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Evaluating The Performance of Open Source GNSS Online Post-Processing Services

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ABSTRACT

Various organisations have recently developed online processing services for GNSS data. However, due to limited information about their performance and accuracy, users struggle to make informed decisions. The objectives of this study are to assess the accuracy of the positioning solutions provided by the three online GNSS processing services (OPUS, AUSPOS, and CSRS-PPP) and determine the optimum observation times needed to achieve high accuracy in GNSS post-processing services. The study was conducted at UiTM Shah Alam, Selangor, with field observations performed at four selected control points using the static observation technique. The coordinates of control points were estimated using TBC software and online processing services, and the differences between the coordinates from these services and TBC software were computed. The results indicate that AUSPOS outperforms other services in terms of accuracy across different observation periods (4 hours, 3 hours, and 2 hours). For the 4-hour observation, the RMSE values are ±0.020 m for northing, ±0.022 m for easting, and ±0.028 m for ellipsoidal height. In the 3-hour observation, AUSPOS also shows the smallest RMSE values of ±0.028 m in northing, ±0.023 m in easting, and ±0.034 m in ellipsoidal height. Similarly, in the 2-hour observation, AUSPOS maintains the best performance with RMSE values of ±0.067 m for northing, ±0.073 m for easting, and ±0.082 m for ellipsoidal height. In conclusion, the study demonstrates that among the three online GNSS processing services evaluated, AUSPOS consistently delivers the highest accuracy across different observation durations, particularly in the 4-hour observation.

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While CSRS-PPP follows closely behind, OPUS shows the least accuracy, especially for shorter observation periods.

INTRODUCTION

Global Navigation Satellite System (GNSS) technology has revolutionised positioning and navigation, enabling high-precision measurements. However, obtaining highly accurate positioning solutions using GNSS requires excellent knowledge of GNSS principles, data processing techniques and reference data sources. Therefore, GNSS online post-processing services have emerged as a convenient and cost-effective way to generate highly accurate and precise positioning solutions from raw GNSS data (Wellenhof et al., 2008).

GNSS online post-processing services typically involve uploading raw GNSS data to a server, where the data is processed using data processing algorithms and reference data sources to generate highly accurate and precise positioning solutions. These services are typically available online and can be accessed from anywhere worldwide, making them highly accessible and convenient for users (Teunissen & Montenbruck, 2017). Several free GNSS online post-processing services are available, including Online Positioning User Service (OPUS), Geoscience Australia's free online Global Positioning System processing service (AUSPOS) and Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP). These services use different data processing algorithms and reference data sources, which can result in varying levels of accuracy and precision in the positioning solutions generated by the services.

Several factors can affect the accuracy and reliability of GNSS online post-processing services, including the quality of the raw GNSS data, the data processing algorithms used by the service, the reference data sources used by the service and the user's level of technical expertise. Therefore, it is essential to understand the limitations and potential sources of error in these services to ensure that the positioning solutions generated by the services meet the required level of accuracy and precision for the user's specific application (Wellenhof et al., 2008).

This study has been conducted to evaluate the accuracy and reliability of GNSS online post-processing services, comparing the performance of different services using Root Mean Square Error (RMSE) approach. The study evaluates the accuracy of the GNSS online post-processing services by analysing the RMSE for different durations of observations. To compare the services in terms of ranking, the study rated their performance across these different observation periods and ranked them based on the accuracy they provided. This ranking helps to identify which service consistently delivers the most precise results. In addition, the intention of this study is to highlight how IGS Stations can be used as reference points while still maintaining the accuracy that is required. Therefore, it is important to evaluate these online processing services so it could be beneficial to users by identifying the best services that provide the highest accuracy in positioning.

LITERATURE REVIEW

Many organisations now offer online services for GNSS processing that are widely accessible, user-friendly and free to use without limitations. Unlike commercial software, which is expensive and requires specialised knowledge of GNSS processing, these services are available without the need for a license or advanced expertise. As a result, these online services have become increasingly popular (Olatunji, 2019).

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Moreover, ongoing advancements in algorithms for GPS point positioning and accuracy improvement have led to significant enhancements in both the quantity and quality of these services.

Online post-processing services are cloud-based GNSS data processing services that use data from GNSS receivers to improve positioning accuracy. These services can correct errors in the GNSS signal caused by atmospheric conditions, satellite clock errors, and other factors. Online post-processing services allow users to upload their GNSS data to a cloud server, which is processed using advanced algorithms to improve positioning accuracy (Dawoud, 2012).

The benefits of online post-processing services include improved accuracy, reduced reliance on local base stations, and the ability to process data from multiple GNSS constellations. These services are also convenient and cost-effective, as users do not need to invest in expensive equipment or software (Abd-Elazeem et al., 2011).

However, there are also some limitations to using online post-processing services. One of the main limitations is the need for a stable and reliable internet connection, as GNSS data can be extensive and require significant bandwidth to upload and download. Additionally, the processing time can vary depending on the amount of data being processed and the algorithms' complexity, which can delay results. Finally, online post-processing services may not be suitable for applications that require real-time positioning, as there is typically a delay between data acquisition and processing (Dawoud, 2012).

Online GNSS Processing Software

In recent years, several organizations have developed advanced online processing services for GNSS data. These services allow users to access GNSS processing data without upload fees and unlimited access. These processing services supply solutions for a user-submitted Receiver Independent Exchange Format (RINEX) file depending on differential technique with reference stations or precise point positioning technique using IGS Orbit Products (Ghoddousi-Fard & Dare, 2006). There are two types of solutions provided by online services which are the relative positioning method and the precise point positioning (PPP) solution method. The relative solution approach uses national Continuously Operating Reference Stations (CORS) or IGS stations as reference control points. In contrast, the PPP solution approach uses GPS-only or GPS+GLONASS products like orbit and clock corrections (Olatunji, 2019). Figure 1 shows the Online-Based GNSS Processing Method.

