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Assessment of the Accuracy and Consistency of GNSS RTK Measurements Based on Private Continuously Operating Reference Stations (CORS) in Nairobi

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Abstract

The advancement of Global Navigation Satellite System (GNSS) technology has enhanced navigation and positioning accuracy, reliability, and availability. In Kenya, private organizations have installed CORS to support positioning and navigation services, allowing users to access GNSS RTK corrections for survey and mapping projects. However, the accuracy and consistency of GNSS RTK measurements from private CORS remain unverified, which this study aimed to address. A study in Nairobi, Kenya, examined the accuracy and consistency of private CORS by comparing GNSS RTK measurements over stable Survey of Kenya (SoK) control points using published coordinates as a reference. Large vertical coordinate value discrepancies (8.5 m - 11 m) and relatively smaller horizontal coordinate value discrepancies (0.3 m - 2.4 m) were observed. The discrepancies arise because the private CORS operate on an independent datum, not integrated with the Survey of Kenya (SoK) geodetic control network. The proximity of control points to CORS (less than 30 km) had minimal impact on measurement accuracy. To ensure accuracy and consistency, it is recommended that private CORS be integrated into the national grid, enhancing the reliability of GNSS RTK measurements for diverse survey and mapping applications. Alternatively, users relying on private CORS must localize or perform a site calibration of their rover receivers using at least three known control points to align their measurements with the National Grid.

Keywords

GNSS, CORS, National Grid, RTK Measurements

1. Introduction

Continuously Operating Reference Stations (CORS) technology was first developed in 1986 to provide accurate High Accuracy Reference Network (HARN) surveys [1]. Initially known as the Cooperative International Global Positioning Network (CIGNET), CORS consisted of ground-based stations equipped with high-quality dual-frequency GPS receivers. In 1989, there were three CIGNET stations in the US that provided dependable tracking data to compute precise ephemerides for GPS satellites. By 1991, these had expanded to 21 sites across all continents except Antarctica. CORS technology made significant contributions to geodetic positioning by providing easy and accurate access to the National Spatial Reference System (NSRS) [2]. CORS can improve the positioning accuracy up to millimeter-level and eliminates the need to set up a base/reference station whenever millimeter-level accuracy is to be obtained in the field. CORS technology is now widely used by surveying engineers, geologists, mapping specialists, and scientists [1]. Additionally, emerging scientific applications include real-time monitoring of land subsidence, structural health monitoring, earthquake, and volcanology monitoring, GNSS reflectometry for mapping soil moisture content, precision farming, and aiding hydrology and meteorology [3].

The quality of CORS is affected by multiple factors, including the station's location, satellite visibility, equipment quality, data processing methods, environmental influences, data management, and network density. In addition, the evaluation of Artificial Neural Networks (ANN) techniques shows an improvement in their application to coordinate transformation, including the optimization of coordinate transformation techniques [4]. Key influences on data quality include signal interference, satellite geometry, differential corrections, and environmental disturbances. Addressing these factors is essential for maintaining the accuracy, reliability, and precision of CORS data [5].

In Kenya, most GNSS users currently depend on standalone base-rover setups for various positioning applications. However, the rapid development of CORS technology has led many private companies to adopt it, allowing users, particularly land and engineering surveyors, to invest in just one rover receiver instead of multiple GNSS receivers. While private companies have filled the gap left by the government's slow adoption of CORS networks, these privately installed and managed CORS Networks aim to meet the International GNSS Service (IGS) guidelines due to the lack of local CORS regulations. To demonstrate the importance of CORS utilisation for ensuring control homogeneity, a study investigated the extent of utilisation of the current CORS network [6]. Many of these private CORS are rooftop installations, raising concerns about their accuracy and consistency. To ensure reliable GNSS RTK corrections for high-accuracy applications, it is crucial to evaluate the accuracy and consistency of the corrections provided by private CORS networks. Recent research has been done on Regional ionospheric correction generation for GNSS PPP-RTK as a theoretical analysis [7], which does not address the accuracy of coordinates computed by the Network receiver based on RTK CORS corrections.

