Congruence through repeatability of position solutions by different GNSS survey techniques

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Abstract

In this study, we determined three-dimensional (3D) position coordinates for eight new Continuous Operating Reference Stations (CORS) in Ghana through three different GNSS positioning techniques. The three GNSS positioning techniques whereby the network of CORS was tied to ITRF14 and War Office 1926 datums included:1) Precise Point Positioning (PPP); 2) Precise Differential GNSS (PDGNSS), using reference stations based on ITRF14; and 3) PDGNSS, using reference stations based on War Office. The PPP solutions were computed using the Canadian Spatial Reference System Precise Point Positioning software (CSRS-PPP), available online and as an open source GNSS laboratory tool software (gLAB). The PDGNSS solutions were obtained from OPUS and AUSPOS online services, as well as from self-post-processing using Topcon Tools software v8.2.3. All solutions were computed using 24-hour data for twelve consecutive days in the month of October 2018 (GPS DoY 284 to GPS DoY 295). The quality, reliability, and acceptability of position solutions were measured by computing the average positioning error, the rate of ambiguity resolution and the repeatability ratios of the solutions. The variability of coordinate differences for each pair of different positioning techniques was computed to determine their solution congruences. Ultimately, , the average positioning errors in northing, easting, and height were 0.003m, 0.005m and 0.009m, respectively. The rate of ambiguity resolution was between 75.3% and 90.3%. Repeatability ratios ranged between 1: 68,500,000 and 1: 411,100,000. Finally, the minimum and maximum range of variability in coordinate differences for each pair of positioning techniques was 1mm to 16mm for horizontal positions and 2mm to 137mm for vertical positions.

Keywords: *PPP, PDGNSS, Congruence, CORS*

1. Introduction

Determination of precise three-dimensional (3D) position coordinates of points using Global Navigation Satellite System (GNSS) positioning techniques has now become the ultimate approach (El-

Tokhey, et al., 2018). Several countries, including Jamaica (Newsome and Harvey 2003), Mexico (Soler and Hernández-Navarro 2006a), Egypt (Rabah, 2015), Korea (Kim and Bae, 2018) and Italy, have already used GNSS measurement techniques to determine accurate 3-D coordinates for their CORS network (BIAGI, et al., 2007; Dardanelli et al., 2020). In addition, several other countries have performed readjustments and reanalysis of their CORS network in order to maintain accurate coordinates (Snay and Soler, 2008; Dardanelli et al., 2020; Saleh et al., 2021; Chinnarat et al., 2021). It is worth noting that the recomputed coordinates always supersede the previous coordinates. Another method of determining accurate three-dimensional (3-D) position coordinates for points is to reprocess using new reference frames (Khoda, 2020; Dardanelli et al., 2020).

In 2019, eight new CORS sites were established by the Licensed Surveyors Association of Ghana (LiSAG) located in Accra, Kumasi, Takoradi, Tarkwa, Akim-Oda, Winneba, Koforidua and Ho. As shown in Figure 1, they have covered southern Ghana with interstation distances ranging between 48km and 231km. The position coordinates of these CORS were determined using reference points based on the War Office datum of 1926, which limits the user of the new CORS to only local coordinates. In order to provide users with access to geocentric coordinates without the need to transform coordinates, this study determined accurate 3-D coordinates for the new CORS in Ghana, using reference stations based on ITRF14 and the following GNSS techniques: 1) Precise Point Positioning (PPP); and 2) Precise Differential GNSS (PDGNSS). This is to comply with the recommendation by the International Union of Geodesy and Geophysics that the ITRF should be the standard terrestrial reference frame for positioning, satellite navigation, Earth Science applications, and for the alignment of none geocentric reference frames (Petit and Luzum, 2010; IUGG, 2015).

The use of the PPP technique to compute the position coordinates of CORS has been presented in a number of research articles including, amongst others, those of Ebner and Featherstone (2008); El-Hattab (2014); and Grinter & Janssen (2012. The algorithms of PPP have also been presented in research articles such as those of Urquhart et al. (2014) and Kouba & Héroux (2001. Ocalan et al. (2016) evaluated the performance of PPP against static positioning results by AUSPOS and obtained an accuracy of 2mm in the northing and easting, respectively, as well as 12.7mm in the Up direction. They concluded that on account of its satisfactory accuracy, the PPP method for next generation positioning has come to the forefront. The PPP technique is promoted by the availability of orbit/clock corrections at IGS data centres. Solutions for PPP techniques have also been enhanced by the development of robust post-processing software in the PPP mode (Chen and Chang, 2021).

On the other hand, the PDGNSS technique was performed using IGS stations tied to the ITRF14 dynamic datum. This technique has been widely accepted as the most accurate in position fixing. As a result, the performance of other techniques has been assessed using the PDGNSS technique as the reference solution (El-Hattab, 2014; El-Hakhey et al., 2018).