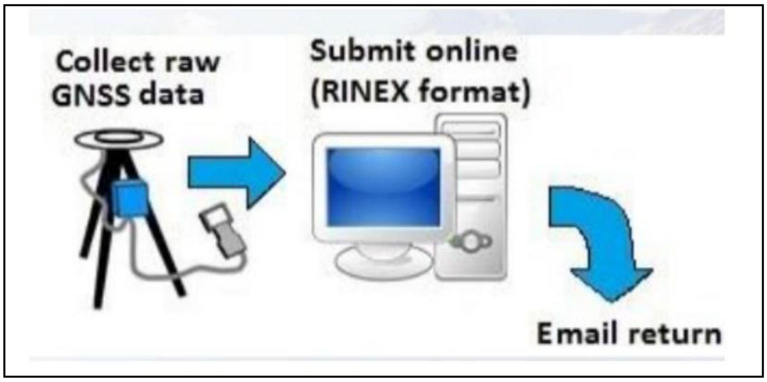

Fig. 1. Online-Based GNSS Processing Method

Source: Ghoddousi-Fard & Dare (2006)

Online Services Solution Method Overview

GNSS relative positioning involves determining the position of one receiver, known as the rover, relative to another receiver, called the base, whose position is already known. This method utilises the common observation of satellite signals by both receivers, resulting in correlated errors that allow for improvements in the rover's position solution. These methods are applicable across various scenarios, from real-time kinematic (RTK) applications to post-processing solutions. They help support various applications that require cooperative positioning (Yang et al., 2020). Additionally, online GNSS processing services now utilise the double-difference technique with IGS or CORS network data to determine point positions globally.

PPP is a GNSS surveying technique that determines precise coordinates of a point on Earth's surface using a single receiver without needing a nearby reference station (Bulbul et al., 2021). It relies on accurate satellite orbit and clock data from the IGS to calculate positioning information. By comparing GNSS observations with precise orbit and clock data, PPP estimates biases from the ionosphere and troposphere and errors from satellite orbits and clocks. It can work with single-frequency and dual-frequency receivers, removing biases for single-frequency and estimating coordinates for dual-frequency. PPP offers high accuracy without needing a reference station and is relatively simple to use, requiring only a receiver and access to IGS data. However, it requires a minimum of four visible satellites, which can be challenging in obstructed or low visibility areas and relies on reliable orbit and clock data from IGS. Table 1 shows this study's online GNSS processing services that employed relative solution and PPP solution methods. These online processing services are free and take little time to submit data.

Table 1. Online GNSS Processing Services Methods

Service	Organisation	Software	Solution Method	Data Transfer Method	Post-Processing Method	Coordinates (Datum)
OPUS	National Geodetic Survey	PAGES	Relative	Web Service	Static or Rapid Static	ITRF2014
AUSPOS	Geoscience Australia	BERNESE	Relative	Web Service	Static	ITRF2014
CSRS-PPP	National Resources Canada	NRCanPPP	Precise Point Positioning	Web Service	Static or Kinematic	ITRF2014

Source: Authors (2024)

METHODOLOGY

Online Processing Services Overview

The availability of platforms such as OPUS, AUSPOS and CSRS-PPP has changed geodetic data processing. The selection of online processing services by identifying the strengths, including processing accuracy, data availability, ease of use, support data format and OPUS, AUSPOS and CSRS-PPP software turnaround time. The first online processing service is OPUS (Online Positioning User Service). It is provided by the National Geodetic Survey (NGS) in the United States and is renowned for its high accuracy in geodetic positioning. It offers precise static and kinematic processing solutions. The accuracy of OPUS results is ensured through complex quality control processes and extensive validation against ground truth data. Users can expect reliable positioning results within centimetre-level accuracy. Next is AUSPOS (Australian Online GPS Processing Service). Geoscience Australia developed it and offered accurate GPS positioning solutions globally. It utilises a vast network of reference stations to process GNSS data and provides reliable positioning results. Lastly, CSRS-PPP (Canadian Spatial Reference System - Precise Point Positioning). Natural Resources Canada operates it and offers high-precision positioning solutions through precise point positioning techniques. It supports static and kinematic processing, making it suitable for various geodetic applications.

International GNSS Service

The study employed IGS (International GNSS Service) stations as the reference points for geodetic analysis. These IGS stations served as essential benchmarks, providing a stable and globally recognised framework for the study's geospatial reference. To establish a standardised reference frame for Online Processing Services, the study adopted ITRF2014 (International Terrestrial Reference Frame 2014). ITRF2014 represents the latest iteration of the globally recognised terrestrial reference frame, incorporating precise coordinates and velocities for a network of tracking stations worldwide. All these stations are shown in Figure 2, and detailed coordinates are provided in Table 2.

Table 2. Coordinates Of IGS Station That Used in This Study

Station ID	Country	Latitude (°)	Longitude (°)	Ellipsoidal Height (m)
NTUS00SGP	Singapore	1° 20' 44.88" N	103° 40' 47.64" E	78.867
CUSV00THA	Thailand	13° 44' 9.2904" N	100° 32' 2.0688" E	76.463
CIBG00IDN	Indonesia	6° 29' 25.314" S	106° 50' 57.0264" E	169.534
BRUN00BRN	Brunei	4° 58' 16.2408" N	114° 57' 8.4996" E	91.069

Source: Authors (2024)

Fig. 2. Location of IGS Station

Source: Authors (2024)

High-quality data is expected for every IGS station. Table 3 shows the parameters and metrics that should be fulfilled. This table outlines the minimal standards that all IGS stations must follow in addition to other desirable qualities which improve a station's value to the IGS station.

Table 3. Parameters for IGS Data

Parameters	Recommendations
Tracking	All (available) satellite systems are tracked. All-in-view tracking is activated. All (available) frequencies and signals are tracked.
Multipath	The station ideally has a multipath below thirty (30) cm for each satellite constellation.
Observations	The number of observations should be above 95% (observed vs. expected) for an elevation of five (5) degrees.
Cycle slips	The station has a low number of cycle slips (<1 per 1000 observations).
Analysis (post-processing)	Phase convergence in PPP analysis < 15 mm.

Source: Authors (2024)

Static Observation Method

GNSS receivers in Figure 3 were set up at selected ground control points (GCPs) for static observation. These points serve as the rover stations for the survey. The receivers were securely mounted on a stable tripod to minimise movement during observation. The receivers remain stationary at the survey points for an extended period of four (4) hours. The longer observation duration allows for collecting a substantial amount of data, improving the accuracy of the positioning results. Table 4 shows the parameters of GNSS for static observation.

Table 4. Parameters for Static Observation Data

Field Parameter	Setting
Observation Information	Carrier Phase (Dual-Frequency Minimum)
Number of Satellite	Minimum of six (6) satellites
Position Dilution of Precision (PDOP)	Maximum seven (7)
Elevation Mask	Fifteen (15) degrees
Recording Interval	Thirty (30) seconds
Type of Antenna	Geodetic Dual-Frequency with ground plane and multipath mitigation technique
Centering of Antenna	On GCPs
Duration of Observation	Four (4) hours

Source: Authors (2024)

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(a) (b)

Fig. 3. (a) and (b) GNSS Receivers at Selected Survey Points

Source: Authors (2024)

Data Processing Analysis

Once the coordinates were acquired from these online processing services and TBC software, they must be evaluated into the same International Terrestrial Reference Frame (ITRF) 2014. To determine the coordinates for these stations, it is necessary to employ the two major phases, including independent baseline processing and network adjustment. The four IGS stations were fixed and set as control stations for TBC processing. Since this study uses network-based processing with fixed IGS stations, TBC's least-squares network adjustment module can be employed. This feature allows to include or exclude vectors from the adjustment, fix control points and achieve high-quality results efficiently. The network adjustment process will display the horizontal and vertical error ellipses for each station, enabling quick inspection of the network's quality. The resulting loop closures were achieved through GNSS baseline processing and implementing constrained network adjustment within the TBC, along with the most likely positions determined for the selected GCPs. The differences between coordinates obtained through online processing software (OPUS, AUSPOS and CSRS-PPP) and TBC software have been computed, along with the RMSE approach of post-processed defined coordinates. Table 5 shows the parameters and settings for TBC processing.

