficulty in identifying accurate trends. Thus, longer data collection periods and more frequent sampling are necessary to capture a comprehensive and accurate picture of crustal deformation trends [22].

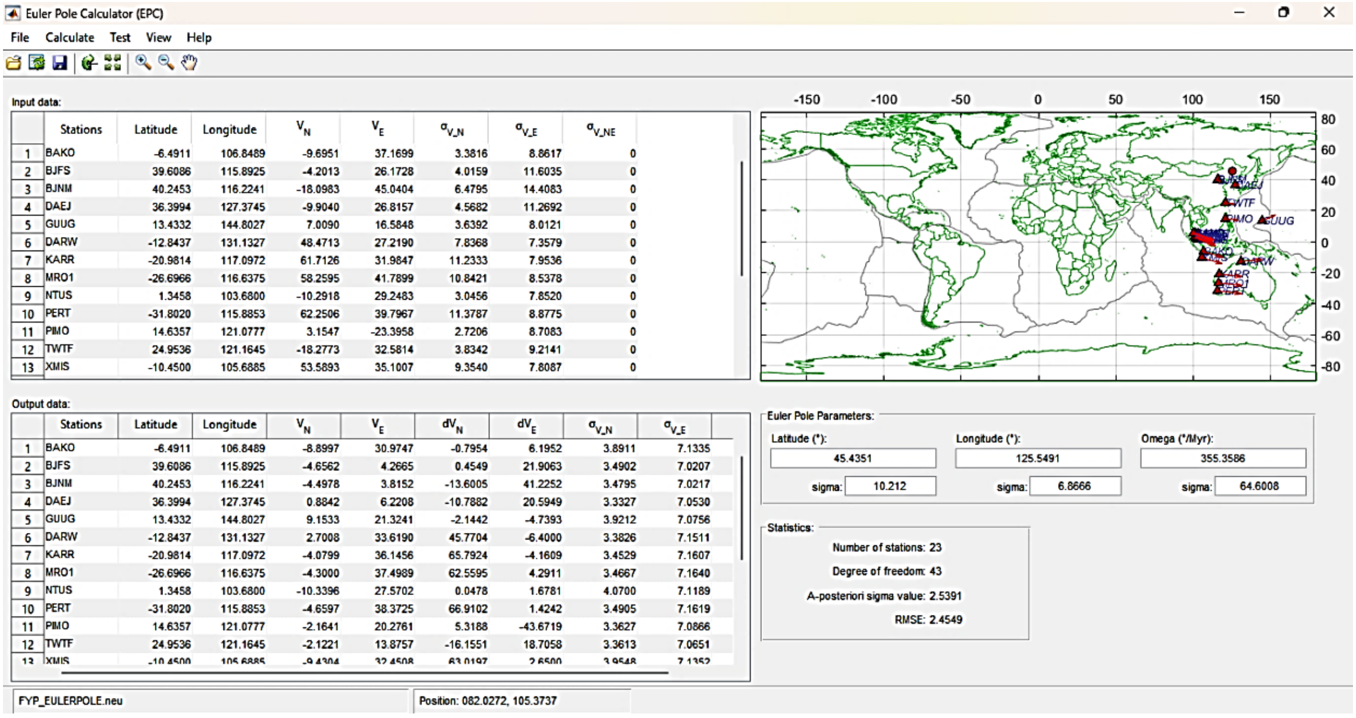

Figure 6. Euler Pole Calculator

4. CONCLUSION

In conclusion, the study of Sunda plate motion is vital for scientific development in geodesy and geodynamic studies. This study has formulated the Euler pole parameter, though restricted to Peninsular Malaysia, to estimate regional velocity for the calendar year in question. The study was able to fulfill all the objectives through the three phases. For the first phase, CTS has been produced with the precision of 0.0139m. As for the second phase, the North, East, and Up components of site velocity were obtained with centimeter-level accuracy; thus, it is possible to use the results of the further analysis with a high degree of confidence. Finally, for the third phase, the angular momentum parameters and the Euler pole location were calculated with the root mean square error being 0.00245m. This parameter turned out to be appropriate for the Malaysia region which indicated deviations from real site velocity within the sub-centimeter range. The findings and discussions confirm that the study objectives were accomplished, which indicates the application of the Euler pole parameter in the assessment of Sunda land plate motion. The Euler pole estimation can be improved by adding more stations, processing weekly data, increasing the period of processing detecting and removing coordinates discontinuity due to station instability. Further research can be done to refine the Euler pole parameter estimation, to support realization of dynamic reference frame in Malaysia.

ACKNOWLEDGEMENT

The authors would like to thank the Department of Surveying and Mapping Malaysia and Petronas Group for providing the GPS data for this study. The author also would like to thank Geomatic Innovation Research Group (GnG) for providing Bernese GNSS software 5.2 for this study.

FUNDING

The support provided by Universiti Teknologi Malaysia for funding through the UTM Fundamental Research Grant Vot Q.J130000.3852.22H47 for this study is highly appreciated.

AUTHOR CONTRIBUTIONS

Nilashini ML Supparamaniyan: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization

Wan Anom Wan Aris: Supervision

Tajul Ariffin Musa: Validation

Mohd Azizi Alim Shah: Reviewing

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] D. Angermann, R. Pail, F. Seitz, and U. Hugentobler, 4 November 2024, “The importance of geodetic reference frames,” *GIM International*. https://www.gim-international.com/content/article/the-importance-of-geodetic-reference-frames.

[2] Y. Y. Ziggah “Regression models for 2-dimensional cartesian coordinates prediction: A case study at University of Mines and Technology,” *International Journal of Computer Science & Engineering Survey*, vol. 3, no. 6, pp. 61–79. 2012.

