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Euler Pole Parameter Estimation of Sunda Plate from Present-Day GPS Site Velocities in Malaysia

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Abstract. Malaysia is situated at Sunda plate that experience highly dynamic of earth's crust with frequent earthquake and volcano activities. The effect of plate motion causing the static-based geodetic reference frame in Malaysia is no longer relevant to support the centimeter level of Global Positioning System (GPS) application. Therefore, an updated Sundaland plate motion model is necessary to cater to the effect thus preserving the reliability of the geodetic reference frame. This study aimed at determining regional plate motion of Sundaland in support of dynamic reference frame. The work involved in generating precise Position Errors Time Series (PETS) from GPS Continuous Operating Reference System (CORS) data in Malaysia and neighbouring country. The Coordinates Time Series (CTS) were then used to estimate velocity vector and the precision form the results depicted at -8.0429±3.0215mm, 3.873±3.288mm, and 0.913±7.775mm for component northing, easting and up, respectively. From the velocity vector, location of Euler pole of Sunda plate was found at latitude 5.8482˚N and longitude -95.1017˚E with estimated angular momentum of 0.201Ω/Myr± 0.0389. It can be expected that the result will be useful for maintaining the reliability of the reference frame in South East Malaysia.

1. Introduction

The earth's crust is divided into 31 to 56 plates as pre-described by global plate motion models such as MORVEL and REVEL. The Sunda plate is covers a large part of Southeast Asia that includes Indochina, Peninsular Malaysia, Thailand, Sumatra, Borneo and the other seas that located in between Eurasian and Australian plate. It is mostly encircled by highly active volcanic zones, which is the effect of plate motion will affect the reference frame. Sundaland presently moves as a coherent lithospheric block, although its geological origin clearly is not monolithic [1].

The plate motion model comprises of Euler pole location and angular momentum are useful in predicting linear crustal deformation in geodetic reference frame maintenance. Wrong model could be falsifying the prediction thus degrading the precision of geodetic reference frame. The estimation of plate motion can be realised from the knowledge of continuous crustal deformation trend in the form of site velocity. The more denser site velocity, the better results will be. Several studies have shown the capability of GPS CORS network in Southeast Asia for estimating site velocity precisely.

However, series of earthquakes that had devastating the region such as 9.2 Mw 2004 Sumatra-Andaman mega earthquake which resulted in long-term post-seismic deformation within the Sunda plate [2][3]. complicate the parameter estimation. Besides the great post-seismic effects, the non-linear behaviour of the region, [3][4] has shown that the effect is minimum after 2018. To the best of author knowledge, this duration is suitable period for re-determination of Euler pole and angular momentum for Sunda plate.

This study also can provide the facility for geodesist at control station GPS CORS to maintained geocentric coordinates in International Terrestrial Reference Frame (ITRF) and need a consistency monitor and to validate its accuracy over time. The earth is moving and it necessary to trace the motion change of coordinate to get the updated coordinates. If not geometry satellite to receiver will inaccurate and ambiguity can't fix. There need to estimate velocity from PETS shown an offset from equipment change to know precision of measurements for tectonics. Thus, the need of crustal deformation modelling for improving GPS CORS station and GNSS will provides high accuracy for positioning applications that most accurate global reference frame available nowadays.

Figure 1 illustrates tectonic map of South East Asia region. The location of Sunda plate is between the zone of convergence of Eurasian, Philippine and Indian–Australian plates. From the figure, large red arrows represent absolute motions of plates on ITRF2000 [2]. Four major earthquakes's epicenter (presented as red star in the figure) were located at subduction zones of Sumatra Andaman dan Mentawai, had caused fatality and damages.

Figure 1. Map of Southeast Asia region from satellite image, superimposed on topography and location of major earthquake's epicenter in Sundaland.

Nowdays, more model recently used to calculate angular velocity and momentum by using MORVEL model [5] to see how many distance of omega, phi and kappa move per second. GPS derived PETS is a result from processing GPS raw data observation that have been undergo GPS processing by using certain software. To investigate crustal deformation and geophysical phenomena, secular velocities of discrete points on the Earth's surface are commonly estimated today from position time series of permanent GPS stations [6]. In order to obtain velocity for each component, PETS for each GPS station must be generated. Station velocities were extracted by linear regression, which implies steady-state motion, and this was verified by analysing the misfits with respect to the linear trends [2]. A brief mathematical function to explain intra-plate site velocity in GPS derived PETS can be written as [7];

$$y(t_i) = y_0 + \bar{V} t_i \quad (1)$$

where, $y(t_i)$ is the daily GPS-derived PETS (either in north, east or up component) and t is epoch where i =1,2,3 ..., N. The term y_0 is initial topocentric coordinate value of each site and taken as the reference epoch. The terms $\bar{V} t_i$ is estimated site velocity from PETS.

