Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

# Enhancing GNSS Accuracy through Advanced Precise Point Positioning Techniques

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**ABSTRACT**

The growing reliance on Global Navigation Satellite Systems (GNSS) necessitates continuous improvement in positioning accuracy to support diverse geospatial applications. This study explores advanced Precise Point Positioning (PPP) techniques, incorporating multi-constellation data and sophisticated correction models. By evaluating PPP performance under various static and dynamic conditions, the research identifies key factors influencing accuracy and reliability. The findings contribute to optimizing PPP methodologies for applications requiring high precision and real-time adaptability.

***Keywords:*** *Global Navigation Satellite Systems, Precise point positioning, online services and offline software*

## 1. Introduction

A new age in location, navigation, and timing was started by the development of satellite-based global navigation systems, known collectively as (GNSS). Everybody now has contact to accurate estimations of velocity, position, and time almost immediately. GNSS, currently constitute the basis for modern applications, such as those used in map projection, agriculture, safety, military, surveying, and Geographic Information Systems (GIS) (Abd-Elazeem et al. 2011). Online processing services overtaken commercial and scientific software in the processing of GNSS data because of their ease of use and lack of essential for GNSS post-processing data (ADAM, S.M. 2017). Conducted an important study in GNSS post-processing (2017). Online processing services (CSRS-PPP, OPUS, and AUSPOS) and offline software were tested for correctness by the authors (LGO v8.3). To get the required data, GNSS observation approaches static and rapid-static were utilized, and the observation time for each point was divided into five phases (2, 4, 6, 8, and 10) hr. The Rapid Static (RS) technique's LGO software produced a result with a root mean square error (RMSE) of 0.011m, making it the software with the closest convergence to field measurements. AUSPOS outperformed other services with RMSE values of 0.041-0.018m, where OPUS and CSRS-PPP processing ranged from 0.043 to 0.260m and 0.046-0.250m, respectively. It was determined none correlation in processing outcomes for various free online processing services at the same location. The scientists further stated that AUSPOS accuracy is consistent with observation time when it is long and that consumers can rely on online services to deliver accurate data during a 10-hour observation period at a millimeter level (Bahadur, B. et al. 2018).

Conducted research for using online and offline processing methods to increase the accuracy of a GPS station. Raw data of GPS totalling around 121 hours was divided into 36 sub-files, each of which contained a complete 24 hours, 12 hours, and 6 hours of data at a 1 second epoch. Processing was carried out using OPUS, CSRS, AUSPOS, and offline-PPP software. The findings showed that as observation duration is increased, both the horizontal and vertical RMSEs decrease. For all sessions and processing services, the RMSE was less than 6mm and 10mm, respectively (Dabove, P. et al. 2014).

Four datasets with lengths of 1, 1.5, 2, and 3hr in three locations to compare two online post-processing systems (AUSPOS and CSRS-PPP). AUSPOS was found to have an accuracy of a few millimeters and centimetres in static

mode for the horizontal coordinates and centimetres in the vertical coordinates, though CSRS-PPP also provided an accuracy of a rare millimetres to centimetres for the positions, but the vertical error reaches a decimetre (de Oliveira, P.S. et al. 2020).
CSRS-PPP used for detecting variations between static, single-frequency GPS readings made at three different places and times of one hour, one and a half hours, and two hours at various baselines of 1.6 kilometers, seven kilometers, and ten kilometers, respectively. The research demonstrates that single-frequency PPP has a limited decimetres of accuracy for the horizontal coordinates. It is clear from all linked studies and no study compared the accuracy of online services to that of offline applications. All research, with the exception of one, did not examine if there is a statistically significant difference between the outcomes from online processing services and offline software (El-Mowafy, A. 2011). RINEX 3 format tests will be performed to get difference between the findings of the online processing services and offline software that will be employed in this study. To assessing the accuracy of free online processing software, (CSRS-PPP) and free offline software, (PPPH). Field observations were approved on nine IGS stations employing an observation and static GNSS observation methods for RINEX 3 format for 24hr for three days in January and three days in March 2022. The acquired data were post-processed using both online and offline software. The coordinates conducted from each software compared with coordinates from IGS stations to determine their relative discrepancies and accuracies (Farah, A. 2015).

## 1 Precise Point Positioning

PPP technique depend on external correction products for satellite orbit, clock, and ionospheric errors, which can be optional depending on the accessibility of dual frequency observations. PPP software packages and online PPP processing services have been developed by some universities and research institutions. These online PPP services are accessible to customers and cost nothing (Herbert, T. et al. 2020). These services are offered around-the-clock. Users merely need to upload or submit RINEX-compressed standard or uncompressed GNSS observation data files to the authorized servers. The online PPP services may automatically process the provided data files and download the required clock and precise ephemerides adjustments from IGS sites. The complete data will be shown on the service website or emailed to users. The outcomes include precise coordinates, quality details about user stations in the International Terrestrial Reference Frame (ITRF), as well as receiver clock adjustments for tropospheric and ionospheric delays (Mahmoud El-Mewafi. et al. 2023). The carrier phase and pseudo range observables on GPS L1 and L2 and GLONASS G1, G2 can be signified as follows:

$$\mathrm{P}_{\mathrm{Li}}^{\mathrm{G}} = \rho^{\mathrm{G}} + c\,(\mathrm{dt}^{\mathrm{G}} - \mathrm{dT}^{\mathrm{G}}) + \mathrm{d}_{\mathrm{ION}}^{\mathrm{G}} + \mathrm{d}_{\mathrm{TROP}}^{\mathrm{G}} + \varepsilon_{\mathrm{P}_{\mathrm{Li}}^{\mathrm{G}}} \tag{1}$$
$$\varphi_{\mathrm{Li}}^{\mathrm{G}} = \rho^{\mathrm{G}} + c\,(\mathrm{dt}^{\mathrm{G}} - \mathrm{dT}^{\mathrm{G}}) + \mathrm{d}_{\mathrm{ION}}^{\mathrm{G}} + \mathrm{d}_{\mathrm{TROP}}^{\mathrm{G}} + \lambda_{\mathrm{Li}}^{\mathrm{G}}\mathrm{N}_{\mathrm{Li}}^{\mathrm{G}} + \varepsilon_{\mathrm{P}_{\mathrm{Li}}^{\mathrm{G}}} \tag{2}$$
$$\mathrm{P}_{\mathrm{Li}}^{\mathrm{R}} = \rho^{\mathrm{R}} + c\,(\mathrm{dt}^{\mathrm{R}} - \mathrm{dT}^{\mathrm{R}}) + \mathrm{d}_{\mathrm{ION}}^{\mathrm{R}} + \mathrm{d}_{\mathrm{TROP}}^{\mathrm{R}} + \varepsilon_{\mathrm{P}_{\mathrm{Li}}^{\mathrm{R}}} \tag{3}$$
$$\varphi_{\mathrm{Li}}^{\mathrm{R}} = \rho^{\mathrm{R}} + c\,(\mathrm{dt}^{\mathrm{R}} - \mathrm{dT}^{\mathrm{R}}) + \mathrm{d}_{\mathrm{ION}}^{\mathrm{R}} + \mathrm{d}_{\mathrm{TROP}}^{\mathrm{R}} + \lambda_{\mathrm{Li}}^{\mathrm{R}}\mathrm{N}_{\mathrm{Li}}^{\mathrm{R}} + \varepsilon_{\mathrm{P}_{\mathrm{Li}}^{\mathrm{R}}} \tag{4}$$

Where G and R represent GPS and GLONASS satellite respectively; Li for GPS L1 and L2 frequencies; G1 and G2 frequencies; φ represents carrier phase (cycle); P represents pseudo range (m); ρ represents the true geometric range (m); c represents the speed of light (m/s); dt represents the receiver clock error (s); dT represents the satellite clock error (s); dION represents the ionospheric delay (m); dTROP represents the tropospheric delay (m); λ represents the wavelength of the carrier phase measurements (m); N represents the non-integer phase ambiguity including bias (cycle); and ε represents the observation noise and residual multipath (m). The applications that necessitate immediate results done by this type of differential positioning (Malinowski, M. et al. 2016).

## 2 Online Post-Processing Services:

To locate with GPS and obtain centimeter-level accuracy, it is necessary using two GNSS receivers. In order to get correct findings, it is too crucial to post-process the acquired data through GNSS data processing software, whether it be commercial or scientific. Today, free open web-based processing engines are available to process static and kinematic GPS data approaches. Currently, a lot of people use GNSS internet processing services rather than the traditional processing method. The popularity of these processing services has been boosted by the GPS processing software's simplicity of use, lack of cost (or low-cost fee), lack of requirement for a licence, and lack of technical competence. (Shehata, A. G. et al. 2023). Users of these services must transform the GNSS data they have collected into Prior to transmitting it by email or posting it to a particular website, it must be converted to Receiver Independent Exchange (RINEX) format. The user's registered email can be used to easily obtain the coordinates a few minutes after the data has been posted. Today, it is possible to handle data for both static and kinematic location modes thanks to these free web-based processing engines (Shehata, Ashraf G. et al. 2023). Numerous organizations, including National Geodetic Survey Canada, Geoscience Australia, SOPAC, NASA JPL, GMV Innovating Solutions and Trimble have developed web services that allow for the processing of dual or single frequency GPS data (Tariq, M. et al. 2017). For this study, CSRS-PPP, a popular PPP technique-based online processing service that accepts RINEX 3 format, was chosen. In order to post-process GNSS data, CSRS-PPP offers an online service that enables users using their original observed data, to calculate high accuracy positions. Single- and dual-frequency receiver observations on code pseudo-range or carrier phase are used to calculate CSRS estimates. For further processing, users could upload observed data in RINEX format (TUSAT, E. et al. 2018).

## 3 PPPH: a PPP multi-GNSS software

To combine PPP processing for multi-GNSS (GPS, GLONASS, Galileo, and Bei-Dou), MATLAB was used in the creation of PPPH. Fundamentally, PPPH aims to be a trustworthy, user-friendly, and successful software solution. PPPH provides a user-friendly GUI to allow users to select the navigation files, select the processing options, and examine the results. Each of the five main PPPH components, together with any related settings, is displayed via a separate tab in the GUI. The PPPH functioning flowchart displays the major parts and how they work in Figure 1. The last part is where the results are evaluated and presented. The first four elements create multi-GNSS PPP solutions by utilising related concepts and theories. Before carrying out further operations, PPPH demands that all data that is required for carrying out the PPP process be properly loaded into the software format. As a result, the procedure in PPPH begins for the definition of the relevant files holding common navigational data, as observations, satellite orbits, clocks, etc as shown in Table 1 (Shehata, Ashraf G. et al. 2023).