Table 5. Processing Parameters and Setting for TBC Processing

Parameter	Setting
TBC Version	5.20
Datum	ITRF2014
Orbits	Broadcast
Type of Solution	Fixed
GNSS Loop Closure Pass/Fail Criteria	1 PPM
Global Test Interval for Network Adjustment	95% Confidence Interval
Elevation Mask	Fifteen (15) degrees

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Processing Interval	Thirty (30) seconds

Source: Authors (2024)

Displacement Computation

The calculation and modelling of variations in coordinates between online processing services and TBC Software involved utilising their respective geographical coordinates presented in the format of (latitude ϕ, longitude λ and height h) following Circular KPUP 3/2021 (JUPEM, 2021). Subsequently, these differences were converted into the local geodetic horizon to prevent potential mathematical errors. The conversion from the geographical system to the local geodetic system was performed using a conversion factor of 1" = 30 metres. The differences in the three components were computed individually, employing the following formulas:

$$\Delta\text{North (N)} = (\phi\text{" Online Processing Services} - \phi\text{" TBC Software}) * 30 \quad (1)$$

$$\Delta\text{East (E)} = (\lambda\text{" Online Processing Services} - \lambda\text{" TBC Software}) * 30 \quad (2)$$

Root Mean Square Error

The Root Mean Square Error (RMSE) is a measure of the average deviation between the predicted values and the actual observed values in a dataset. These differences, also known as residuals, are combined together using the RMSE to give a single measure of how well the values can be predicted. In the case of comparing processed coordinates obtained from GNSS online processing services to observed coordinates obtained from GNSS observations, the RMSE is the square root of the average of the squared errors. A lower RMSE suggests that the model or prediction method has a better overall accuracy in capturing the relationship or pattern within the data. It indicates that the predicted values are closer to the actual observed values implying a more accurate fit or prediction. The root mean square spatial residual in the Northing (ΔN), Easting (ΔE) and Ellipsoidal Height (Δh) directions can be estimated using the following formulas:

The ΔN -direction: $$rmse\Delta\text{E} = \pm\sqrt{\frac{\sum_{i=1}^{n}(N - N_O)^2}{n}} \quad (3)$$

The ΔE -direction: $$rmse\Delta\text{N} = \pm\sqrt{\frac{\sum_{i=1}^{n}(E - E_O)^2}{n}} \quad (4)$$

The Δh-direction: $$rmse\Delta\text{h} = \pm\sqrt{\frac{\sum_{i=1}^{n}(h - h_O)^2}{n}} \quad (5)$$

RESULTS AND ANALYSIS

The results obtained from this study are the coordinates of four selected control points, which were observed through GNSS observation and post-processed using three Online GNSS processing services.

Results of Post-Processing for TBC Software and OPUS Processing Service

Table 6 shows the results of RMSE of OPUS Processing Service in four (4) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by OPUS Processing Service in four (4) hours were ±0.038m, ±0.040m and ±0.048m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 6. RMSE for OPUS in 4 Hours

ΔN	**OPUS**	**TBC**	**Difference (m)**
GCP1	3°3'52.4347"	3°3'52.433"	0.041
GCP2	3°4'4.6994"	3°4'4.6985"	0.025
GCP3	3°4'15.2734"	3°4'15.274"	-0.030
GCP4	3°4'6.0855"	3°4'6.087"	-0.052
RMSE (ΔN) = ± 0.038m			
ΔE	**OPUS**	**TBC**	**Difference (m)**
GCP1	101°29'47.7919"	101°29'47.790"	0.059
GCP2	101°29'54.1174"	101°29'54.119"	-0.038
GCP3	101°30'6.3888"	101°30'6.390"	-0.028
GCP4	101°29'33.4765"	101°29'33.476"	0.023
RMSE (ΔE) = ± 0.040m			
Δh	**OPUS**	**TBC**	**Difference (m)**
GCP1	13.315	13.3638	-0.049
GCP2	12.863	12.9082	-0.045
GCP3	49.893	49.9422	-0.049
GCP4	2.7971	2.8441	-0.047
RMSE (Δh) = ± 0.048m			

Source: Authors (2024)

Table 7 shows the results of RMSE of OPUS Processing Service in three (3) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by OPUS Processing Service in three (3) hours were ±0.085m, ±0.078m and ±0.091m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 7. RMSE for OPUS in 3 Hours

ΔN	**OPUS**	**TBC**	**Difference (m)**
GCP1	3°3'52.4312"	3°3'52.43329"	-0.062
GCP2	3°4'4.6970"	3°4'4.69854"	-0.046
GCP3	3°4'15.2711"	3°4'15.27434"	-0.096
GCP4	3°4'6.0833"	3°4'6.08721"	-0.117
RMSE (ΔN) = ± 0.085m			
ΔE	**OPUS**	**TBC**	**Difference (m)**

GCP1	101°29'47.7886"	101°29'47.78999"	-0.043
GCP2	101°29'54.1164"	101°29'54.11862"	-0.067
GCP3	101°30'6.3884"	101°30'6.38955"	-0.035
GCP4	101°29'33.4714"	101°29'33.47569"	-0.130
RMSE (ΔE) = ± 0.078m			
Δh	**OPUS**	**TBC**	**Difference (m)**
GCP1	13.323	13.4004	0.087
GCP2	12.892	12.9506	-0.089
GCP3	49.887	49.9883	-0.101
GCP4	2.811	2.8862	-0.085
RMSE (Δh) = ± 0.091m			

Source: Author (2024)

Table 8 shows the results of the RMSE of OPUS Processing Service in two (2) hours for Northing (N), Easting (E), and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by OPUS Processing Service in two (2) hours were ±0.094m, ±0.085m and ±0.103m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 8. RMSE for OPUS in 2 Hours