2. Data and methods

2.1. Study Area

The study region focuses on Peninsular Malaysia, Sabah and Sarawak facing the South China Sea, which is confined from 0° to 8° latitude and from 100° to 120° longitude as shown in Figure 2.

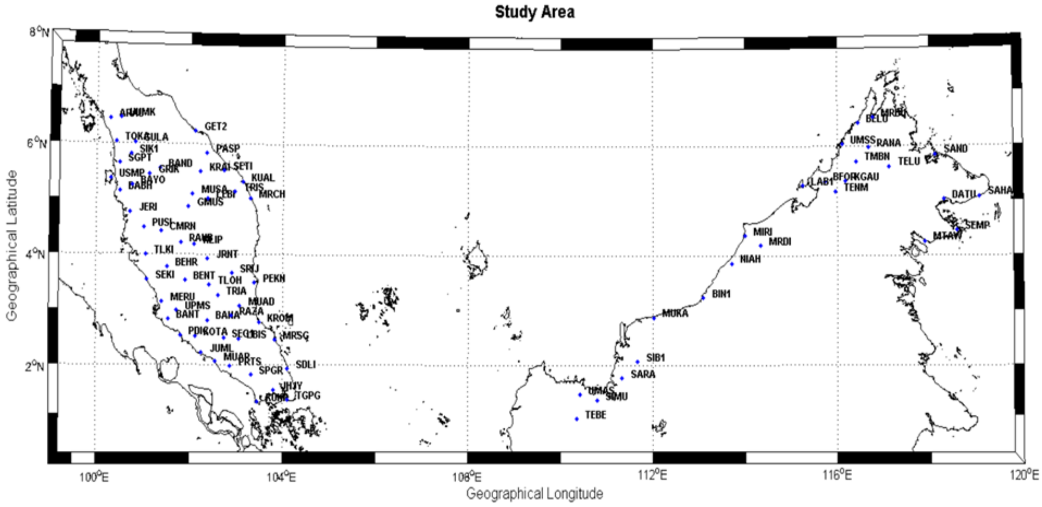

Figure 2. Selected MyRTKnet station in this study

2.2. GPS-derived PETS

In this study GPS raw RINEX data (comprised L1 and L2 signals with sampling rate of 30 seconds) from observation date of DoY 001/2018 – DoY 265/2018 at eighty (80) MyRTKnet station as illustrated in Figure 2 were utilised in order to obtain GPS coordinates time series for MyRTKnet stations. The GPS coordinate time series were planned to be relative to ITRF2014 in order to ensure coordinate consistency to the latest global reference frame [8][9]. Twenty-five (25) selected IGS stations. The selection IGS stations were based on their availability in 2018 and GPS coordinate time series in order to maintain consistency of global network.

2.2.1. Baseline Processing. Data preparation was conducted such as a location in 3D Cartesian coordinate for every stations and ocean tide loading for the purpose to minimize the error. To determine three-dimensional (3D) baseline vector, the double-differencing processing method was applied, where differences of the phase observables between two satellites and two stations are used between the GPS sites. Baseline vector were processed using Quasi-Ionosphere Free (QIF) approach as daily batches at 30 seconds intervals with a cut-off elevation angle of 10° degrees. Then, the need of data preparation such as a location in 3D Cartesian coordinate for every stations and ocean tide loading for the purpose to minimize the error. Besides, baseline vector has to satisfy at RMS less than 2 cm with fixed ambiguity resolution at least at 75%.

2.3. Site Velocity Estimation.

In this stage, the site velocity of each station was estimated by applying linear fitting model in the PETS based on the equation [4];

$$P = m\text{t} + b \tag{2}$$

where t is time in day of year and P are the position of a point, m is the slope of a line and b is the y intercept at t=0. It to present the trend of the deformation and the time series graph to reveal the significant of movement at each station. The analysis was conducted based on GPS-derived PETS and the site velocity computed.

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2.4. Angular Momentum Estimation.

