

Homogenizing coordinates through the use of the active CORS¹ in Ghana

Osman Mohammed Abukari¹, Akwasi Afrifa Acheampong², Samuel Osah², John Ayer²

¹ Survey and Mapping Division, Lands Commission, Accra, Ghana

² Geomatic Engineering Department, KNUST, Kumasi, Ghana

DOI: <http://dx.doi.org/10.4314/sajg.v12i.2.2>

Abstract

In this study, the course towards determining the homogeneous three-dimensional (3D) coordinates of the newly established active Continuously Operating Reference Station (CORS), based on ITRF2014 in Ghana, is revealed. The aim is to address coordinate inconsistencies and inhomogeneity in the published positions of the new active CORS in Ghana. In order to attain homogeneity, the coordinates of two primary control points, GCS 305 and GCS 306, were obtained using AUSPOS online services via email. These were subsequently used as reference stations to compute the position of the LISAG_KUMASI CORS. Adjustments to the position coordinates were performed using Topcon Tools v8.2.3 software at a 1mm standard deviation. The adjusted coordinates of LISAG_KUMASI were used as the reference points to compute the positions of the LiSAGNet CORS in differential mode by using 24 hour data for 11 consecutive days. The GPS data covered DoY 284 to DoY 295 in 2021. The final positions of the CORS, computed by this approach, indicate some differences from the officially published coordinates of the same CORS, confirming the suspicion of inhomogeneity in the source coordinates used in determining the coordinates of the local CORS. Furthermore, a test network, consisting of five COR stations, was designed and used to address the coordinate inconsistencies in the officially published coordinates. Using the officially published coordinates as reference inputs, the ROVER I station was fixed by three different CORSs, thus resulting in average coordinate variabilities of 2.78m and 0.80m in the northing (N) and easting (E) directions, respectively. Through substitution, the coordinates computed in this study as reference inputs, namely, the ROVER I station, were fixed by the same three CORSs, thus resulting in a coordinate variability of 0.002m and 0.006m in the northing (N) and easting (E) directions, respectively. The analysis revealed inconsistencies and inhomogeneity in terms of the officially published coordinates. It is, therefore, recommended that the officially published coordinates of the CORS be replaced by the adjusted homogeneous and consistent values determined through the approach adopted in this study.

Keywords: CORS, Inhomogeneity, Coordinate Variability

1. Introduction

The basic coordinates used in Ghana were determined on pillar G.C.S. 547 in 1904 by Sir F. G. Guggisburg through astronomical observations of fifteen pairs of stars for latitude, and the

¹ CORS : Continuously Operating Reference Station; CORSs: Continuously Operating Reference Stations

telegraphic signal exchange with Cape Town for longitude (Ayer and Fosu, 2008). Pillar G.C.S. 547 was involved in a triangulation with Gold Coast Survey beacon, G.C.S. 121, at Leigon, and the resulting values of the Leigon pillar subsequently used in other triangulation networks. Coordination of other beacons in the relatively flat northern areas was conducted through traverses (Ayer and Fosu, 2008).

Thus, the complete geodetic reference framework of Ghana was developed from blending a chain of triangulation networks in the mountainous southern parts of the country, and a series of traverses carried out between 1904 – 1929 in the relatively flat northern territories (Ayer, 2008; Annan, et.al., 2016; Laari, et al., 2016). Each of these traverses and triangulation blocks had been adjusted separately, but not in a single harmonized manner; hence, homogeneity within the coordinates of the complete framework cannot be guaranteed - a situation which often leads to distortions in the coordinate values. The impacts of these distortions on engineering works, as well as on cadastral mapping, are enormous. For instance, land boundary overlaps causing disputes often result from such disparities in the coordinates. The different traverses and triangulation blocks also need to be adjusted in a single adjustment loop in order to address the problem of coordinate inconsistencies.

In 2019, the Licensed Surveyors Association of Ghana (LISAG) established eight Continuously Operating Reference Stations (CORs) (Poku – Gyamfi et al., 2021). Their positions were published by the Survey and Mapping Division (SMD) of the Lands Commission of Ghana in December, 2020, with reference number M01/13/1/4. Soon after, users of these COR stations started experiencing coordinate inconsistencies and inhomogeneity when different COR stations were used for fixing the same boundary points for cadastral purposes. This means that the COR coordinates in the Ghana coordinate datum have possibly retained the inhomogeneity that prevails within the coordinates of the Ghana reference framework which would prevent the COR station from becoming a means of harmonizing the coordinates in the country. The need to re-compute more consistent and homogeneous coordinates for the new active CORs has, therefore become apparent.

In order to attain homogeneity, the position coordinates of two primary control points, GCS 305 and GCS 306, were obtained using an AUSPOS online service. These were adjusted by means of a least squares approach (LSA) carried out in conjunction with the LISAG_KUMASI CORs site at a 1mm standard deviation. The positions of these control points were based on the War Office datum of 1926. The resultant coordinates of GCS 305 and GCS 306 from the LSA were used as reference points to compute the position coordinates of the newly established active COR station in differential mode by using 24 hour data for 11 consecutive days. The GPS data covered DoY 284 to DoY 295 in 2021. Topcon Tools version 8.2.3 software was used in differential mode and based on ITRF2014 to post process the positions of the new COR station. When used as reference points for the same boundary points, the final positions of the new active COR station computed in this study, produced average coordinate variabilities of 0.002m and 0.006m in the northing (N) and easting (E) directions, respectively. The use of the officially published coordinates as reference points

obviously proved to be far better than the average coordinate variability of 2.78m and 0.80m in the N and E directions, respectively.

2. Background to Geodetic Control Points in Ghana

The geodetic control points of Ghana were established as far back as the 1920s (Ayer, 2008). They were marked by “A” type pillars and connected by primary traverses and triangulation techniques. In view of the level of technology at the time, the aforementioned methods were employed in the establishment of the frame-of-reference networks. The survey, also known as the Gold Coast Survey, took several years, but was completed in 1929 (Survey Records, 1936). For the purposes of the triangulation networks, several figures were formed by selecting suitable ground points on hills and ridges in southern Ghana. Base measurements were carried out in each of the figures thus formed. The first base was selected between Akuse and Odumasi in the Eastern Province, now called the Eastern Region. In this case, distances and angles were measured by means of tapes and theodolites. On the other hand, traverse networks were used in northern Ghana and other low-lying regions. Figural adjustments to the triangulation and traverse networks to satisfy the geometric conditions and the closure between the bases could not be carried out in one operation. Thus, the practice of breaking the chains into suitable figures for adjustment was adopted. Astronomical observations and the computation of coordinates were carried out earlier and, as such, it was easier to transfer the relevant positions to the adjusted figures and networks.