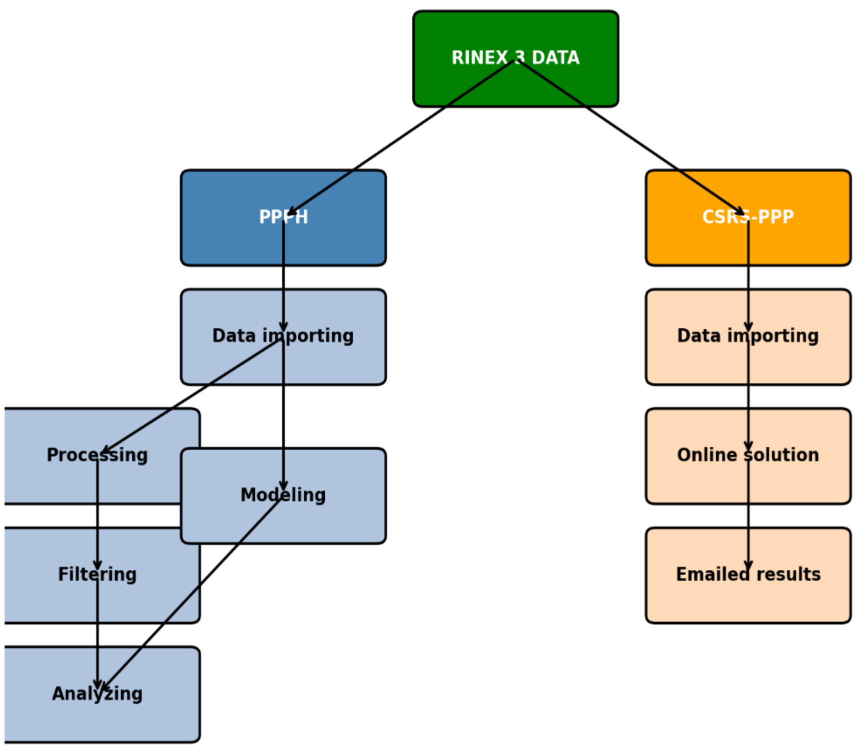



*Figure 1 Data processing steps*

*Table 1 Online solutions parameters*

| | PPPH | CSRS-PPP |
|---|---|---|
| Feature | PPPH | CSRS-PPP |
| Developer | Hacettepe University, Ankara, Turkey | Natural Resources Canada (NRCan) |
| Web site | https://www.ngs.noaa.gov/gps-toolbox/PPPH.htm | http://www.geod.nrcan.gc.ca/ |
| Latest version | The only version | CSRS-PPP V1.05_34613 |
| Supported process mode | Static, kinematic | Static, kinematic |
| Observation data | Single or dual- frequency | Single or dual- frequency |
| Limitations of uploaded file | No limit | B100 Mb |
| Constellation | MULTI GNSS | MULTI GNSS |
| Coordinate frame | ITRF2008 | ITRF2008/NAD83 |
| Precise satellite products | Support all | IGS |
| Tropospheric delay model and mapping function | (Saastamoinen 1973) | Dry delay: Davis Wet delay: Hopf |
| Estimation of tropospheric delay | Zenith total tropospheric delay | Zenith total tropospheric delay |

## 4 Results and Discussion

For the purposes of this study, observations were made on nine (9) IGS stations using static GNSS observation methods and an observation RINEX 3 format for a period of 24 hours across three (3) days in January and three (3) days in March 2022 as shown in Table 2 and Figure 2. Both online and offline software were used for the post-processing of the collected data. By comparing the coordinates created by each piece of software to those obtained from the IGS station, the relative discrepancies and accuracy of those coordinates were then evaluated. The result analysis employed root mean square error. Calculations have been made of the differences between coordinates found from the IGS station and those produced using the GNSS observation post-processing approach. These calculations were done using the online GNSS processing service (CSRS-PPP) and offline software (PPPH). The online PPP service Web sites received and handled all of the chosen daily observation data sets in static mode. Results from the vast majority of the data sets were processed and downloaded without error (Shehata, Ashraf G. et al. 2023). The chosen stations' estimated longitudes and latitudes were translated into north (N) and east (E) components using the Universal Transverse Mercator (UTM) projection. Each day, a calculation is made to determine the coordinate discrepancies between the static assessed results of the N/E components of these stations and the associated IGS reference values.

*Table 2 Station information and countries*

| Station | country | Tectonic plate | Receiver type | Antenna type |
|---|---|---|---|---|
| **AJAC** | France | EURASIAN | LEICA GR50 | TRM15000-NONE |
| **BRST** | France | EURASIAN | TRIMBLE ALLOY | TRM57971-NONE |
| **GOPE** | Czechia | EURASIAN | TRIMBLE ALLOY | TPSCR.G3-TPSH |
| **LICC** | United Kingdom | EURASIAN | CHC P5E | CHCC220GR2 |
| **MELI** | Spain | AFRICAN | LEICA GR50 | LEIAR25 R4-LEIT |
| **METS** | Finland | EURASIAN | JAVAD TRE-3 | ASH700936C-M-NONE |
| **NICO** | Cyprus | AFRICAN | LEICA GR50 | LEIAR25 R4-LEIT |
| **PTBB** | Germany | EURASIAN | SEPT POLARXS | LEIAR25 R4-LEIT |
| **SULP** | Ukraine | EURASIAN | TRIMBLE NETR9 | TPSCR.G5-TPSH |

