Scientific Research Publishing

International Journal of Geosciences, 2026, 17(4), 264-287
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Study on the Redefinition of the Senegalese Geodetic Reference Frame Using GNSS PPP Technology

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How to cite this paper: Diouf, D., Morel, L. and Sidibe, D.K. (2026) Study on the Redefinition of the Senegalese Geodetic Reference Frame Using GNSS PPP Technology. *International Journal of Geosciences*, **17**, 264-287.
https://doi.org/10.4236/ijg.2026.174013

Received: March 2, 2026
Accepted: April 26, 2026
Published: April 29, 2026

Abstract

Techniques for establishing geodetic reference frames have evolved considerably with the use of global navigation satellite systems (GNSS) in geodesy through spatial positioning techniques. These techniques have made it possible to replace two-dimensional and local terrestrial reference frames, which were generally established using triangulation or geodetic polygonation techniques, or sometimes by simple astro-geodetic points. This development has therefore made it possible today to modernize most geodetic infrastructures by establishing more consistent three-dimensional reference frames at the global, regional, or national level. However, the technical constraints associated with the resources required to establish such benchmarks using differential GNSS positioning techniques (previously favored or even exclusively used) severely limit the level of modernization, maintenance, densification, and upkeep of geodetic reference frames in developing countries. The simplicity and performance of Precise Point Positioning (PPP) demonstrated in this study prove that this technique can be a real alternative for such geodetic work in these countries. Indeed, the recalculation of Senegalese Geodetic Reference Frame of 2004 (RRS04) carried out in this study based on a GNSS observation campaign over four sessions for sixteen points in the reference frame, in differential mode using the AUSPOS online tool and GAMIT/GLOBK scientific software, and in PPP mode using the CSRS-PPP tool, showed good agreement between the solutions provided by the three tools. The average deviations obtained for the X, Y, and Z components of the different points in the network are less than 2 cm, which is consistent with the accuracies generally associated with these geodetic networks.

Keywords

PPP, Geodetic Reference Frame, GNSS, RRS04

1. Introduction

Precise GNSS positioning has seen many advances in recent years, with multiple and varied fields of application.

The quality of measurements, calculations, and the performance of the equipment used have contributed greatly to these advances in many disciplines [1]-[4]. Two positioning strategies currently characterize this type of positioning: relative positioning and Precise Point Positioning (PPP). PPP, far from being a new positioning technique, is now, thanks to its performance, a real alternative to differential positioning in many cases, which until now used the relative precise GNSS positioning technique [5] [6]. This situation has been facilitated by its simplicity, the availability of numerous calculation tools, including online tools, the availability of accurate external products, and improvements in processing techniques that have enabled rapid convergence of ambiguities [7]-[10].

These technological advances have greatly contributed to changes in the techniques and working methods used in the creation of geodetic reference frames. However, it should be noted that the implementation of terrestrial reference systems does not always take place in the same way from one country to another, from one continent to another, or from one structure to another. This reality can be explained by various factors such as the availability of resources, the level of qualification of the work teams, the working conditions and environment, technical specifications and requirements, etc.

However, the goal sought today by the scientific community and international organizations working in the field of precise positioning is to achieve homogeneous reference frames from one country to another with a good level of accuracy that can meet the needs of all stakeholders who will be future users. This should lead to the creation of reference systems that can be used to support all studies carried out in these areas, providing a consistent and reliable terrestrial reference frame anywhere in the world [11].

There is often a lack of documentation (metadata) on the methodology used to establish these geodetic reference frames. However, such documentation should enable an initial assessment of the quality of the points established and assist with any future updates. These problems can also be explained by insufficient scientific publications on the subject, which should serve as references for professionals to help them take full advantage of technological advances.

These advances with PPP are therefore a real asset for positioning stakeholders in developing countries such as Senegal. However, certain parameters related to the equipment used, the local reference frame, or the calculation parameters can lead to a PPP calculation solution that does not meet user expectations. Senegal is one of many developing countries whose geodetic reference systems are represented by ground markers and/or sparse Continuously Operating Reference Stations (CORS). Unfortunately, these geodetic reference points generally suffer from a lack of maintenance, monitoring, and updating, which means that the reliability expected of such geodetic reference frames cannot be guaranteed. These anomalies may be linked to the relatively significant resources (financial, technical, and human) required for such operations with the differential GNSS positioning generally applied. The sustainability and stability of such points are among the challenges facing these types of reference systems. With the advances made in recent years and the relatively low resources required for its use, PPP could be a real positioning strategy option that would overcome some of the problems encountered by those who develop such geodetic reference systems. The use of this zero-difference GNSS positioning method in this field in Africa would also provide an opportunity to evaluate and demonstrate the influence of plate velocity models in Africa.

The objectives of this study are to:

- Propose a new calculation of the Senegalese geodetic reference frame using PPP and evaluate its quality in relation to the current determination;
- Propose an approach for maintaining the RRS04 by PPP and, more broadly, PPP attachment for other African reference frames of the same type.

To this end, the methodology used for GNSS observations and calculations will be presented in this document, along with the results obtained, followed by a discussion and the perspectives adopted.

2. Methodology

2.1. Description of the GNSS Observation Campaign

As part of this study, a GNSS observation campaign was carried out over four days. This campaign covered sixteen of the twenty first-order control points of the RRS04, spread across virtually the entire national territory (**Figure 1**). The observations were made using Spectra SP80 receivers over four observation sessions, which were to be used for both PPP and differential network calculations (for external control and validation of PPP solutions). Ten antennas of the same brand mounted on tripods were used with baselines forming an observation pattern with sessions ranging from 52 to 238 km.

The SP80 (non-choke-ring) antennas used in this study are patented for optimal GNSS performance and to attenuate multipath interference. They are therefore not the most recommended antenna models for geodetic work (choke-ring type), which should be more efficient and less sensitive to multipath interference, but are more expensive. As such antennas were not available to us, the use of “topographic” antennas will enable us to validate or invalidate their suitability for use in such geodetic work and to better meet the expectations of this study on optimizing the resources required to set up a high-quality geodetic reference network.