This study aimed to evaluate the accuracy and consistency of GNSS RTK measurements based on corrections broadcast by private CORS in Nairobi through GNSS RTK observations made at selected national (SoK) geodetic control points. The results of this assessment sought to provide valuable information on the accuracy and consistency of GNSS RTK measurements obtained from the private CORS. This information will be useful for various applications such as surveying, mapping, and geodetic positioning.

The majority of CORS installed in Kenya by private institutions and the Survey of Kenya (SoK) primarily cover Nairobi County, as well as southern, central, and western regions. Plans for CORS installation in northern and eastern Kenya are still under consideration [8]. To evaluate the accuracy and consistency of GNSS RTK measurements using private CORS, five national geodetic control points were selected as reference points for statistical assessment.

This paper is organised into four sections; section one gives a brief outline of the use of CORS in Kenya. Section 2 describes the data and methods used in the study. Section 3 elaborates on the results obtained after analysing the data collected during the study. Finally, section 4 covers the conclusions and recommendations of the study.

2. Data and Methods

Assessment of the accuracy and precision of GNSS RTK measurements based on private CORS required several control points whose coordinates were well known to a higher degree of accuracy. Five published Survey of Kenya (SoK) control points were selected for this study. These control points served as a reference for comparison during the statistical evaluation of the accuracy and consistency of the GNSS RTK measurements. The analysis becomes more robust with an increased number of available control points.

2.1. Area of Study

Nairobi, the capital of Kenya, has a population of approximately 4.7 million [9] and spans 696 square kilometers at an average altitude of 1,684 m. It borders Kiambu to the north, Kajiado to the southwest, and Machakos to the southeast. The study focused on SoK control points in Nairobi's central region, as many have been vandalized due to scrap metal trade or misinformation about mercury beneath the monuments. Stable and existing control points were used for the study.

2.2. Methodology

To assess the accuracy and consistency of GNSS RTK measurements from private CORS, published coordinates of SoK control points were obtained, and a reconnaissance survey was conducted to validate their suitability. A methodology that integrated the use of multiple constellations was used in the collection of control point data [10]. Control points were selected away from high-voltage power lines, buildings, and trees to minimize signal interference and errors. Login credentials were obtained from private CORS providers to access GNSS RTK corrections. Field data collection was followed by data pre-processing, processing, and adjustment. Finally, GNSS RTK measurements were compared with published coordinate values to evaluate accuracy.

2.3. Mission Planning, Reconnaissance, and Acquisition of Relevant Data

2.3.1. Mission Planning

Mission planning is crucial in GNSS data collection to achieve desired accuracy efficiently. Control points were carefully selected to represent the study area's terrain and elevation, while avoiding high-rise buildings and powerlines to minimize multipath errors and signal interference, respectively [11]. The coordinates of these points were plotted in ArcMap, converted to KML format, and used with Google Earth on a smartphone to facilitate efficient field navigation to the control points.

Figure 1 shows the study area map, distribution of the Private CORS, and the Survey of Kenya Control Points in Nairobi County, Kenya.