ΔN	**OPUS**	**TBC**	**Difference (m)**
GCP1	3°3'52.4352"	3°3'52.43315"	0.061
GCP2	3°4'4.7012"	3°4'4.69842"	0.083
GCP3	3°4'15.42712"	3°4'15.2743"	-0.092
GCP4	3°4'6.0829"	3°4'6.0871"	-0.127
RMSE (ΔN) = ± 0.094m			
ΔE	**OPUS**	**TBC**	**Difference (m)**
GCP1	101°29'47.7875"	101°29'47.79013"	-0.080
GCP2	101°29'54.1215"	101°29'54.11875"	0.081
GCP3	101°30'6.3866"	101°30'6.38965"	-0.091
GCP4	101°29'33.4729"	101°29'33.47580"	-0.086
RMSE (ΔE) = ± 0.085m			
Δh	**OPUS**	**TBC**	**Difference (m)**
GCP1	13.5226	13.3898	-0.1328
GCP2	13.0382	12.942	-0.0962
GCP3	50.0826	49.9929	-0.0897
GCP4	2.791	2.8762	0.0854
RMSE (Δh) = ± 0.103m			

Source: Authors (2024)

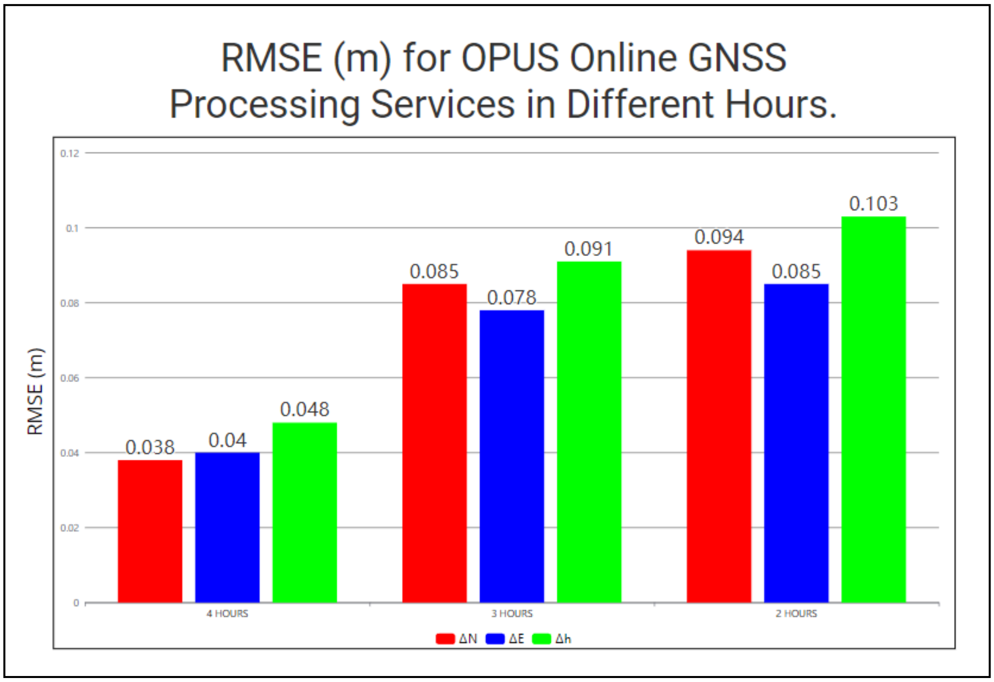

Fig. 4. RMSE (m) for OPUS Online Processing Service in Different Hours

Source: Authors (2024)

Figure 4 shows the RMSE of OPUS Online Processing Service for differences between hours with a duration of four (4) hours, three (3) hours and two (2) hours of the data. Based on the results obtained, the smallest RMSE accuracy for the difference hours was four (4) hours, with the calculated RMSE being ±0.038m, ±0.040m and ±0.048m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. The biggest RMSE accuracy was two (2) hours, with the calculated RMSE were ±0.094m, ±0.085m and ±0.103m Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively.

Results of Post-Processing for TBC Software and AUSPOS Processing Services

Table 9 shows the results of RMSE of AUSPOS Processing Service in four (4) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by AUSPOS Processing Service in four (4) hours were ±0.020m, ±0.022m and ±0.028m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 9. RMSE for AUSPOS in 4 Hours

ΔN	AUSPOS	TBC	Difference (m)
GCP1	3°3'52.4325"	3°3'52.433"	-0.025
GCP2	3°4'4.6982"	3°4'4.6985"	-0.012
GCP3	3°4'15.2738"	3°4'15.274"	-0.018

GCP4	3°4'6.0865"	3°4'6.087"	-0.021
RMSE (ΔN) = ± 0.020m			
ΔE	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	101°29'47.7894"	101°29'47.790"	-0.017
GCP2	101°29'54.1180"	101°29'54.119"	-0.019
GCP3	101°30'6.3891"	101°30'6.390"	-0.020
GCP4	101°29'33.4747"	101°29'33.476"	-0.030
RMSE (ΔE) = ± 0.022m			
Δh	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	13.3288	13.3638	-0.035
GCP2	12.875	12.9082	-0.033
GCP3	49.921	49.9422	-0.021
GCP4	2.8224	2.8441	-0.022
RMSE (Δh) = ± 0.028m			

Source: Authors (2024)

Table 10 shows the results of RMSE of AUSPOS Processing Service in three (3) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by OPUS Processing Service in three (3) hours were ±0.028m, ±0.023m and ±0.034m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 10. RMSE for AUSPOS in 3 Hours

ΔN	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	3°3'52.4326"	3°3'52.43329"	-0.021
GCP2	3°4'4.6977"	3°4'4.69854"	-0.026
GCP3	3°4'15.2733"	3°4'15.27434"	-0.031
GCP4	3°4'6.0861"	3°4'6.08721"	-0.034
RMSE (ΔN) = ± 0.028m			
ΔE	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	101°29'47.7886"	101°29'47.78999"	-0.042
GCP2	101°29'54.1180"	101°29'54.11862"	-0.019
GCP3	101°30'6.3894"	101°30'6.38955"	-0.006
GCP4	101°29'33.4756"	101°29'33.47569"	-0.004
RMSE (ΔE) = ± 0.023m			
Δh	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	13.359	13.4004	-0.041
GCP2	12.9818	12.9506	0.031

GCP3	49.9551	49.9883	-0.033
GCP4	2.859	2.8862	-0.027
RMSE (Δh) = ± 0.034m			

Source: Authors (2024)

Table 11 shows the results of RMSE of AUSPOS Processing Service in two (2) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by AUSPOS Processing Service in two (2) hours were ±0.067m, ±0.073m and ±0.082m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 11. RMSE for AUSPOS in 2 Hours

