Development of Low Cost Real-Time Kinematic GNSS System for Precise Positioning in Bangladesh

Md. Sajjad Hossen
Electrical and Electronic Engineering
Jatiya Kabi Kazi Nazrul Islam University
Mymensingh, Bangladesh-2224
orcid.org/0009-0004-6019-2208

MD. Shameem Ahammed
Electrical and Electronic Engineering
Jatiya Kabi Kazi Nazrul Islam University
Mymensingh, Bangladesh-2224
orcid.org/0009-0003-9824-6884

Kazi Md. Shahiduzzaman
Electrical and Electronic Engineering
Jatiya Kabi Kazi Nazrul Islam University
Mymensingh, Bangladesh-2224
orcid.org/0000-0002-4323-7177

***Abstract*—Accurate real-time positioning remains a major challenge in developing regions where access of nearby Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) reference networks is limited. This study design and establishes a low-cost RTK GNSS reference station for centimeter-level positioning. The system uses a dual-frequency GNSS receiver and an open-access NTRIP caster for real-time correction data. The base station's position was determined using CSRS-PPP and validated against known geodetic control points. The system consistently achieved relative horizontal accuracy within 2 cm and vertical accuracy within 3 cm at a 11 km baseline. Compared to existing expensive commercial solutions, the proposed setup offers a significantly lower cost while providing competitive precision. This implementation establishes the foundational basis for constructing a national Real-Time Kinematic Global Navigation Satellite System infrastructure in Bangladesh, thereby enabling critical support for applications such as geospatial surveying, precision agriculture, and autonomous navigation systems.**

***Keywords*—GNSS, RTK, Low-cost GNSS receivers, Positioning, PPP**

I. Introduction

The Global Navigation Satellite System (GNSS) plays a crucial role in providing accurate positioning solutions for numerous applications, including surveying, precision agriculture, autonomous vehicles, construction, and geospatial research. With advancements in satellite constellations such as Global Positioning System-GPS (United States), GLObal NAvigation Satellite System-GLONASS (Russia), Galileo (European Union), BeiDou (China), Navigation with Indian Constellation-NavIC (India), and Quasi-Zenith Satellite System-QZSS (Japan), GNSS receivers can now achieve sub-meter accuracy. However, many applications demand centimeter-level precision, which is traditionally only possible with geodetic-grade GNSS equipment [1].

In developing countries like Bangladesh, the adoption of high-accuracy Global Navigation Satellite System technologies has been limited. This is primarily due to the high cost of precision equipment and the scarce availability of reliable correction services. Consequently, Bangladesh has yet to fully leverage the capabilities and potential benefits offered by Real-Time Kinematic GNSS systems. While developed countries have fully functional Continuously Operating Reference Station (CORS) networks that provide Real-Time Kinematic (RTK) corrections, Bangladesh currently has only one publicly available Continuously Operating Reference Station (CORS) operated by the Survey of Bangladesh (SOB) [2]. This limitation affects industries such as land surveying, disaster management, and precision agriculture, where highly accurate geospatial data is essential. Establishing a cost-effective RTK GNSS system with open-access correction services is, therefore, a crucial step toward improving high-precision positioning in the context of Bangladesh.

High-accuracy GNSS positioning has historically relied on expensive geodetic instruments, primarily used for military, governmental, and large-scale industrial applications [3]. With technological advancements, dual-frequency consumer-grade GNSS receivers such as the u-blox ZED-F9P and Septentrio Mosaic-X5 have made high-precision positioning more accessible [4]. These receivers, when integrated with RTK correction services, enable centimeter-level accuracy at a fraction of the cost of traditional geodetic equipment [5].

Existing studies have explored different methods of improving GNSS accuracy, including Real-Time Kinematic (RTK) [3], Precise Point Positioning (PPP) [6], and Post-Processing Kinematic (PPK) [5]. However, most of these studies have been conducted in regions with well-established CORS networks, limiting their applicability in countries like Bangladesh where correction services are not widely available. Moreover, the potential of open-access NTRIP-based RTK services has not been thoroughly investigated in the context of Bangladesh. The lack of a comprehensive framework for establishing a low-cost RTK correction network remains a significant research gap.

This research aims to establish a low-cost high-accuracy RTK GNSS positioning system in the context of Bangladesh. The primary contributions of this work are:

- Establishing a standalone RTK base station to provide correction data in areas without a CORS network.
- Implementing an open-access NTRIP service to facilitate RTK corrections for multiple users.
- Conducting high-precision geospatial measurements using a low-cost dual-frequency GNSS receiver.
- Evaluating the accuracy of acquired the initial base station absolute position through PPP by collecting and process-

ing 24-hour static GNSS data.
- Evaluating the rover's positional accuracy against geodetic control points under both RTK-enabled and RTK-disabled conditions.