The figure of the earth adopted for the Gold Coast (Ghana) was one suggested by the British War Office; hence, it was named the War Office Ellipsoid, 1926. The elements of the War Office Ellipsoid are: - $a = 20,926,201.2257$ feet; $b = 20,855,504.6001$ feet; $f = (a-b)/a = 1/296$; $\log. (\text{feet}/\text{metres}) = 9.484\ 014\ 544\ 967$. Where a is the semi major axis, b is the semi minor axis and f is the inverse flattening of the referenced ellipsoid.

Because geographical coordinates are unsuitable for the purposes of cadastral mapping, plane rectangular coordinates on the transverse Mercator (Gauss-Krüger) projection were adopted in their place. The whole country was placed on the same origin, the central meridian being 1° W and the origin of the X coordinates $4^{\circ}\ 40'$ N. In order to avoid negative coordinates, 900,000 were added to all Y coordinates and the maximum scale error was reduced by $1/4000$ along the Central Meridian so that the scale error nowhere exceeded this value - except along the extreme edges of the country. The formulae used in the conversion of geographical into Ghana grid coordinates and the computation of convergence can be found in Ayer and Fosu (2008).

2.1. The new active CORS in Ghana

The new active CORS, also called the LiSAGNet, currently consists of eight stations out of a proposed 27 stations across Ghana (Opoku – Gyamfi *et al.*, 2021). The Accra Spintex and Adum Kumasi stations were mounted with Leica GR50 dual frequency receivers supported by LEIAR10 NONE antennas. The remaining stations in Tarkwa, Koforidua, Takoradi, Winneba, Oda and Ho

were mounted with Leica GRX1200GGPRO dual frequency receivers supported by LEIAS10 NONE antennas. As shown in Figure 1, the antenna monuments were built above the main buildings housing the receivers to reduce obstructions and minimize the multipath effects of the GNSS signals. Arrestors were also installed at each station to mitigate the impacts of thunderstorms. These pieces of GNSS equipment are state of the art and highly suitable for contemporary surveying and mapping services.



Figure 1: Antenna Monuments of LiSAGNet CORS in Ghana

The data centre is located in the Spintex area of Accra where the first CORS, LSA1, is mounted. Data are stored virtually using cloud data storage. LiSAGNet uses Leica Spider software for data quality checks, sampling and conversion. LiSAG Management Systems (LMS) software is currently being developed to track usage and transactions online. The expansion of the LiSAGNet is demand driven; hence, all of the eight COR stations were established in the southern parts of Ghana where land surveying and positioning activities are in great demand. The distribution of the LiSAGNet COR station, together with the proposed nineteen COR stations across Ghana, is presented in Figure 2.

The initial objective of LiSAGNet was to supply reference data for static post processing services for cadastral mapping in Ghana and additional products and services that would include Real Time Kinematics (RTK), Virtual Reference Services (VRS) and Network RTK (NRTK) services. It was initially envisaged that these network services would use the Networked Transport Radio Technical Commission for Maritime services (RTCM) via Internet Protocol, NTRIP (Weber *et al.*, 2005; RTCM, 2016).

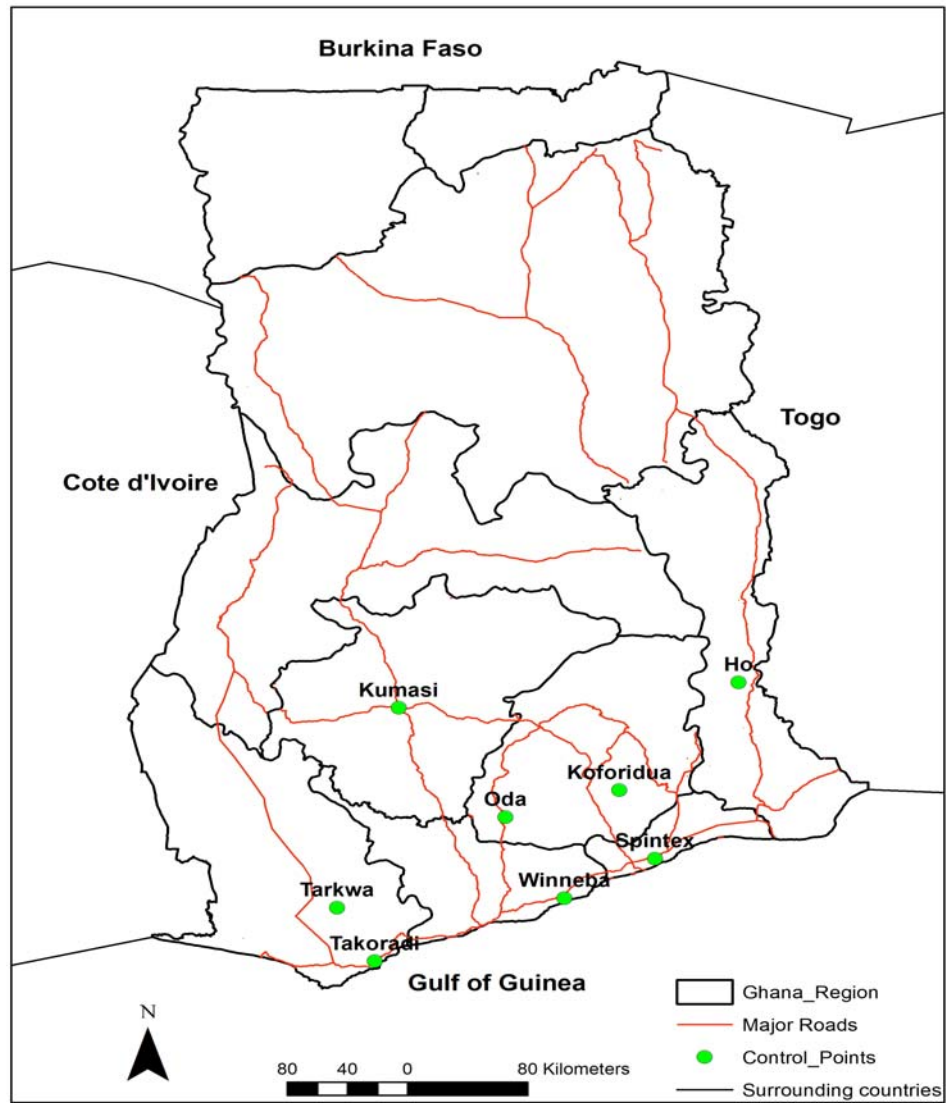


Figure 2: Distribution of Existing and Proposed COR stations of the LiSAGNet.

3. Methodology

This section presents the methodology used in this study (Figure 3).

