ASSESSING EFFICIENCY OF GPS EPHEMERIDES IN DIFFERENT REGION USING PRECISE POINT POSITIONING

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ABSTRACT:

Precise Point Positioning (PPP) is a technique that process Global Positioning System (GPS) observation that can achieve sub-decimetre accuracy. Precise ephemerides that contain satellite clock and position plays a vital role in minimising orbital and clock error in PPP. This study hypothesize that the efficiency of ephemerides varies across region, influenced by the density of stations involved in generating the ephemerides. GPS observations from stations in five different regions were processed using PPP technique by using RTKLIB. Four types of ephemerides were used namely broadcast, ultra-rapid, rapid, and final ephemerides during the processing of each station. Root-mean-squared error (RMSE) of 3D error of the PPP solution for the stations in each region is quantified. Among the five regions selected, Europe has the lowest RMSE of 155.67 cm, 27.93 cm, 27.38 cm and 27.06 cm for broadcast, ultra-rapid, rapid, and final ephemeris respectively. This high accuracy can be attributed to the density of International GNSS Service (IGS) stations in Europe that are available for the generation of ephemerides. Position Dilution of Precision (PDOP) was also found to contribute to the accuracy of PPP solution in a region, whereby a low PDOP often promises higher positioning accuracy. More regional stations are suggested to be involved in the generation of ephemerides to improve the efficiency of ephemerides in that region.

1. INTRODUCTION

GPS is a space-based technology that offers services in positioning, navigation, and timing. For the common public, GPS can be seen contributing to ease daily activities such as navigation, delivery tracking and e-hailing (Kealy & Moore, 2017; Kin-Chung, 2020). The application of GPS extends beyond that and covers multiple economic and research activities such as precision agriculture (Davis et al., 1998), surveying in construction (Rizos, 2017), maritime and aviation positioning (Kealy & Moore, 2017; Richard Farnworth & Orge, 2017), meteorology (Musa et al., 2011) and geodynamics studies (Wan Aris et al., 2018).

One of the reasons why GPS has many applications is due to the accuracy that GPS can provide. GPS can provide accuracy up to sub-centimetre level by using relevant processing techniques (Rizos, 2017). The processing technique can be generalized into two categories: relative positioning and absolute positioning.

Relative positioning requires two GPS receiver performing simultaneous observation and be processed together. A baseline is formed between the two receivers and the coordinates of one of the receivers are normally known or fixed to a certain value. Relative positioning offers accuracy from decimetre up to millimetres (Rizos, 2017). It is the common GPS observation and processing technique used and recognized by local survey and mapping authority in Malaysia (Azhari, 2021).

Absolute positioning on the other hand requires only one receiver. Absolute positioning works using the concept of trilateration, whereby a minimum of four satellites are required to determine the user position (Hofmann-Wellenhof et al., 2012). Absolute positioning can be further categorized into two, namely Single Point Positioning (SPP) and PPP. SPP uses pseudorange which has relatively lower accuracy at around metre level (Hofmann-Wellenhof et al., 2007). It is commonly used for navigation purposes.

PPP is an absolute positioning technique that uses undifferenced carrier-phase and pseudorange to determine user position. PPP can achieve accuracy of up to sub-decimetre (Kouba et al., 2017). PPP differs from SPP whereby errors in measurement such as ionospheric delays, tropospheric delay, relativity, Sagnac delay, ocean tide loading, code biases, antenna phase offset, antenna phase windup, satellite orbital error and satellite clock error (Kouba et al., 2017) are properly modelled and minimised using models or high accuracy products. The effect of each error is listed in Kouba et al. (2017).

Among the errors in PPP, Witchayangkoon (2000) highlighted that PPP is characterized by the usage of precise satellite position and satellite clock. The information of satellite position and clock can be found in ephemerides. Precise ephemerides are one of the products produced by various IGS analysis centres (AC) using globally distributed Continuous Operating Reference Station (CORS) (Weiss et al., 2017). CORS supply GPS measurements to the ACs such that the ACs can perform precise orbit determination to calculate highly accurate satellite position. The ACs are also commonly equipped with timing equipment for satellite clock synchronization.