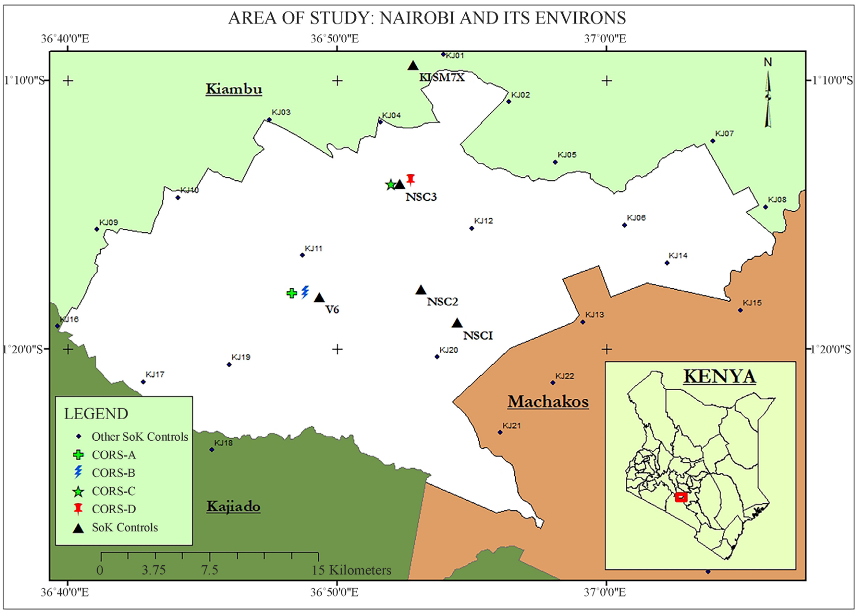

Figure 1. Study area map, SoK control points, and private CORS in Nairobi.

From the Study Area Map in Figure 1, it is critical to recognize that all four private CORS installed in Nairobi are clustered within a radius of 15 kilometers. Moreover, CORS A and B, as well as CORS C and D, are within a radius of 2 kilometers from each other. The uneven station distribution is a consequence of uncoordinated CORS installation, therefore compromising spatial coverage within the study area.

2.3.2. Reconnaissance and Acquisition of Relevant Data and Information

Visits to private companies managing CORS were conducted to gather key information for successful data collection. This included determining the number of operational CORS in the study area, collecting the coordinates of the installed CORS for accurate data collection, post-processing, and understanding the coordinate systems used to ensure the data was correctly referenced.

To effectively plan the data collection mission, it was important to understand access restrictions and the coverage of the CORS network [6]. Information on compatible receivers for the operational CORS was sought to ensure proper equipment was used. Additionally, login credentials, including IP address, username, port, and password, were obtained to configure the rover receiver and access RTK corrections from private CORS in Nairobi.

2.4. GNSS RTK Data Collection

This phase involved collecting GNSS RTK measurements based on corrections from private CORS at chosen SoK control points in the area of study.

Table 1 shows the SoK control points and their coordinates within the area of study in UTM Arc 1960 datum, Clarke 1880 ellipsoid.

Table 1. TC & ST chart 1511 control point coordinates in UTM Arc 1960 Datum zone 37 M.

Point Name	Northing (m)	Easting (m)	Elevation (m)	Description
KISM7X	9,872,069.740	264,174.210	1592.768	Brass in concrete
V6	9,856,148.286	257,722.959	1663.914	Brass in concrete
NSCI	9,854,395.219	267,191.144	1627.721	I.P.C New
NSC2	9,856,697.208	264,729.463	1631.756	I.P.C New
NSC3	9,863,872.317	263,246.503	1624.459	I.P.C New

The GNSS RTK field data collection was done using a UniStrong GNSS receiver with an Android data collector installed with Surpad Version 4.2 field data collection software. During data collection, one had to make sure that the data collector had stable internet access. For this purpose, a Safaricom SIM card (GSM Card) loaded with data bundles (at least 50 megabytes) was inserted into the data collector. It was also important to create a new project and define the coordinate system parameters.

The next step was to connect the data collector with the Rover receiver via Bluetooth and to ensure that the receiver was tracking an optimum number of satellites needed for it to compute its position. This was then followed by connecting the rover receiver to a chosen private CORS. At each control point, four different readings were made by logging into the four different private CORS available. Before recording the observations, that is, the X, Y, and Z coordinates for the control points, one had to check that the rover receiver had a fixed solution and the PDOP value was below 3.0. The RTK measurements were averaged for at least 30 seconds. The same procedure was repeated on all five chosen SoK control points.

It is important to note that the four Private CORS used in the study were all transmitting RTK corrections as single bases using the averaged coordinates of the antenna location.