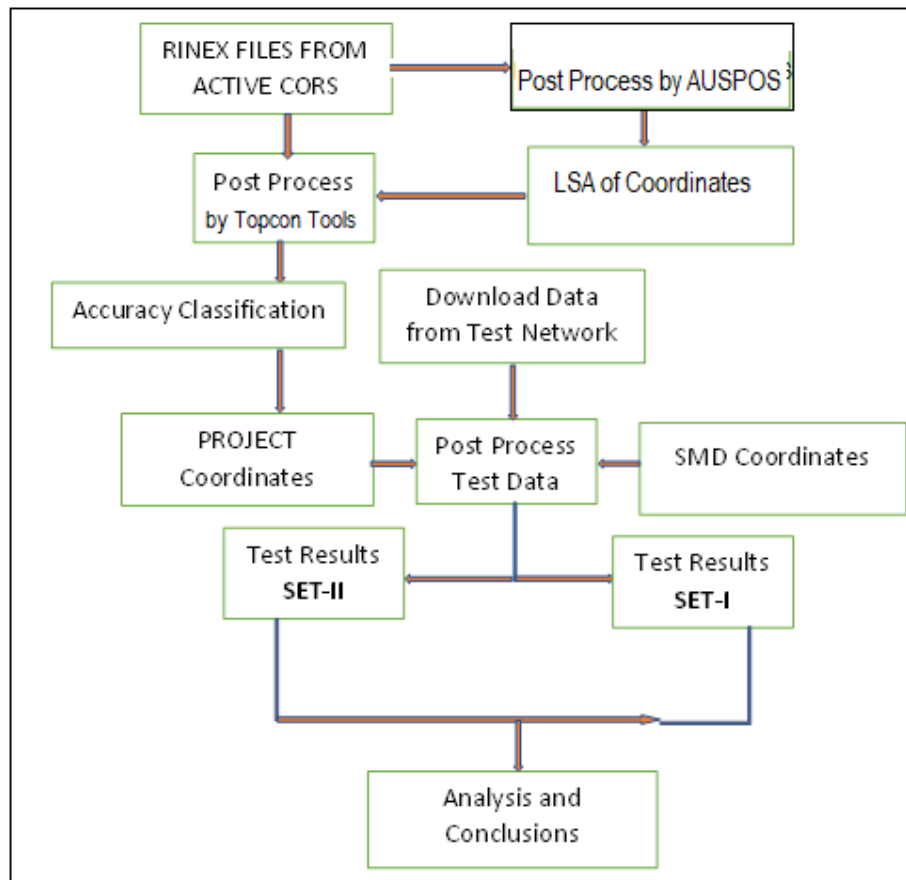


Figure 3: Outline of Study

3.1. Description of Data

Receiver Independent Exchange Format (RINEX) data files ranging from DoY 84 and DoY 89 (Gurtner & Estey, 2007) were simultaneously obtained in 2020 for GCS 305, GCS 306 and the LISAG_KUMASI CORS. GCS 305 and GCS 306 were mounted with Trimble R8 dual frequency receivers (Lemmon & Wetherbee, 2005), whereas the LISAG_KUMASI CORS was mounted with Leica GRS50 dual frequency receivers (Fairhurst *et al.*, 2010). The data were recorded at a 10-degree elevation mask angle and sampled at a rate of 30, with a session duration of 10 hours per day. These data were used in computing the position of the LISAG_KUMASI CORS.

In a separate campaign in 2021, we downloaded dual frequency RINEX data files spanning DoY 284 to DoY 295 for 11 consecutive days from the LiSAGNet data centre. The data were recorded at a 10-degree elevation mask angle and sampled at a rate of 30, with a session duration of 24 hours per day. These data were used in computing the positions of the active CORS, with LISAG_KUMASI CORS as the reference station (See Figure 6).

We downloaded the next category of RINEX data from the experimental test network, which consists of five CORS sites (See Figure 7). Simultaneous observations for seven consecutive days were carried out on the test stations to obtain 24 hours of dual frequency data each day, at a 10-degree elevation mask angle, and at a rate of 30. The data covered DoY 255 to DoY 261, 2020.

These data were used in examining the consistencies and inhomogeneity of the officially published coordinates of the active COR station.

3.2. Selection and Description of Reference Stations

We selected GCS 305 and GCS 306 as reference stations after considering factors such as coordinate homogeneity and consistency, pillar stability, site conditions for multipath effects and baseline length. Both pillars were located within 30km of the LISAG_KUMASI CORS and as prescribed by Mageed (2015), thereby qualified for use as reference stations. Comparison of the GPS Commercial Software Packages to processing static baselines up to 30km have been described in Majeed (2015).

Stations GCS 305 and GCS 306, marked by “A” type pillars, formed part of the geodetic network of Ghana established by the British during colonial rule in 1926. Pillar GCS 305 is located at Berekesse, near Kumasi, and GCS 306 is located at Asuboi, both in the Ashanti region and maintained by the Survey and Mapping Division of the Lands Commission of Ghana. However, owing to concerns of inhomogeneity in the coordinate framework, as earlier discussed, their positions were recomputed using AUSPOS online service and tied to the IGS network.

3.3. Selection of software

As stated earlier, the reference stations, GCS 305 and GCS 306, were within 30km of the LISAG_KUMASI COR station, the position of which was to be fixed. According to Mageed (2015), commercial software, such as Topcon tools, outperforms scientific software when baselines of less than 30km are processed. Similar studies which supported this assertion can be found in Hamidi and Javadi (2017); and Andritsanos *et al.* (2016). Since Topcon Tools uses the Modified Hopfield Model for tropospheric corrections (Innac *et al.*, 2020), all post processing tasks in this study were carried out by Topcon Tools software version 8.2.3 in differential mode (Zinoviev, 2005; Azhari, 2015 and Topcon, 2017).

3.4. Post Processing Data

Before post processing, the data were checked against systematic errors using Leica QC version 2.2 software. Cycle slips, percentage of data completeness and multipath metrics were also assessed to ensure compliance with IGS standards (Zuo, *et al.*, 2019; Johnston *et al.*, 2017). The post processing was performed in two steps:

Step I: The position coordinates of GCS 305 and GCS 306 were obtained from the AUSPOS online service in ITRF2014 and based on the IGS network. They were later used as reference inputs to obtain the baseline vectors between G.C.S 305, G.C.S 306 and the LISAG_KUMASI CORS, as shown in Figure 4. Then, by performing two-dimensional (2D) baseline adjustments using Topcon Tools software, the position of the LISAG_KUMASI CORS was obtained with G.C.S 305 and

G.C.S 306 as the reference stations. The mean position was computed to attain the final adjusted coordinates (N, E) of the LISAG_KUMASI CORS.