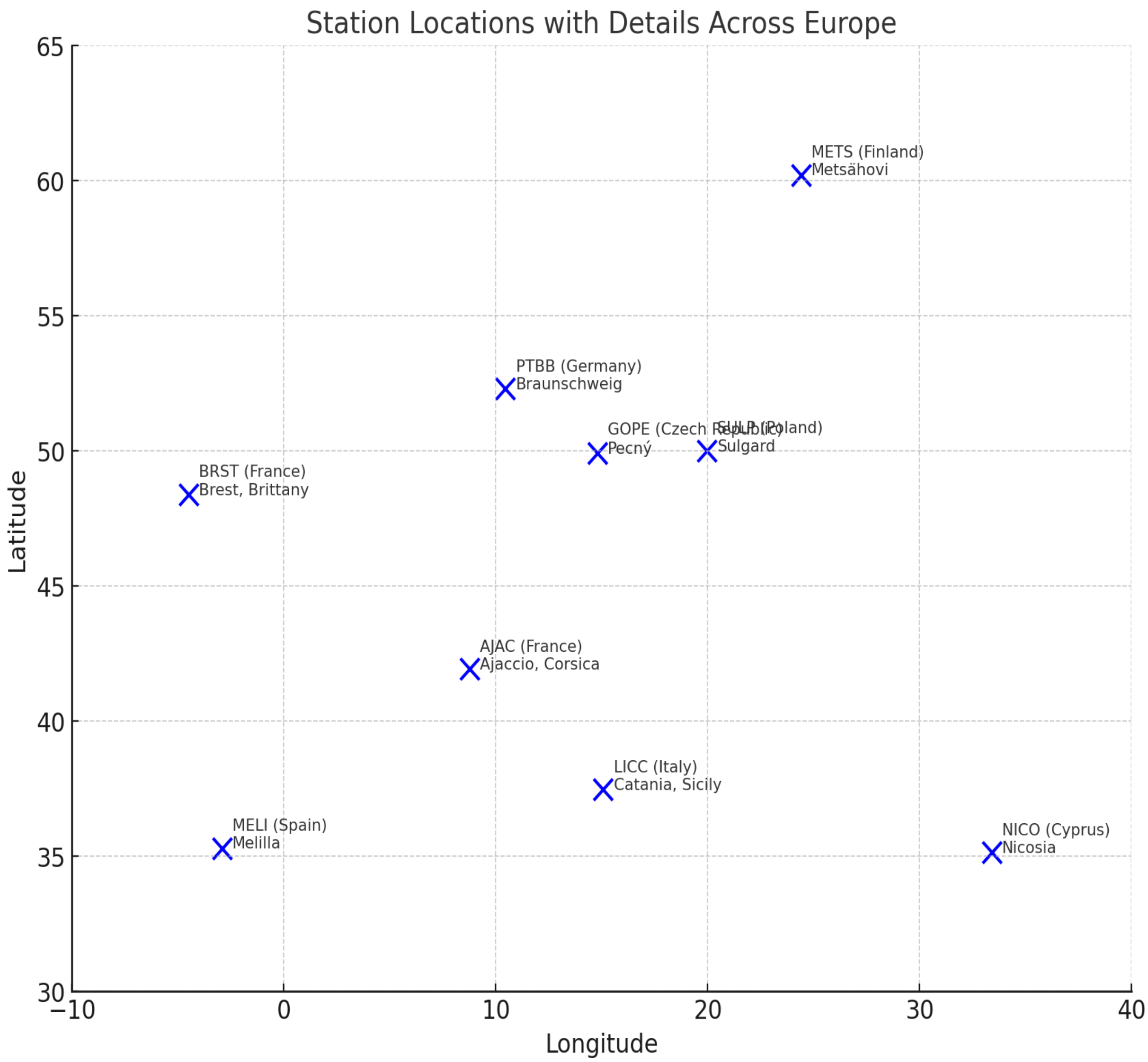



*Figure 2 Geographical location of IGS station*

*Table 3 Difference between coordinates of reference station and (online and offline processing) (cm)*

| **DAY1** | **PPPH** ΔE | ΔN | **CSRS** ΔE | ΔN | **DAY4** | **PPPH** ΔE | ΔN | **CSRS** ΔE | ΔN |
|---|---|---|---|---|---|---|---|---|---|
| **AJAC** | 0.168 | 1.282 | 0.926 | 1.001 | AJAC | 0.152 | 0.252 | 0.916 | 1.005 |
| **BRST** | 0.050 | -0.790 | 0.646 | -0.192 | BRST | -0.164 | -0.645 | 0.652 | -0.187 |
| **GOPE** | -1.090 | -0.522 | 0.345 | 0.260 | GOPE | -0.408 | -0.215 | 0.350 | 0.263 |
| **LICC** | 0.224 | -0.078 | 0.030 | 0.035 | LICC | -0.002 | 0.000 | 0.034 | 0.040 |
| **MELI** | -1.608 | -3.067 | -0.719 | -3.260 | MELI | -1.528 | -4.111 | -0.716 | -3.257 |
| **METS** | 0.320 | 0.520 | 0.592 | 0.369 | METS | 0.054 | -0.154 | 0.596 | 0.371 |
| **NICO** | 0.221 | 0.576 | 1.563 | 0.933 | NICO | 0.403 | 0.535 | 1.566 | 0.935 |
| **PTBB** | 0.375 | 0.384 | 0.455 | 0.434 | PTBB | -0.625 | 0.082 | 0.459 | 0.439 |
| **SULP** | 0.091 | -1.015 | -0.219 | -0.209 | SULP | -0.036 | -0.051 | -0.187 | -0.208 |
| **DAY2** | PPPH ΔE | ΔN | CSRS ΔE | ΔN | DAY5 | PPPH ΔE | ΔN | CSRS ΔE | ΔN |
| **AJAC** | 0.164 | 1.28 | 0.912 | 1.001 | AJAC | 0.152 | 0.256 | 0.915 | 1.007 |
| **BRST** | 0.489 | -0.878 | 0.646 | -0.191 | BRST | 0.547 | -0.508 | 0.650 | -0.186 |
| **GOPE** | -0.784 | -0.335 | 0.345 | 0.259 | GOPE | -0.493 | -0.467 | 0.350 | 0.266 |
| **LICC** | 0.348 | 0.476 | 0.031 | 0.035 | LICC | 0.000 | 0.000 | 0.033 | 0.041 |
| **MELI** | -1.605 | -3.06 | -0.719 | -3.26 | MELI | -1.442 | -4.189 | -0.717 | -3.256 |
| **METS** | 0.38 | 0.636 | 0.591 | 0.367 | METS | -0.089 | -0.188 | 0.597 | 0.372 |
| **NICO** | 0.229 | 0.586 | 1.563 | 0.934 | NICO | 0.502 | 0.219 | 1.567 | 0.937 |
| **PTBB** | -0.409 | 0.132 | 0.453 | 0.434 | PTBB | -0.705 | -0.013 | 0.459 | 0.442 |
| **SULP** | 0.095 | -1.001 | -0.208 | -0.213 | SULP | -1.404 | -3.663 | -0.186 | -0.207 |
| **DAY3** | PPPH ΔE | ΔN | CSRS ΔE | ΔN | DAY6 | PPPH ΔE | ΔN | CSRS ΔE | ΔN |
| **AJAC** | 0.734 | -0.041 | 0.913 | 1.001 | AJAC | 0.153 | 0.26 | 0.915 | 1.007 |
| **BRST** | 0.516 | -0.872 | 0.646 | -0.192 | BRST | -0.06 | -0.983 | 0.65 | -0.186 |
| **GOPE** | -0.766 | -0.326 | 0.345 | 0.259 | GOPE | -0.5 | -0.476 | 0.35 | 0.266 |
| **LICC** | 0.613 | -0.376 | 0.03 | 0.035 | LICC | 0 | 0 | 0.034 | 0.041 |
| **MELI** | -1.606 | -3.055 | -0.718 | -3.261 | MELI | -1.442 | -4.189 | -0.718 | -3.257 |
| **METS** | 0.445 | 0.763 | 0.591 | 0.365 | METS | -0.089 | -0.236 | 0.596 | 0.373 |
| **NICO** | 0.235 | 0.596 | 1.565 | 0.932 | NICO | 0.603 | 0.336 | 1.568 | 0.935 |
| **PTBB** | -0.015 | 0.11 | 0.455 | 0.436 | PTBB | -0.579 | -0.105 | 0.459 | 0.441 |
| **SULP** | -1.077 | -0.438 | -0.207 | -0.213 | SULP | 0.093 | 0.269 | -0.182 | -0.206 |