3. Results and Discussion

The measured coordinates for every control point were collated and matched with the corresponding published Survey of Kenya control point coordinates. Subsequently, the differences between the two sets of data were determined. Additionally, the distance between each control point and the base station was calculated to evaluate if the baseline length had any impact on the measurement. The coordinates obtained at the SoK control points based on all four private CORS used in the study are presented in Tables 2-5. Four Private CORS sites, that is, A, B, C, and D, were used in the study.

Table 2 is a comparison of coordinates measured at the five selected Survey of Kenya Control points based on RTK corrections from CORS site A.

Table 3 is a comparison of coordinates measured at the five selected Survey of Kenya Control points based on RTK corrections from CORS site B.

Table 4 is a comparison of coordinates measured at the five selected Survey of Kenya Control points based on RTK corrections from CORS site C.

Table 5 is a comparison of coordinates measured at the five selected Survey of Kenya Control points based on RTK corrections from CORS site D.

Table 2. Comparison of coordinates measured based on CORS-A.

Station ID	SOK Published Control Point Coordinates			Measured Control Point Coordinates Based on CORS-A						
	Y (m)	X (m)	Z (m)	Y (m)	X (m)	Z (m)	Distance from Base (m)	ΔY	ΔX	ΔZ
KISM7X	9,872,069.740	264,174.210	1592.768	9,872,072.129	264,174.567	1583.730	17,375.842	−2.389	−0.357	9.038
V6	9,856,148.286	257,722.959	1663.914	9,856,150.365	257,723.295	1653.962	1029.360	−2.079	−0.336	9.952
NSC1	9,854,395.219	267,191.144	1627.721	9,854,397.160	267,191.501	1617.272	10,657.680	−1.941	−0.357	10.449
NSC2	9,856,697.208	264,729.463	1631.756	9,856,699.195	264,729.820	1621.524	8017.076	−1.987	−0.357	10.232
NSC3	9,863,872.317	263,246.503	1624.459	9,863,874.551	263,247.018	1614.564	9941.120	−2.234	−0.515	9.895

Table 3. Comparison of coordinates measured based on CORS-B.

Station ID	SOK Published Control Point Coordinates			Measured Control Point Coordinates Based on CORS-B						
	Y (m)	X (m)	Z (m)	Y (m)	X (m)	Z (m)	Distance from Base (m)	ΔY	ΔX	ΔZ
KISM7X	9,872,069.740	264,174.210	1592.768	9,872,071.266	264,174.842	1584.237	17,762.265	−1.526	−0.632	8.531
V6	9,856,148.286	257,722.959	1663.914	9,856,149.491	257,723.564	1654.524	1912.836	−1.205	−0.605	9.390
NSC1	9,854,395.219	267,191.144	1627.721	9,854,396.280	267,191.793	1617.851	11,539.492	−1.061	−0.649	9.870
NSC2	9,856,697.208	264,729.463	1631.756	9,856,698.330	264,730.109	1622.089	8909.025	−1.122	−0.646	9.667
NSC3	9,863,872.317	263,246.503	1624.459	9,863,873.351	263,247.118	1614.564	10,536.976	−1.034	−0.615	9.895

Table 4. Comparison of coordinates measured based on CORS-C.

Station ID	SOK Published Control Point Coordinates			Measured Control Point Coordinates Based on CORS-C						
	Y (m)	X (m)	Z (m)	Y (m)	X (m)	Z (m)	Distance from Base (m)	ΔY	ΔX	ΔZ
KISM7X	9,872,069.740	264,174.210	1592.768	9,872,071.002	264,175.177	1584.013	8349.290	−1.262	−0.967	8.755
V6	9,856,148.286	257,722.959	1663.914	9,856,149.506	257,723.689	1654.297	9155.276	−1.220	−0.730	9.617
NSC1	9,854,395.219	267,191.144	1627.721	9,854,396.441	267,191.961	1617.805	10,493.265	−1.222	−0.817	9.916
NSC2	9,856,697.208	264,729.463	1631.756	9,856,698.413	264,730.275	1622.082	7455.281	−1.205	−0.812	9.674
NSC3	9,863,872.317	263,246.503	1624.459	9,863,873.584	263,247.394	1615.469	587.923	−1.267	−0.891	8.990

Table 5. Comparison of coordinates measured based on CORS-D.