This study hypothesize that the accuracy of ephemerides is region dependent. Ephemerides are expected to perform better in minimising orbital and clock error in region where more stations contribute to the generation of the ephemerides. This performance can be reflected in the accuracy of PPP solution as the accuracy of PPP is highly related with accuracy of ephemerides.

This paper is divided into five (5) sections. The first section briefly introduces GPS, GPS processing techniques and hypothesis of the study. The second section introduces GPS ephemerides including type of ephemerides and IGS ACs. The third section discusses the methodology of the experiment used in this research, including the dataset used and software and setting used. The fourth section presents and analyse the result to support the hypothesis. The last section provides a simple conclusion and further recommendation on the research.

2. GPS EPHEMERIDES

IGS categorizes ephemerides into four (4) from its accuracy and latency, namely broadcast ephemerides, ultra-rapid ephemerides, rapid ephemerides, and final ephemerides (Johnston et al., 2017). The specification of each of the ephemerides are tabulated in **Table 1**.

Type		*Accuracy*	*Latency*
Broadcast	Orbit	100 cm	Real time
	Satellite clock	5 ns RMS 2.5 ns standard deviation	
Ultra-rapid (predicted half)	Orbit	5 cm	Real time
	Satellite clock	3 ns RMS 1.5 ns standard deviation	
Ultra-rapid (observed half)	Orbit	3 cm	3 – 9 hours
	Satellite clock	150 ps RMS 50 ps standard deviation	
Rapid	Orbit	2.5 cm	17 – 41 hours
	Satellite clock	75 ps RMS 25 ps standard deviation	
Final	Orbit	2.5 cm	12 – 18 days
	Satellite clock	5 ns RMS 2.5 ns standard deviation	

Table 1. Accuracy and latency of ephemerides (Johnston et al., 2017)

Broadcast ephemerides are provided by GPS control segment based on observations at the monitor stations (Hofmann-Wellenhof et al., 2012). Broadcast ephemerides are predicted trajectory (Urs Hugentobler, 2017) and can be obtained directly from the GPS signal as satellite message. The information is given in Keplerian parameters with temporal variations.

On the other hand, ultra-rapid, rapid, and final ephemerides are orbital product are often collectively known as precise ephemerides. The precise ephemerides are generated by various IGS analysis centers around the world using CORS from IGS network. **Figure 1** shows the distribution of IGS stations around the world (IGS, 2022b).

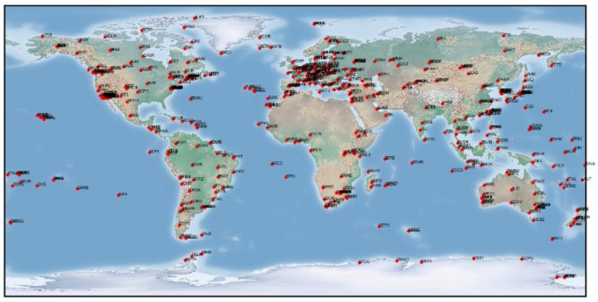

Figure 1. Distribution of IGS network (IGS, 2022b)

Different analysis centres uses slightly different models, software, strategy and station selection that involved in ephemerides generation (IGS, 2020). The products from different analysis centres are then combined using interactive weighting to form the IGS ephemerides (Urs Hugentobler, 2017). Not all stations in the IGS network are involved in the ephemeris generation. **Figure 2** shows an example of the station selected processed by Centre for Orbit Determination in Europe (CODE) on 23rd August 2019. Red squares are stations coordinates estimated with constraints while yellow circle are stations coordinates estimated without constraints.