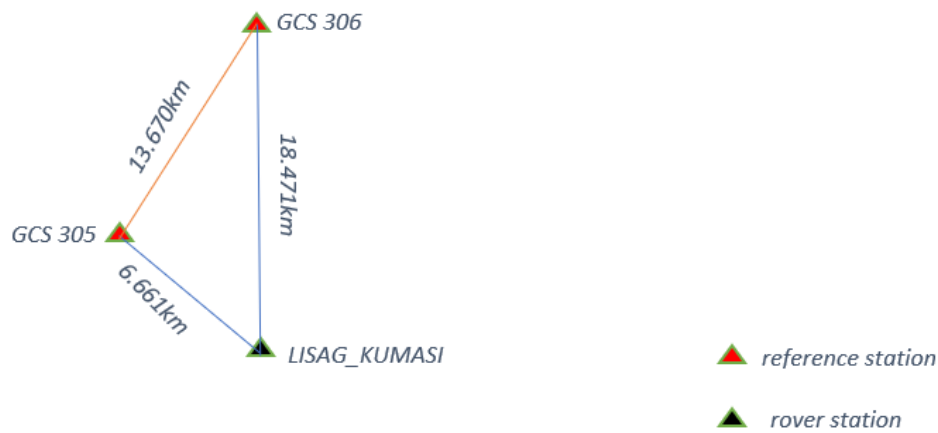


Figure 4: Network used for computing the position of the LISAG_KUMASI CORS

3.5. Least squares approach

The Topcon Tools v8.2.3 software for post processing GNSS data has an inbuilt function for performing a least squares adjustment to the processed coordinates. As shown in Figure 5, and by using G.C.S 305 and G.C.S 306 as reference stations, this function was employed to adjust the position coordinates of LISAG_KUMASI. Subsequently, the adjusted position of LISAG_KUMASI was used in a closed loop to compute the positions of the remaining new COR stations, as shown in Figure 6. The same coordinate adjustment function of Topcon Tools software was used to adjust the final coordinates.

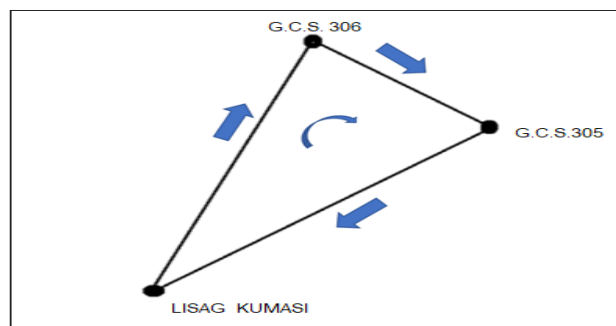


Figure 5: Least Squares Adjustment by the method of Variation of Coordinate, Angle and Distance

Step II: Using the LISAG_KUMASI CORS as a reference point to obtain the baseline vectors of the remaining COR stations in the network, this step involved the processing of the observations, as shown in Figure 6. Similarly, baseline adjustments by Topcon Tools were performed to obtain the final coordinate solutions for the COR stations. Thus, by using the LS method, a network of GNSS baselines can be adjusted to produce the most likely or probable values for unknown coordinates.

The GNSS baseline adjustment is similar to the adjustment of the level nets. Details of the GNSS baseline adjustments can be inferred from Ghilani and Wolf (2006) and Okiemute and Oduyebo (2018), two sources which are well explained. However, it is worth mentioning that all the baseline adjustments were performed using the MATLAB coded script, ‘BaselineAdj.m’, as written in this study.

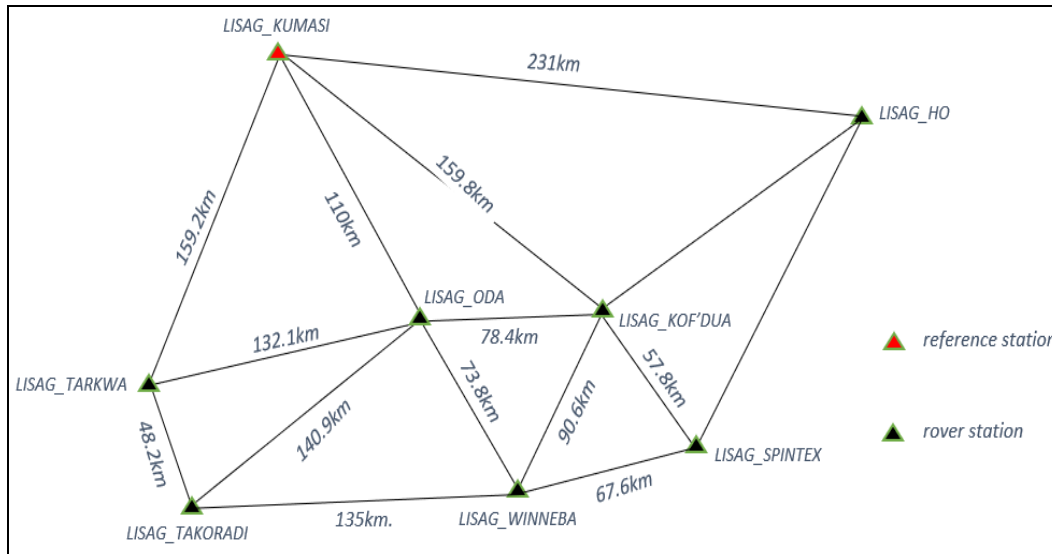


Figure 6: Main loop used in computing the positions of the COR stations in the LiSAGNet.

3.5.1. Accuracy Classification

Horizontal accuracy standards for the First Order Geodetic Survey between one trigonometric point and another are $\pm 0.004\text{m}$ plus 0.001m per 100m ; and between one trigonometric point and the traverse point are $\pm 0.003\text{m}$ plus 0.001m per 100m (Abukari et al., 2019). This means that in fixing any geodetic position on a baseline of up to 0.1km , the coordinates for a repeat baseline in any one component (x, y or z) should not exceed 0.004m plus 0.01m . (The details of the computations can be found in Abukari et al. (2019). The internal consistency of the LiSAGNet CORS was measured through the repeatability of the observations and the adjustment of the coordinates at a 95% confidence level.

3.5.2. Experimental Test

An experimental test network was designed to examine the consistency and inhomogeneity of the positions of the active COR stations, firstly, as published by the SMD of the Lands Commission of Ghana, and secondly, as computed in this study. For this reason, five COR stations were processed using RINEX data files that were observed for seven consecutive days.(See Figure7).

