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Potential and limitations of free online Precise Point Positioning services for GNSS rover-base surveys in low-density CORS areas.

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Abstract. In the last years, the diffusion of the Precise Point Positioning (PPP) technique has constantly increased thanks to the more precise and accurate results that it can reach. Until some years ago, this technique was limited by long measurement sessions to obtain good precisions (centimetre-level), using only one GNSS dual frequency receiver. Online PPP free services that permit broad access to PPP technique have spread. In this contribution, two PPP online services (Canadian Spatial Reference System Precise Point Positioning tool; Automatic Precise Positioning Service) are analysed as potential solutions for realising GNSS surveys in disadvantaged areas for the lack of geodetic infrastructures. The PPP online services are compared with a relative positioning online tool (AUSPOS). Their elaboration power was tested for different stationing times (three scenarios of 3 hours, 1 hour and 30 minutes, respectively). The data PPP-treated were collected in southwest Niger, along the Sirba river. The results reveal precisions and relative accuracies lower than 5 cm for three hours sessions. The short observation sessions (i.e. one hour and half hour) emerged that APPS provide the most confident solutions. The less performant service is AUSPOS, which provides 0,612 cm precision for one hour. CSRS-PPP has precision values between the ones of AUSPOS and APPS.

Keywords: Point Positioning, High-Precision GNSS, NRTK, Free and Open Services, Sub-Saharan Africa, Niger, Sirba River, Sahel, Topographic Survey, Geodetic Disadvantaged Areas.

1 Introduction

In recent years, the Global Navigation Satellite System (GNSS) has overcome traditional survey methods, becoming a standard tool in many surveying sectors. Nowadays, GNSS systems play a lead role in data acquisition thanks to the increasing number of satellites, the low cost, the efficiency, and the variety of available products. From 2002 forward [1], Real-Time Kinematic networks (NRTK) have spread. These networks are composed of GNSS stations of known coordinates, called Continuously Operating Reference Stations (CORS), and managed by network software installed in a control centre. The introduction of the CORSs has allowed users to collect data using one GNSS multi-frequency receiver (instead of two). This is possible thanks to the direct connection between the CORS and the dual-frequency receiver through the control centre. Today, a dense world network of permanent stations to process GNSS data exists [2], revolutionising the data acquisition modalities [3,4].

Although CORSs cover most of the world's countries today, some areas are still not included in the network, such as some sub-Saharan countries (**Fig. 1**). Considering the real-time positioning and the NRTK method, the rover receiver must be within a short distance (less than 60 km) from the reference stations [5,6].

A short baseline is fundamental to minimise the distance-dependent errors induced by the troposphere, the ionosphere, and the orbital errors [7]. This specific requirement can be an obstacle to realising NRTK surveys where there are no CORS within hundreds of kilometres [8]. A possibility to overcome the lack of CORS is resorting to two GNSS dual-frequency receivers in the rover-base modality. This data collection method requires two GNSS receivers to communicate with each other (usually via radio): one works as "base" or "master" (substituting the permanent station) and the other as "rover" that collects the coordinates of the points of interest for the survey. The coordinates of the base station must be known.

When a known-coordinates point is unavailable, post-processing operations are compulsory to obtain the base's correct position. One of the most common post-processing methods is the PPP (Precise Point Positioning). To perform it, data regarding satellites' orbits and the ionosphere are needed to process the pseudo-range and carrier phase measures of GNSS multi-frequency receivers [9–11]. These data are collected by permanent stations that can also be located very far from the surveyed area [10]. In terms of East, North, and Up components, the PPP can provide centimetre-level precisions in static mode [12,13] if the phase ambiguities are correctly fixed as integer values [14,15]. The precision of PPP corrections depends on the measurement session's duration [16,17]. Its effectiveness for the estimation of the positions has been demonstrated by several authors, e.g. [10,11,18,19], using precise orbits and satellite clocks from IGS [20,21] and many other providers [17,22,23]. RTK is a relative positioning technique based on carrier-phase. A minimum of four shared satellites between the two receivers is required. Tracking more than four satellites improves the GPS position solution's precision and allows it to obtain a sub-centimetre accuracy level. The excellent accuracy results are also because errors and bias from the same satellite should be equal. Thus, shorter is the baseline, and more similar are the errors. Several error sources affecting positioning accuracy in GNSS surveys exist [24]. Today relative technique provides better solutions than the PPP technique in terms of accuracy [25]. The primary reason is the lower effects of satellite orbit errors over relative techniques than the PPP technique.