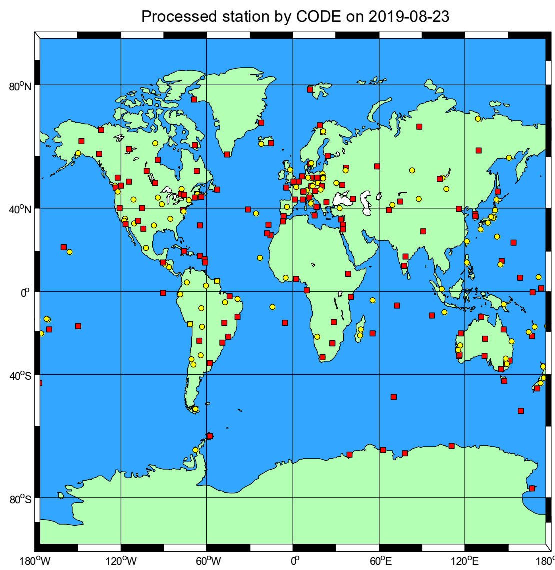

Figure 2 Processed station by CODE on 23rd August 2019

3. METHODOLOGY

Five (5) regions were selected for this study, namely Malaysia, South America, North America, Europe, and Australia. The latitude and longitude of the region are summarized in **Table 2**. It should be noted that the region in this study is defined geographically and does not represent the actual political boundary of the region and the country in it.

Table 2. Boundary and numbers of stations used in the region defined for this study

Region	*Latitude*	*Longitude*	*Approx. Surface Area (km²)*	*No. of station used in this study*
Malaysia	0.8°N - 7.5°N	99°E - 121°E	1816685.48	28
North America	10°N - 75°N	180°W - 50°W	72964789.53	49
South America	40°S - 8°N	110°W - 30°W	44316708.55	20
Europe	20°N - 60°N	25°W - 40°E	24129125.44	43
Australia	45°S - 10°S	108°E - 170°E	23430685.30	21

Stations in IGS network was used for all the region except Malaysia. Local CORS stations were used in Malaysia region that consists of Malaysia Real-Time Kinematic Network (MyRTKnet) and National Research & Development CORS Network (NRC-net).

It should be noted that stations in Malaysia are originally defined in local datum, Geodetic Datum of Malaysia 2000 (GDM2000). GDM2000 is a static datum (Jaffar et al., 2019), as opposed to the International Terrestrial Reference Frame 2014 (ITRF14) used by IGS network which is a semi-kinematic reference frame (Azhari et al., 2020). The coordinates of stations in Malaysia are pre-processed using Bernese GNSS Software 5.2 such that it is defined in the ITRF14 reference frame on the experiment day.

Observation data on 23rd August 2019 was selected for this study. 24 hours data with interval of 30 seconds were used. The observation data are first converted into Receiver Independent Exchange Format (RINEX) version 2.1. It is then edited using TEQC to remove non-GPS measurement (Estey & Meertens, 1999).

Four different ephemerides are used in this study, namely broadcast, ultra-rapid, rapid, and final ephemerides. IGS precise ephemerides are used while broadcast ephemeris was taken from the combined broadcast ephemeris. It should be noted that next day ultra-rapid (observed half) ephemeris was chosen to represent the ultra-rapid ephemerides in this study. This was done to ensure that the ultra-rapid ephemeris was fully observed throughout the duration of the experiment.

RTKLIB, an open-source GPS processing software was used to process the observation data using PPP positioning technique. RTKLIB offers many processing schemes including kinematic positioning, static positioning, SPP and PPP. Error modelling is a vital part in PPP. Supporting models such as differential code bias (DCB) and earth orientation parameters (EOP) from CODE (Dach et al., 2016) are used while antenna phase variation are taken from IGS (IGS, 2022a). Online ocean tide loading calculator was used to determine the ocean tide loading effect of the stations using FES2014b ocean tide loading model. The settings in RTKLIB used in this study is shown in **Figure 3**. The option ‘Satellite Ephemeris/Clock’ option is switched to ‘Broadcast’ when broadcast ephemeris is used. Two satellites (G04 and G18) were excluded as these stations were experiencing outage during the day selected. Including the observation from these two satellites will incur unnecessary error in the PPP solution.

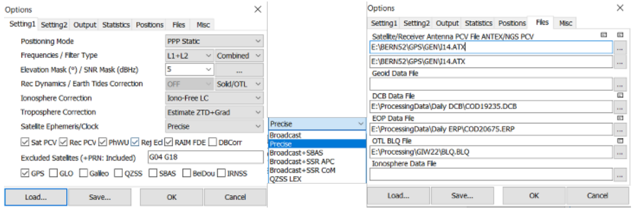

Figure 3. Settings in RTKLIB

Each PPP solution covers 1 hour of observation, totaling 24 results for each station. Small portion of solution was not produced as the result did not pass the internal test by RTKLIB.