ΔN	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	3°3'52.4304"	3°3'52.43315"	-0.082
GCP2	3°4'4.6960"	3°4'4.69842"	-0.074
GCP3	3°4'15.2729"	3°4'15.2743"	-0.043
GCP4	3°4'6.0851"	3°4'6.0871"	-0.061
RMSE (ΔN) = ± 0.067m			
ΔE	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	101°29'47.7881"	101°29'47.79013"	-0.061
GCP2	101°29'54.1168"	101°29'54.11875"	-0.058
GCP3	101°30'6.3871"	101°30'6.38965"	-0.076
GCP4	101°29'33.4727"	101°29'33.47580"	-0.0932
RMSE (ΔE) = ± 0.073m			
Δh	**AUSPOS**	**TBC**	**Difference (m)**
GCP1	13.319	13.3898	-0.0708
GCP2	13.0089	12.942	0.0669
GCP3	49.907	49.9929	-0.0859
GCP4	2.9747	2.8762	0.0985
RMSE (Δh) = ± 0.082m			

Source: Authors (2024)

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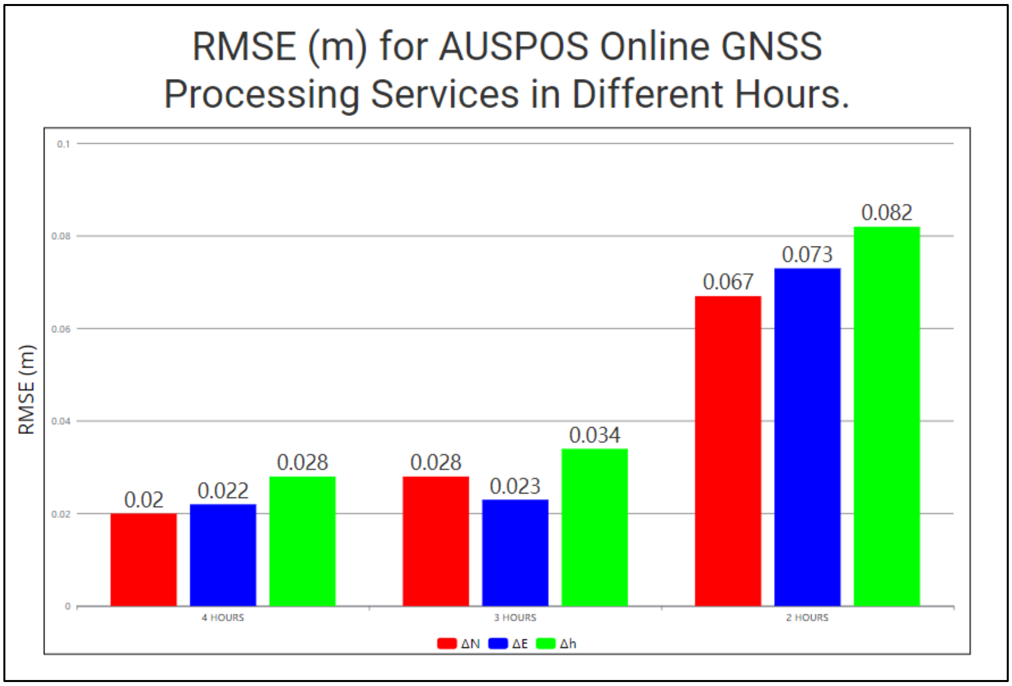

Fig. 5. RMSE (m) for AUSPOS Online Processing Service in Different Hours

Source: Authors (2024)

Figure 5 shows the RMSE of AUSPOS Online Processing Service for differences between hours with a duration of four (4) hours, three (3) hours and two (2) hours of the data. Based on the results obtained, the smallest RMSE accuracy for the difference hours was four (4) hours with the calculated RMSE of ±0.020m, ±0.022m and ±0.028m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. The biggest RMSE accuracy was two (2) hours, with the calculated RMSE being ±0.067m, ±0.073m and ±0.082m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively.

Results of Post-processing in TBC Software and CSRS-PPP Processing Services

Table 12 shows the results of RMSE of CSRS-PPP Processing Service in four (4) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by CSRS-PPP Processing Service in four (4) hours were ±0.032m, ±0.034m and ±0.044m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 12. RMSE for CSRS-PPP in 4 Hours

ΔN	CSRS-PPP	TBC	Difference (m)
GCP1	3°3'52.4325"	3°3'52.433"	-0.025
GCP2	3°4'4.6975"	3°4'4.6985"	-0.033
GCP3	3°4'15.2737"	3°4'15.274"	-0.021
GCP4	3°4'6.0858"	3°4'6.087"	-0.043

RMSE (ΔN) = ± 0.032m			
ΔE	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	101°29'47.7889"	101°29'47.790"	-0.032
GCP2	101°29'54.1176"	101°29'54.119"	-0.031
GCP3	101°30'6.3885"	101°30'6.390"	-0.036
GCP4	101°29'33.4745"	101°29'33.476"	-0.038
RMSE (ΔE) = ± 0.034m			
Δh	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	13.359	13.3638	-0.005
GCP2	12.980	12.9082	0.072
GCP3	49.977	49.9422	0.035
GCP4	2.879	2.8441	0.035
RMSE (Δh) = ± 0.044m			

Source: Authors (2024)

Table 13 shows the results of RMSE of CSRS-PPP Processing Service in three (3) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by CSRS-PPP Processing Service in three (3) hours were ±0.033m, ±0.038m and ±0.046m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 13. RMSE for CSRS-PPP in 3 Hours

ΔN	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	3°3'52.4324"	3°3'52.43329"	-0.027
GCP2	3°4'4.6973"	3°4'4.69854"	-0.037
GCP3	3°4'15.2729"	3°4'15.27434"	-0.042
GCP4	3°4'6.0864"	3°4'6.08721"	-0.025
RMSE (ΔN) = ± 0.033m			
ΔE	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	101°29'47.7887"	101°29'47.78999"	-0.040
GCP2	101°29'54.1170"	101°29'54.11862"	-0.049
GCP3	101°30'6.3887"	101°30'6.38955"	-0.026
GCP4	101°29'33.4746"	101°29'33.47569"	-0.032
RMSE (ΔE) = ± 0.038m			
Δh	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	13.451	13.4004	0.051
GCP2	13.001	12.9506	0.050
GCP3	50.0198	49.9883	0.032

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GCP4	2.935	2.8862	0.049
RMSE (Δh) = ± 0.046m			

Source: Authors (2024)

Table 14 shows the results of RMSE of CSRS-PPP Processing Service in two (2) hours for Northing (N), Easting (E) and Ellipsoidal Height (h) directions and the coordinates computed by TBC coordinates estimation. According to the obtained results, the RMSE provided by CSRS-PPP Processing Service in two (2) hours were ±0.073m, ±0.076m and ±0.086m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 14. RMSE for CSRS-PPP in 2 Hours