In this study, PPP and PDGNSS techniques were used to compute the coordinates of new CORS in Ghana from different GNSS positioning techniques. These sources included CSRS-PPP and gLAB post-processed results for the PPP solutions; Topcon Tools post-processed results for the PDGNSS solutions; and lastly, OPUS and AUSPOS post-processed results for the PDGNSS solutions.

Unlike most scientific studies which use the solutions of the PDGNSS as 'true values' for comparison with other techniques, this study analysed the congruences of the solutions from PDGNSS and PPP techniques in relation to repeatability for twelve consecutive days between GPS days of the year 284 and 295 in 2019. The PDGNSS results were compared to PPP solutions by CSRS and gLAB.

The quality, reliability, and acceptability of position solutions were measured by computing the average positioning errors, the rate of ambiguity resolutions, and the repeatability ratios of the solutions. The variability of coordinate differences for each pair of different positioning techniques was computed to determine their solution congruences. Finally, accurate three-dimensional (3-D) position coordinates for eight new CORS in Ghana were determined.

2. Materials and Methods

2.1. The new GNSS CORS network in Ghana

The distribution of the new CORS is presented in Figure 1.

Figure 1: Map of Ghana showing locations of LiSAG's new CORS.

All the new CORS were mounted with Leica GR50 dual-frequency receivers with LEIAR10 NONE antennae capable of receiving GPS and GLONASS signals only. As shown in Figure 2, the antennae monuments were chosen above the roofs of buildings to reduce obstructions and multipath effects. The data centre is located at Spintex residential area in Accra, where daily observations are stored with epoch intervals of 30s in Receiver Independent and Exchange (RINEX) Format. Users can access data via info@lisagh.org or lisagh2016@gmail.com or www.lisagh.org.

Figure 2: Antennae Monuments of LiSAG's new CORS in Ghana.

2.2. Reference Stations used

The official coordinates of the new CORS stations in Ghana were determined by the Survey and Mapping Division (SMD) using relative positioning techniques with GPS data observed at the ACRA CORS station and selected primary ground control points. The position coordinates of the ACRA CORS station were computed using GPS data from the nearest International GNSS Service (IGS) stations according to the DGNSS technique and based on ITRF05 datum (Poku-Gyamfi, 2009).

In computing the final position coordinates of the new CORS according to the PDGNSS technique, this study used the IGS stations as listed in Table 1. These stations were selected because they were all included in the analysis of ITRF2014, had suitable network geometry, and had high quality data that could be simultaneously observed with the new CORS in Ghana.

The reference stations were selected across continents because longer baseline lengths produce best ambiguity resolution when scientific processing software is used (Lee et al., 2008).

For the post processing using Topcon Tools, primary ground control points GCS 305 and GCS 306, both of which are based on War Office datum, were used. They are part of the geodetic network of

Ghana, established by the British in 1926 and located in Kumasi, in the Ashanti region and maintained by the Lands Commission of Ghana.Table 1: IGS Stations used for the PDGNSS Technique

Site Name	ID	Country	Site Name	ID	Country
DAKR	DAKR	Senegal	Springbok	SBOK	S. AFRICA
La Palma	LPAL	Spain	Saint Helena	STHL	UK
Yamousoukro	YKRO	Cote d' Voire	Cotonou	BJCO	Benin
Matera (Maspalomas)	MAS1	Spain	Ponta Delgada	PDEL	Portugal
Rabat	RABT	Morocco	Toulouse	TLSE	France
San Fernando	SFER	Spain	Villafranca	VILL	Spain
NKOLTANG	NKLG	GABON	Yebes	YEBE	Spain
Mbarara	MBAR	Uganda	Caussols	GRAS	France
Lusaka	ZAMB	Zambia	Matera	MAT1	Italy

3. Description of Data

These researchers downloaded 24-hour CORS data for twelve consecutive days between 11 and 22 October 2019 from the new CORS in Ghana. The raw data in Receiver Independent and Exchange format (RINEX) version 2.11 were downloaded directly from LISAG data centre. Data were sampled at a 30s rate and at a 10 degrees cut-off angle using Leica GNSS QC. The data quality metrics were checked using the translate, edit, and quality check (TEQC) software version 2.2.0.35. In addition, reference stations GCS 305 and GCS 306 were occupied for a 10-hour session on 25 and 30 March 2021 using Trimble R8 receivers with TRMR8 antennae. The raw data were converted to RINEX version 2.11 using the Trimble RINEX convertor, sampled at a 30s rate and at a 10-degree cut-off angle. For each set of data, simultaneous observations were made to offer PDGNSS post-processing techniques. Precise orbital data were downloaded from the IGS data centre for post processing via ftp://cddis.gsfc.nasa.gov/gnss/data/daily.