Moreover, relative techniques can eliminate clock errors using double differencing phase measurements [26]. The primary error sources of PPP (such as ionospheric and tropospheric delay and clock bias) are usually mitigated by: i) employing the combinations of dual-frequency GNSS measurements to eliminate the first-order ionospheric delay [10,25]; ii) applying external error correction data (including satellite orbit and clock corrections); and iii) modelling the tropospheric delay to correct it. Since a part of tropospheric delay cannot be efficiently modelled because of its high variability, it is estimated (wet component of tropospheric delay). Precise satellite orbit and clock information are used to calculate the tropospheric residuals and associated gradients with proper stochastic models, which means that the estimates are constrained by the prior variance and its propagation value. Thus, PPP depends on the accuracy level of this information [25].

Fig. 1. CORS in north Africa. The blue dots indicate the stations that provide observations to the International GNSS Service (IGS), while the red square is the study area. Data Source: International GNSS Service (IGS), (https://www.igs.org/).

Though RTK and PPP techniques provide similar precision and accuracy, they require different setups. On the one hand, RTK needs a complex configuration and (generally) expensive equipment, but it rapidly provides higher accuracy. It is worth remembering that the base station must be placed precisely on a known-coordinate point to achieve high accuracy. On the other hand, the PPP technique needs a more straightforward setup, but it has lower accuracy and a longer initial convergence time [25,26]. Also, since PPP does not use a base station, it is not affected by baseline length bias and can provide full accuracy anywhere in the world.

Until some years ago, the satellites' data, the ionosphere information, and the specific software necessary to perform PPP were not easily obtainable. The PPP was limited to a few expert users, such as academia and research institutes. Today, some commercial and scientific solutions to perform PPP exist (e.g., Bernese, GIPSY, and GAMIT). Such software can efficiently perform PPP as long as infrastructures with adequate computational power and skilled users are available. The PPP technique has raised the attention of academia, industry, and governments [9]. In particular, the last ones have dedicated specific attention to PPP, and some shared the socio-economic benefits of PPP with the public, providing ad hoc coordinates online estimation services [9]. Some governmental research centres provide PPP online free services. It is sufficient to upload the GNSS raw data to obtain the correct position data from the services. These free web solutions for PPP do not require high computational power or exceptionally skilled users, but each service uses its estimation algorithms. Thus, the results provided can be very different. The scientific literature offers some interesting analysis of PPP online services, where known coordinates points are processed with various PPP online services [27–29], and the estimated coordinates are compared with known ones. Nevertheless, as far as the authors know, few of these studies analyse data collected in geodetic disadvantaged areas. Indeed, the lack of CORS and known coordinates points is quite a frequent condition in sub-Saharan rural regions, strongly affecting topographic surveys.

This work compares two PPP online free services to correct RTK data collected through rover-base modality (i.e., static mode) in low-density CORS areas. The PPP services considered are the Canadian Spatial Reference System Precise Point Positioning tool (CSRS-PPP) and the Automatic Precise Positioning Service (APPS). A CORS-based post-processing free service is considered in the analysis as a non-PPP post-processing online tool: the AUSPOS Online GPS processing service (AUSPOS). The precision, the convergence time (meant as the length of time required to reach centimetre-level positional solutions), and the structure and condition of the services' use are analysed in this paper. The data used for the comparison were collected in February 2018 along the Sirba River (southwest Niger) in the framework of the ANADIA 2.0 project[1] and this work is premised on the outcomes of the tests that have been presented in [30]

2 The case study

ANADIA 2.0 project was born in 2017 to develop an early warning system against floods and strengthen the local technicians' competencies in monitoring and forecasting river floods [31]. Indeed, Sahelian floods have become a relevant issue in the last decades due to the ongoing climatic and land use changes [32,33]. In this framework, high-precision surface and hydraulic numerical models are necessary as inputs for the development of forecast flood models [34–36]. Hence, to meet the project's data requirements, a topographic survey was carried out on the Middle Niger River Basin's main tributary, the Sirba River. More than 100 cross-sections were measured along a reach of 108 km (one section per km), and flood-risked-exposed infrastructures were measured during the dry period (February) to take advantage of the intermittent flow [37,38]. 10 cm accuracy for the Up component was required [31].

Although the closest CORS to the study area are in Nigeria and Ivory Coast, they are more than 900 km away from the study region.