ΔN	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	3°3'52.4308"	3°3'52.43315"	-0.072
GCP2	3°4'4.6952"	3°4'4.69842"	-0.097
GCP3	3°4'15.2730"	3°4'15.2743"	-0.038
GCP4	3°4'6.0847"	3°4'6.0871"	-0.071
RMSE (ΔN) = ± 0.073m			
ΔE	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	101°29'47.7904"	101°29'47.79013"	0.009
GCP2	101°29'54.1155"	101°29'54.11875"	-0.098
GCP3	101°30'6.3867"	101°30'6.38965"	-0.090
GCP4	101°29'33.4734"	101°29'33.47580"	-0.071
RMSE (ΔE) = ± 0.076m			
Δh	**CSRS-PPP**	**TBC**	**Difference (m)**
GCP1	13.4818	13.3898	0.092
GCP2	13.0166	12.942	0.0746
GCP3	49.8969	49.9929	-0.096
GCP4	2.9572	2.8762	0.081
RMSE (Δh) = ± 0.086m			

Source: Authors (2024)

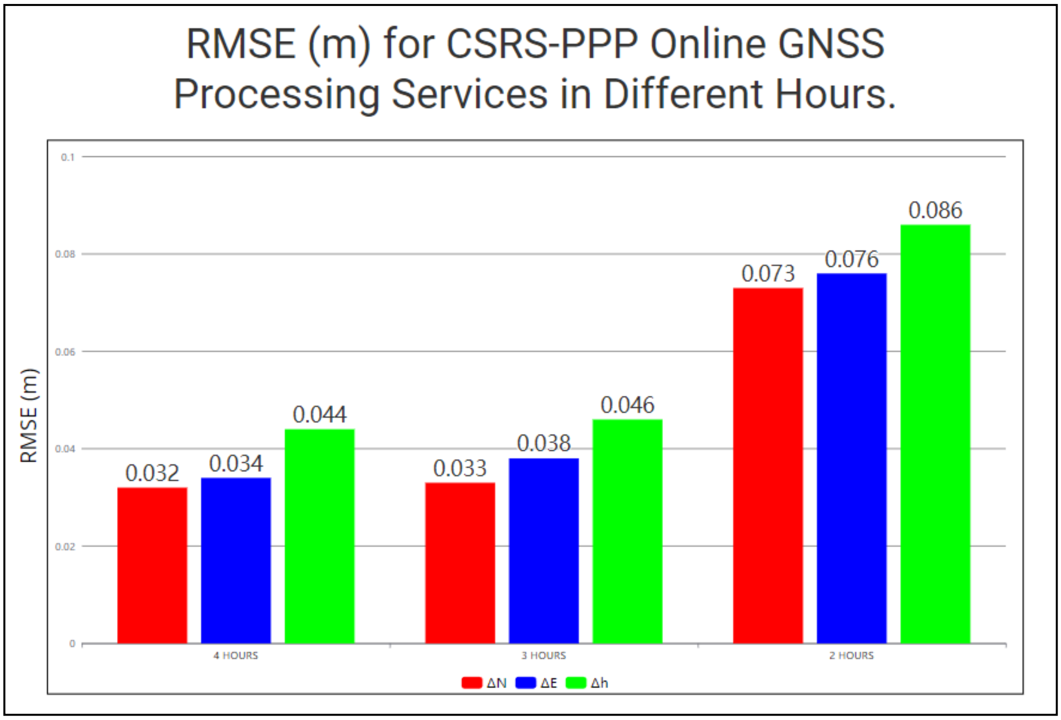

Fig. 6. RMSE (m) for CSRS-PPP Online Processing Service in Different Hours

Source: Authors (2024)

Figure 6 shows the RMSE of CSRS-PPP Online Processing Service for differences between hours with a duration of four (4) hours, three (3) hours and two (2) hours of the data. Based on the results obtained, the smallest RMSE accuracy for the difference hours was four (4) hours with the calculated RMSE of ±0.032m, ±0.034m and ±0.044m Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. The biggest RMSE accuracy was two (2) hours, with the calculated RMSE of ±0.073m, ±0.076m and ±0.086m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively.

Ranking of Free GNSS Online Processing Services

The ranking was based on RMSE in different hours analysis between three Online Processing Services (OPUS, AUSPOS and CSRS-PPP) against TBC estimated coordinates, whereby the service with the smallest RMSE is ranked the best. Table 15 shows the ranking of free Online Processing Services in four (4) hours of observations, which was based on the calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. From the obtained analysis, AUSPOS was the best Online Processing Service in four (4) hours with the smallest RMSE among others with ±0.020m, ±0.022m and ±0.028m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. CSRS-PPP was average with slightly different RMSE between OPUS with ±0.032m, ±0.034m and ±0.044m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. OPUS was the worst with ±0.038m, ±0.040m and ±0.048m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively.

Table 15. Ranking of Online Processing Services based on RMSE in 4 Hours

Ranking of Online Processing Services based on RMSE (m) in 4 hours				
Online Processing Service	**Ranking**	**RMSE-ΔN (m)**	**RMSE-ΔE (m)**	**RMSE-Δh (m)**
AUSPOS	1	0.020	0.022	0.028
CSRS-PPP	2	0.032	0.034	0.044
OPUS	3	0.038	0.040	0.048

Source: Author (2024)