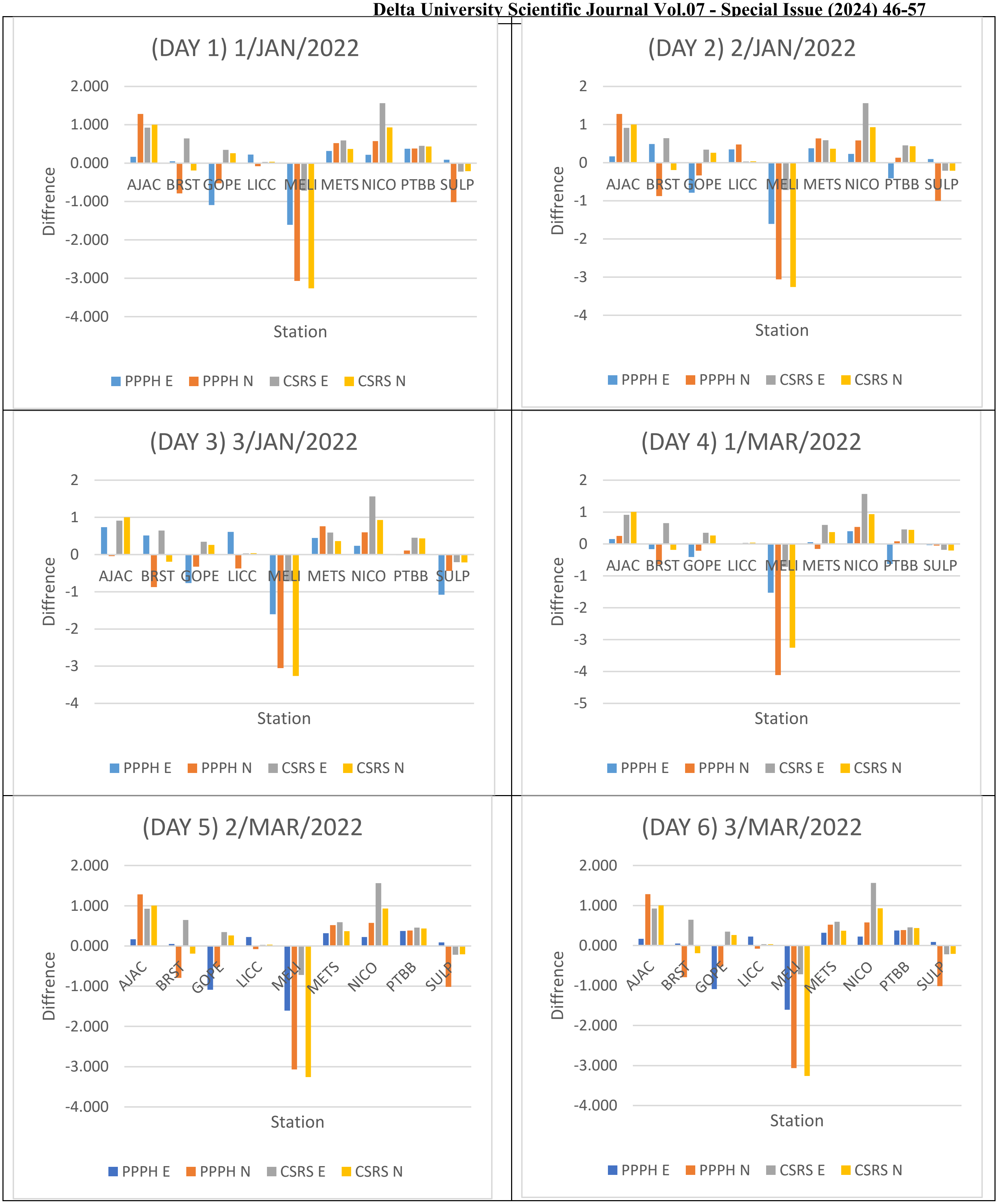



*Figure 3 Difference between coordinates of reference station and (online and offline processing)*

From Table 3 and Figure 3 there is no discernible difference between the online PPP services and PPPH as regards coordinate estimations, with the minimum difference being 0 cm for both solutions and the largest difference being 1.568 cm for online and 1.404 for offline. Along the six days the results very close to each other and the difference depends on the satellite orbit file and clock file. station MELI must eliminated because it has the biggest difference due to a smaller number of satellites detected and less fixed ambiguity according to Table 4 and Figure 4.