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[1] ANADIA 2.0 (Adaptation to climate change, disaster prevention and agricultural development for food security) is a project funded by the Italian Agency for Development Cooperation (AICS) and executed by Institute of BioEconomy of the National Research Council of Italy (IBE-CNR) in partnership with the Department of Regional and Urban Studies and Planning of the Politecnico di Torino (DIST) and the National Directorate for Meteorology of Niger (DMN).

As discussed in the previous section, 900 km is a too-long baseline to guarantee centimetre accuracy. Besides, the closest known-coordinates points are around 200 km from the surveyed area. Considering these conditions, the only feasible way to collect data was an RTK survey in master-rover modality with a radio-modem connection. The PPP technique was used to post-process the data and estimate the base stations' coordinates. The data were collected with two STONEX S10 dual-frequency receivers. The master receiver was placed in 17 stations along the Sirba River (**Fig. 2**), and 3,150 points were measured with the rover receiver. Each master station acquired data for at least two hours, considering a session length of 3 hours and 22 minutes as maximum. GPS, GLONASS, BEIDOU and SBAS constellations were tracked.

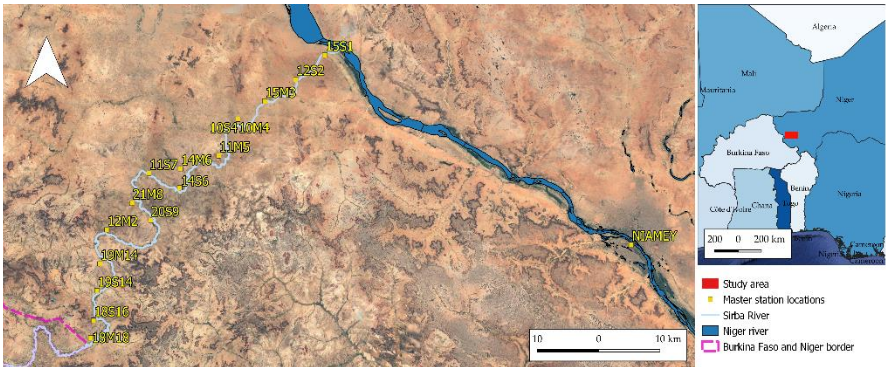

Fig. 2. Surveyed area of Sirba River basin. The yellow squares identify the locations of the stations along the river.

Some instruments malfunctioning, attributed to the high temperature, slowed down the data collection. In the hottest hours of the day, the temperature reached 40°C, and the master receiver often overheated and stopped communication with the rover receiver. The communication happened via radio using RTCM communication protocol at 410-470 MHz frequency. The overheating prevented acquisition longer than 3 hours for most of the stations. The receivers' communication was even more limited by the local topography (**Fig. 3**) and the abundant vegetation along the river. Regularly, if the receivers were more than 3 km away from each other, the communication stopped. In 9 days, 103 cross-sections along a river reach of 108 km were measured. The raw measurements were saved in the Receiver Independent Exchange Format (RINEX) 3.01 version with a sampling rate of 1s.

3 Methodologies

As previously discussed, two possible techniques are available for post-processing: the phase-based relative solution (base-rover) or the PPP [6]. This paper will focus on the PPP approach [39]. Today many possibilities for obtaining PPP solutions from online services exist [40,41]: some of them consider only the GPS constellation (e.g., APPS), and others ones also GLONASS satellites (CSRS-PPP). The data collected by the master receiver were stored in RINEX 3.01 version. Then, they were post-processed using two online PPP free services: i) The Canadian Spatial Reference System (CSRS-PPP) and ii) the Automatic Precise Positioning Service of the Global Differential GPS System (APPS). Additionally, data were processed using a relative positioning online service, iii) Online GPS Processing Service (AUSPOS), as a comparison against PPP technique geodetic disadvantaged areas. A summed table was created (**Table 1**) to recap the functioning of the three services.

Fig. 3. Environmental conditions during the survey activities in the field. The master receiver (on the tripod) is in the foreground, while the rover receiver is in the background.

3.1 Canadian Spatial Reference System Precise Point Positioning tool (CSRS-PPP)

Operative since 2003, the CSRS-PPP is an online free tool provided by the Canadian Government [42]. It calculates the positions of the information collected by GNSS receivers with high accuracy based on the RINEX files [43].

The CSRS-PPP uses GNSS ephemerides to produce absolute accuracy coordinates, meaning using accuracy values independent of the collection's location. The estimated coordinates are as much accurate as long in the acquisition session. The CSRS-PPP uses IGS ephemerides of three types, Final, Rapid, and Ultra Rapid that have the following accuracy values [44]:

- FINAL (±2 cm), available after 13-15 days from the acquisition day, from the end of the data collection week.
- RAPID (± 5 cm), available from the day after the data collection.
- ULTRA RAPID (± 15 cm), available every 90 minutes.