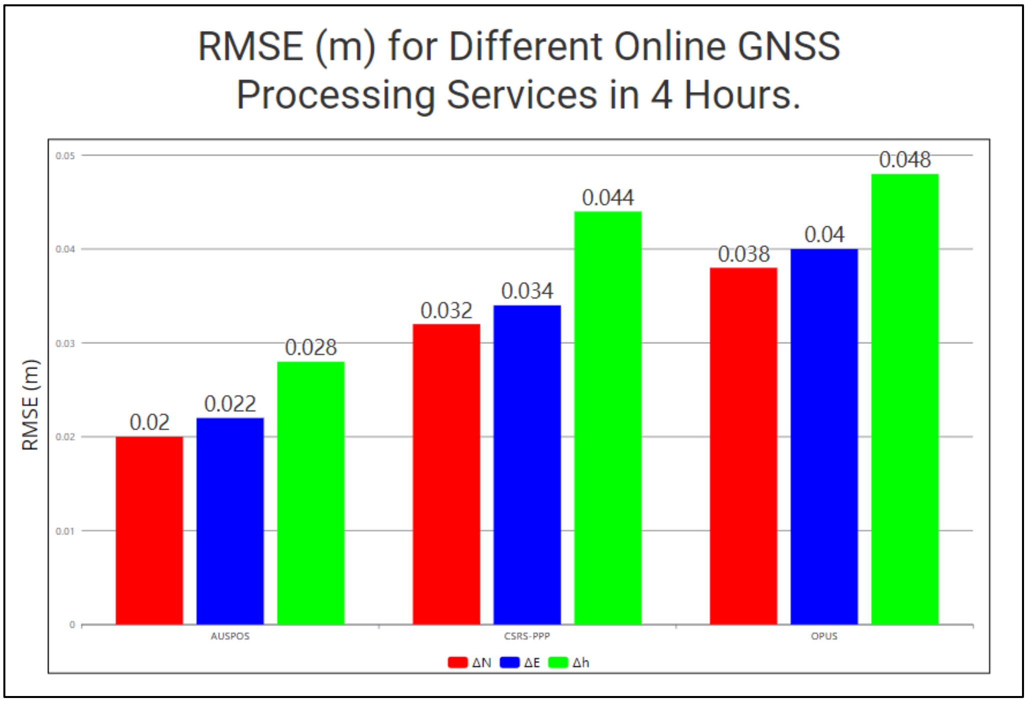

Fig. 7. RMSE (m) for Different Online Processing Services in 4 Hours

Source: Authors (2024)

Figure 7 shows the graph calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. AUSPOS has ranked first compared to other services because it has the smallest RMSE value in four (4) hours of observation. The best accuracy of Online Processing Services was obtained from AUSPOS with the smallest RMSE. Then, it was followed by CSRS-PPP with average RMSE and OPUS with high RMSE in four (4) hours of observation.

Table 16 shows the ranking of free Online Processing Services in three (3) hours of observations, which was based on the calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. From the obtained analysis, AUSPOS was the best Online Processing Service in three (3) hours with the smallest RMSE among others with ±0.028m, ±0.023m and ±0.034m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. CSRS-PPP was the average with slightly different RMSE between AUSPOS with ±0.033m, ±0.038m and ±0.046m in Northing (N), Easting (E) and

Ellipsoidal Height (h) directions, respectively, while OPUS was the worst with ±0.085m, ±0.078m and ±0.091m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 16. Ranking of Online Processing Services based on RMSE in 3 Hours

Ranking of Online Processing Services based on RMSE (m) in 3 hours				
Online Processing Service	**Ranking**	**RMSE-ΔN (m)**	**RMSE-ΔE (m)**	**RMSE-Δh (m)**
AUSPOS	1	0.028	0.023	0.034
CSRS-PPP	2	0.033	0.038	0.046
OPUS	3	0.085	0.078	0.091

Source: Authors (2024)

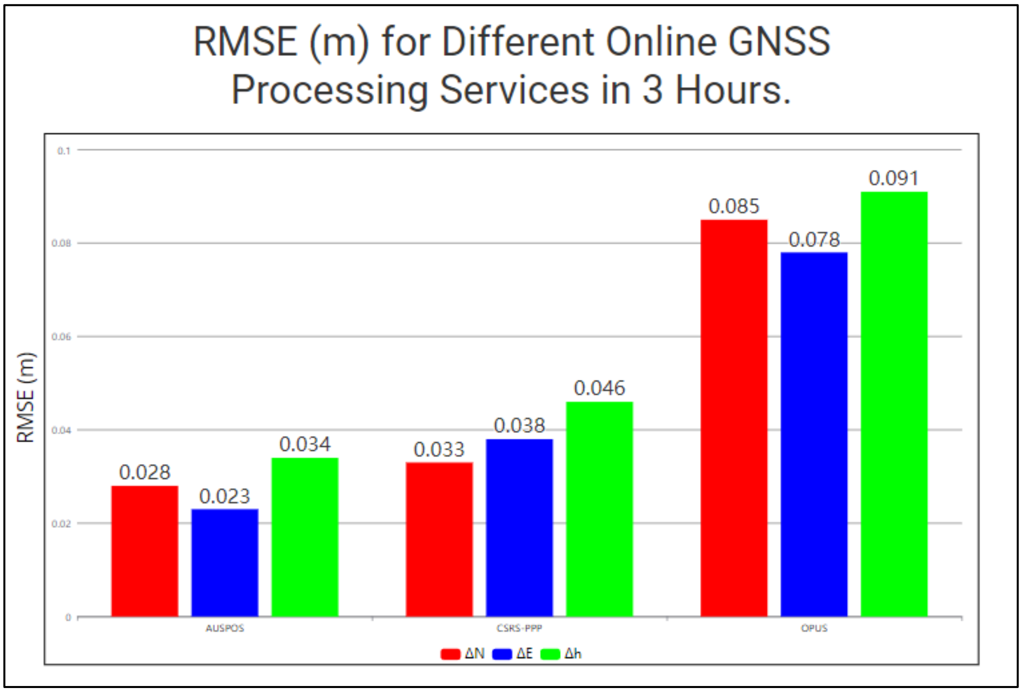

Fig. 8. RMSE (m) for Different Online Processing Services in 3 Hours

Source: Authors (2024) Figure 8 shows the graph calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. AUSPOS has ranked first compared to other services because it has the smallest RMSE value in 3 hours of observation. The best accuracy of Online Processing Services was obtained from AUSPOS, with the smallest RMSE among others, followed by CSRS-PPP with slightly different RMSE between AUSPOS and OPUS with high RMSE in three (3) hours of observation.

Table 17 shows the ranking of free Online Processing Services in three (3) hours of observations, which was based on the calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. From the obtained analysis, AUSPOS was the best Online Processing Service in three (3) hours with the smallest RMSE among others with ±0.028m, ±0.023m and ±0.034m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. CSRS-PPP was the average with slightly different RMSE between AUSPOS with ±0.033m, ±0.038m and ±0.046m in Northing (N), Easting (E) and

Ellipsoidal Height (h) directions, respectively, while OPUS was the worst with ±0.085m, ±0.078m and ±0.091m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively.