3.1. Post Processing Data

As indicated earlier, three techniques were used to obtain the required post-processed results, as detailed below.

3.1.1. PDGNSS Solutions

We uploaded the RINEX files of the new CORS to OPUS (https://geodesy.noaa.gov) and AUSPOS (https://www.ga.gov.au) web services and received the first and second sets of processed solutions, as shown in Figure 3. The IGS stations were constrained with an initial standard deviation of 1mm and 2mm for the horizontal and vertical components respectively during the post processing by AUSPOS to obtain solutions based on the ITRF 2014 datum. For purposes of statistical analysis, the cartesian coordinates were converted to UTM northings, eastings, and the up direction using MATLAB script.

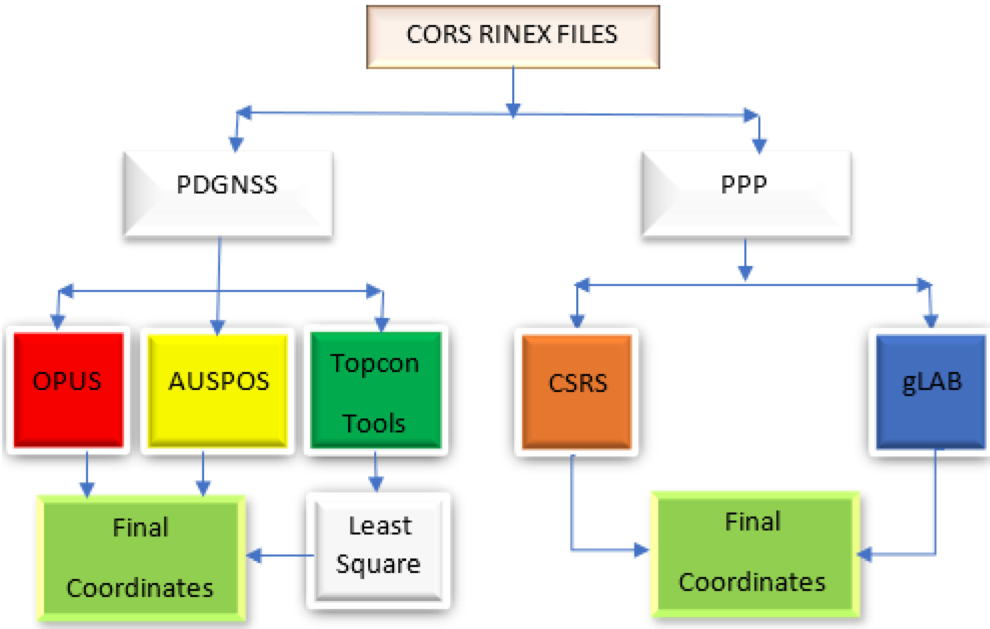

Figure 3: Scheme of data post processing.

The third set of solutions was obtained through self-processing using Topcon Tools version 8.2.3. software in the DGNSS static mode. We selected reference stations, GCS 305 and GCS 306, to process the position coordinates of LISAG_KUMASI CORS in a reference loop, as shown in Figure 4. Subsequently, the LISAG_KUMASI CORS was used as a reference station in the main loop, as shown in Figure 5, to compute the positions of the other new CORS in the network based on War Office datum. Final coordinates were obtained after applying the least squares adjustment technique using the MATLAB script. Details of the least squares adjustments can be found in Ghilani, (2017).

Figure 4: Reference loop used in computing coordinates of LISAG_KUMASI CORS.