The service can process data in Kinematic and Static modes. Data can be post-processed inNAD83 (inserting the referring epoch) or ITRF (International Terrestrial Reference Frame) reference systems. It is possible to automatically convert ellipsoid height into orthometric height by choosing between CGDV28 (Canadian Geodetic Vertical Datum of 1928) or CGDV2013 (Canadian Geodetic Vertical Datum of 2013), both valid only for surveys realised in Canada. It is possible to upload an Ocean Tidal Loading (OTL) file. The results are sent by email.

3.2 Automatic Precise Positioning Service (APPS)

The APPS is an online free service provided by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology of USA National Aeronautics and Space Administration (NASA). Its elaboration is based on the Global Differential GPS System (GDGPS) products of JPL and the software GIPSY-OASIS developed by JPL. It applies a broad and spread geodetic structure (more than 200 stations distributed worldwide). The GDGPS operates since 2000 and declares a 99.999% reliability and precision under 10 cm [45]. The APPS uses the Jet Propulsion Laboratory's final products of three types: Final, Rapid, and Ultra Rapid Real-time [45]. The declared accuracy values are:

- FINAL (±3cm), called FlinnR, are available after ten days from the acquisition day.
- RAPID (± 5 cm), called QuickLookR), are available the day after the data collection.
- ULTRA RAPID (± 8 cm), 1 minute after data is collected.

Registration is compulsory to have full access to the service. The available options for the PPP are the processing mode (static or kinematic); the L1 code (C/A or P), if an atmospheric pressure model is requested (it can be helpful in the calculation of the hydrostatic delay for the troposphere modelling), the type of weight to assign to the elevation datum (flat, sin or sqrt). The advanced options allow the user to set the value of the cut-off angle and the output rate in seconds (clearly available only for kinematic surveys). 10 Mb is the maximum file size allowed, and the files must be in RINEX version 2.x. The results are provided directly in the upload window.

3.3 AUSPOS Online GPS processing service

It is an online free service provided by the Australian Government. It uses the relative positioning technique to estimate the coordinate of an unknown-positioned mark when it is over a reference station of known coordinates [23]. The Bernese Software System, used to correct the coordinates, is very rigorous in the definition of orbital parameters, and everything concerns the modelling of the geodetic aspects [46]. IGS provides the information and the parameters regarding the orbit and the Earth's orientation. Like the CSRS-PPP and APPS, it uses the best available ephemerides. It is fundamental to underline that AUSPOS does not provide a PPP service since the applied data correction uses data of the nearest IGS and Asia Pacific Reference Frame (APREF) stations. Consequentially, the data confidence and the time dependency are influenced by the distance of the reference stations used for the coordinates estimation. It was included in this analysis as representative of the relative positioning of online free tools. The service does not require any registration. The only information needed for the elaboration is the model, the antenna height, and an email address. The files must be in RINEX version 2.11. The upload limit is 20 files at once, but data must be referred for seven days. AUSPOS sends the results via email.

Table 1. Summary of the main characteristics of the three services at the processing time, calculated on a 10Mb file. *If users submit RINEX V3 file, C2S (code measurement) and L2S (phase measurement) from L2 frequency will NOT be accepted as presented in [30].

	CSRS-PPP	**APPS**	**AUSPOS**
RINEX version	3.x	2.x	2.11*
Maximum file size	300 Mb	10 Mb	Not specified
Multi-file upload	Yes	Yes	Only via FTP
FTP	No	Yes	Yes
Height of the antenna	Automatically detected	Automatically detected	Manually set
User-defined elevation-dependent data weighted	No	Yes	No
User-defined cut-off angle	No (default 7.5)	Yes	No
L1 code	Yes	Yes	No
Upload of pressure model	No	Yes	No
Direct results	No	Yes	No
Compulsory registration to the website	Yes	No	No
Processing time (minutes)*	20	3	20
Reference system(s) of the results	ITRF 2014, NAD83	ITRF 2014	ITRF 2014
Orthometric heights	Yes	No	Yes
Elaboration report	Yes	No	Yes
Graphic restitution of the elaboration statistics	Yes	No	Yes
Ambiguity resolution	No	Yes	Yes
GNSS constellations processed	GPS+GLONASS	GPS	GPS