Euler pole parameter comprises of Euler pole (i.e., Euler's location) and Euler's rotation also known as angular momentum. The more the number of site velocities, the better estimation of Euler pole parameter. The Euler pole parameter estimation enables for predicting site velocities for any points on the Earth's surface. The Euler theorem can be mathematically formulated as [10]:

$$v_i^p = \Omega^p \times \boldsymbol{X}_i = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}^p \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (3)$$

where v_i^p and $\boldsymbol{X}_i(x_i, y_i, z_i)^T$ are the velocity and the position of the station i, and $\Omega^p(\omega_x^p, \omega_y^p, \omega_z^p)$ is the angular velocity or the Euler vector of the plate p associated with the station i. The P in the Eq. 3 assumed plate and does not refer to the reference frame. The cross product is taken between the angular velocity vector and the station position vector in an Earth-Centered Earth Fixed Cartesian Coordinate System (ECEF). Therefore, the velocity v_i^p is also expressed in the ECEF. The magnitude of the Euler vector $\Omega^p = |\Omega^p|$ is the rate of rotation of the plate p around its pole and is usually expressed in degrees per million years (˚/Myr). The direction of the Euler vector $\Omega^p = \Omega^p/|\Omega^p|$ is often expressed as a spherical latitude and longitude in degrees. In this rotation model, the plate p is basically constrained to move rigidly on the spherical earth's surface without radial motion. We can rewrite Equation 4 for site velocity prediction using basic skew-symmetric matrix properties [11] as follows:

$$v_i^p = \begin{bmatrix} 0 & z & -y \\ -z & 0 & x \\ y & -x & 0 \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}^p = \boldsymbol{\Omega}^p \times \boldsymbol{X}_i \quad (4)$$

The site velocity from phase 2 is classify in northing and easting for each component. The data is input in MATLAB Euler Pole Calculator (EPC), [10]. The input data can be either in ECEF Coordinates or Local Geodetic Coordinates and it calculates and estimates Euler pole parameter. The Euler pole parameter that comprises of Latitude, Longitude and Omega (◦Myr) showing in Euler pole calculator. Besides, this study uses LG data for Euler pole estimation.

3. Results and discussion

This section comprises of three (3) subsections for explanation on GPS baseline solution, site velocity estimation from PETS, euler pole parameter estimation and assessments.

3.1. GPS Baseline Solution

There were up to eighty-six (86) baseline per day, post-processed from sites MyRTKnet to the selected IGS station. The quality of each baseline was justified by percentages of QIF ambiguity resolution. Figure 3 demonstrate averaged percentage of ambiguity resolution of daily solution. In the plots of Figure 3, the averaged percentage of ambiguity resolution over (265) days stands at 71.32% with standard deviation ±2.639%. the highest percentage of QIF ambiguity resolution of the study is 78% at DoY 015 and the lowest is 65.7% at DoY 143. It about eighty (80) station of MyRTKnet has been processed using Bernese 5.2 software.

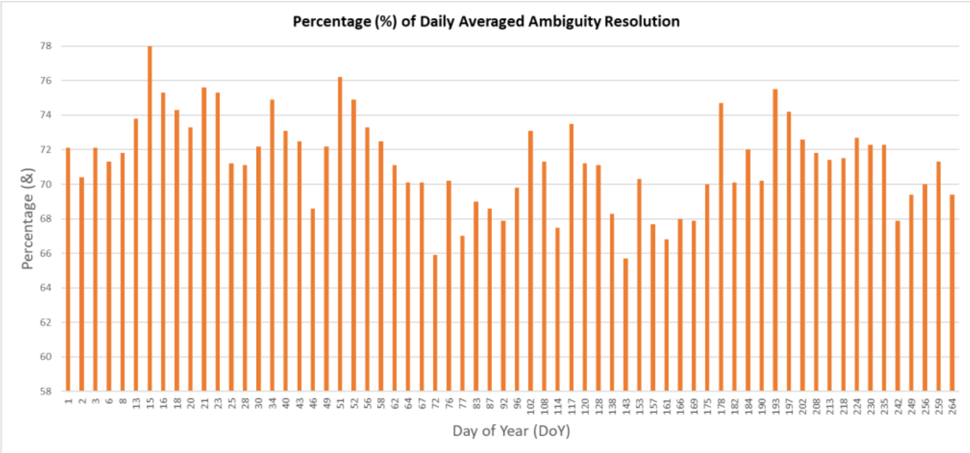

Figure 3. Percentage of daily averaged ambiguity resolution.

3.2. *PETS & Site Velocity Estimation*

Site BIN1 in 2018 is chosen to demonstrate PETS after outlier detection and removal as shown in Figure 4. The PETS comprises of north, east and up component in local topocentric. It shows that precision of PETS at BIN1 at standard deviation of 2.7mm, 2.7mm and 7.7mm for north, east and up components respectively. Similar outlier inspection has been applied to determine the precision of GPS-derived PETS at MyRTKnet sites. Summary of standard deviation of GPS-derived PETS for certain sites is shown in Figure 5, whereby blue, orange, and grey bar indicates standard deviation of north, east and up components respectively.