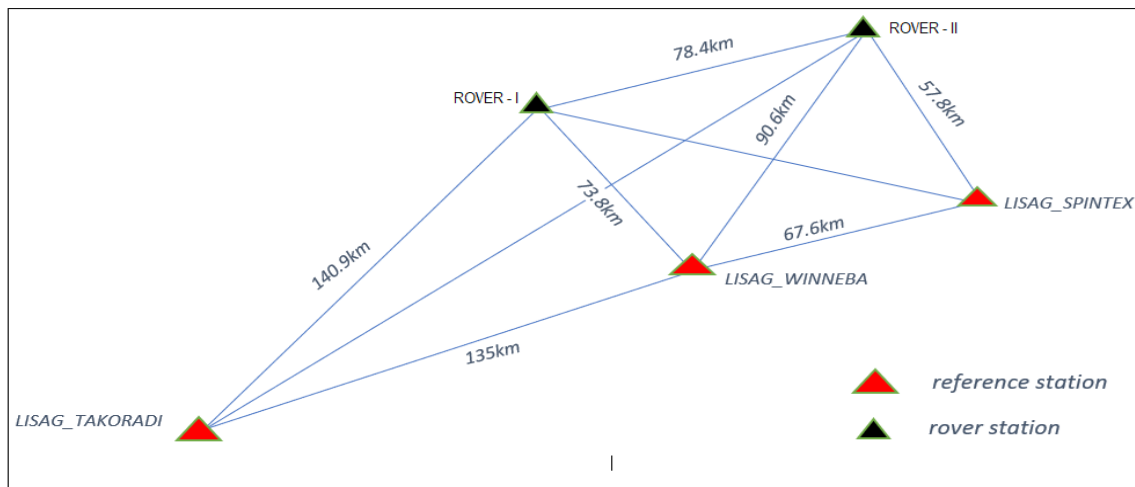


Figure 7: Experimental Test Network

In the field experiment, LISAG_SPINTEX, LISAG_WINNEBA and LISAG_TAKORADI were used as reference stations to compute the positions of ROVER I and ROVER II in two scenarios.

Scenario I: We used the coordinates of the active COR station published by the Lands Commission as reference input to compute the positions of ROVER I and ROVER II in which the LISAG_SPINTEX, LISAG_WINNEBA and LISAG_TAKORADI are kept in turns as reference stations. The mean positions of ROVER I and ROVER II were tabulated as results SET I.

Scenario II: We used the computed coordinates of the active COR station in this study as reference input to compute the positions of ROVER I and ROVER II, as in **STEP I**. The mean positions of ROVER I and ROVER II obtained from each reference station were tabulated as results SET II.

4. Results and Discussion

The results of the post processed positions of the new active COR station in Ghana, based on ITRF2014, are presented in this section. Other statistical computations are also presented here. For the purpose of this discussion, we shall refer to the positions of the LiSAGNet CORS computed in this study as PROJECT coordinates and those published by the Survey and Mapping Division of Ghana as SMD coordinates.

First of all, in order to obey the principle of surveying from ‘whole-to-part’, the positions of G.C.S 305 and G.C.S 306 were tied to the IGS network using the AUSPOS online service. Table 1 presents the mean position coordinates of the LISAG_KUMASI CORS in UTM, with G.C.S 305 and G.C.S 306 retained as the reference stations. The high residual between the LISAG_KUMASI coordinates may be attributed to the inconsistencies between the coordinates of GCS 305 and GCS 306. Hence, mean coordinates were used for LISAG_KUMASI, the former being based on ITRF 2014. Using LISAG_KUMASI, the remaining COR stations were subsequently tied to the IGS network which ultimately contributed partly to the attainment of the aim of this study. No

minimally constrained adjustment was made. Instead, the single baseline solutions using alternative base stations, GCS 305 and GCS 306, were processed. The mean of the two separate solutions was used for post processing.

Table 1: Adjusted coordinates of LISAG KUMASI in UTM

Reference Station	Rover	Northings (m)	Eastings (m)	Mean position (m)	
GCS 305	LISAG_KUMASI	739467.234	651957.883		
GCS 306	LISAG_KUMASI	739467.172	651957.823		
				739467.203	651957.853

The final positions for the remaining Approach.active COR stations in the LiSAGNet were obtained in post processing and based on Step II, as presented in Table 2. It can be seen from Table 2 that apart from LISAG_HO, with its position in UTM zone 31 north, the remaining COR stations are positioned in UTM zone 30 north. This indicates that the entire Ghana does not fall into a single zone of the UTM system. The approach used in this study relates to that proposed by Schwieger *et al.*, 2009.

Table 2: UTM positions of new active CORs published by SMD and as determined in this study

Location	Pillar ID	Source				Zone North
		SMD published coordinates		PROJECT coordinates		
		Northings (m)	Eastings (m)	Northings (m)	Eastings (m)	
ACCRA	LISAG_SPINTEX	623517.676	822653.02	623519.22	822654.369	30
KUMASI	LISAG_KUMASI	739464.928	651956.754	739467.203	651957.853	30
TARKWA	LISAG_TARKWA	585658.822	610802.584	585663.184	610803.501	30
TAKORADI	LISAG_TAKORADI	544550.037	635924.764	544554.798	635925.372	30
KOFORIDUA	LISAG_KOFORIDUA	676031.492	798597.712	676034.11	798598.653	30
ODA	LISAG_ODA	655450.954	722918.544	655453.753	722919.334	30
WINNEBA	LISAG-WINNEBA	593030.915	762294.382	593033.747	762295.449	30
HO	LISAG HO	731270.35	219177.661	731273.051	219178.351	31

In Table 2, it was found that the PROJECT coordinates did not compare well with the SMD coordinates. The coordinate differences between the SMD coordinates and the PROJECT coordinates are presented in Figure 8. The maximum and minimum coordinate differences in the northings were 4.77m and 1.54m. They occurred at the LISAG_TAKORADI and LISAG_TARKWA stations, respectively. Similarly, the maximum and minimum coordinate differences in the eastings were 1.35m and 0.62m. They occurred at the LISAG_SPINTEX and LISAG_TAKORADI stations, respectively. These coordinate differences were significantly large, and thereby call for further investigation into the inconsistencies and inhomogeneity in both the PROJECT and the SMD coordinates.