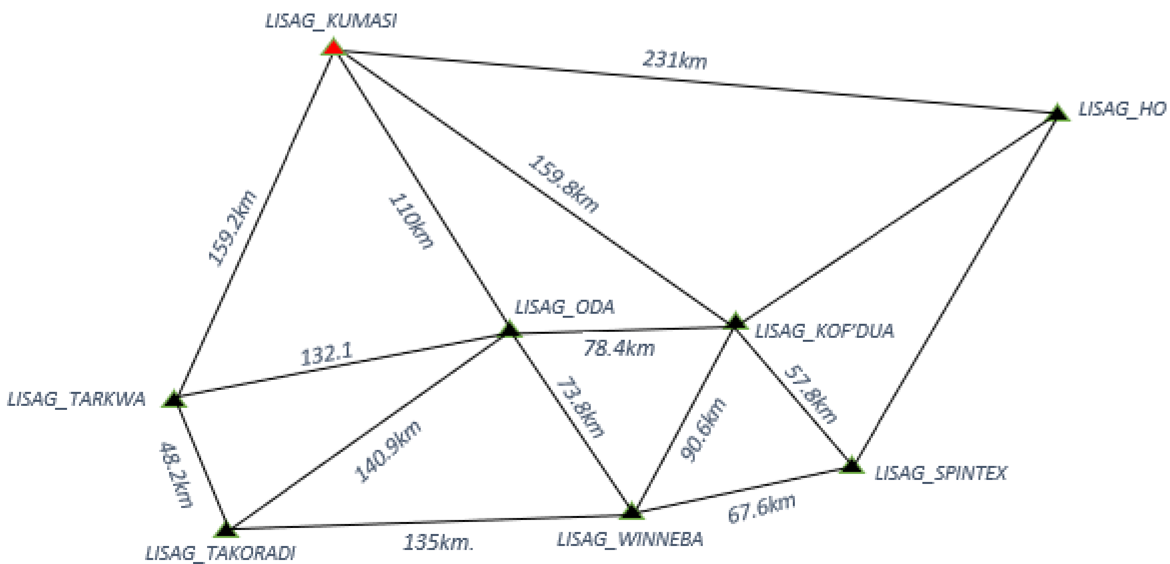

Figure 5: Main loop used in computing the coordinates of the new CORS in the network.

3.1.2. PPP Solutions

We used two different software packages, namely, CSRS-PPP (https://www.nrcan.gc.ca) and gLAB version 5.4.3 (http://www.gage.es/gLAB), as presented in Hernandez-Pajares et al., (2010) to process the same 24-hour data in the PPP mode. For the CSRS-PPP solutions, we uploaded data for eleven consecutive days via the internet, and the results were received via email. We did self-processing by gLAB to compute the positions of all eight CORS in accordance with similar studies (Andritsanos et al., 2016; Akpınar & Aykut, 2017; Soni et al., 2020).

We selected the ionospheric-free linear combinations option, the undifferentiated GPS pseudo-range measurements option, the carrier-phase measurements option, and the IGS combined orbit/clock products measurements option to compute the position solutions in the PPP mode using simplified equations [1] – [4] (Gao et al., 2002; Yigit et al., 2014; Mohammed et al., 2016).

$P_1 = \rho + c(dt_r - dt^s) + T + I_1 + cd_{rp1} - 1.546c.DCB_{p1-p2} + dm_{p1} + e_1$ ... [1]
$P_2 = \rho + c(dt_r - dt^s) + T + I_2 + cd_{rp2} - 2.546c.DCB_{p1-p2} + dm_{p2} + e_2$ ... [2]
$\lambda_1\varphi_1 = \rho + c(dt_r - dt^s) + T - I_1 + \lambda_1 N_1 + c(\partial_{r1} + \partial_1^s - 2.546d_{p1}^s + 1.546d_{p2}^s) + \partial_{m1} + \varepsilon_1$ ... [3]
$\lambda_2\varphi_2 = \rho + c(dt_r - dt^s) + T - I_2 + \lambda_2 N_2 + c(\partial_{r2} + \partial_2^s - 2.546d_{p1}^s + 1.546d_{p2}^s) + \partial_{m2} + \varepsilon_2$ ... [4]

where P_1, P_2 are pseudo-range measurements, φ_1, φ_2 are carrier-phase measurements, and λ_1, λ_2 are wave lengths for L1 and L2 signals respectively; ρ is the true geometric range between the satellite and receiver antennal phase centre; c is the speed of light in vacuum; dt_r , dt^s are the receiver and satellite clock errors; DCB is the satellite differential code bias; T is the tropospheric delay in range units, and I_1, I_2 are the ionospheric delays in the range units on L1 and L2 respectively; ∂_{r1} , ∂_1^s, ∂_{r2} , ∂_2^s are the frequency-dependent carrier-phase hardware delays for the receiver and satellite; d_{p1}^s, d_{p2}^s, d_{rp1} , d_{rp2} are the code hardware delays for the satellite and receiver; dm_{p1}, dm_{p2} are the code multipath effects; ∂_{m1}, ∂_{m2} are the carrier-phase multipath effects; e_1, e_2, ε_1, ε_2 are the unmodelled error sources; and N_1, N_2 are the integer ambiguity parameters for L1 and L2 respectively.

In all, as presented in Tables 5 and 6, two sets of position coordinates were obtained through PPP techniques.