The proposed system was implemented using two dual-frequency GNSS receiver, one configured as a base station, and another one was configured as the rover station which is then tested for positional accuracy against geodetic control points placed by the Survey of Bangladesh (SOB). By leveraging PPP, we determined the initial absolute position of our base station before connecting the rover station for receiving the RTK corrections.

The results demonstrate that the open-access RTK system achieves a static positioning accuracy of 2–3 cm horizontally and 4–6 cm vertically under optimal conditions, which aligns with existing high-accuracy GNSS solutions [7]. Compared to traditional geodetic systems, our approach significantly reduces hardware costs while maintaining comparable accuracy for short baselines. The absolute accuracy of the base station was determined using PPP and validated against geodetic control points [8]. Furthermore, real-time RTK corrections significantly improved rover positioning accuracy, demonstrating the feasibility of an open-access RTK GNSS system for practical use in Bangladesh.

The rest of this paper is structured as follows: Section II provides an overview of the Materials and Method that usage in this paper, where included Hardware in Context, Precise Point Positioning Method and GNSS Derivation Analysis. Section III discusses the Experimental Setup including Setting up the reference station, Performance Assessment. Section IV analyzes the Result and Discussion including Precise Point Positioning Result, Evaluating the Deviation Between Rover Measurements and Geodetic Control Points, and Geodetic Point reference for the base station. Finally, Section V concludes the paper and suggests potential future research directions.

II. Materials and Method

This section describes the experimental hardware and measurement methodology used in this study. It provides details on the specific equipment and techniques employed to conduct the research and gather the necessary data.

A. Hardware in context

The rooftop of the Faculty of Science and Engineering at Jatiya Kabi Kazi Nazrul Islam University (JKKNIU) was chosen as the location for the RTK fixed base station. In this project, we utilized the ublox ZED-F9P board and antenna. The ardusimple which is ublox ZED-F9P based hardware was employed for this study.

The hardware list includes:

- 2 simple RTK2B Budget boards
- 2 Radio Modules LR + 2 radio antennas (915-927MHz)
- 2 u-blox GNSS Multiband antennas ANN-MB-00
- One mini Windows PC for the base station
- 10cm Antenna base plate

Additionally, we fabricated all the supporting materials for the base station antenna and permanently installed them on the rooftop of the building. In our case, the ardusimple hardware did not have any enclosure, so we 3D printed all the necessary enclosure parts and survey mounting materials. The 3D printed files can be accessed through the supporting material section.

B. Precise Point Positioning (PPP) Method

Precise Point Positioning improves upon single-point positioning by using carrier-phase measurements to achieve centimeter-level accuracy [9]. Unlike Real-Time Kinematic, which relies on local base station corrections, PPP uses precise satellite orbit and clock data from global networks [10]. Dual-frequency antennas and receivers mitigate ionospheric effects, and factors like tidal motion, offsets, and tropospheric delays are modeled (PPP Standards, 2020). Centimeter-level accuracy is typically achieved within 30 minutes, with millimeter-level accuracy requiring longer observation periods [5]. PPP is essential for static and kinematic applications, from surveying to tsunami detection. Combining PPP and RTK can enhance accuracy if latency is minimized and ambiguities are resolved quickly. This research used the CSRS-PPP [11] online service to determine the base station's absolute position within the Canadian Spatial Reference System.

C. GNSS Deviation Analysis

To assess the accuracy of the static GNSS measurements, we compared each recorded position against a known geodetic control point. The deviations were calculated in a projected coordinate system (Universal Transverse Mercator, UTM) to ensure consistency in distance measurements.

The horizontal deviations were analyzed using root mean square error. The vertical deviations were also evaluated to understand the overall accuracy of the static GNSS surveys.

1) Coordinate Transformation and Deviation Calculation: Given a geodetic control point with coordinates (E_c, N_c) and a set of GNSS static measurements (E_i, N_i), the deviations in the Easting (ΔE_i) and Northing (ΔN_i) directions are computed as follows:

$$\Delta E_i = E_i - E_c \quad (1)$$

$$\Delta N_i = N_i - N_c \quad (2)$$

where:

- E_c, N_c represent the Easting and Northing coordinates of the control point.
- E_i, N_i represent the Easting and Northing coordinates of the i-th GNSS measurement.

Each static points is then plotted in a deviation map, where the control point is positioned at the origin $(0, 0)$. The coordinate transformation follows a 3-parameter transformation model [12]:

$$X_o = X_i + t_x, \quad Y_o = Y_i + t_y, \quad Z_o = Z_i + t_z \quad (3)$$

where (X_o, Y_o, Z_o) are the transformed coordinates, (X_i, Y_i, Z_i) are the original coordinates, and (t_x, t_y, t_z)

are the translation parameters derived from the arithmetic mean of coordinate differences.

2) Positional Deviation Measurement: To quantify the overall deviation of each GNSS measurement from the control point, the Euclidean distance is used [12]:

$$D_i = \sqrt{(\Delta E_i)^2 + (\Delta N_i)^2} \tag{4}$$

where D_i represents the absolute positional deviation (in meters) for the i-th GNSS measurement.