[3] U. Arifin, U. Smart, M. Husemann, S. T. Hertwig E. N. Smith, D. T. Iskandar, and A. Haas, “Phylogeographic inference of sumatran ranids bearing gastromyzophorous tadpoles about the pleistocene drainage systems of Sunda land,” *Scientific Reports*, vol. 12, no. 1, p.12013, 2022.

[4] N. A. A. Rahman, T. A. Musa, W. A. Wan Aris, and A. H. Omar, “Proposed strategy to obtain optimum inter-station distance for gps cors development scenario,” *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 48, pp. 431-437, 2023.

[5] A. Schettino, and C. R. Scotese, “Apparent polar wander paths for the major continents (200 ma to the present day): A palaeomagnetic reference frame for global plate tectonic reconstructions,” *Geophysical Journal International*, vol. 163, no. 2, pp. 727-759, 2005.

[6] C. R. Scotese, and B. A. Pluijm, “Deconstructing tectonics: ten animated explorations,” *Earth and Space Science*, vol. 7, no. 11, p. e2019EA000989, 2020.

[7] W. J. F. Simons, A. Socquet, C. Vigny, B. A. C. Ambrosius, S. Haji Abu, C. Promthong et al., “A decade of gps in southeast Asia: Resolving sundaland motion and boundaries,” *Journal of Geophysical Research: Solid Atmospheres*, vol. 112, no. B6, 2007.

[8] B. J. Haines, Y. E. Bar-Sever, W. I. Bertiger, S. D. Desai, N. Harvey, A. E. Sibois et al., “Realizing a terrestrial reference frame using the global positioning system,” *Journal of Geophysical Research: Solid Earth*, vol. 120, no. 8, pp. 5911-5939, 2015.

[9] Z. Altamimi, P. Rebischung, L. Métivier, and X. Collilieux, “ITRF2014: A new release of the international terrestrial reference frame modeling nonlinear station motions,” *Journal of Geophysical Research: Solid Earth*, vol. 121, no. 8, pp. 6109-6131, 2016.

[10] Z. Altamimi, X. Collilieux, and L. Métivier, “ITRF2008: An improved solution of the international terrestrial reference frame,” *Journal of Geodesy*, vol. 85, no. 8, pp. 457-473, 2011.

[11] M. Azhari, Z. Altamimi, G. Azman, M. Kadir, W. J. F. Simons, R. Sohaime, et al., “Semi-kinematic geodetic reference frame based on the ITRF2014 for Malaysia,” *Journal of Geodetic Science*, vol. 10, no. 1, pp. 91-109, 2020.

[12] W. I. Hatin, A. R. Nur-Shafawati, M. K. Zahri, S. Xu, L. Jin, S. G. Tan, et al., “Population genetic structure of peninsular Malaysia malay sub-ethnic groups,” *PLoS ONE*, vol. 6, no. 4, p. e18312, 2011.

[13] Y. Lin, L. Colli, J. Wu, and B. S. A. Schuberth, “Where are the Proto-South China Sea slabs? SE Asian plate tectonics and mantle flow history from global mantle convection modeling,” *Journal of Geophysical Research: Solid Earth*, vol. 125, no. 12, p. e2020JB019758, 2020.

[14] O. Montenbruck, U. Hugentobler, R. Dach, P. Steigenberger, and A. Hauschild, “Apparent clock variations of the block iif-1 (svn62) GPS satellite,” *GPS Solutions*, vol. 16, no. 3, pp. 303-313, 2011.

[15] M. Hernández-Pajares, J. M. Juan, J. Sanz, and R. Orús, “Second-order ionospheric term in GPS: Implementation and impact on geodetic estimates,” *Journal of Geophysical Research: Solid Earth*, vol. 112, no. B8, 2007.

[16] X. Li, M. Ge, X. Dai, X. Ren, M. Fritsche, J. Wickert, et al., “Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo,” *Journal of Geodesy*, vol. 89, no. 6, pp. 607–635, 2015.

[17] Y. Tanaka, M. Kano, T. Nishimura, Y. Ohta, and K. Yano, “Numerical experiment toward simultaneous estimation of the spatiotemporal evolution of interseismic fault slips and block motions in Southwest Japan,” *Earth Planets and Space*, vol. 76, no. 1, p. 69, 2024.

[18] V. I. Kaftan, and V. N. Tatarinov, “An analysis of possibilities of GNSS local strain monitoring networks in earthquake-prone areas,” *Journal of Volcanology and Seismology*, vol. 15, no. 6, pp. 379–386, 2021.

[19] M. Jagoda, and M. Rutkowska, “An analysis of the eurasian tectonic plate motion parameters based on GNSS stations positions in ITRF2014,” *Sensors*, vol. 20, no. 21, p. 6065, 2020.

[20] M. A. A. Shah, W. A. W. Aris, A. Z. Sha'ameri, T. A. Musa, and S. S. A. Manan, “Seismic wave time of arrival and path velocity estimation using 1-hz GPS data,” *Jurnal Teknologi*, vol. 85, no. 6, pp. 111–119, 2023.

[21] L. Prawirodirdjo, and Y. Bock, “Instantaneous global plate motion model from 12 years of continuous GPS observations,” *Journal of Geophysical Research: Solid Earth*, vol. 109, no. B8, 2004.

[22] M. Nemati, A. Rashidi, M. Ezati, and R. Derakhshani, “Quantitative analysis of crustal deformation, seismic strain, and stress estimation in iran via earthquake mechanisms,” *Frontiers in Earth Science*, vol. 12, p. 1408873, 2024.