4 Results and discussion

Before the PPP processing, the RINEX data were pre-processed. The RINEX files version 3 were converted into RINEX version 2.11 with the RTKCONV tool that is part of the open source software RTKLIB (http://www.rtklib.com/) [47]. Furthermore, the frequency rate of acquisition was reduced to one observation every 5 seconds to have files of less than 10 Mb, which is the file size limit of APPS service. The analysis considers the precisions of the estimation of each service and the relative accuracy (measured as the difference between coordinates) of 17 stations (one station of ANADIA 2.0 was excluded from this analysis because it is located outside the Sirba

River basin). The final coordinates have been converted into WGS84/UTM31N coordinates system. The APPS service provides the σ values with 68% confidence, while CSRS-PPP and AUSPOS calculate 95% uncertainties. Therefore, the uncertainty values of APPS were related to 2σ confidence. **Table 2** shows the session length and the date of acquisition for each station.

Table 2. Characteristics of the positions of the master receivers (Stations) analyzed in [30] and resumed in this work. Gr =group, *dd/mm/yyyy

Station ID	Date of acquisition*	Starting time	Ending time	Session length	Gr
12S2	12/02/2018	12:58	14:49	01:51	1
10S4	10/02/2018	15:08	17:07	01:59	
14M6	14/02/2018	09:28	11:43	02:15	
10M4	10/02/2018	10:28	12:54	02:26	
15S1	15/02/2018	13:46	16:30	02:44	2
19S14	19/01/2018	14:02	16:49	02:47	
20S9	20/01/2018	14:24	17:12	02:48	
15M3	15/01/2018	08:17	11:08	02:51	
18S16	18/01/2018	14:09	17:02	02:53	
21M8	21/01/2018	08:53	11:46	02:53	
14S6	14/01/2018	13:38	16:35	02:57	
11M5	11/01/2018	09:05	12:05	03:00	
11S7	11/01/2018	13:43	16:52	03:09	3
12M2	12/01/2018	08:50	12:05	03:15	
18M18	18/01/2018	08:05	11:28	03:23	
20M12	20/01/2018	08:45	12:09	03:24	
19M14	19/01/2018	08:25	11:52	03:27	
12S2	12/02/2018	12:58	14:49	01:51	

For the analysis, the stations were distributed in three groups of uniform acquisition length: *group 1* less than 2,5 hours acquisition length; *group 2* between 2,5 and 3 hours; and *group 3* more than 3 hours. The CSRS-PPP values had been taken as a reference for comparing the services, as shown in Equations 1 and 2.

$$\Delta CSRS\text{-}APPS = EC\_\ CSRS - EC\_APPS \quad (1)$$

$$\Delta CSRS\text{-}AUSPOS = EC\_CSRS - EC\_AUSPOS \quad (2)$$

Where *EC_ CSRS* are the North, East and Ellipsoidal height coordinates of each sample point estimated by CSRS; *EC_ APPS* are the North, East and Ellipsoidal height coordinates of each sample point estimated by APPS; *EC_ AUSPOS* are the North, East and Ellipsoidal height coordinates of each sample point estimated by AUSPOS. According to [48], a minimum of one hour is required for the horizontal solution from a standard PPP static processing to converge to 5 cm. Approximately 20 minutes are needed for 95% of solutions to reach a horizontal accuracy of 20 cm [49]. Thus, three different scenarios of time acquisition were created using RTKLIBCONV [47] to investigate the effectiveness of the services on short acquisition time: full acquisition length, one hour, and a half-hour session.

Table 3 presents the minimum, maximum and average values of Δ CSRS-APPS and ΔCSRS-AUSPOS, calculated as illustrated in equations 1 and 2.

Table 3. Minimum, Maximum, and Average of the differences between the coordinates estimated by CSRS, APPS, and AUSPOS for each station as reported by [30].

Gr			**Min**	**Max**	**Av**
1	Δ CSRS-APPS	East	0.007	0.019	0.014
		North	0.008	0.014	0.011
		Up	0.005	0.046	0.024
	Δ CSRS-AUSPOS	East	0.005	0.067	0.023
		North	0.001	0.014	0.007
		Up	0.018	0.046	0.032
2	Δ CSRS-APPS	East	0.001	0.026	0.01
		North	0.002	0.011	0.006
		Up	0.006	0.037	0.016
	Δ CSRS-AUSPOS	East	0.001	0.013	0.008
		North	0.002	0.005	0.003
		Up	0.006	0.069	0.029
3	Δ CSRS-APPS	East	0.003	0.029	0.016
		North	0.001	0.008	0.003
		Up	0.001	0.024	0.011
	Δ CSRS-AUSPOS	East	0.000	0.04	0.021
		North	0.002	0.004	0.003
		Up	0.006	0.031	0.017