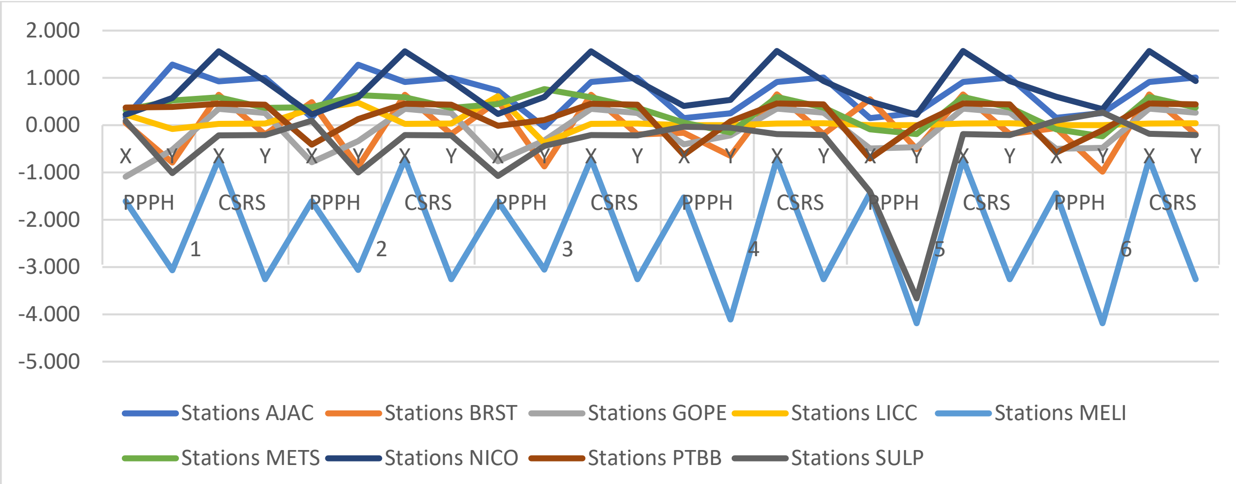
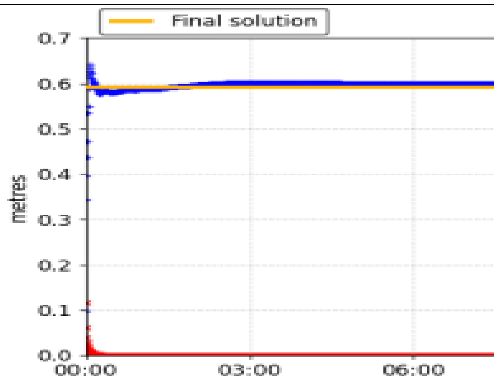
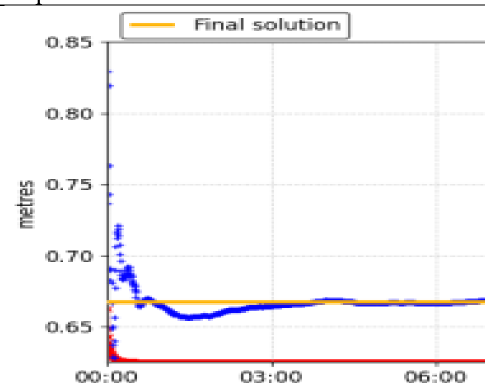
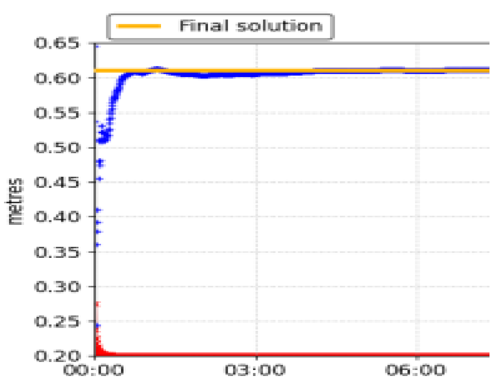
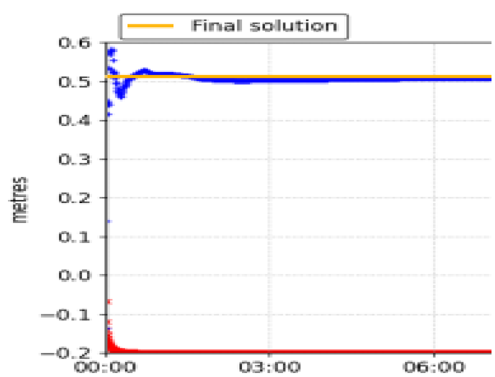
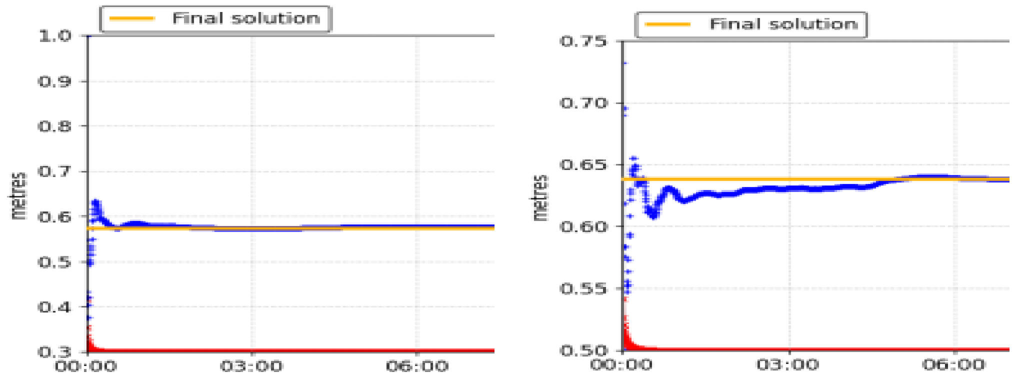