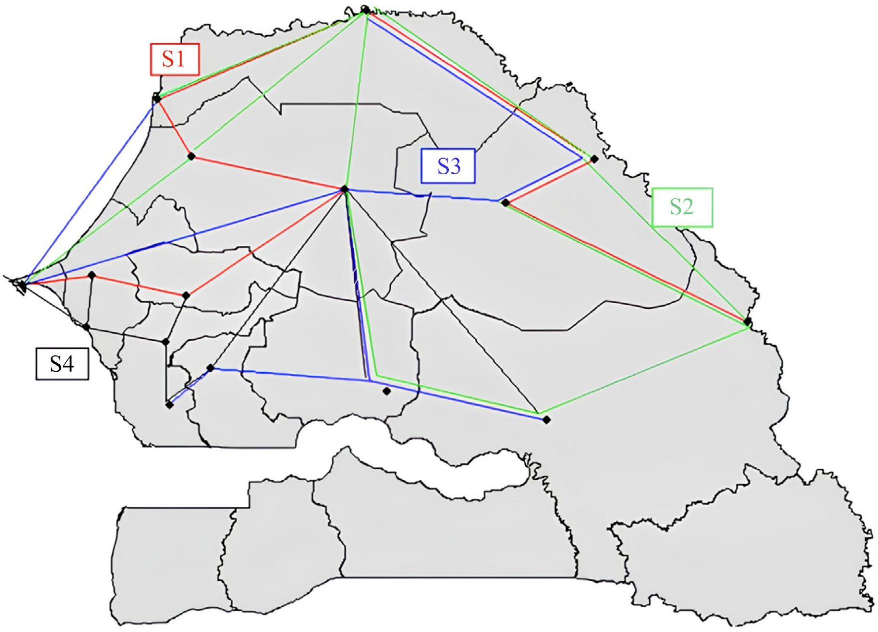

Figure 1. Observation project located on the map (1/200,000) of Senegal. * S1, S2, S3, and S4 correspond to the first, second, third, and fourth GNSS observation sessions, respectively.

To ensure that sufficient observation time was available at each point for PPP calculation with correct ambiguity resolution, but also to ensure that the reference frame could be calculated differentially by block calculation, we established an observation plan taking these two types of strategy into account. To this end, in addition to the minimum observation time required for PPP and differential calculations according to the baselines, certain criteria necessary for establishing a high-quality geodetic reference frame, such as baseline redundancy, closed geometric shapes for closure calculations, session durations (6 hours on average), were taken into account with the four observation sessions established (**Figure 1**).

This observation project (**Figure 1** and Equation (1)), with the duration set for each session, was therefore expected to be completed in four days according to our forecasts. Applying the empirical formula for calculating the redundancy factor (f_r), we found (with $r = 10$; $j = 4$; $s = 1$ and $n = 16$) a value of f_r for our observation project equal to 2.4, which is higher than the minimum value of 2 proposed by Duquenne *et al.* (2005) for such a reference frame.

The equation giving the value of f_r is defined as follows [12]:

$$f_r = \frac{(r-1)s * j}{n-1} \tag{1}$$

where:

- r, the number of receivers used;
- s, the number of sessions per day;
- n, the total number of parking spots;
- j, the number of days.

Specific control procedures were adopted throughout the observation phase so that any errors could be detected and corrected. For example, antenna height measurements were taken at the beginning and end of each session, and the tape measure was photographed for each measurement so that an independent check could be carried out afterwards. After checking, no errors in antenna height measurement were noted.

Observations were made day and night, depending on the start time of the session. The observation time for each session averaged six hours (6 h), with points observed continuously for up to 72 h and others re-observed with a new station setting, so a new centering of the antenna on a tripod (for certain points). The baselines formed by the four sessions ranged from 52 to 238 km. For each session, the antennas maintained the same orientation (antenna height measurement face) towards the north in order to eliminate antenna phase center errors in differential calculations (a principle replaced by the use of antenna calibration files in PPP calculations).

The observation campaign went well overall, with no incidents (Table 1).

Table 1. Summary of the GNSS observation campaign.

Registration numbers	Locations	Sessions	Duration of observations	Comments
RS.1	Dakar	S.1; S.2; S.3; S.4	98 h	Data from the IGS network's permanent station (DAKR) can be used for the calculation. However, point RS01 (the first point in the current network) was observed almost continuously throughout the four sessions (with a short interruption on 28/03 between 6:02 p.m. and 6:07 p.m.) for overall network control.
RS.2	Thiès	S.1; S.4	7 h/14 h	Point observed over two non-consecutive sessions with two different teams.
RS.3	Diourbel	S.1; S.4	7 h/13 h	Point observed over two non-consecutive sessions with two different teams.
RS.5	Louga	S.1; S.2	31 h	Point observed continuously from the start of session S1 until the end of session S2.
RS.4	Linguère	S.1; S.2; S.3; S.4	94 h	Point observed continuously throughout the observation campaign. There was a brief interruption in recordings on March 31 between 12:57 p.m. and 1:02 p.m. because the receiver was turned off when the operator wanted to change one of the batteries.
RS.6	Saint-Louis	S.1; S.2; S.3	58 h	Light rain noted during the night of March 29 to 30. No other incidents.
RS.7	Podor	S.1; S.2; S.3	55 h	
RS.8	Ouro-Sogui	S.1; S.2; S.3	56 h	Presence of two trees 8 m and 3 m from the point.
RS.9	**Ranérou**	S.1; S.2; S.3	56 h	Point observed continuously for the first three sessions. There was a brief interruption in recordings on 03/30 between 12:59 p.m. and 1:01 p.m. due to the receiver being turned off. Light rain was also noted on March 29.

Continued

RS.10	Kidira	S.1; S.2; S.4	32 h	
RS.11	Tamba	S.2; S.3; S.4	69 h	Point observed continuously for the last three sessions. There was a brief interruption in recordings on March 30 between 6:54 p.m. and 7:12 p.m. because the receiver was turned off when the operator wanted to change one of the batteries.
RS.18	Koungheul	S.2; S.3; S.4	6 h/8 h/6 h	Point reoccupied at each new session because the site is not secure enough to allow continuous observations between sessions.
RS.17	Kaolack	S.3; S.4	25 h	Presence of two buildings 20 and 28 m from the point.
RS.16	Sokone	S.3; S.4	45 h	
RS.19	Fatick	S.4	6 h	
RS.20	Mbour	S.4	14 h	

The **PDOP**s obtained throughout the observations ranged from **0.8** to **1.1** and the number of satellites from **19 to 32**, which was very satisfactory.

An observation rate of **30 seconds** and a cut-off angle of **0˚** were chosen for all sessions. The processing was designed to eliminate satellites that did not provide good signal quality if necessary and to introduce an appropriate cut-off angle depending on the type of software in order to eliminate low-elevation signals.

2.2. Presentation of Processing and Referencing Tools

In this study, various GNSS processing tools were used. These included the CSRS-PPP tool for PPP calculations, the GAMIT/GLOBK scientific software, and the AUSPOS online calculation tool for double difference calculations.