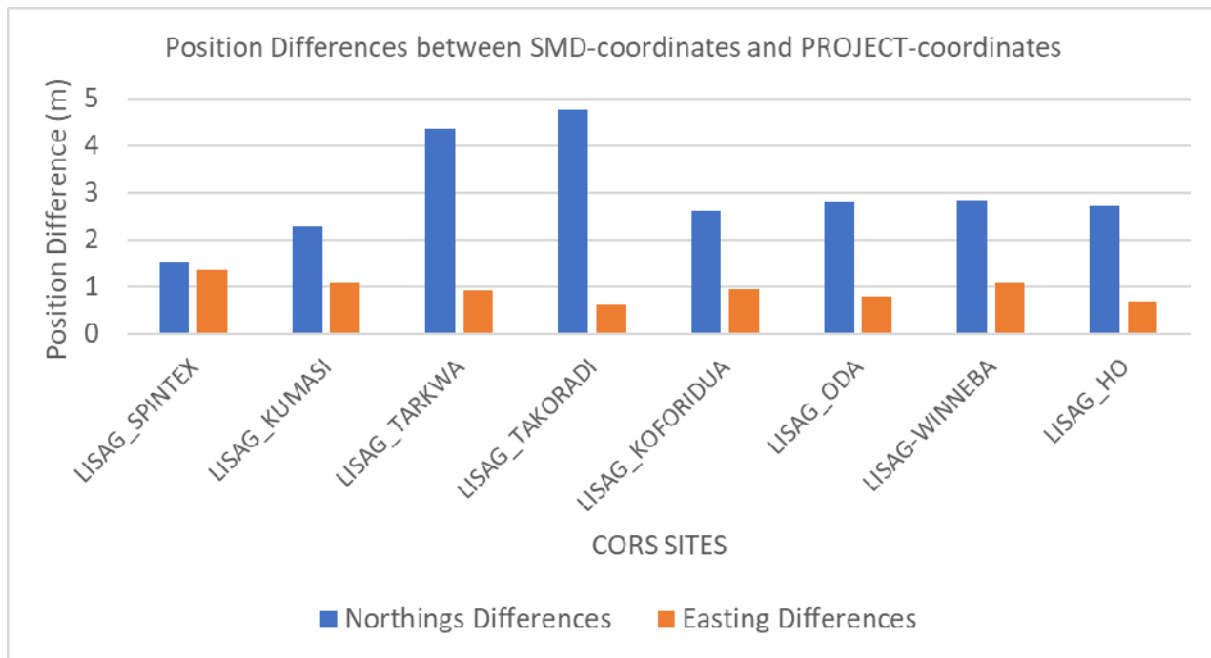


Figure 8: Differences between the published SMD coordinates and the PROJECT coordinates

For the purpose of investigating the coordinate inconsistencies and inhomogeneity, the experimental test results for **Scenario I**, where the SMD coordinates were used as reference inputs to compute the rover stations, and for **Scenario II**, where the PROJECT coordinates were used as reference inputs to compute the rover stations, are presented in Figure 9 and Figure 10.

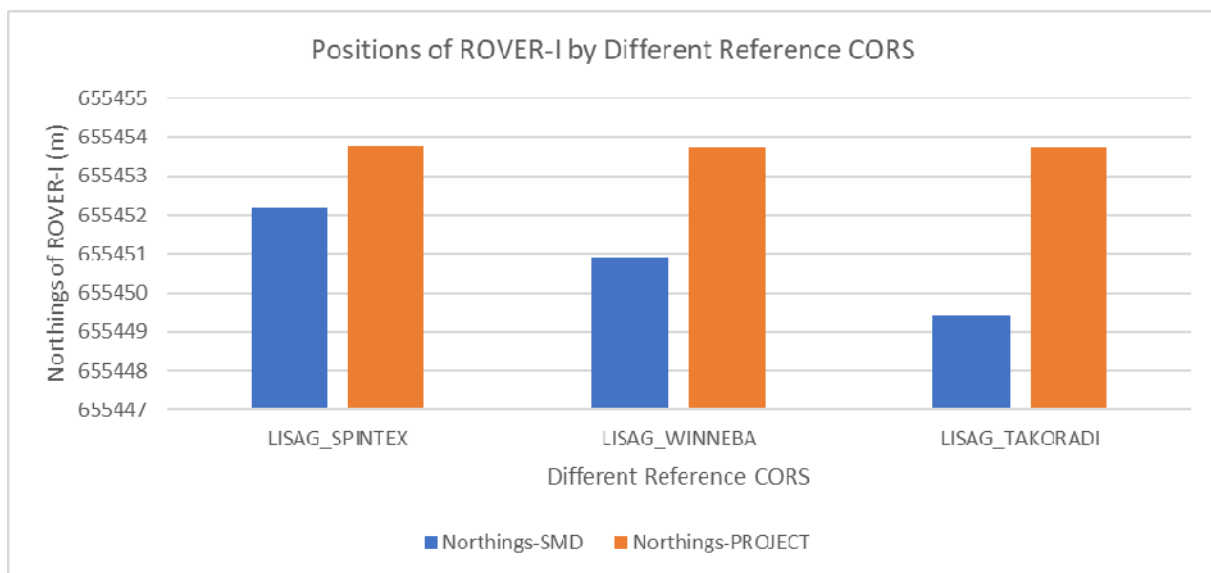


Figure 9: Northing Positions of ROVER I based on SMD coordinates and PROJECT coordinates as referenced inputs.

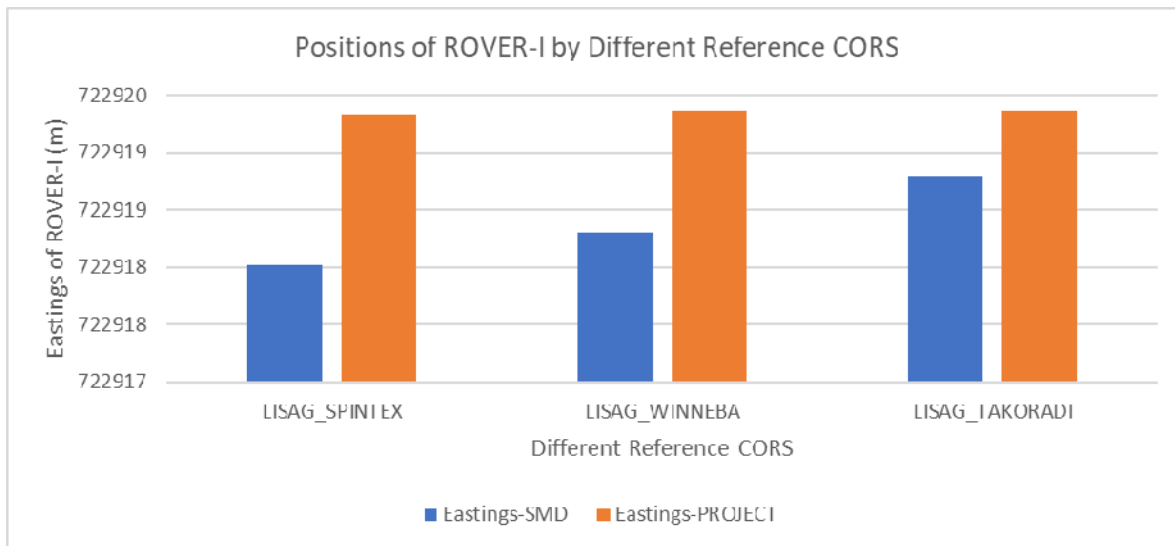


Figure 10: Eastings Positions of ROVER I based on SMD coordinates and PROJECT coordinates as referenced inputs.

Figures 9 and 10 present the northing and easting positions of ROVER I as computed from three different referenced COR stations, namely, LISAG_SPINTEX, LISAG_WINNEBA and LIASG_TAKORADI. Figures 9 and 10 show that the position of ROVER I varied significantly when fixed by different referenced COR stations using SMD coordinates as the referenced inputs. The inconsistencies in the position of ROVER I when fixed by different COR stations indicate that the positions of the referenced COR stations are not homogeneous. Figures 11 and 12 further present the mean variability in the coordinates of ROVER I using SMD coordinates and PROJECT coordinates as inputs.