*Figure 4 Station difference from online and offline processing*

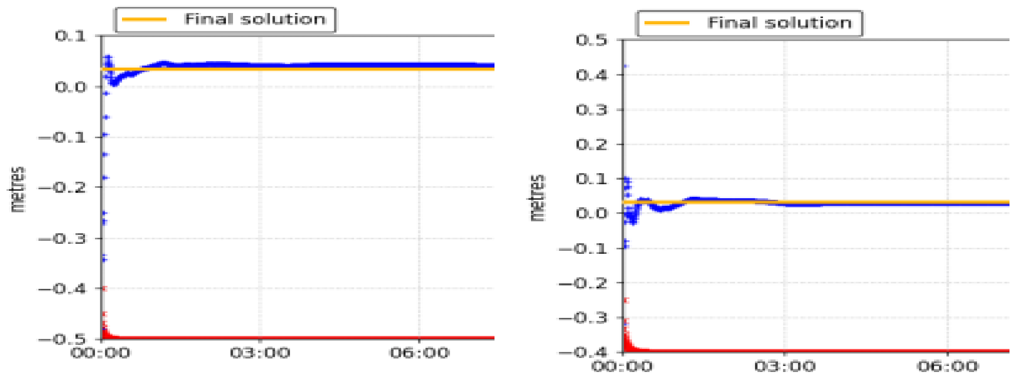
*Table 4 Initial time needed to solve the ambiguity*

| Station | Latitude | Departure |
| --- | --- | --- |
| AJAC |  |  |
| BRST |  |  |