2.2.1. PPP Solutions

CSRS-PPP is an online PPP calculation tool (with a command line software version) developed by Natural Resources Canada (NRCan) in 2003 [13]. It can process both GPS and GLONASS observations (single-frequency or dual-frequency) in static and kinematic PPP modes. The CSRS-PPP uses IGS or NRCan orbit, clock, and satellite bias corrections calculated from a global network of permanent GNSS stations to obtain the exact positions of users anywhere in the world [14]. The calculations performed by CSRS-PPP (version 3) now provide solutions with PPP ambiguity resolution (PPP-AR) for data collected after January, 2018 (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp). This new version allows for faster convergence of solutions and multi-GNSS processing. The CSRS-PPP indicates that horizontal and vertical accuracies of 1 cm and 2 cm (68% confidence level), respectively, can be obtained using dual-frequency static data [15]. Station coordinates are calculated in the reference system of the orbits/clocks used based on the date of the observations (ITRF) or in the North American geodetic system (NAD83) at the time chosen by the user. As part of this study, calculations using CSRS-PPP for all points were performed in static mode for an elevation angle of 7.5˚, using VMF for tropospheric corrections and an OTL model for oceanic overload effects. GNSS processing (using GPS and GLONASS constellations) for all points was thus performed using IGS precise orbits and clocks, and IGS and NRCan antenna calibration files (igs14_2045_nrcan.atx).

After submitting the RINEX format observation file for each point, a compressed folder containing the files from the CSRS was retrieved by email:

- CSRS-PPP service calculation report with observation metadata (RINEX file header data, ACP (Antenna Center Phase) offsets on the different carriers, observation rejection percentages, estimated coordinates and associated accuracies, etc.) for each point. Figures on the geometry and trajectories of the satellites used, phase and pseudo-range noise, clock offsets, ambiguity resolution percentages for each satellite, etc. are also included in the file;
- .sum file containing parameters (orbits, clocks, oceanic and tropospheric overloads, etc.) and results (estimated coordinates and the a priori coordinates used in the calculation);
- .pos file containing the positions of the point at each observation epoch with GDOP, RMS on code and phase measurements, and estimates of zenith tropospheric delays and receiver clock delays;
- .csv file containing the geographic coordinates and clock information for each epoch;
- A .txt file describing the files contained in the compressed folder described above.

2.2.2. Software for Relative Positioning (DD)

To better evaluate the quality of our PPP calculations and see how these solutions perform compared to differential solutions (networked and independent), we used the advanced processing software GAMIT/GLOBK and the online differential processing tool AUSPOS to calculate our differential network. GAMIT/GLOBK was chosen for its proven performance in advanced differential calculations, and AUSPOS was chosen for its simplicity as an online tool requiring virtually no user prerequisites, unlike GAMIT/GLOBK.

AUSPOS is a free online dual-frequency GPS data processing service provided by Geoscience Australia. Static dual-frequency GPS data can be submitted and is processed differentially only.

When a RINEX format data file is submitted, a star calculation is performed between the station and the 15 nearest IGS and APREF (Asia-Pacific Reference Frame) reference stations using the BERNESE scientific software from the University of Bern in Switzerland. It uses double differences to determine accurate solutions [16]. It can perform calculations for any station on the Earth's surface by expressing its coordinates in the latest version of the ITRF at the time of observation and in the Australian terrestrial reference system (GDA94) for users in Australia. AUSPOS uses external IGS products (ultra-fast, fast, and precise orbits) in GPS data processing.

The effects of observation error sources, such as clock offsets, the troposphere, and the ionosphere, are taken into account by default by the tool thanks to the models used and the estimation of associated parameters [16].

GAMIT/GLOBK is a software suite for calculating GNSS data accuracy developed by MIT from a collection of phase data processing programs whose initial purpose was to study the deformation of the Earth's crust. These programs are the result of collaboration between a number of institutions (Massachusetts Institute of Technology, Scripps Institution of Oceanography, Harvard University, and the Australian National University) with the assistance of the National Science Foundation for the analysis of GPS measurements.

Various parameters can be determined by the software (satellite orbits, atmospheric zenith delays, and Earth orientation parameters) (http://geoweb.mit.edu/gg/), designed to run on Linux, which will be used to determine relative coordinates, materializing floating positions. The software uses the least squares method to calculate the solution.

The GLOBK suite uses a Kalman filter to fix the relative floating solutions provided by GAMIT in a global reference system such as the ITRF and, if necessary, the displacement velocities of stations in a network with time series.

GAMIT/GLOBK is one of the world's leading scientific software packages for differential GNSS processing used in geodetic reference frame calculations and other applications, similar to the BERNESE software.

For example, it was used to process observations in 1993 and then in 1998 during the implementation of the first precision GPS reference frame in the Alpes Occidentales Western Alps (http://www.geologie.ens.fr/~vigny/gps-alpes-f.html). In this study, versions 10.71 for GAMIT and 5.34 for GLOBK were used for the calculation and connection of the differential reference frame.

2.2.3. Reference Setting

In this study, the coordinates of the various points were estimated in ITRF2014 at the time of observation (2019.2), which differs from the implementation of ITRF and the epoch used to reference the RRS04 realization, namely ITRF2000, epoch 2004.5. Another reference was therefore required to assess the level of agreement between our PPP solutions and the coordinates of the points calculated in 2004. This new reference for the ITRF2014@2019.2 to the ITRF2000@2004.5 is first based on a change of epoch (2019.2 → 2004.5), followed by a change of reference point using a Helmert 3D transformation (ITRF2014 → ITRF2000). However, this epoch change requires the use of an appropriate velocity model to apply adequate displacement velocities for the stations in the coordinate transformation calculations.

The coordinate transformation from the observation epoch (2019.2), which we call epoch t_1, to the 2004 coordinate epoch (2004.5), which we call epoch t_0, can be defined as follows:

$$X_0 = X_1 - \left(t_1 - t_0\right) * V \tag{2}$$

where:

$$X_1 = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{2019.2} \quad ; \quad X_0 = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{2004.5} \quad ; \quad V = \begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix}$$

The transition from ITRF2014 to ITRF2000 at epoch 2004.5 consists of performing a 7 parameters Helmert transformation ($T_X, T_Y, T_Z, D, R_X, R_Y, R_Z$). These parameters are defined by three translations, three rotations, and a scale factor. The transformation parameters from ITRF2014@2010.0 to older versions of ITRF are available on the ITRF website (https://itrf.ign.fr/).