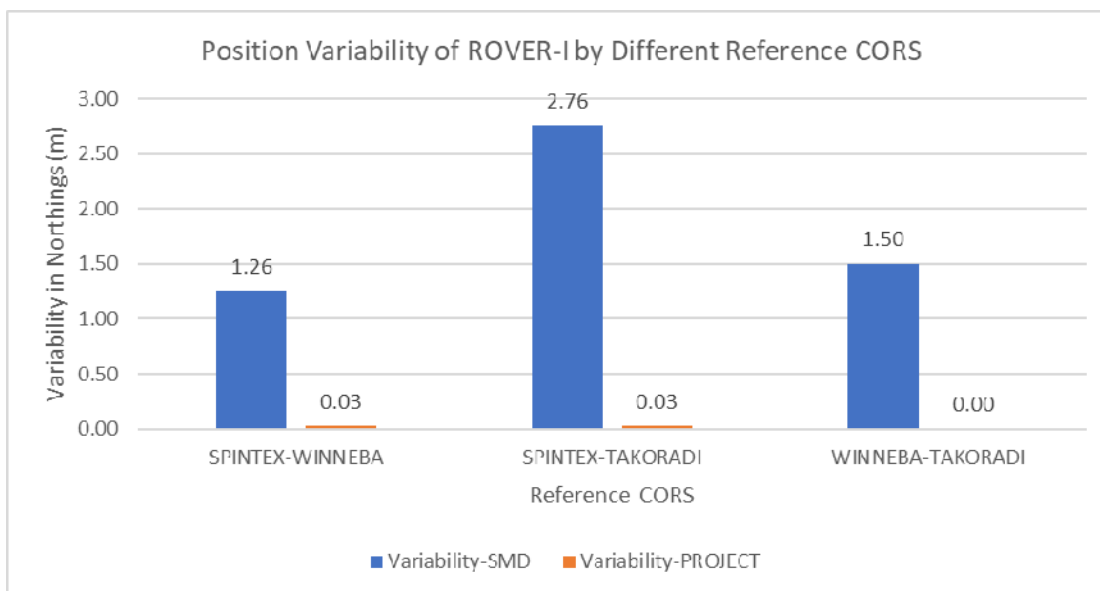


Figure 11: Mean northing variability of ROVER I using SMD coordinates and PROJECT coordinates as inputs

Ideally, the position of ROVER I should not have varied significantly if the positions of the referenced CORS used as inputs were homogeneous. This was not the case as the maximum and minimum variability in the northings of ROVER I in Figure 11 reached 2.76m and 1.26m, respectively. Similarly, the maximum and minimum variability in the eastings of ROVER I in Figure 12 were 0.78m and 0.28m, respectively. Therefore, the variability values above show that the positions of the different referenced CORSs were not homogeneous.

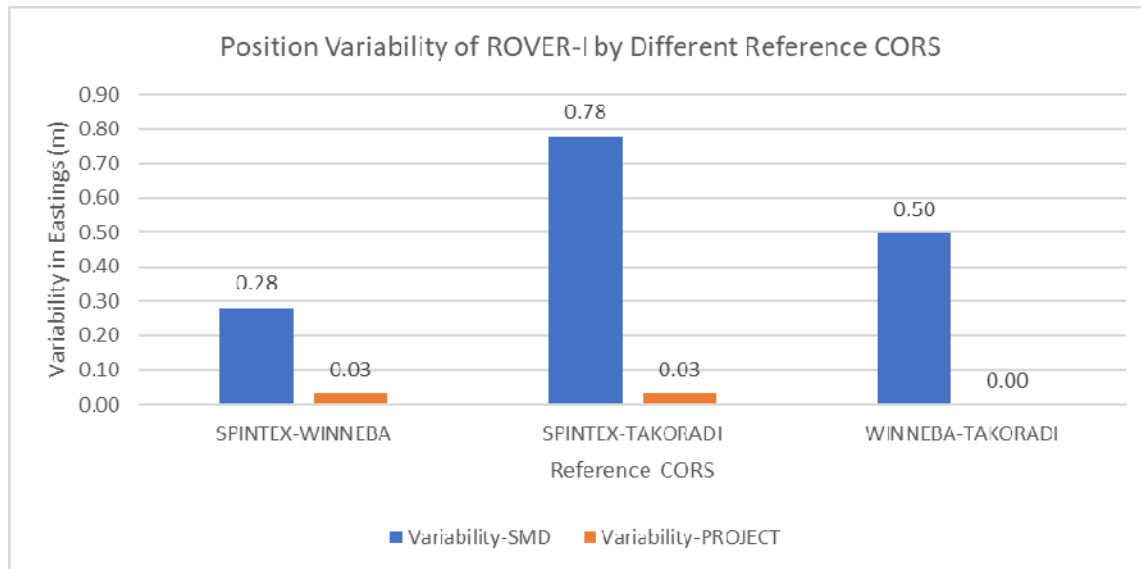


Figure 12: Mean variability of eastings of ROVER I using SMD coordinates and PROJECT coordinates as inputs

On the other hand, the mean variability in the position of ROVER I using PROJECT coordinates as inputs reached a maximum of only 0.03m. As computed in this study, this indicates a very huge improvement in the level of homogeneity among the positions of the referenced CORSs, and can be attributed to the approach in Figure 6, where all the coordinates were adjusted in a single loop by Topcon Tools software. Furthermore, this corroborates the approach proposed by Metin & Ercenk (2011). It is important to note that similar results were obtained for ROVER II which also presented a similar discussion.

In order to determine the accuracy class of the positions of the new active CORS, the variance and standard deviation were computed from the Topcon Tools software as 0.000178 and 0.0138 mm, respectively. Comparing these values with the threshold stated in Abukari *et al.* (2019) as 0.004m plus 0.001m per 100m, we classified the final adjusted coordinates of the LiSAGNet CORS as ‘first order’ coordinates.

5. Conclusion

We successfully determined the homogeneous positions of the LiSAGNet CORS, as based on ITRF2014, and using the IGS network of CORSs. The study revealed that the positions of the new CORS, as published by the SMD, are inconsistent and inhomogeneous. The results of the designed

field test revealed that the positions of the new CORS computed in this study are more homogeneous and consistent than the positions published by the SMD.

6. Recommendations

It is recommended that the Lands Commission of Ghana re-adjust the CORS coordinates to eliminate their inhomogeneity and publish the same for users in Ghana and beyond. It is also recommended that the SMD should adopt the procedure used in this study as a means of harmonizing the coordinates of the new active CORS in Ghana.