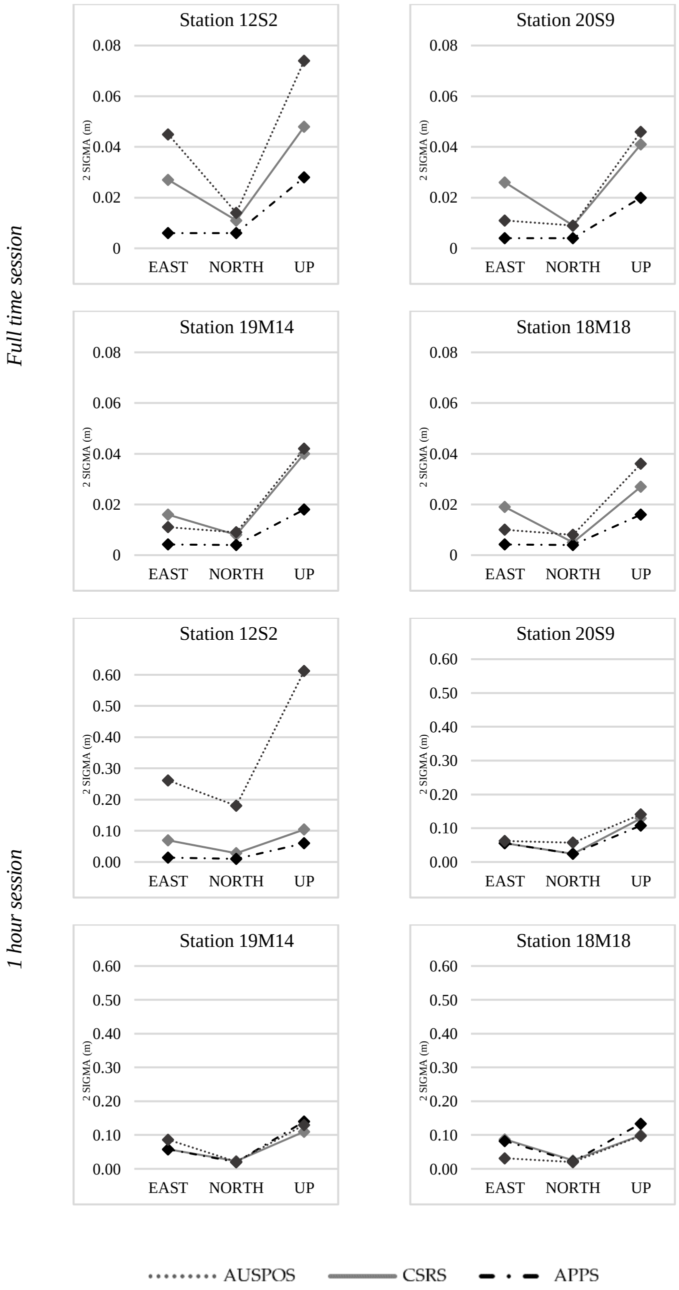

Fig. 4. Graphical analysis of the uncertainties values of East, North, and Up coordinates of the three services, obtained considering the full acquisition time and 1-hour acquisition time [30].

The difference between CSRS and AUSPOS of the East component ranges between 0 cm and 6.7 cm, which is a clue of high data dispersion. This is particularly evident from distances between the average values of Groups 1 and 2, and it clearly indicates the importance of stationing time longer than 1 hour for improved precision. On the contrary, the North component of the Δ CSRS-AUSPOS (and the Δ CSRS-APPS, too) is more stable.

Regarding the coordinates' precision, the calculated uncertainty values range from 0.2 cm (East and North of APPS) to 65 cm (Up component of AUSPOS). The latter is not representative of the analysis and was interpreted as an exceptional event; thus, it was excluded from the average computation. For AUSPOS, the distance from the reference CORS is crucial in estimating the coordinate. The baseline ranges from 500 km to 1500 km on 14 reference stations in these analyses. From the reference literature, we aspect Root Mean Square (RMS) values of position errors for baseline around 500 km less than 4 cm, and less than 6 cm on each component (E, N, U) for baseline more than 1000 km. Such values are calculated over 24 hours of acquisitions [50]. For shorter stationing time, the precisions fall.