Station ID	SOK Published Control Point Coordinates			Measured Control Point Coordinates Based on CORS-D						
	Y (m)	X (m)	Z (m)	Y (m)	X (m)	Z (m)	Distance from Base (m)	ΔY	ΔX	ΔZ
KISM7X	9,872,069.740	264,174.210	1592.768	9,872,071.362	264,176.169	1582.683	7980.254	−1.622	−1.959	10.085
V6	9,856,148.286	257,722.959	1663.914	9,856,149.925	257,724.871	1653.206	10,129.290	−1.639	−1.912	10.708
NSC1	9,854,395.219	267,191.144	1627.721	9,854,396.665	267,193.028	1616.420	11,984.912	−1.446	−1.884	11.301
NSC2	9,856,697.208	264,729.463	1631.756	9,856,698.742	264,731.412	1620.710	7429.020	−1.534	−1.949	11.046
NSC3	9,863,872.317	263,246.503	1624.459	9,863,873.928	263,248.462	1613.943	793.164	−1.611	−1.959	10.516

From analysis of the disparities between the published control point coordinates and the measured control point coordinates illustrated in Tables 2-5, it was established that the baseline length between the control points and the CORS did not have a noteworthy impact on the average measured control point coordinates. For example, NSC3 is 600 metres from CORS-C, but the Root Mean Square Error (RMSE) value is greater than that of KISM7X, which is over 8 km away. This is because all the control points were situated within a 20 km radius of the CORS, while the minimum distance that can potentially influence CORS measurement is over 30 km [12].

Table 6 compares the discrepancies between the published SoK control point coordinates and the GNSS RTK measured coordinates based on the four private CORS used in the study. The discrepancies are arranged in the order: Nothing (ΔY), Easting (ΔX), and Elevation (ΔZ) for each of the five control points. Table 6 also shows the mean, standard deviation, and RMSE of the discrepancies for the five control points with respect to the individual CORS.

From Table 6, it is observed that there are discrepancies in the Eastings ranging from −0.336 m to −1.959 m, Northings ranging from −1.034 m to −2.389 m, and elevation ranging from 8.531 m to 11.046 m. Evidently, the Z coordinate values have the largest discrepancies. The significant variation in Z coordinates can be attributed to the fact that the SoK control points have orthometric heights, while

Table 6. Comparison of coordinate discrepancies at SoK controls based on the four private CORS.