RTKLIB outputs the PPP solution in 3D Cartesian coordinates. 3D error is computed by comparing the 3D Cartesian coordinates from PPP solution with reference coordinate. The reference coordinate for Malaysia region is the coordinates pre-processed using Bernese GNSS Software 5.2 while other region uses the daily coordinate solution by CODE. Equation 1 shows the formula to compute 3D error where *X*, *Y* and *Z* represents Cartesian coordinate.

$$3D\ Error = \sqrt{(X_{Ref} - X_{PPP})^2 + (Y_{Ref} - Y_{PPP})^2 + (Z_{Ref} - Z_{PPP})^2} \quad (1)$$

4. RESULT & ANALYSIS

RMSE of 3D error is used to quantify the accuracy of the PPP solution using different ephemerides in different region. A lower RMSE value indicates higher accuracy of PPP solution. The results are tabulated in **Table 3** and illustrated in **Figure 4**.

Table 3. 3D Error RMSE of PPP solution

EPHEMERIDES	REGION				
	Malaysia	North America	South America	Europe	Australia
BROADCAST	202.32	171.95	179.02	155.67	159.19
ULTRA-RAPID	29.64	30.27	35.25	27.93	31.50
RAPID	28.68	30.48	33.48	27.38	31.13
FINAL	28.68	30.23	33.35	27.06	30.95

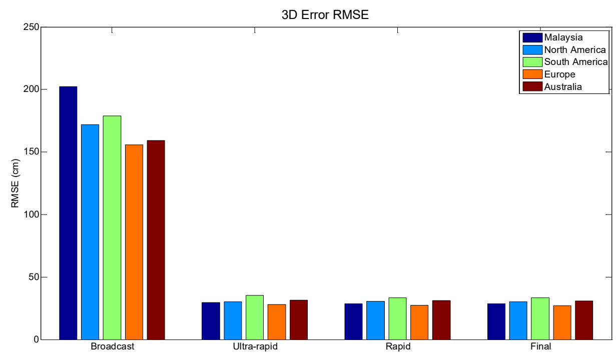

Figure 4. 3D Error RMSE of PPP solution

The accuracy of PPP solution is dependent on the type of ephemerides used. Using precise ephemerides greatly improve the accuracy of PPP solution, as compared to broadcast ephemerides. It should be noted that the PPP solution by broadcast ephemerides is contaminated with datum bias. The results from PPP are defined based on the datum used by the ephemeris. Broadcast ephemeris are defined in World Geodetic Datum 1984 (WGS84) while precise ephemerides are defined in International Terrestrial Reference Frame 2014 (ITRF2014). The reference coordinates were also defined in ITRF2014, thus using broadcast ephemeris in PPP will absorb the datum bias into the

PPP solution. WGS84 claims to be consistent with ITRF14 around 10cm (Qinsy, 2020).

Final ephemerides performed the best in PPP, followed by rapid and ultra-rapid ephemerides. This is consistent with the theory that the more accurate the ephemerides, the lower the orbital and satellite clock error and consequently higher accuracy in PPP positioning (Kouba et al., 2017).

This study also likes to highlight the accuracy of PPP solution in regions that uses IGS stations. The accuracy of PPP solution decreases from Europe region to North America, followed by South America and Australia. Europe region has high quantity of IGS stations available (43+) to be involved in generating ephemeris in a relatively smaller area. North America comes in second with the highest quantity of stations (49+) and large area to be covered. South America and Australia has relatively lesser stations as compared to the two previous regions. From this result, it could stand to support the hypothesis that ephemerides are expected to perform better regions where more stations are potentially able to contribute to the generation of the ephemerides. Densifying CORS stations in a region are expected to improve the accuracy of precise ephemerides in a region.