According to the report by Novatel [51], we can expect around 10 cm RMS values of the position errors for baseline lengths between 700 km and 1000 km in 3-hour stationing. These values reflect our measures: AUSPOS is closed 8 cm on the Up component. For groups 1 and 2, the uncertainties on the East component estimated by APPS are slightly lower than those of other services (**Fig. 3**). **Fig. 3** shows the graphical analysis of the uncertainty values of the East, North, and Up components and considers the full and 1-hour acquisition time. Similarly to **Table 3**, what stands out in **Fig. 3** is the decrease in uncertainties from Full-time acquisition (Group 3) and one-hour sessions (Group 1).

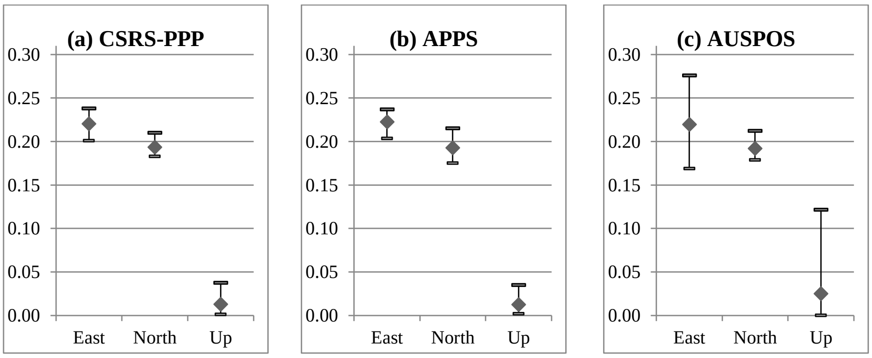

Fig. 5. Average (square), Minimum and Maximum values of the difference between the coordinates estimated by online post-processing services and the real coordinates. Average, minimum, and maximum are calculated for AUSPOS (a), CSRS (b), and APPS (c) in [30].

CSRS-PPP and APPS provide the lowest uncertainty values. With a shorter acquisition time, the confidence levels of CSRS-PPP and APPS get closer (**Fig. 3**), while AUSPOS shows similar trends for some stations (i.e., 19M14 and 18M18) and very different for others (station 12S2). **Table 4** lists the difference values between the coordinates elaborated with the services on the 1-hour session. Even if these trends are similar to full acquisitions, a significant distance between the Up components can be observed: the ΔCSRS-APPS peaks at 40 cm. For 30 minutes-acquisition time, AUSPOS did not provide any results because one hour is the minimum acquisition time required to perform the coordinates estimations. CSRS-PPP and APPS's performances peak in the East component of 20 cm and reach 50 cm on the Up component.

Table 4. Minimum, Maximum, and Average of the difference between the coordinates estimated by CSRS, APPS, and AUSPOS for each sample station (1hour session), [30].

Service	**ITRF**	**One-hour session Δ (m)**		
		Min	Max	Av
Δ CSRS-APPS	East	0.001	0.140	0.030
	North	0.000	0.374	0.032
	Up	0.005	0.108	0.044
Δ CSRS-AUSPOS	East	0.006	0.432	0.099
	North	0.002	0.403	0.037
	Up	0.033	0.286	0.165

5 Data validation

The lack of CORS in Niger makes it challenging to test the accuracy of PPP services. Since there are no known-coordinates points to be used as a reference for accuracy analysis, only the precision values can be evaluated. To overcome this major constraint, we analysed accuracies of post-processing services solutions in sub-Saharan areas considering the data of CORS settled in countries close to Niger. CORS at the same latitude of the study area was sought to guarantee both the mean atmospheric conditions (ionospheric and tropospheric delays) and satellite geometry distribution. Another possible approach could be to collect 24 hours of data to obtain results independent of the satellite geometry distribution and guarantee the solution's convergence, as described in the literature [52,53]. However, it was impossible to realise long-session sessions due to weather conditions. Hence, to check the estimations' accuracy, raw observations of a CORS close to the surveyed area were analysed with online services. The selected CORS was the YKRO station (Yamoussoukro Tracking Station) in Cote d'Ivoire (1000 km away from the study area) and part of the IGS network (**Table 5**).

Table 5. Main characteristics of YKRO. Source: IGS website, [30].