Station ID	CORS-A					CORS-B					CORS-C					CORS-D				
	ΔY (m)	ΔX (m)	ΔZ (m)	**RMSE (m)**	**Distance from Base (m)**	ΔY (m)	ΔX (m)	ΔZ (m)	**RMSE (m)**	**Distance from Base (m)**	ΔY (m)	ΔX (m)	ΔZ (m)	**RMSE (m)**	**Distance from Base (m)**	ΔY (m)	ΔX (m)	ΔZ (m)	**RMSE (m)**	**Distance from Base (m)**
KISM7X	−2.389	−0.357	9.038	**5.401**	**17375.842**	−1.526	−0.632	8.531	**5.017**	**17762.265**	−1.262	−0.967	8.755	**5.137**	**8349.290**	−1.622	−1.959	10.085	**6.005**	**7980.254**
V6	−2.079	−0.336	9.952	**5.873**	**1029.360**	−1.205	−0.605	9.39	**5.477**	**1912.836**	−1.22	−0.73	9.617	**5.613**	**9155.276**	−1.639	−1.912	10.708	**6.351**	**10129.290**
NSC1	−1.941	−0.357	10.449	**6.139**	**10657.680**	−1.061	−0.649	9.87	**5.744**	**11539.492**	−1.222	−0.817	9.916	**5.788**	**10493.265**	−1.446	−1.884	11.301	**6.667**	**10204.848**
NSC2	−1.987	−0.357	10.232	**6.021**	**8017.076**	−1.122	−0.646	9.667	**5.631**	**8909.025**	−1.205	−0.812	9.674	**5.648**	**7455.281**	−1.534	−1.949	11.046	**6.536**	**7429.020**
NSC3	−2.234	−0.515	9.895	**5.864**	**9941.120**	−1.034	−0.615	9.895	**5.755**	**10536.976**	−1.267	−0.891	8.99	**5.267**	**587.923**	−1.611	−1.959	10.516	**6.246**	**793.164**
Mean	**−2.126**	**−0.3844**	**9.9132**			**−1.190**	**−0.629**	**9.471**			**−1.235**	**−0.843**	**9.390**			**−1.570**	**−1.933**	**10.731**		
STDEV	**0.185**	**0.074**	**0.538**			**0.199**	**0.019**	**0.563**			**0.028**	**0.090**	**0.493**			**0.080**	**0.033**	**0.471**		
RMSE	**2.132**	**0.390**	**9.925**			**1.203**	**0.630**	**9.484**			**1.235**	**0.847**	**9.401**			**1.572**	**1.933**	**10.739**		

the measured coordinates based on CORS are ellipsoidal heights. Additionally, there is a significant difference between the published and measured coordinates because the private CORS used in the study are not integrated with the SoK national geodetic network.

Figure 2-4 indicates a plot of comparison of discrepancies in X, Y, and Z coordinates, respectively, at the five selected Survey of Kenya controls based on GNSS RTK corrections from the four CORS Sites. Discrepancy is computed by subtracting the measured coordinate values from the published SOK control coordinate values.

Table 7 shows averages of the Mean, STADEV, and RMSE for the Four Private CORS-A, B, C, and D. From the data presented in Table 7, the study was able to assess the accuracy and consistency of each private CORS as discussed in the preceding sections 3.1 and 3.2.

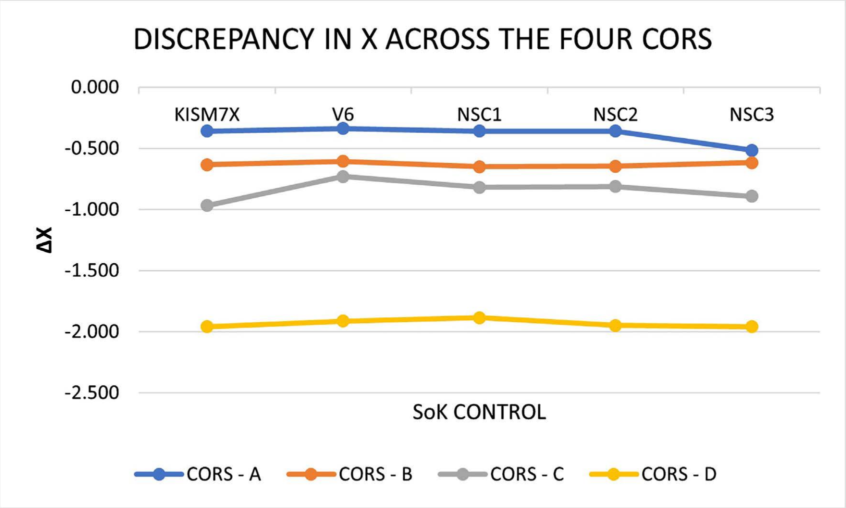

Figure 2. A Plot of the discrepancies in the X coordinate values for the five control points based on GNSS RTK corrections from the four CORS.