The ITRF2000 coordinates of the stations can therefore be obtained using the following Helmert equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\text{ITRF2000@2004.5}} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\text{ITRF2014@2004.5}} + \begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} + \begin{pmatrix} D & -R_Z & R_Y \\ R_Z & D & -R_X \\ -R_Y & R_X & D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\text{ITRF2014@2004.5}} \tag{3}$$

For the various transformation calculations, we used the EPN website (http://www.epncb.oma.be/_productsservices/coord_trans). This online tool allows you to calculate the coordinates corresponding to the ITRS realization (for a given realization and time period) of a point (or list of points) entered by the user, based on a set of Cartesian coordinates (X, Y, Z) and associated velocities (for a given realization and epoch) of a point (or list of points) entered by the user, to calculate the coordinates corresponding to the ITRS realization (or EUREF for Europe) and the epoch chosen by the user. This reference calculation therefore requires a model of displacement velocities that are sometimes neither homogeneous nor linear in order to apply the epoch change. The products provided by the IGS include the velocities of the IGS network stations and velocity models calculated from the velocities of the various stations that make up the ITRF. This shows that the quality of the attachment of a geodetic system using these types of products could depend heavily on the number and distribution of IGS stations available on the plate concerned in general and in the coverage area of the geodetic reference frame in particular, with possible intra-plate movements. However, we have noted that, for the IGS, there is only one station (DAKR) in the far west of Senegal and a fairly limited number of CORS throughout Africa. Although the influence of this observation may not be significant, given that this part of the African plate, known as the West African craton, has long been considered geologically stable [17], we nevertheless took an interest in another velocity model, namely the Global Strain Rate Model (GSRM V2.1). More recent studies combining seismic, geological, geodetic, and other data have shown intraplate movements on the two large Nubian and Somali subplates that define the African plate, ranging from 0.16 mm/year to 0.40 mm/year, for example on the western part of the plate [18] and [19]. This GSRM V2.1 model is based on geodetic data from IGS CORS (ITRF2014) and other GNSS stations located in several countries and not integrated into the IGS network, as well as on a few geological estimates made on certain plates. However, stations for which variations appear to be related to post-seismic or temporary movements are always excluded so as not to influence the estimated plate velocities [20].

These different data sources mean that the GSRM model takes more data into account than the ITRF. Unfortunately for Africa, we do not have as much data as for other plates, but slightly more stations have been listed for this model than those used for the ITRF2014 model (**Figure 2**).

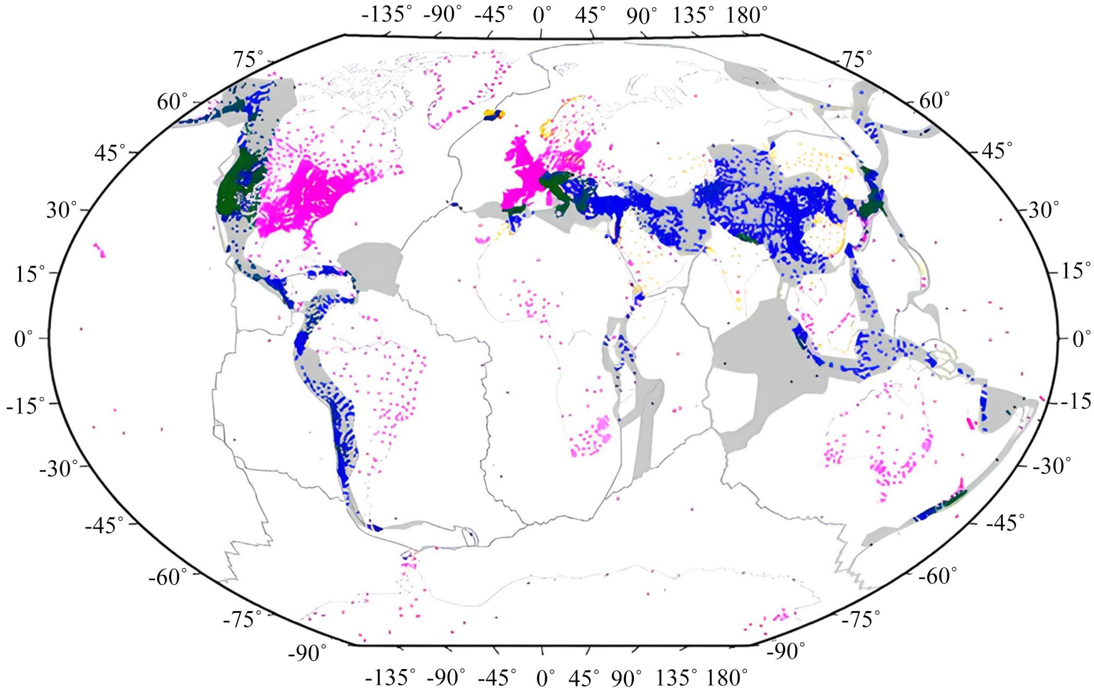

Figure 2. Distribution of measurements used for the GSRM V2.1 model [20].

The gray shading is the outline of all areas likely to deform. The white areas include 50 plates assumed to be rigid. The purple and green dots correspond to GNSS stations on rigid plates or in deforming areas, respectively, for which a velocity has been derived. The yellow and blue points correspond to GNSS stations on rigid plates or in deforming areas, respectively, for which velocities from other sources were used.

By superimposing the ITRF2014 and GSRM V2.1 models with the ITRF2020 velocity of the DAKR station applied to all points, and considering the inter-plate displacements on this section to be zero, we observe average differences of 0.3 mm/year between the ITRF solutions and 1.4 mm/year between the two models (**Figure 3**). This allowed us to choose the GSRM V2.1 model for the reference calculation, as it takes into account more data than the ITRF models and should therefore better represent the movements of continental plates. With this GSRM V2.1 model, the velocity of each point on the X, Y, and Z components was interpolated from the GSRM V2.1 grid. This reference calculation made it possible to estimate the coordinates of the network points in ITRF2000, at the time 2004.5.

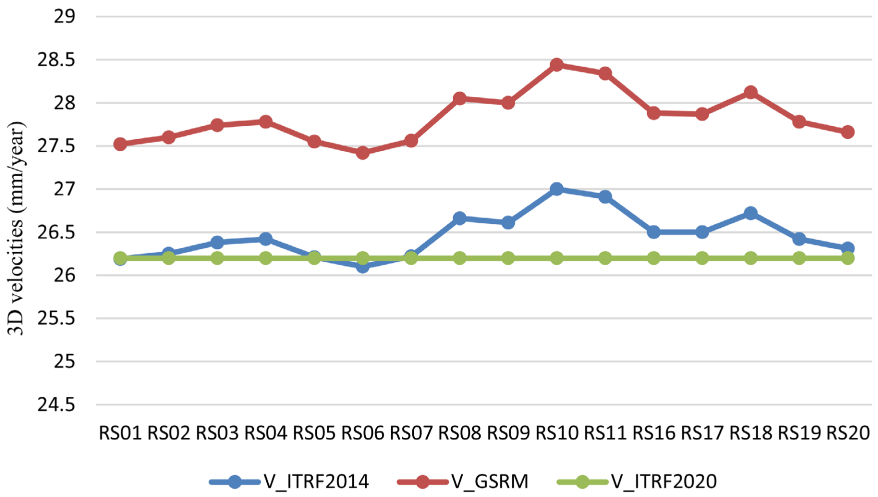

Figure 3. Absolute 3D velocities of the different points in the network.

3. Results

The quality of the GNSS observations was also verified using the TEQC software developed by UNAVCO in the United States.