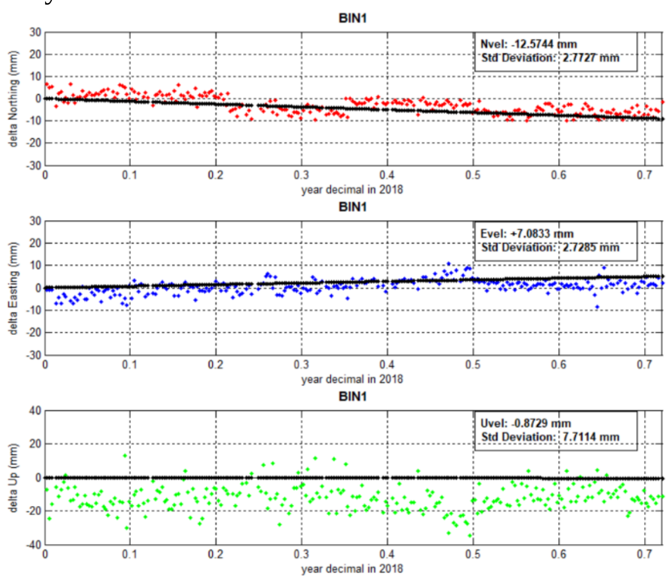

Figure 4. PETS of BIN1 in 2018 after outlier removal.

From Figure 5, one that can inspect that some of the sites in term of up component showed standard deviation value greater than 1cm. In this case, has shown a good standard deviation of PETS at less than 15mm. Thus, these up components were excluded for further parameter estimation in Euler Pole parameter because only north and east component will be use in this Euler Pole parameter estimation.

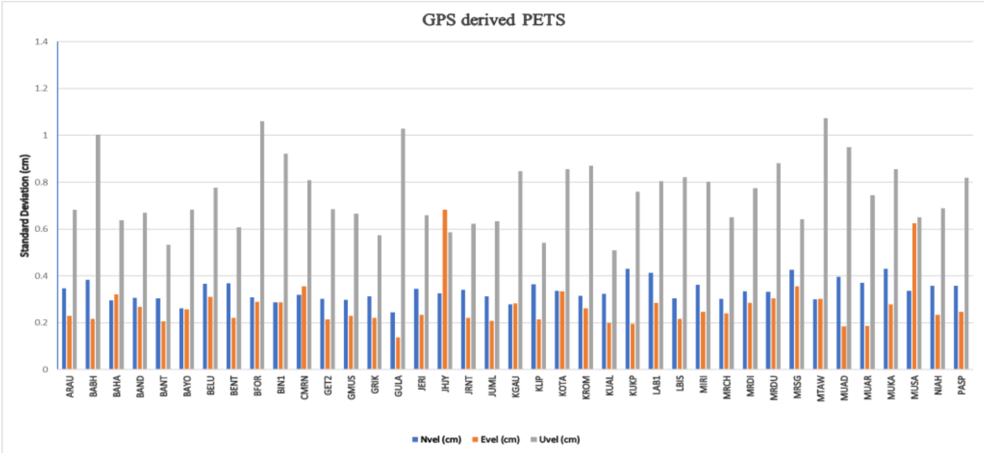

Figure 5. Standard deviation of GPS-derived PETS.

For Peninsular Malaysia, forty-two (42) stations of MyRTKnet in 2018 is illustrated in Figure 6. The study shows significant value of velocities on that year. It can be observed that the site velocity at this region moves in south and southeast direction. There were several sites in northern Peninsular comprises of non-ideal site velocity such as stations ARAU, UUMK, SIK1 and SGPT. The station will be excluded because is not similar following the other trend.

Twenty-two (22) stations of MyRTKnet in east Malaysia were selected for site velocities estimation as shown in Figure 6. It can be observed that the site velocity at East Malaysia region moved in south-eastward. Unlike SIMU and TELU, the sites moved south-westward which occur due to insufficient data for that station from DoY 080 to DoY 265. This degrades the process of estimating the velocity as there were no observation available between the days stated.