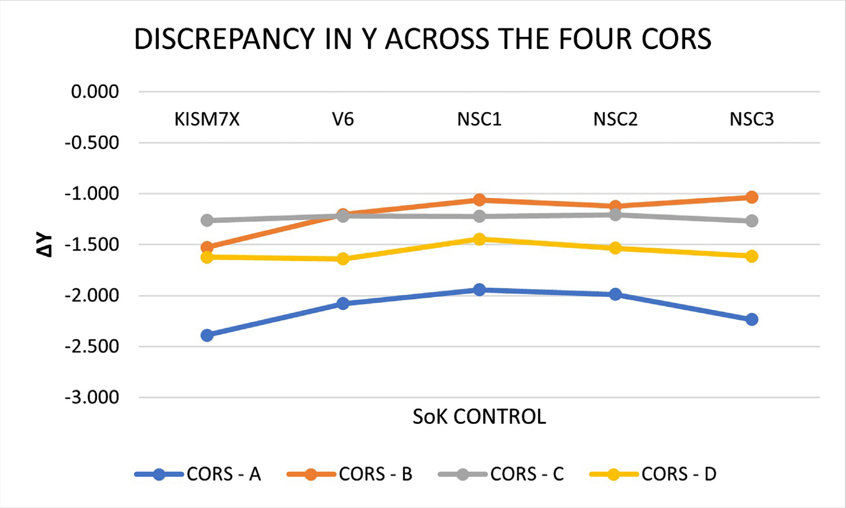

Figure 3. A plot of the discrepancies in the Y coordinate values for the five control points based on GNSS RTK corrections from the four CORS.

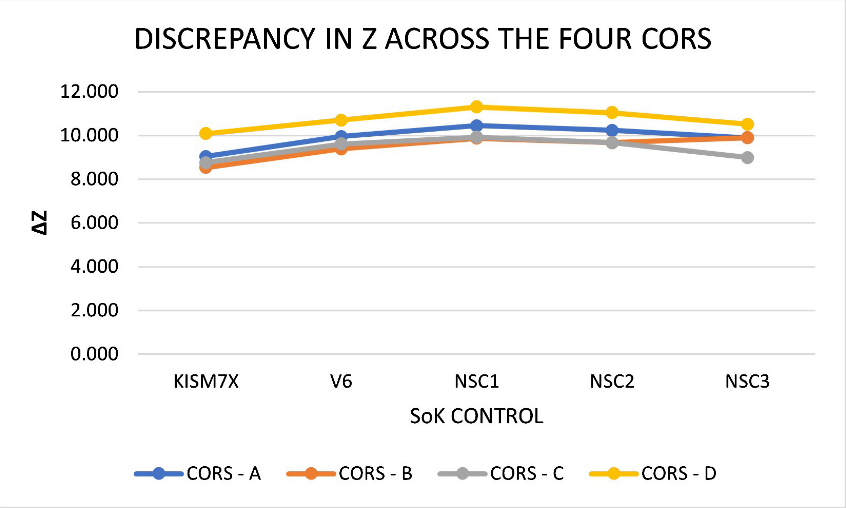

Figure 4. A plot of the discrepancies in the Z coordinate values for the five control points based on GNSS RTK corrections from the four CORS.

Table 7. Averages of the mean, STADEV, and RMSE for the four private CORS.

Description	CORS-A	CORS-B	CORS-C	CORS-D
Average Mean	2.468	2.551	2.437	**2.409**
Average STDEV	0.265	0.260	0.203	**0.195**
Average RMSE	4.149	**3.772**	3.828	4.748

3.1. Accuracy

Accuracy is a measure of how close a measurement or set of measurements is to the true or accepted value [13] [14]. To evaluate accuracy, the average discrepancies at each control point were calculated (see Table 6 and Table 7). Typically, the CORS with the smallest average value provides the most accurate measurement. The objective is to minimize the differences between the SoK control points and the CORS GNSS RTK-measured coordinates of the same control points. Among the private CORS, CORS-D had the lowest average discrepancy, with a mean value of 2.409.

3.2. Consistency and Reliability

Consistency refers to the repeatability and internal agreement of measurements over time and between different receivers or measurement techniques. Consistency is estimated based on standard deviation and Root Mean Square Error values (see Table 7).