TEQC made it possible, for each observation file, to verify the number of satellites used for each constellation, the number of epochs, observations below and above 10˚ elevation angle made in relation to predictions, multipaths, the number of rejected observations, etc.

In analyzing the results obtained in PPP and the calculation parameters used with the CSRS-PPP tool, the first two files provided are the most important and allowed us to verify the quality of the results for each point with formal standard deviations (Table 2), measurement noise, the percentage of rejected observations, and the level of ambiguity resolution.

Table 2. A posteriori precision of PPP solutions.

Points	$\sigma_\lambda\,(\mathrm{m})$	$\sigma_\varphi\,(\mathrm{m})$	$\sigma_h\,(\mathrm{m})$	Percentage of observations rejected (%)
RS01	0.004	0.008	0.015	0
RS02	0.006	0.015	0.031	0
RS03	0.006	0.012	0.026	12.93
RS04	0.006	0.013	0.024	0
RS05	0.006	0.012	0.025	0
RS06	0.005	0.011	0.022	0
RS07	0.005	0.011	0.019	0
RS08	0.005	0.013	0.023	0
RS09	0.005	0.010	0.020	0
RS10	0.005	0.011	0.023	0

Continued

RS11	0.004	0.006	0.017	0
RS16	0.005	0.009	0.021	0
RS17	0.007	0.019	0.028	0
RS18	0.003	0.009	0.016	0
RS19	0.006	0.011	0.025	0
RS20	0.005	0.009	0.022	0
Averages	**0.005**	**0.011**	**0.022**	
Standard deviations	**0.001**	**0.003**	**0.004**	

These formal errors (**Table 2**) show an average of 12 mm in planimetry and 22 mm in altimetry, with a maximum value in planimetry (on the component φ) of 19 mm (RS17) and a maximum value on the vertical component of 31 mm at point RS02.

These formal errors have standard deviations averaging less than 5 mm on the three components (E, N, h), which shows a low dispersion in the planimetric and altimetric accuracies obtained on the different points and, consequently, an accuracy that can be considered satisfactory for these calculations concerning the different points. These standard deviations are therefore in line with the performance of the tool demonstrated in numerous research studies [16] [21]-[24].

A second check was carried out on the three points (RS02, RS03, RS18) that were reoccupied during the observation campaign, although reoccupation of all points is still recommended if conditions allow. The solutions obtained at each point were compared to verify their level of agreement and any problems with stationing or antenna height measurements. The deviations obtained are almost all satisfactory, except for the deviation of 48 mm on point RS02, which is certainly linked to an error in the antenna height measurement by one of the teams that observed this point (**Table 3**).

Table 3. Differences in coordinates obtained by PPP for the reoccupied points.

Reoccupied points	Observation day	ΔE (m)	ΔN (m)	Δh (m)
RS02	087 090	0.000	0.011	0.048
RS03	087 090	0.027	−0.008	0.007
RS18	088 089	−0.002	0.004	−0.004

The reference established using the two velocity models provided coordinates in ITRF2000@2004.5, which were compared with the official coordinates calculated in ITRF2000 in 2004 for the same epoch (Table 4).

Table 4. Differences between RRS04 coordinates (ITRF2000, epoch 20004.5) and transformed coordinates (CSRS-PPP).

	Differences calculated using the GSRM v2.1 velocity model			
	Δ*E* (m)	Δ*N* (m)	Δ*h* (m)	RMS
RS01	−0.074	0.006	0.07	**0.102**
RS02	−0.064	0.003	0.026	**0.069**
RS03	−0.059	−0.007	0.10	**0.116**
RS04	−0.053	−0.007	0.061	**0.081**
RS05	−0.071	−0.006	0.082	**0.108**
RS06	−0.061	−0.009	0.03	**0.069**
RS07	−0.06	−0.028	0.059	**0.088**
RS08	−0.046	−0.039	0.168	**0.178**
RS09	−0.042	−0.003	0.066	**0.078**
RS11	−0.088	0	0.077	**0.117**
RS16	−0.143	−0.041	−0.032	**0.152**
RS17	−0.039	0.01	0.234	**0.237**
RS18	−0.062	−0.001	0.085	**0.105**
RS19	−0.076	0.008	0.097	**0.123**
RS20	−0.071	0.01	0.083	**0.110**
Averages	**0.067**	**0.012**	**0.085**	
Standard deviations	**0.025**	**0.013**	**0.054**	

We can note, with the calculations performed using the GSRM velocity model, a fairly similar trend with differences between the PPP solutions linked to ITRF2000, epoch 2004.5, and the 2004 solutions (RRS04) that vary for the E component between 4 and 9 cm (except for point RS16 with a deviation of 14 cm), for the N component, even smaller deviations across all points, varying between 0 mm and 4 cm (in RS16), and for the vertical component h, the deviations vary between 3 cm and 10 cm (except for points RS16 and RS17 with respective deviations of 17 cm and 23 cm). An average deviation of 7 cm, 1 cm, and 9 cm was obtained for these three components, respectively, with respective standard deviations of 25 mm, 13 mm, and 54 mm. These deviations resulted in RMS of the three-dimensional positions calculated in PPP attached to RRS04 with this GSRM model, which vary between 7 cm (in RS06) and 24 cm (in RS17). These high values can also be explained by the significant deviations noted on the E and h components.

We can therefore note that the deviations between the PPP solutions attached to ITRF2000, epoch 2004.5, and the RRS04 solutions are relatively large, generally smaller in N and much larger (>6 cm) on the E and vertical components (**Table 4**). Point RS16 shows a significant deviation in planimetry on the E component of approximately 15 cm, as do points RS08 and RS17 on the h component. The deviations on the latter point could be justified by the fact that it was rebuilt in 2008 when the second-order control points network was set up.

4. Discussion

The significant average 3D deviations of around 11 cm obtained (between the PPP solution and the official 2004 coordinates) could be linked to the following hypotheses.

1) A problem with the 2019 observation campaign (errors in antenna height measurements, station setup, etc.), which seems unlikely as it would affect most teams at this time, even though rigorous methods have been adopted for independent checks with verifications on the completed observation sheets and photos taken before processing. If such a hypothesis is confirmed, it should also be reflected in the differential calculation. Some large discrepancies obtained on certain points (RS16 and RS08) could be related to the displacement of the point, a station setting error, or a problem with the homogeneity of the RRS04. Repeating the observations on these points would make it possible to locate the source of these discrepancies.

2) Poor quality of the velocity models used for Africa, which would lead to larger errors with significant differences between epochs. This hypothesis does not seem to justify the discrepancies obtained, given the discrepancies noted at point RS01 (10 m from DAKR), which follow the overall trend, and the quality of the solutions provided by the IGS. Only velocities 3 to 4 times higher could explain these discrepancies, which seems unlikely. Using, for example, typical GSRM speed uncertainties of ~1 to 2 mm/year over 15 years, we also find that speed modeling alone cannot plausibly explain shifts of 10 to 20 cm.