3.1.3. Quality, reliability, and acceptability of solutions

Three parameters were used to evaluate the quality, reliability, and acceptability of the solutions in Tables 2 – 6, namely, the mean positioning errors, the rate of ambiguity resolution, and the baseline repeatability ratio, as outlined by the US Army Corps of Engineers' (USACE) Manual in 2003. The USACE set a repeatability ratio of 1:100,000 for a baseline length of 10,000 km as an acceptable ratio. The repeatability ratio is computed using the formula: $\text{Ratio} = \frac{\sqrt{(dN)^2 + (dE)^2 + (dU)^2}}{\text{Baseline length}}$ [6]

According to the AUSPOS solution report, an ambiguity resolution success rate of 50% or higher indicates a reliable solution. The ambiguity resolution success rate is computed using the GPS processing software. On the other hand, Mills (1998) and El-Diasty (2020) have set the threshold for mean positioning errors as 0.1m at 95% confidence level.

The mean positioning error is computed as: $\sigma = \text{sqrt}(dN^2 + dE^2 + dU^2)$ [5]

4. Results and Analysis

The mean position coordinates of the new CORS are presented in this section.

Table 2: PDGNSS solutions from AUSPOS based on ITRF2014 datum epoch 2019.7768

SATION	**X (m)**	**Y (m)**	**Z (m)**	**N (m)**	**E (m)**	**U (m)**
LISAG_SPINTEX	6347602.235±0.001	-9709.441±0.001	621964.716±0.005	623516.992	822654.949	75.570
LISAG_KUMASI	6332780.164±0.001	-179680.802±0.001	737906.145±0.002	739465.090	651958.268	308.327
LISAG_TARKWA	6347312.102±0.001	-221657.535±0.001	584981.613±0.001	585660.942	610803.862	108.269
LISAG_TAKORADI	6351738.053±0.001	-196733.473±0.001	543978.629±0.010	544552.500	635925.774	43.570
LISAG_KOFORIDUA	6342287.132±0.001	-33465.349±0.001	674297.864±0.005	676031.922	798599.215	222.334
LISAG_ODA	6343500.150±0.001	-109219.163±0.002	654158.249±0.004	655451.544	722919.842	164.490
LISAG_WINNEBA	6350084.203±0.001	-70179.545±0.002	591901.995±0.007	762295.986	593031.479	44.847
LISAG_HO	6336056.542±0.002	50909.724±0.007	729252.6±0.006	731270.019	219177.661	232.517

Table 3.: PDGNSS solutions from OPUS based on IGS08 datum epoch 2019.7768

SATION	**X (m)**	**Y (m)**	**Z (m)**	**N (m)**	**E (m)**	**U (m)**
LISAG_SPINTEX	6347602.370±0.029	-9709.442±0.016	621964.734±0.024	623516.997	822654.947	75.707
LISAG_KUMASI	6332780.299±0.014	-179680.811±0.025	737906.166±0.022	739465.096	651958.263	308.461
LISAG_TARKWA	6347312.220±0.067	-221657.540±0.021	584981.627±0.004	585660.944	610803.861	108.388
LISAG_TAKORADI	6351738.172±0.062	-196733.480±0.023	543978.640±0.028	544552.501	635925.771	43.690
LISAG_KOFORIDUA	6342287.248±0.047	-33465.348±0.022	674297.877±0.012	676031.922	798599.216	222.451
LISAG_ODA	6343500.274±0.023	-109219.166±0.022	654158.263±0.021	655451.545	722919.841	164.616
LISAG_WINNEBA	6350084.326±0.041	-70179.550±0.018	591902.008±0.018	593031.480	762295.983	44.971
LISAG_HO	6336056.542±0.026	50909.724±0.035	729252.6±0.011	731270.019	219177.661	232.517

Table 4: PDGNSS solutions from Topcon Tools based on War Office datum 1926

STATION	NOTHINGS	EASTINGS
LISAG_SPINTEX	349992.998	1231445.540
LISAG_KUMASI	732289.131	673150.400
LISAG_TARKWA	228157.880	536287.449
LISAG_TAKORADI	93022.156	618292.390
LISAG_KOFORIDUA	522404.723	1153216.686
LISAG_ODA	455837.316	904839.600
LISAG_WINNEBA	250722.483	1033251.489
LISAG_HO	704379.224	1429664.401

The results obtained for twelve consecutive days from 11 to 22 October 2019 for the eight new CORS stations through the application of PDGNSS techniques are presented in Tables 2, 3, and 4, while the results gained through, the PPP techniques are presented in Tables 5 and 6.