Standard deviation measures the degree of variability or dispersion of the differences from the mean, while Root Mean Square Error is one of the standard ways to measure the error rate of a model in predicting quantitative data. Measurements based on the private CORS with the lowest standard deviation and Root Mean Square Error are considered the most consistent. Table 7 shows that CORS-D had the lowest average standard deviation of 0.195, while CORS-B had the lowest average Root Mean Square Error of 3.772.

Reliability, on the other hand, refers to the trustworthiness and correctness of the measurements. It is the ability of a system to detect, isolate, and resist errors (blunders). A low standard deviation suggests high reliability, as it reflects the consistency of repeated measurements or observations. From the study, CORS-D has the lowest standard deviation, therefore, it is the most reliable CORS, followed by C, B, and A, in that order.

4. Conclusions and Recommendations

4.1. Conclusions

Analysis of GNSS RTK measurements from the four private CORS (A, B, C, and D) revealed discrepancies with SoK-published control point coordinates. It was noted that the large deviations in the vertical coordinate component were due to the fact that GNSS measurements recorded in the field during the study were referenced to the ellipsoid (ellipsoidal heights), while published SoK control point heights were geoid-based (orthometric heights). This is because the field data collection software used during the study did not incorporate a local geoid model (that gives the specific values of the Geoid separation, N, for the location of the different control points observed in Nairobi) to enable real-time conversion of ellipsoidal heights to orthometric heights, which is the direct cause of the observed discrepancy.

The variation between measured and published coordinates is attributed to the fact that the four private CORS are not integrated into the Kenya National Geodetic Network, and the RTK corrections computed and transmitted were based on averaged single base coordinates. In this study, the baseline length between the CORS and control points was below 30 km, meaning it did not significantly affect the observed discrepancies.

RTK measurements based on private CORS without site calibration do not meet industry accuracy standards, such as the +/−0.03 m required for cadastral surveys in Kenya. Reliability of corrections from the private CORS is also an issue, with interruptions in RTK correction services due to mobile network disruptions. Furthermore, uncoordinated deployment of CORS has led to a spatial clustering of all four private stations within a 15 km radius in Nairobi, creating a significant geographic disparity in RTK correction coverage.

It is prudent to note that the findings in this study are based on five control points within Nairobi and may not be generalizable to other regions of Kenya or to CORS networks with different configurations.

4.2. Recommendations

To optimize private CORS networks for better RTK measurement accuracy, reliability, and consistency, it is recommended that the Survey of Kenya take a lead role in the coordination and development of standards for the installation of CORS by both public agencies and private companies, ensuring that all installed

CORS are integrated into the Kenya National Geodetic Network. Activities such as network design for public and private CORS should be centrally coordinated to reduce duplication of effort.

CORS application and usage is a new concept to most users; therefore, there is a need to develop field manuals to be followed during the execution of survey projects in the field using CORS. For one to tie the measurements based on CORS to the National Grid, it is mandatory to localize or carry out a site calibration of the GNSS rover receiver in the field using published coordinates of SoK control points. These field procedures should be clearly stated in the GNSS field manual developed by both the Survey of Kenya and private players in the industry.

GNSS site calibration also known as localization is a critical process of establishing a precise mathematical relationship between a global GNSS based coordinate system such as WGS84 or ITRF and a local project coordinate system for instance UTM Arc Datum 1960 Zone 37 South for Nairobi Kenya, by using a set of control points (usually a minimum of three points) with known coordinates in both systems to calculate transformation parameters—specifically a translation, rotation, and scale factor (Helmert transformation). This calibrated model, once validated with independent checkpoints to ensure accuracy within project tolerances, is then applied within the GNSS receiver, allowing real-time measurements from a rover to be output directly in the desired local coordinates, thereby seamlessly linking global satellite positioning coordinate systems with local coordinates that support project-specific mapping and construction needs.

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Conflicts of Interest

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

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