3) Difficulties in the conduct and processing of the 2004 GNSS observation campaign contributed to a lack of homogeneity in the RRS04 reference frame and/or an imprecise connection to ITRF2000.

4) PPP calculations would be limited in terms of accuracy, which would mean errors of more than 6 cm for more than 6 hours of PPP observations. Such an assumption would contradict the current state of the art in PPP and the accuracy indicators in the calculation report provided by the CSRS-PPP. It would also mean a discrepancy between the solutions obtained and those resulting from a differential calculation using the same observations.

In order to better identify the problem or the causes of such discrepancies, a PPP calculation using only the 2004 observations from point RS01 was performed with the same tool. After investigation, only the raw data from this RS01 point from the 2004 observations were still available. This point had also been used in 2004 for the attachment of the RRS04 (from five IGS stations) and the referencing of the nineteen (19) other points in the reference frame.

The differences in E and N between the PPP treatments from the two observation campaigns in 2004 and 2019 (less than 3 cm) show a concordance between the 2004 and 2019 observations (**Table 5**), which allows us to rule out hypothesis 4 even if only one point is concerned. They also seem to show that the velocity models used allow for a certain level of quality that can be considered satisfactory for such planimetric reference frame (a comparison of the altimetric component is not possible). However, it should also be noted that this calculation does not suffer from velocity extrapolation problems, given that point RS01 is less than 10 m from the DAKR station, whose velocity are determined in the ITRF solutions.

Table 5. Comparison between the PPP solution from the 2004 observations and those from 2019 on RS01 (top) and between the PPP solution from the 2004 observations and the official coordinates calculated at the time (bottom).

RS01	ΔE (m)	ΔN (m)
2004 PPP reprocessing vs. 2019 PPP processing	0.026	0.01
2004 PPP restatement vs. 2004 RRS04 calculation	0.064	0.01

On the other hand, the differences between the PPP solution from the 2004 observations and the RRS04 coordinates of point RS01 (6.4 cm in E and 1.4 cm in N) are similar to the biases obtained with the GSRM model (**Table 4**), which tends to confirm hypothesis 3.

These results thus indicate possible systematic shifts in certain parts of RRS04, particularly near RS01, suggesting that the original campaign and adjustment may not have fully taken into account the definition of ITRF2000.

In order to reinforce our conclusions on the invalidity of hypothesis 4 (inaccurate or false PPP calculations), differential calculations were also performed with AUSPOS and then GAMIT/GLOBK, using the 2019 observations (**Table 5**).

After running the calculations for the observations of the different points on AUSPOS, the coordinates obtained in ITRF2014 at the time of the observations were compared with the solutions provided by CSRS-PPP for the same points (**Figure 4** and **Table 6**).

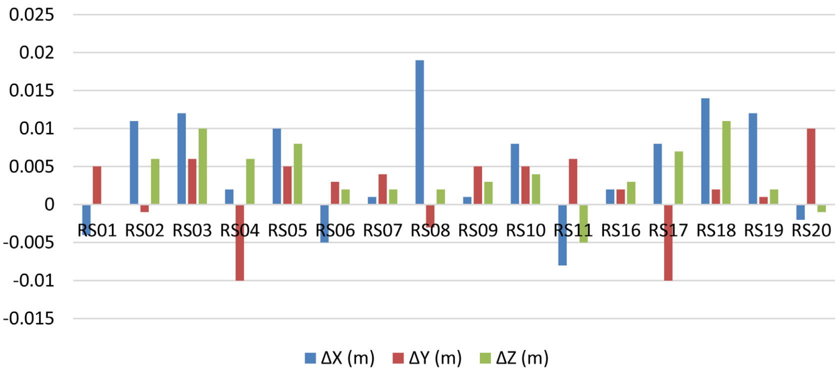

Figure 4. Differences between coordinates provided by AUSPOS and CSRS-PPP at the time of the observations.

Table 6. Differences between AUSPOS and SCRS-PPP solutions.

Points	ΔX	ΔY	ΔZ	RMS
RS01	−0.004	0.005	0	**0.006**
RS02	0.011	−0.001	0.006	**0.013**
RS03	0.012	0.006	0.01	**0.017**
RS04	0.002	−0.01	0.006	**0.012**
RS05	0.01	0.005	0.008	**0.014**
RS06	−0.005	0.003	0.002	**0.006**
RS07	0.001	0.004	0.002	**0.005**
RS08	0.019	−0.003	0.002	**0.019**
RS09	0.001	0.005	0.003	**0.006**
RS10	0.008	0.005	0.004	**0.010**
RS11	−0.008	0.006	−0.005	**0.011**
RS16	0.002	0.002	0.003	**0.004**
RS17	0.008	−0.01	0.007	**0.015**
RS18	0.014	0.002	0.011	**0.018**
RS19	0.012	0.001	0.002	**0.012**
RS20	−0.002	0.01	−0.001	**0.01**
Averages	**0.007**	**0.005**	**0.005**	
Standard deviations	**0.005**	**0.003**	**0.003**	

Referring to Figure 4 and Table 6, we see that the solutions obtained from the differential calculation with AUSPOS converge towards the PPP solutions of the CSRS-PPP to within 2 cm in X, Y, and Z. Average deviations of 7 mm in X and 5 mm in Y and Z were obtained with respective standard deviations of 5 mm and 3 mm.

For the calculation and reference with GAMIT/GLOBK, twenty-four IGS stations with good geometric distribution around our reference frame were used (Figure 5).

It should be noted that, unlike the referencing approach used in the calculation of RRS04, the quality of the referencing of a GNSS point network is higher when the distribution of reference stations (in this case, those of the IGS) is dense and balanced. However, reference stations that are poorly distributed geometrically can lead to significant errors [25].

The final coordinates of the field points derived from the network solution adjusted after calculation with GLOBK (for the combination of GAMIT solutions from days 087 to 091) were compared with the coordinates provided by the CSRS-PPP tool (Figure 6 and Table 7).

Figure 5. Distribution of IGS CORS used for referencing with the GAMIT/GLOBK suite.

Table 7. Differences between GAMIT/GLOBK and SCRS-PPP solutions.