Table 17. Ranking of Online Processing Services Based on RMSE in 2 Hours

Ranking of Online Processing Services based on RMSE (m) in 2 hours				
Online Processing Service	**Ranking**	**RMSE-ΔN (m)**	**RMSE-ΔE (m)**	**RMSE-Δh (m)**
AUSPOS	1	0.067	0.073	0.082
CSRS-PPP	2	0.073	0.076	0.086
OPUS	3	0.094	0.085	0.103

Source: Authors (2024)

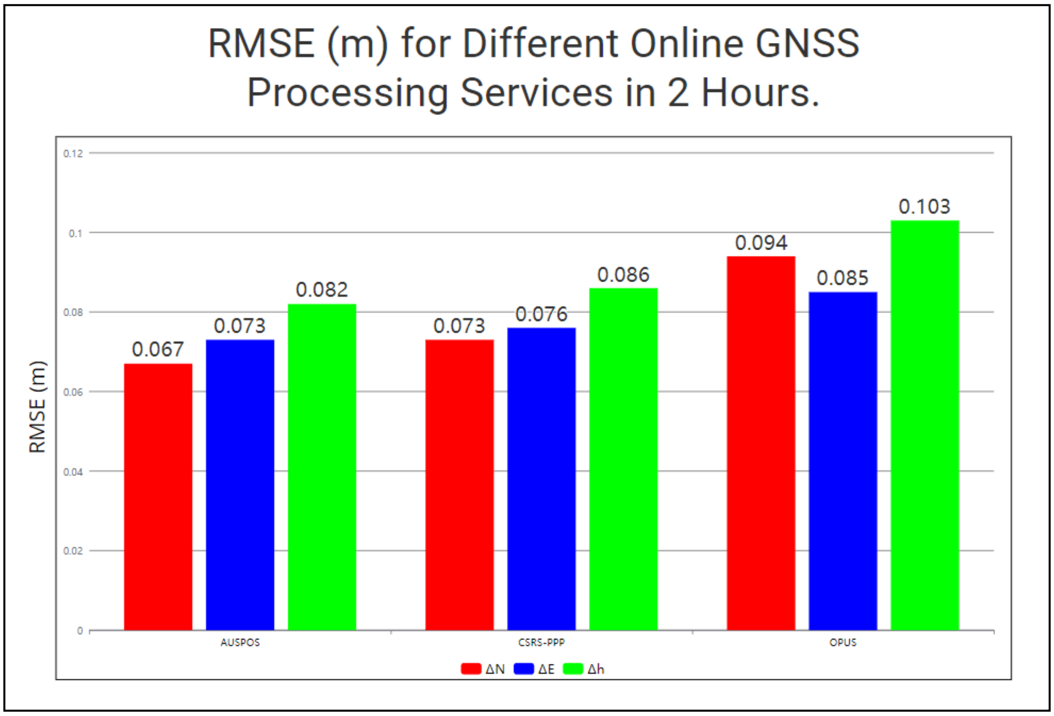

Fig. 9. RMSE (m) for Different Online Processing Services in 2 Hours

Source: Authors (2024)

Figure 9 shows the graph calculated RMSE in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. AUSPOS has ranked first compared to other services because it has the smallest RMSE value in two (2) hours of observation. The best accuracy of Online Processing Services was obtained from AUSPOS, with the smallest RMSE among others, followed by CSRS-PPP with a slightly different RMSE between AUSPOS and OPUS with a high RMSE in two (2) hours of observation.

The RMSE provided by the AUSPOS online service was less than that of other services, and these can be attributed to the 13 networks of IGS reference points used in the processing (Olatunji, 2019). In comparison, OPUS only used three networks of IGS reference points and one NGS control point. AUSPOS showed the lowest rejection rate among these services in a comparative evaluation of online static GNSS post-processing.

Moreover, AUSPOS demonstrated superior performance in terms of rejection rate when compared to OPUS. Despite encountering various data challenges and outliers, AUSPOS exhibited the lowest rejection rate among all services evaluated. This indicates AUSPOS's robustness in handling problematic data points and ability to produce reliable processing results even under challenging circumstances. In contrast, OPUS may need help to achieve similar data integrity and reliability levels.

A previous study by Soko et al. 2022, shows the RMSE of OPUS is smaller than this study. This is caused by the long baselines used in the processing, as there are no specific IGS stations accessible for selecting as reference points. Thus, shorter baselines will thereby improve data quality and the dependability of online services. While AUSPOS shows similar results as this service using many IGS stations as reference points compared to other services. While Janssen and McElroy, 2020 demonstrated that extending the observation period from two (2) hours to around four (4) – five (5) hours results in significant improvements in the quality of AUSPOS solutions. Observation sessions longer than 12 hours offer markedly higher quality solutions, particularly in the vertical component.

CONCLUSIONS

A test study was conducted considering three online GNSS processing services used frequently and widely worldwide. For this purpose, the coordinates of four selected control points were determined by using static observation for four (4) hours and based on the IGS Station selected, which NTUS00SGP, CUSV00THA, CIBG00IDN and BRUN00BRN have been used as a reference or fixed points to do the GNSS observations. The accuracy provided by the services was obtained by comparing online processing service coordinates with TBC Software coordinates.

The RMSE obtained for the AUSPOS online processing service in four (4) hours of observation was very small, which can be attributed to its use of scientific processing software. In the Northing (N), Easting (E), and Ellipsoidal Height (h) directions in four (4) hours of observation, the best accuracy was obtained from the AUSPOS online processing service with the calculated RMSE of ±0.020m, ±0.022m and ±0.028m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions respectively. Another obtained result, CSRS-PPP, gives slightly different results than AUSPOS online processing service in three (3) hours with the calculated RMSE of ±0.033m, ±0.038m and ±0.046m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively and two (2) hours with the calculated RMSE of ±0.073m, ±0.076m and ±0.086m in Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively. The maximum error was provided by OPUS online service in two (2) hours, with the calculated RMSE were ±0.094m, ±0.085m and ±0.103m Northing (N), Easting (E) and Ellipsoidal Height (h) directions, respectively which makes OPUS an inaccurate online processing service compared to others.

According to the results, AUSPOS has more accurate results than other services in all hours of observation, making AUSPOS occupy the first place in the ranking. In addition, CSRS-PPP ranked second after AUSPOS, and OPUS ranked last. All the online processing services used in this study provide the final coordinates with a precision of a couple of meters to a few errors of decimetres, which is attributed to the observation time of four (4) hours.

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This study makes a significant contribution by providing a comprehensive evaluation of open source GNSS online post-processing services, offering valuable insights into their accuracy. The findings help users and researchers identify the most effective services for precise positioning, guiding informed decisions in various applications where GNSS accuracy is important these days.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTION

Muhammad Nasruddin Bin Yusri conducted research on evaluating the performance of open-source GNSS online post-processing services and contributed to manuscript writing. Amir Sharifuddin Ab Latip supervised the research progress, provided expertise in data analysis, and contributed to manuscript editing and revision. Ami Hassan Md Din conceptualised the research ideas and developed the methodology for evaluating the performance of open-source GNSS online post-processing services. Abdul Aziz Ab Rahman contributed to manuscript writing and review. Sharifah Nur Attasyah Mohd Zaiddien was involved in GNSS data processing and contributed to manuscript revision.

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