7. References

- Abukari, O. M., Acheampong, A. A., & Fosu, C. (2019). Analysis and Improvement of GNSS Baseline Solutions in Ghana. *South African Journal of Geomatics*, 8(1), 1-11.
- Andritsanos, V. D., Arabatzi, O., Gianniou, M., Pagounis, V., Tziavos, I. N., Vergos, G. S., & Zacharis, E. (2016). Comparison of various GPS processing solutions toward an efficient validation of the Hellenic vertical network: the ELEVATION project. *Journal of Surveying Engineering*, 142(1), 04015007.
- Annan, R. F., Ziggah, Y. Y., Ayer, J., & Odutola, C. A. (2016). Hybridized centroid technique for 3D Molodensky-Badekas coordinate transformation in the Ghana geodetic reference network using total least squares approach. *South African Journal of Geomatics*, 5(3), 269-284.
- Ayer, J. (2008). Transformation models and Procedures for Framework Integration of the Ghana National Geodetic Network. *The Ghana Surveyor*, 1(2), 52–58.
- Ayer, J., & Fosu, C. (2008). Map Coordinate Referencing and the use of GPS Datasets in Ghana. *Journal of Science and Technology (Ghana)*, 28(1).
- Azhari, A. (2015). Penggunaan GPS geodetik Topcon hiper II beserta pengolahannya menggunakan Topcon Tools v. 8.2 (Doctoral dissertation, Universitas Pendidikan, Indonesia).
- Deakin, R. E. (1991). A review of Least Squares theory applied to traverse adjustment. *Australian Surveyor*, 36(3), 245-253.
- Fairhurst, P., Glueckert, U., & Richter, B. (2010, September). The New Leica Viva GNSS Receiver. In *Proceedings of the 23rd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2010)*, 1386-1394.
- Ghilani, C. D. (2017). *Adjustment computations: spatial data analysis*. John Wiley & Sons.
- Ghilani, D. C., & Wolf, P. R. (2006). *Adjustment Computations. Spatial Data Analysis*, John Wiley & Sons. Inc, Hoboken, New Jersey, USA.
- Grillmayer, E. (2010). Baumaschinensteuerung in inhomogenen Koordinatenrahmen. Presentation 27 January 2010, Austrian Society for Surveying and Geoinformation.
- Gurtner, W., & Estey, L. (2007). Rinx - the receiver: independent exchange format - version 3.00. *Astronomical Institute, University of Bern and UNAVCO*, Bolulder, Colorado.
- Hamidi, M., & Javadi, P. (2017). The Analysis of Scientific and Commercial Softwares: Accuracy in GPS Observation Processing. *Open Journal of Geology*, 7(3), 267-278.
- Innac, A., Angrisano, A., Dardanelli, G., Della Corte, V., Martellato, E., Rotundi, A., ... & Gaglione, S. A. (2020). Kalman filter: single point positioning for maritime applications using a smartphone. *Geographica Technologica*, 16, 29.
- Johnson, J., & Yilmaz, E. T. (2020). Horizontal Network Least Squares Adjustment with Tau Criterion Blunder Detection and FGCS Standards Assessment with MATLAB. *Surveying and Land Information Science*, 79(2), 99-112.

- Johnston, G., Riddell, A., & Hausler, G. (2017). The international GNSS service. In *Springer Handbook of Global Navigation Satellite Systems*, 967-982. Springer, Cham.
- Laari, P. B., Ziggah, Y. Y., & Annan, R. F. (2016). Determination of 3D transformation parameters for the Ghana geodetic reference network using ordinary least squares and total least squares techniques. *International Journal of Geomatics and Geosciences*, 7(3), 245-261.
- Lemmon, T., & Wetherbee, L. (2005). Trimble® Integrated Surveying™ Techniques. *White Paper*, 1-7.
- Mageed, K. M. A. (2015). Comparison of GPS commercial software packages to processing static baselines up to 30 km. *ARPJ Journal of Engineering. Applications Science*, 10, 10640-10650.
- Metin, S., & Ercken, A. (2011). Precise point positioning *versus* traditional solutions for GNSS networks. *Scientific Research and Essays*, 6(4), 799-808.
- Mikhail, E. M., & Gracie, G. (1981). Analysis and adjustment of survey measurements. Van Nostrand Reinhold.
- Navratil, G., Kabashi, I., Ragoßnig-Angst, M., & Ragoßnig-Angst, M. Homogeneous Coordinate Frames vs Existing Inhomogeneous Data.
- Okiemute, E. S., & Oduyebo, O. F. (2018). Understanding Horizontal Geodetic Network Precision and Accuracy Determination using the Least Squares Technique. *International Journal for Innovative Research in the Multidisciplinary Field*, 4(7), 129-135.
- Okwuashi, O., & Asuquo, I. (2014). Basics of Least Squares Adjustment Computation in Surveying. *International Journal of Science and Research*, 3(8), 188-193.
- Poku-Gyamfi, Y., Kwame, T., Isaac, D., Herbert, D., and Michael, N., (2021). Establishing Ghana's active geodetic reference network as a tool for enhancing national socio-economic development buoyed by the realities of a pandemic. *FIG e-Working Week 2021 virtually in the Netherlands*, 21–25 June 2021.
- RTCM. (2016). Radio Technical Commission for Maritime Services (RTCM) Standard 10403.3, Differential GNSS (Global Navigation Satellite Systems) Services.
- Schwieger, V., Lilje, M., & Sarib, R. (2009, October). GNSS CORS-reference frames and services. In *7th FIG Regional Conference*, Hanoi, Vietnam (Vol. 19, No. 22.10, p. 2009).
- Survey Records, 1936. Reports on Triangulation Networks in Ghana.
- Topcon. (2017). HiPer V-Topcon Positioning Systems, Inc.
- Weber, G., Dettmering, D., & Gebhard, H. (2005). Networked transport of RTCM via internet protocol (NTRIP). In *A Window on the Future of Geodesy*, 60-64. Springer, Berlin, Heidelberg.
- Yaw POKU – GYAMFI, Kwame TENADU, Isaac DADZIE, Herbert DJABA and Michael NYOAGBE, (2021). Establishing Ghana's active Geodetic Reference Network as a Tool for enhancing National Socio-Economic Development buoyed by the Realities of a Pandemic. *FIG e-Working Week 2021 virtually in the Netherlands*, 21–25 June 2021.
- Ziggah, Y. Y., Ayer, J., Laari, P. B., & Frimpong, E. (2017). Coordinate transformation using Featherstone and Vaníček's proposed approach - a case study of the Ghana geodetic reference network. *Journal of Geomatics and Planning*, 4(1), 19-26.
- Zinoviev, A. E. (2005, September). Topcon Positioning Systems CIS, LLC. In *ION GNSS 18th International Technical Meeting of the Satellite Division*, 13-16.
- Zuo, Xiaoqing, Jinwei Bu, Xiangxin Li, Jun Chang, and Xiangmei Li ((2019). "The quality analysis of GNSS satellite positioning data." *Cluster Computing* 22, 3: 6693-6708.