Points	ΔX (m)	ΔY (m)	ΔZ (m)	RMS (m)
RS01	0.009	0.014	−0.006	0.018
RS02	0.008	0.015	−0.003	0.017
RS03	−0.001	0.014	−0.012	0.018
RS04	0.02	0.017	−0.003	0.026
RS05	0.018	0.007	−0.003	0.020
RS06	0.021	0.012	−0.002	0.024
RS07	0.018	0.01	−0.003	0.021
RS08	0.001	0.016	−0.004	0.017
RS09	0.014	0.01	−0.003	0.017
RS10	0.01	0.012	−0.004	0.016
RS11	0.01	0.013	−0.002	0.017
RS16	0.009	0.018	−0.003	0.020
RS17	0.024	0.018	−0.003	0.030
RS18	0.005	0.016	−0.002	0.017
RS19	0.004	0.016	−0.005	0.017
RS20	0.01	0.009	−0.002	0.014
Averages	**0.011**	**0.014**	**0.004**	
Standard deviations	**0.007**	**0.003**	**0.002**	

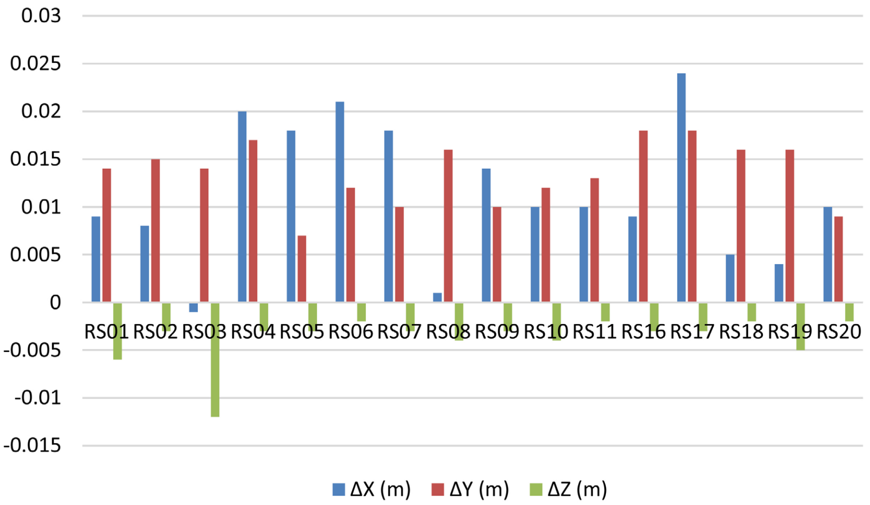

Figure 6. Differences between GAMIT/GLOBK and CSRS-PPP solutions (ITRF2014, epoch 2019.2).

The **CSRS-PPP** and **GAMIT/GLOBK** tools show average deviations in their X, Y, and Z solutions of 1.1 cm, 1.4 cm, and 0.4 cm, respectively. Relatively larger deviations were also noted on the X component, with a maximum deviation of 2.4 cm on point RS17, which has the maximum **RMS** on the three-dimensional positions of the points of 3 cm (**Figure 6**). The standard deviation of a few millimeters on each of the three components also shows the satisfactory level of consistency noted between the solutions obtained from the PPP calculation with CSRS-PPP and the differential solution obtained with GAMIT/GLOBK, even though the deviations obtained with AUSPOS remain relatively slightly lower.

These results allow us to definitively rule out hypothesis 4 and to consider hypothesis 3, relating to a problem of consistency and quality of the 2004 reference frame connection, as justifying the deviations obtained in relation to the 2019 reference.

5. Conclusion and Outlook

The results of this study have shown that it is now possible to establish, control, maintain, or densify a modern geodetic reference frame using precise GNSS positioning. Due to the simplicity of the technique and the relatively manageable resources required, this would be a real opportunity for countries without a modern geodetic reference frame in line with modern positioning techniques, or with a poorly densified, poorly maintained, or decades-old network.

PPP calculations yielded results consistent with deviations (after transformation) from the RRS04 coordinates averaging approximately 7 cm in E, 8 cm in h, and less than 2 cm in N. Although certain factors (inconsistencies in antenna calibration, shortcomings in tropospheric modeling, inaccurate modeling of ocean load, uncertainty in the velocity model in Africa, scarcity of IGS GNSS stations in Africa) could explain these large deviations in the E and particularly h components, a repeat of the observation campaign (at a minimum on a few points) or access to all of the 2004 observation data for new PPP calculations would provide more certainty about the causes of such discrepancies. However, it should be noted that the generalization of these discrepancies across all points (a kind of bias) and the consistency of the PPP solutions with the solutions obtained from advanced differential processing with AUSPOS and GAMIT/GLOBK make a problem with the 2019 observations less likely.

In this study, we were also able to show the possibility of using the velocities of a single station on this part of the African plate to connect our different points in the RRS04. However, one question remains: to what extent (accuracy, distances from other points, level of stability of the area, etc.) can such an approach be applied?

The performance of PPP also allows it to make a real contribution to numerous geodetic studies and projects, such as the establishment and maintenance of a modern geodetic reference frame, the connection of traditional networks, and the determination of the displacement velocities of stations or geodetic markers.

To this end, the results obtained in this study have enabled us to evaluate the contribution of PPP in the context of PPP GNSS observations for the establishment and maintenance of the Senegalese geodetic reference frame and in the context of the connection of traditional reference frames outside Senegal using PPP.

- **Organization of a PPP observation campaign for the establishment and maintenance of a geodetic reference frame: the case of RRS04**

In the case of the establishment and maintenance of the Senegalese geodetic reference frame, if we consider that observations must be made exclusively within the framework of ***PPP*** processing on the same points, then a different, adapted plan for our observation campaign could be drawn up. For example, two scenarios would have been possible for us: a first scenario involving only two teams for the observation campaign and a second scenario without a specific budget, with an observation campaign carried out gradually by the teams of the Directorate of Geographical and Cartographic Works (DTGC) in charge of geodetic infrastructure in Senegal and its partners. However, it should be noted that the state of the art in PPP [6] [26]-[28] shows a good level of convergence between PPP solutions and differential solutions after 4 hours of observations or even after just 1 hour of observations (using the CSRS-PPP tool). This is why we believe that a 6-hour observation period will be more than sufficient to guarantee PPP solutions of a quality equivalent to that of solutions obtained by differential calculations, as shown in this study.

First scenario: Two teams of two (operator and driver) would be formed. The first team (***EP1***) would start at point RS01 in Dakar, passing through Mbour to Kidira to observe points (**RS20, RS19, RS16, RS17, RS18, RS11, RS10**). The second team (***EP2***) would leave from point RS02 in Thiès, passing through Diourbel to Saint-Louis and Louga to observe points ***RS03***, ***RS04***, ***RS09***, ***RS08***, ***RS07***, ***RS06***, and ***RS05*** (**Figure 7** and **Table 8**). The estimated time to complete this work (including travel) is five days. Some points may be revisited and observed again when the teams return, with observation times of two to three hours for verification purposes, for example.