YKRO Site Information	
City	Yamoussoukro
Country	Cote d'Ivoire
Tectonic Plate	African Plate
Approximate Position, DMS (ITRF)	LAT: +06°52' 14.0170" LON: -05°14' 24.3347"
Elevation ellipsoid (m)	270.263
Date Installed	18-07-1999

This station was chosen because it is the closest station (considering latitude) to the investigated area, and it was operative at the time of the survey, February 2018. Besides, it is away from the sea. This may ensure atmosphere conditions as similar as possible to the ones in the study area. YKRO data of the survey days and the daily observations (12th of each month of 2018) were downloaded from the IGS website. The YKRO dataset was reduced to 3 hours-lasting RINEX from 14.00 to 17.00, as the average lasting and representative time for Sirba River acquisitions. Data were processed with the online free services and estimated coordinated compared to the reference ones of the YKRO CORS (**Table 5**). The results show relatively constant performances for the North component and more dispersed results for the East and Up components. **Fig. 4** compares summary statistics (average, minimum and maximum values) for the differences calculated between real and estimated coordinates. The highest dispersion of the East component stands out in the graphs. CSRS and APPS have similar trends on the components, while AUSPOS, even if it has average values close to one of the PPP, provided varying results for the Up and East components. The results are never below 10 cm on the East and North components while reaching 1 cm on the Up component. According to the literature, we should obtain precision under 20 cm on horizontal components in 20 minutes. In our case, CSRS-PPP did not provide results under 20 cm in a half-hour on the East component. For example, in 30 minutes of session length, we reach the average precision of 0.247 cm on the East component. The results expected for one-hour sessions are approximately 5 cm on the horizontal component. APPS fits well these general rules on East and North components, while CSRS only focuses on the North component.

The coefficients of determination (R^2, listed in **Table 6**) confirm these observations. They verify that the estimated East component is the closest to the three services' reference values, reaching 0.737 for the CSRS-PPP service. AUSPOS records the most dispersed results in the Up component. In parallel, the Root Mean Square Error (RMSE) calculated over each service's estimations' position errors provides a view of the accuracy. The East component presents the highest values, followed by the North component. The lowest-RMSE service is the APPS for the Up component.

Table 6. R2 and RMSE values for the 2018 monthly dataset of solutions provided by the analysed services, [30].

R^2			
Online Service	**East**	**North**	**Up**
CSRS	0.235	0.737	0.273
AUSPOS	0.070	0.292	0.017
APPS	0.253	0.391	0.104
RMSE (m)			
CSRS	0.220	0.193	0.016
AUSPOS	0.221	0.192	0.040
APPS	0.223	0.193	0.015

Regarding YKRO analysis, even if remarkable differences between the coefficients of determination are present, the RMSE values differ for no more than 0.2 centimetres in the North and East components. The estimated height above the ellipsoid by APPS is the closest to the YKRO reference, only 1 mm on average values from CSRS-PPP. It is worth mentioning that AUSPOS does not use YKRO for ambiguity resolution, but it relies on stations located approximately 500-2000 km from YKRO.

CSRS-PPP and APPS use different ephemerids. This may affect the estimated coordinates because they strongly affect PPP results; thus, we might have different effects in the case of every other product. Besides this, the ephemerids seem not to interfere in the estimations. Additional considerations regarding the efficiency of PPP online free services can be addressed. APPS is the most rapid service in the data processing. It permits the analysis of a large quantity of data (industrial application) by uploading the RINEX files on an FTP provided by JPL (not tested in this contribution). APPS results are delivered directly from the website after a few seconds (depending on the data size), while AUSPOS and CSRS send the results via email. Nevertheless, APPS has an interface that may look complicated for non-GIPSY-expert users and does not provide the results in a report. CSRS-PPP is functional because the upload process is intuitive, and the results report is easily interpretable.

6 Conclusions

This manuscript tests and describes PPP online free services to correct RTK data collected through rover-base modality (i.e., static mode) in geodetic disadvantaged areas. Three GNSS post-processing services are analysed, the Canadian Spatial Reference System Precise Point Positioning tool (CSRS-PPP) and the Automatic Precise Positioning Service (APPS), and the AUSPOS Online GPS processing service (AUSPOS, CORS-based post-processing free service). The services are adequate and effective for the post-processing corrections of the master-rover RTK survey.

According to our analysis of Niger data, APPS reveals to be the most precise PPP free online service among the ones investigated in this paper, followed by CSRS-PPP, which guarantees satisfying performances in an easily interpretable report, and, finally, AUSPOS presents the less precise results, but it is highly intuitive.

The Canadian CSRS-PPP was used in the ANADIA 2.0 project. The obtained results have ± 4 cm precision, a value that satisfies the needs of the ANADIA II project in Niger. Nigerien technicians of the ministerial office in charge of meteorology and water resources have actively participated in the field surveys, appreciating the potential of the RTK master-rover survey.

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