Table 5: PPP solutions from CSRS-PPP based on ITRF14 datum epoch 2019.7768

SATION	X (m)	Y (m)	Z (m)	N (m)	E (m)	U (m)
LISAG_SPINTEX	6347602.242±0.002	-9709.440±0.005	621964.720±0.009	623516.995	822654.950	75.578
LISAG_KUMASI	6332780.162±0.002	-179680.803±0.005	737906.147±0.009	739465.093	651958.267	308.325
LISAG_TARKWA	6347312.101±0.002	-221657.536±0.006	584981.617±0.009	585660.945	610803.861	108.268
LISAG_TAKORADI	6351738.103±0.002	-196733.4820.006	543978.6380.009	544552.504	635925.766	43.622
LISAG_KOFORIDUA	6342287.186±0.003	-33465.358±0.007	674297.876±0.011	676031.927	798599.206	222.389
LISAG_ODA	6343500.205±0.002	-109219.171±0.006	654158.260±0.009	655451.549	722919.835	164.546
LISAG_WINNEBA	6350084.261±0.002	-70179.552±0.006	591902.005±0.010	593031.483	762295.979	44.906
LISAG_HO	6336056.542±0.002	50909.724±0.007	729252.6±0.011	731270.019	219176.857	232.517

Table 6: PPP solutions from gLAB based on IGS08 datum epoch 2019.7768

SATION	X (m)	Y (m)	Z (m)	N (m)	E (m)	U (m)
LISAG_SPINTEX	6347602.329±0.006	-9709.449±0.010	621964.729±0.002	623516.995	822654.941	75.665
LISAG_KUMASI	6332780.252±0.006	-179680.813±0.011	737906.153±0.001	739465.087	651958.260	308.416
LISAG_TARKWA	6347312.199±0.006	-221657.555±0.010	584981.627±0.005	585660.946	610803.846	108.367
LISAG_TAKORADI	6351738.120±0.008	-196733.483±0.003	543978.633±0.004	544552.498	635925.766	43.638
LISAG_KOFORIDUA	6342287.231±0.035	-33465.357±0.026	674297.881±0.001	676031.928	798599.207	222.434
LISAG_ODA	6343500.257±0.027	-109219.166±0.015	654158.262±0.002	655451.545	722919.840	164.599
LISAG_WINNEBA	6350084.325±0.005	-70179.546±0.007	591902.009±0.007	593031.481	762295.986	44.970
LISAG_HO	6336056.542±0.026	50909.724±0.017	729252.6±0.031	731270.019	219176.857	232.517

Table 7: Mean positioning errors for each CORS position solution (95% confidence level).

	Positional Uncertainty (95% C.L)		
Station	**Easting (m)**	**Northing (m)**	**Up (m)**
LiSAG-Spintex	0.005	0.003	0.008
LiSAG-Kumasi	0.005	0.003	0.009
LiSAG-Takoradi	0.005	0.003	0.009
LiSAG-Tarkwa	0.005	0.003	0.009
LiSAG-Koforidua	0.005	0.003	0.008
LiSAG-Oda	0.005	0.003	0.008
LiSAG-Winneba	0.005	0.003	0.011
LiSAG-Ho	0.005	0.003	0.009

5. Discussion

In this section, two main analyses were made. The first analysis focused on the quality, reliability, and acceptability of the position solutions and the second analysis on the range of variability of coordinates differences for all pairs involved.

According to Mills (1998) and El-Diasty (2020, the mean positioning error should not exceed 0.1m at a 95% confidence level when geodetic satellite positioning methods are used to establish CORS. This threshold was confirmed by the International Hydrographic Survey Standards. Comparing this threshold of 0.1m with the values in Table 6, it can be concluded that the final solutions are acceptable for geodetic purposes. A similar conclusion was drawn in Mader et al. (2003) when the mean OPUS position differences were analysed. The mean positioning errors in the northings were consistently lower than those of the eastings. This was attributed to the clustering of the IGS reference stations to the northern side of Ghana, as shown in Figure 6. This attribution is supported by a similar accession by El-Tokhey (2018). Thus, apart from the YKRO, NKLG and MBAR reference stations, which are located in the west, south and east respectively, the remaining reference stations are located to the north of Ghana. The mean positioning error values for the Up direction were higher than both their eastings and northings counterparts. Further investigation is needed to explain this.