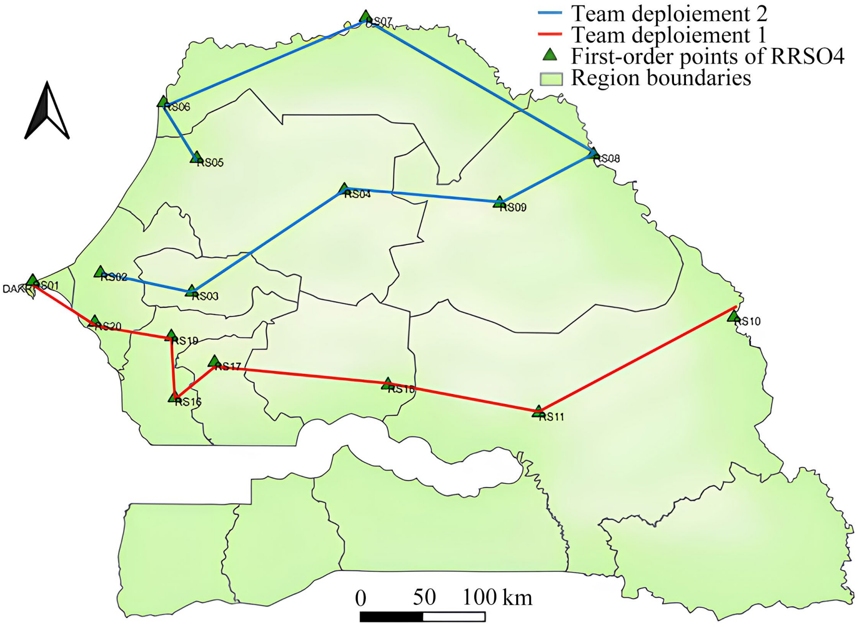

Figure 7. Deployment scenario for two teams for PPP observations.

Table 8. Schedule for 6-hour observations in PPP, taking into account distances and travel time.

	Points observed by EP1	Points observed by EP2
Day	RS01 and RS02	RS02 and RS03
Day 2	RS19 and RS16	RS04
Day 3	RS17 and RS18	RS09 and RS08
Day 4	RS19	RS07
Day 5	RS10	RS06 and RS05

This scenario will require fewer resources than those needed to deploy teams to make observations at the same differential points, as shown in **Table 9**.

Table 9. Differences noted between the differential observation campaigns carried out and the PPP projected on our network.

Required	Differential	PPP
Vehicle	5	2
GNSS receiver	10	2
People involved	20	4
Team	10	2

Continued

Team support	45,000 CFA francs/day	45,000 CFA francs/day
Duration	4 days	5 days
Risk of having to repeat observations due to a problem with a team	Real	None
Estimated costs (excluding the cost of receivers)	**5,600,000 CFA francs**	**1,600,000 CFA francs**

Estimating the cost of renting a vehicle per day at 40,000 CFA francs and that of a GNSS receiver at 75,000 CFA francs (this cost was 100,000 CFA francs in 2018), we can estimate the budget required (*deliberately omitting certain common expenses such as fuel and the non-purchase of vehicles and GNSS receivers*) for the differential observation campaign at **5,600,000 CFA francs** and that for PPP observations at **1,600,000 CFA francs**. This shows that the PPP observation campaign, in addition to the risk of wasted time and/or much less likely observation resumption, in addition to the very optimal deployment that has been defined, **would cost more than three times less** (see four times less with a higher differential redundancy factor) than differential positioning.

Second scenario: In collaboration with the Land Registry Department and the Department of Geographic and Cartographic Works (DTGC), equivalent to national geographic institutes in some countries, ask a surveyor chosen from each land registry office for which we have one or more points in our network in its coverage area to make ***PPP*** observations with suitable ***GNSS*** antennas according to a protocol and instructions that will be sent to them. These observations will be repeated at least once on a different day and, if possible, by a different operator in order to independently check each of the points. If it is not possible to meet with the operators with the field observations (which will not be necessary), virtual meetings can be organized with them to ensure that they understand the work to be done, the instructions given, the information provided in the observation protocol, etc.

We note that this scenario, unlike the first one and the differential GNSS observation campaign, will not require any specific budget.

- **Reliability of traditional reference frames outside Senegal using PPP**

Regarding the connection of traditional reference frames outside Senegal via PPP, the results obtained lead us to believe that PPP, due to its simplicity and performance, could facilitate the connection of traditional geodetic reference systems that are still in use in certain countries that do not yet have a modern reference frame, as well as in countries that have modern geodetic reference frames connected to the ITRF but still coexisting with a few local reference frames. Indeed, the technical and financial requirements involved in setting up modern geodetic reference frames generally delay their implementation in certain developing countries. The flexibility of PPP positioning and calculation techniques, combined with the other advantages mentioned above, could make it possible to eradicate local geodetic frame that still serve as official reference frames in certain countries such as Gabon and Congo.

To this end, we propose two approaches for making such connections, the quality of the results of which will depend on the accuracy of the old reference frames, the observations, and the velocity model used.

- For countries that do not have modern three-dimensional reference frames, re-observe the old geodetic points (as many as possible) for PPP processing with ITRF2014 or ITRF2020 solutions, referencing the time of the first observations. Then calculate the transformation parameters (similarity, polynomial, grid, etc.) between this new three-dimensional network and the old networks in order to obtain a transformation. For future PPP work, these can then be brought back into the national reference by first applying a simple epoch change with a precise velocity model and then applying the transformation. The challenge will remain to ensure that such a velocity model is available or to assess the validity or otherwise of using the velocity of a single point.
- For countries where a modern national three-dimensional reference frame coexists with local frame, some points of the modern network can be observed in PPP. The PPP processing of these observed points will be followed by a linking of the solutions obtained in ITRF2020 to the current national three-dimensional reference frame. This operation will make it possible to estimate the average deviations ("bias") between the PPP solutions linked to the national reference frame and the official reference coordinates of the points. It may also involve calculating transformation parameters (recommended) between the PPP solutions (ITRF2020 at present, at the time of the observations) and the national frame. It will then be possible to observe a few old points (from the local network(s)) in PPP to obtain their positions in the PPP reference frame (currently ITRF2020), before applying the parameters found in one of the two previous cases (old reference frame → PPP → modern reference frame).

It should be noted, however, that despite its many advantages and opportunities, PPP has certain limitations:

- Relatively long observation and initialization times are required to estimate ambiguities, despite the advances made in this area in recent years;
- Coordinates calculated directly in ITFR2014 or ITRF2020 at the time of observation. This generally requires a transformation of the coordinates in the local system;
- The need for a reference frame (global for orbits and clocks, regional for atmospheric corrections) of CORS to accurately estimate the various models used to calculate the solution;
- Fairly long time interval between observations and processing (approximately two weeks) to obtain accurate satellite orbit and clock files for standard PPP;
- Dual-frequency GNSS receivers are necessary to eliminate ionospheric errors, which is essential for sub-meter positioning.

A certain level of user expertise is required to check and correct certain parameters (type of antenna used, use of ARP or ACP depending on the tool used, etc.).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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