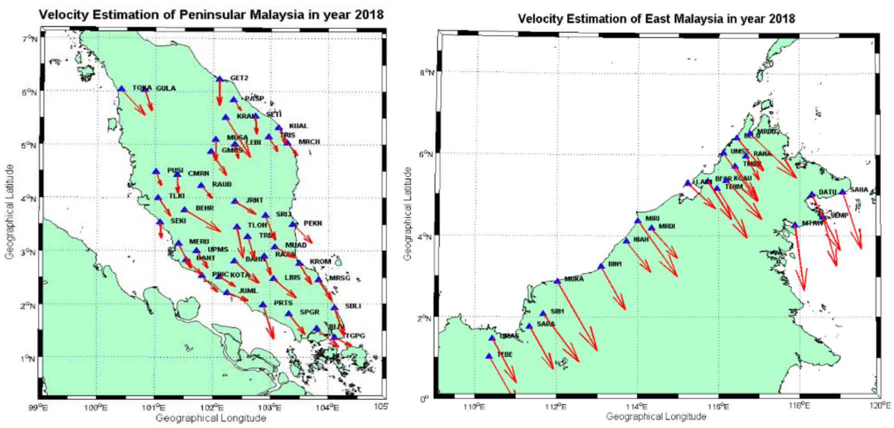

Figure 6. Velocity estimation in Peninsular and East Malaysia.

3.3. Euler Pole Parameter Estimation

The Euler pole's parameter estimation were performed by using selected station. The analysis shows the best fit of Sunda Plate's Euler pole parameter estimation from 64 sites, while another 16 sites treated as independent check. Table 1 tabulates the parameters in term of Euler pole's location and angular momentum at 0.2012 Omega/Myr.

Table 1. Estimated plate kinematic parameter.

Reference Plate	Reference Frame	Num. Of Site	Euler's Pole and Rotation Parameters		
			Latitude	Longitude	Angular Momentum (Omega/ Myr)
SUNDA	ITRF2014	64	5.8482	-95.1017	0.2012 ±0.0389

3.4 Assessment on the Euler Pole Parameter
Figure 7 shows predicted site velocity, meanwhile Table 2 lists a predicted site velocity for a certain selection station. Residual in predicted site velocity shows offset less 2mm in north components and 4mm in east component. The result indicates that the Euler pole parameter estimation is acceptable. However due to less stations involved in the parameter estimation, it can be expected that the parameter is suitable for Peninsular Malaysia and Borneo regions.

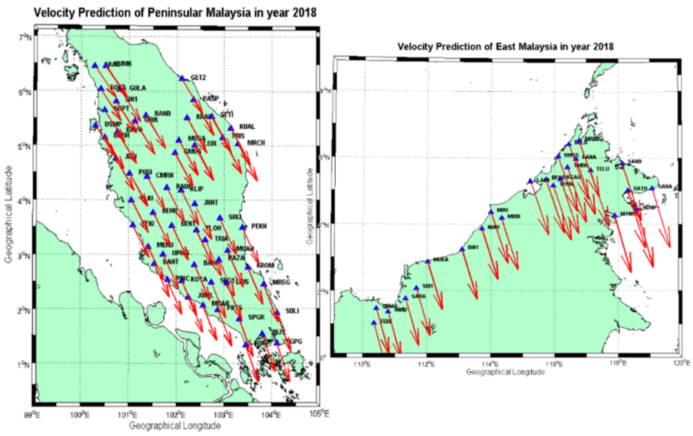

Figure 7. Predicted Site Velocity

Table 2. Estimated plate kinematic parameter.

8 Station	Predicted Site Velocities from Euler Pole parameter		Residual between predicted and observed site velocities	
	Vn (mm/yr)	Ve (mm/yr)	Vn (mm/yr)	Ve (mm/yr)
BAHA	-6.6906	3.3190	-1.1238	4.6666
BANT	-6.3782	3.3309	1.1091	2.0119
GMUS	-6.5368	4.0784	-1.7628	1.0406
JHJY	-7.2145	2.8459	0.5319	4.3817
KROM	-7.1044	3.2965	-0.3161	0.7050
LBIS	-6.9411	3.1924	0.0316	4.1441
NIAH	-10.736	3.5909	1.8189	3.5775
PRTS	-37.182	4.1622	-1.1252	-4.1022
RAZA	-6.8822	3.3491	0.3728	-1.3237
UPMS	-6.4475	3.3918	0.3501	-0.2520

4. Conclusion

From the finding of this study, it can be concluded that the precision of MyRTKnet stations were considered good as a root mean square in ECEF coordinates does not exceed ±2cm. The outliers in the PETS were removed in order to achieve better precision in GPS derived PETS. The position error time series as generated throughout this study shows the velocity and its standard deviation in components of North, East and Up can achieved in millimeter level. It can be concluded that by using large number of MyRTKnet and IGS stations for 1-year GPS PETS will improve the estimated Euler pole parameter and on presenting of complete of an accurate Sundaland plate motion modelling. The great post-seismic affects the non-linear behaviour of the region and it has shown that the effect is minimum after 2018.

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