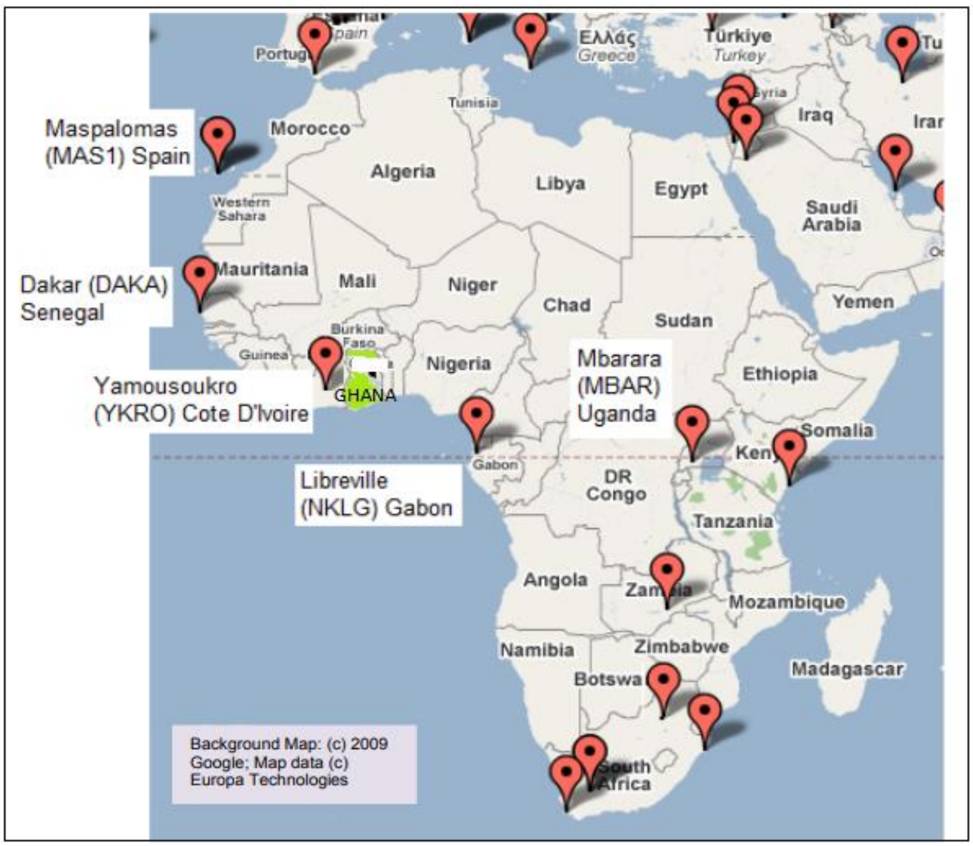

Figure 6: Selected IGS reference stations for Ghana.

In order to assess the quality and reliability of the position solutions obtained in this study, the rate of ambiguity resolutions per baseline was computed using Bernese software version5.0., and these data are presented in Table 8.

Table 8: Average Ambiguity Resolution per Baseline

Baseline	Ambiguities Resolved (%)	Baseline Length(km)
LiSAG-Spintex – NKLG	90.3	1229.835
LiSAG-Kumasi – NKLG	89.5	1433.871
LiSAG-Takoradi – NKLG	82.1	1366.608
LiSAG-Tarkwa – NKLG	89.0	1404.988
LiSAG-Koforidua – NKLG	88.0	1275.759
LiSAG-Oda – NKLG	89.4	1332.546
LiSAG-Winneba – NKLG	75.3	1270.074
LiSAG-Ho – NKLG	80.6	778.160

According to Jia et al. (2014), the percentage of ambiguities resolved at a rate of 50% or more indicates a reliable solution for the baseline formed. Ambiguities were resolved in a baseline-by-baseline mode using the Code-Based and Quasi-Ionosphere-Free (QIF) strategies. The lowest ambiguity resolution at a rate of 75.3% occurred on the LISAG_WINNEBA - NKLG baseline. The remaining baselines recorded an ambiguity resolution rate above 80%, thus indicating high quality and reliable solutions. The baseline length did not influence the percentage of ambiguity resolution. For instance, as seen in Table 8, there were instances where shorter baselines produced a lower ambiguity resolution rate than was the case with the longer baselines, and *vice versa*,

The third parameter used for assessing the quality and reliability of the baseline solutions was the baseline repeatability ratio. Pryseley et al. (2010) define repeatability as the precision obtained under repeatable conditions, when independent test results are obtained using the same method on identical test items, by the same operator, using the same equipment, and within short intervals of time. Repeatability leads to an estimate of the minimum value of precision. In Table 8, the average baseline repeatability was computed using 24-hour data based on Equation 6 for eleven consecutive days. The repeatability ratios ranged between 1: 68,500,000 and 1: 411,100,000, thus indicating acceptable precision in the position results obtained in this study.

Table 9 also reveals that the maximum coordinate differences among redundant baselines in the northings, eastings and up directions are 2mm, 5mm and 8mm respectively. This resulted in each baseline measuring up to an average of 0.5mm + 1ppm, thereby making all the repeatability rations acceptable.

Table 9: Average Baseline Repeatability for the new CORS sites in Ghana.