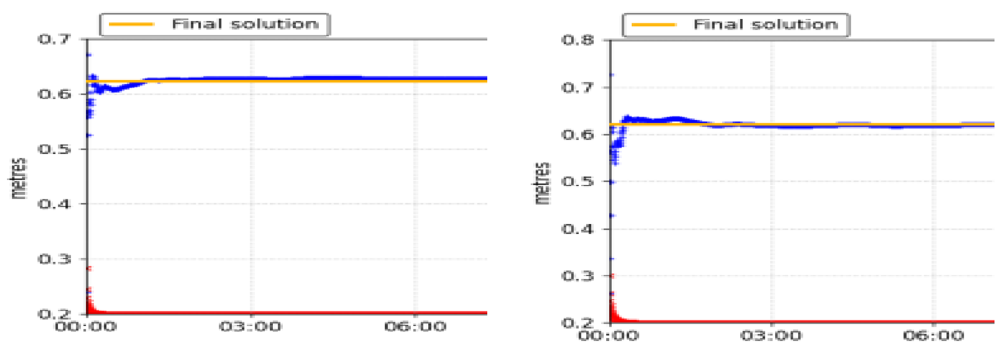
GOPE



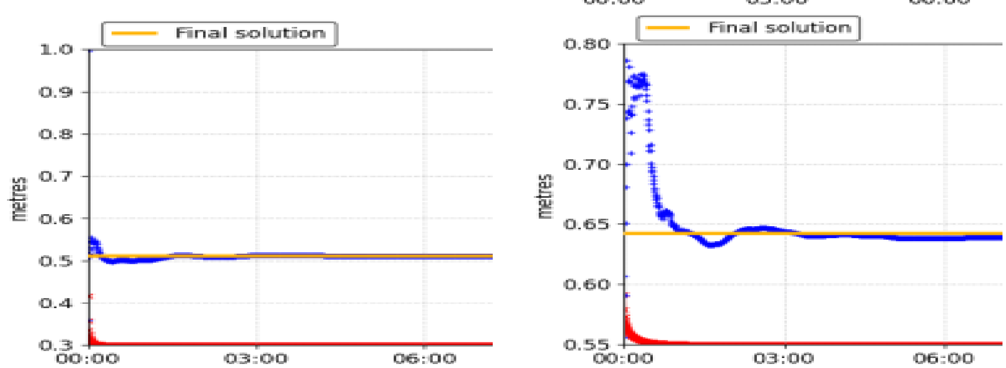

LICC



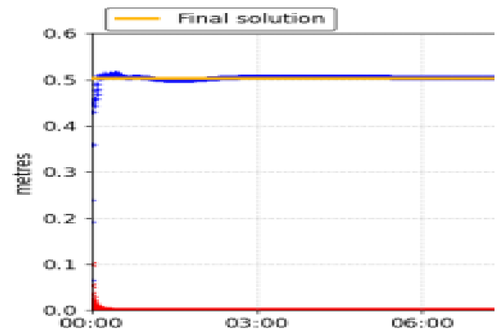

MELI

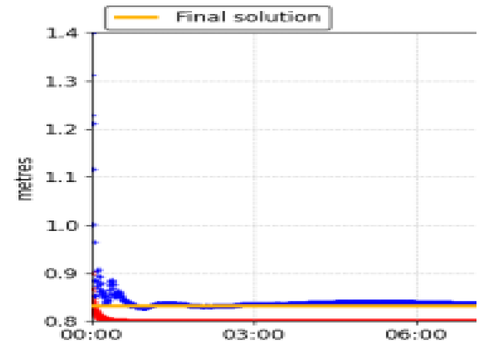



METS

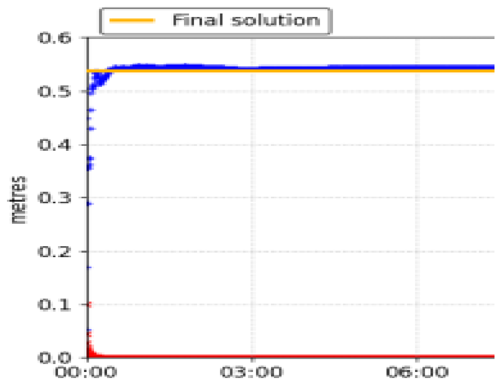


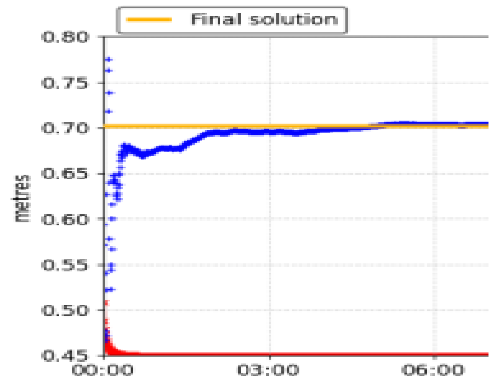
NICO




PTBB




## 5 The hypothesis testing

To further examine their level of significance using the T-distribution in light of the population variance being unknown and the mean (co-ordinates) vectors being equal, the coordinates generated by CSRS-PPP and PPPH software (both offline and online) were compared. The null hypothesis is rejected in this two-tail test if the calculated statistic is greater than the higher limit and lower limit of the table statistic. The t-test hypothesis was achieved using SPSS program. To test the hypothesis shows the coordinates produced by offline software and online software observation processing are not significantly different. Decision Rule: At a significance level of 0.05, a hypothesis test may be rejected. Decision: The hypothesis test was accepted since the p-values for the offline software PPPH are 0.016, 0.005, 0.012, 0.048, 0.049, and 0.004 and for the online software CSRS-PPP are 0.031, 0.031, 0.030, 0.031, 0.030. The coordinates produced by offline and online applications are not significantly different from one another.

Table 5 ANOVA test by SPSS program

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| | | Sum of Squares | df | Mean Square | F | Sig.5 |
| **AJAC** | Between Groups | 7.105 | 19 | .374 | 5.918 | .048 |
| | Within Groups | .253 | 4 | .063 | | |
| | Total | 7.358 | 23 | | | |
| **BRST** | Between Groups | 4.855 | 19 | .256 | 282.943 | .000 |
| | Within Groups | .004 | 4 | .001 | | |
| | Total | 4.859 | 23 | | | |
| **GOPE** | Between Groups | 36.184 | 19 | 1.904 | 2059.124 | .000 |
| | Within Groups | .004 | 4 | .001 | | |
| | Total | 36.188 | 23 | | | |
| **LICC** | Between Groups | 1.998 | 19 | .105 | 41.130 | .001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Within Groups | .010 | 4 | .003 | | |
| | Total | 2.008 | 23 | | | |
| **MELI** | Between Groups | 5.615 | 19 | .296 | 240.995 | .000 |
| | Within Groups | .005 | 4 | .001 | | |
| | Total | 5.620 | 23 | | | |
| **METS** | Between Groups | 3.457 | 19 | .182 | 227.283 | .000 |
| | Within Groups | .003 | 4 | .001 | | |
| | Total | 3.461 | 23 | | | |
| **NICO** | Between Groups | 13.773 | 19 | .725 | 3.099 | .141 |
| | Within Groups | .936 | 4 | .234 | | |
| | Total | 14.709 | 23 | | | |
| **PTBB** | Between Groups | 6.000 | 19 | .316 | 41.130 | .001 |
| | Within Groups | .000 | 4 | .000 | | |
| | Total | 6.000 | 23 | | | |
| **SULP** | Between Groups | .826 | 19 | .043 | 69557.460 | .000 |
| | Within Groups | .000 | 4 | .000 | | |
| | Total | .826 | 23 | | | |

From table 6 there is no statistically significant difference between the mean of the results.

**Conclusion**

In this work, the accuracy of GNSS processing software employing online and offline software was examined. In this investigation, an IGS station served as the standard for comparison of the disparity. The IGS station and the employed GNSS observation method were compared by taking into account the coordinate measurements of the identical sites in both ways. On each of the nine stations, the observations were conducted for three consecutive days in January and for three consecutive days in March. The precise point positioning (PPP) technique is part of the software being used. To determine each point's most likely value in UTM, the coordinates obtained from post-processing were then averaged.

This is true even though the outcomes of data processing through online processing software depend on a number of variables. The minimum difference 0 cm for both solutions and the maximum difference 1.568 cm for online and 1.404 cm for offline.

Along the six days the results very close to each other and the difference depends on the satellite orbit file and clock file. station MELI must eliminated because it has the biggest difference due to a smaller number of satellites detected and less fixed ambiguity.

For user multi-GNSS combinations with centimeter to millimeter level, PPPH can offer PPP solutions. The software allows users to specify the options, models, and parameters. Additionally, PPPH offers an output file with the estimated parameters for each epoch individually as well as a variety of statistical analysis tools for evaluating the outcomes. Accuracy is impacted by the number of satellites found and fixed ambiguity.

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