The accuracy of PPP solution in Malaysia is ranked second among the five regions selected in this study. While Malaysia does not have stations directly involved in the generation of precise ephemerides, it is supported by IGS stations in nearby region such as in Thailand, Singapore, Philippines, Indonesia and India. In addition, stations in Malaysia have the added advantage of having low Position Dilution of Precision (PDOP). PDOP can be used to correlate the geometry of GPS satellite with positioning accuracy (Teng & Wang, 2016). Low PDOP in Malaysia can be attributed to the location of Malaysia that are situated near equatorial region where satellite from both northern and southern hemisphere can be observed, and the GPS satellites are distributed in all four quadrants. **Figure 5** illustrates the mean PDOP value for each of the region.

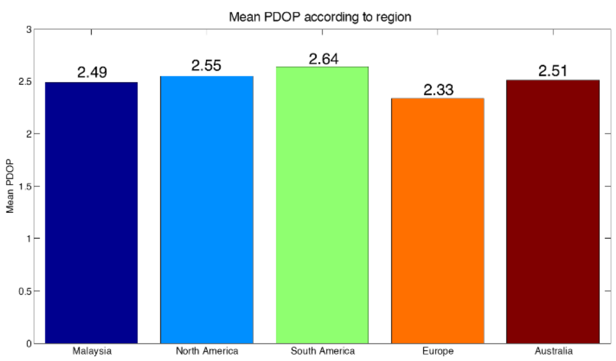

Figure 5. Mean PDOP according to region

Europe has the lowest mean PDOP, followed by Malaysia, Australia, North America, and South America. The ranking is slightly different when comparing accuracy whereby Australia outperforms North America in 3D error RMSE while North America has a lower mean PDOP. This reflects that having more stations in the region (North America 49+, Australia 21+) is more influential in the accuracy of PPP solution but having a low mean PDOP is an added advantage in PPP positioning.

The value of PDOP is dependent on the satellite geometry. It can be further reduced by having more satellites or inclusion of satellite from other Global Navigation Satellite System (GNSS) such as Galileo or GLONASS. Nevertheless, it would be dependent on agencies or countries developing these GNSS infrastructure.

On the other hand, accuracy of ephemerides in a region can be improved by having more stations in the region to participate in generating the ephemerides. This study shows that PPP solution can achieve higher accuracy in region with high quantity of station over a relatively smaller area of IGS CORS stations such as Europe.

5. CONCLUSION AND RECOMMENDATION

GPS observation data from five (5) regions are processed using RTKLIB by using PPP processing algorithm. Different ephemerides from IGS were used in the processing namely broadcast, ultra-rapid, rapid, and final ephemerides. The accuracy of PPP is dependent on the efficiency and accuracy of ephemerides used during processing. This study finds that current accuracy of ephemerides is region-dependent, whereby the ephemerides are more accurate in region with dense IGS stations such as Europe. PDOP also plays an important factor in the accuracy of PPP solution, but not as vital as the density of CORS involved in the generation of ephemerides.

The accuracy of PPP can be further improved by minimising errors in the measurement by using local a priori models such as My-Iono Services (Pathy et al., 2019). In terms of ephemeris, improvement of PPP accuracy can be realized using two solutions, decreasing PDOP and increasing efficiency of ephemerides in the region. The first solution can be realized either by increasing number of satellites or the inclusion of satellites from other GNSS. Yet, this solution is dependent on the countries or agencies that maintains the GNSS.

The second solution is more viable whereby the efficiency of ephemerides in a region is expected to improve when more stations in the region contributes to the generation of the ephemerides, especially in the accuracy of satellite position. This can be done by volunteering more regional or local stations into the IGS network. It would be better if these stations become part of the core IGS stations for better accuracy of PPP solution in the region.

Some countries such as Malaysia has laws that protect geospatial data such as safety instruction circular on protected geospatial documents (*Pekeliling Arahan Keselamatan Terhadap Dokumen Geospatial Terperingkat*). GPS or GNSS observation data cannot be shared or contributed directly into the IGS network, thus slightly limiting the efficiency of ephemerides in the region. A regional orbital product can be generated that uses these dense local CORS observations by local government agencies or research institution. A regional orbital product is expected to improve accuracy of the ephemerides in the region, contributing towards the realization of higher accuracy PPP for more application in the region.

This study is a preliminary study to investigate the impact of PPP using different ephemerides in different region. The study can be improved by including more region, use varying duration of observation, extends the numbers of days, or uses different GPS/GNSS processing software.

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