	Average Differences (m)				
Station	**dE(m)**	**dN(m)**	**dU(m)**	**baseline (m)**	**Repeatability Ratio**
LiSAG-Spintex	0.001	0.002	0.005	1229835	1:217,198,500
LiSAG-Kumasi	0.002	0.001	0.003	1433871	1:411,100,000
LiSAG-Takoradi	0.002	0.000	0.008	1366608	1:105,351,000
LiSAG-Tarkwa	0.002	0.001	0.008	1404988	1:168,365,000
LiSAG-Koforidua	0.002	0.002	0.007	1275759	1:163,956,200
LiSAG-Oda	0.002	0.002	0.005	1332546	1:231,857,000
LiSAG-Winneba	0.001	0.002	0.011	1270074	1:112,213,000
LiSAG-Ho	0.005	0.002	0.010	778160	1:68,500,000

The second analysis, which was focused on the range of variability of coordinate differences, was presented by Dardanelli et al., (2021) at an earlier stage. It compared position solutions by different techniques in pairs for their congruences and also analysed the statistics descriptors of the north, east, and ellipsoidal height differences amongst different pairs of solutions. In this section, the range of variability of coordinate differences for all pairs involved were analysed on the basis of Table 10. Excluding the differences in height (ΔU), the N and E components showed agreement between 9mm and 16mm for each pair of solutions. The ΔU components showed agreement between 2mm and 137mm for each the pairs of solutions. Strong congruences were observed between solution pairs for AUSPOS *vs* CSRS, OPUS *vs* gLAB and CSRS *vs* gLAB. The remaining pairs, involving AUSPOS *vs*. OPUS, AUSPOS *vs*. gLAB and OPUS *vs*. CSRS, recorded coordinate differences between 1mm and 136mm, thus indicating relatively strong congruences as opposed to those of their counterparts. It can be observed that results from the PPP technique compared well with those from the PDGNSS technique in the range of 1mm to 16mm for horizontal and 2mm to 137mm for vertical positions.

Table 10: Range of variability of coordinate differences (min – max in mm).

Min & Max Components (mm)	**AUSPOS vs. OPUS**	**AUSPOS vs. CSRS-PPP**	**AUSPOS vs. gLAB**	**OPUS vs. CSRS-PPP**	**OPUS vs. gLAB**	**CSRS-PPP vs. gLAB**
ΔN	-6	-5	-6	-5	-6	-1
	3	7	3	3	9	6
ΔE	-1	-4	-2	-4	-3	-7
	5	9	16	6	15	9
ΔU	-137	-59	-123	0	0	-99
	0	2	0	136	52	0

In order to further emphasise the congruences of the solution pairs involved in this study, the standard deviation of coordinate differences for each pair of techniques was computed and presented in

Table 11. Without removing extreme values, the AUSPOS *vs* OPUS pair showed the lowest standard deviation of 3mm, 2mm, and 42 mm respectively for ΔN, ΔE and Δh, thus signifying agreement between the solutions from AUSPOS and OPUS. The standard deviation values have further placed emphasis on the congruences between the pairs of solutions involved in this study. Column 3 of Table 10 showed the maximum solution differences between AUSPOS and CSRS-PPP as 7mm, 9mm and 59mm in the north, east and up directions, respectively.

Table 11: Standard deviations of coordinate differences for pairs of techniques

Standard deviation (m)	**AUSPOS vs. OPUS**	**AUSPOS vs. CSRS**	**AUSPOS vs. gLAB**	**OPUS vs. CSRS**	**OPUS vs. gLAB**	**CSRS vs. gLAB**
ΔN	0.003	0.004	0.003	0.003	0.004	0.003
ΔE	0.002	0.004	0.005	0.004	0.005	0.005
ΔU	0.042	0.027	0.035	0.042	0.019	0.033

This showed that CSRS-PPP solutions were not significantly different from PDGNSS solutions. Therefore, for applications in which the solution differences above are satisfactory, it would be cheaper to use PPP since no additional reference receiver is required.

6. Conclusion

The study was set to determine accurate three-dimensional (3-D) coordinates for the new active CORS in Ghana. It was based on ITRF 2014 and War Office 1926 datums and used PPP and PDGNSS techniques to compare the congruences of the solution pairs. The quality, reliability, and acceptability of the solutions were assessed on the basis of the USACE Manual (2003), and the International Hydrographic Organization Standards (2019).

This goal was achieved by analysing the results emanating from the various positioning techniques. Some of the statistical descriptors of the north, east, and height differences amongst the different pairs of solutions were analysed in terms of the PDGNSS and PPP techniques.

Strong congruences were observed between the respective solution pairs for AUSPOS *vs* CSRS, OPUS *vs* gLAB and CSRS *vs* gLAB. From the discussions in this study, it is clear that the PPP solutions were not significantly different from the processing data in the PDGNSS mode using any type of software. The results of the PPP compared very well with the PDGNSS, yielding 3mm, 2mm, and 42 mm for ΔN, ΔE and Δh, respectively. While it is acknowledged that PPP proved to be inherently less accurate than PDGNSS, this can be balanced against the advantages of PPP.

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