3) Root Mean Square Error (RMSE) Calculation: RMSE is a widely used metric for evaluating GNSS accuracy. It considers the squared differences between observed and reference values, thus emphasizing larger discrepancies more heavily. The mathematical definition is as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} D_i^2} \tag{5}$$

where:

- N is the total number of GNSS points observations.
- D_i is the positional deviation of the i-th GNSS measurement, computed as:

$$D_i = \sqrt{(\Delta E_i)^2 + (\Delta N_i)^2} \tag{6}$$

- ΔE_i and ΔN_i represent the deviations in Easting and Northing directions, respectively.

A lower RMSE value indicates increased precision in GNSS positioning compared to the reference geodetic control point.

4) Circular Deviation Reference Thresholds: The magnitudes of the deviations are visualized by drawing circular reference lines around the geodetic control point at predetermined threshold values. [12]:

$$D = r \tag{7}$$

where r represents a predefined accuracy threshold (e.g., $r =$ 0.5m, $r = 1.0$m). These circles help classify the deviation levels, with smaller circles indicating higher precision.

5) RMSE Calculation for Ellipsoidal Height: We evaluated the accuracy of the collected ellipsoidal height values by calculating the Root Mean Square Error against the reference ellipsoidal height.

The RMSE is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{8}$$

where:

- y_i represents the collected ellipsoidal heights from the dataset.
- $\hat{y}_i$ is the geodetic point reference ellipsoidal height.
- n denotes the total number of data points.

III. Experimental Setup

A. Setting up the reference station

The reference station was established on the rooftop of the Faculty of Science and Engineering at JKKNIU in Bangladesh as shown in the fig. 1. The base station was equipped with a ublox ZED-F9P dual-frequency GNSS receiver and U-blox ANN-MB GNSS antenna on top of a 10cm cicular base plate. The hardware used in this study included the ardusimple simpleRTK2B Budget board, a ublox ZED-F9P-based hardware solution. A 3D printed box was used to house the GNSS receiver.

Fig. 1. GNSS permanent reference station setup on the rooftop of the Faculty of Science and Engineering at JKKNIU

To ensure the stability and reliability of the reference station, it was permanently installed on the rooftop and provided with a dedicated power supply.

The reference station was configured to operate in NTRIP mode, enabling it to provide real-time 1Hz GNSS observations to users within its coverage area. A mini Windows PC connected via LAN was used to broadcast the RTK correction. The mini PC was configured with auto power-on in the BIOS, ensuring the reliability of the base station.

The base station was registered with the rtk2go NTRIP Caster service, and its mount point information is publicly available to enable user access. As described in the supporting materials [13], open-source software RTKLIB was used to broadcast the RTK correction data [14]. Within RTKLIB, the STRSVR module served as the Caster to transmit the correction data. The STRSVR module used a USB serial port as the input, and the NTRIP server was selected as the output to cast the RTK correction data to the desired NTRIP caster service. In our case, the free community-based caster service rtk2go.com was utilized.

To determine the accurate position of the base station, the Precise Point Positioning method was utilized. The base station was surveyed for a duration of 24 hours, and its position was subsequently computed using the Canadian Spatial Reference System online service [11]. The u-center [15] software was employed to collect the static GNSS log data. Additionally, the RXM-RAWX message was enabled for the USB connection to gather the raw GNSS data required for the PPP processing.

B. Performance Assesment

To evaluate the performance of the RTK-based positioning system, a series of static GNSS measurements were conducted at multiple distances from the base station. The test locations were chosen to span a range of distances, encompassing areas both within and beyond 12 km from the base station as shown in the fig. 2. The yellow circular line indicates the acceptable range of the base station, which is about 30 km. The red line denotes the radius of this circular coverage area. Additionally, green lines represent the direct connections between the base station and the rover data collection points.

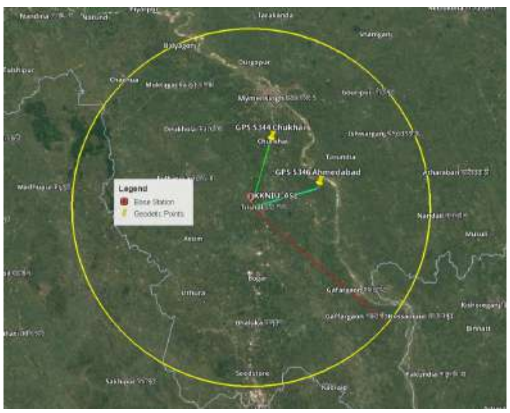

Fig. 2. The base station range and the geodetic control point positions were overlaid on a Google Earth map.

The SimpleRTK2B board, equipped with the u-blox ZED-F9P receiver, was configured as the rover. It was connected to a Windows laptop using the port of power+GPS by an USB cable. The laptop was connected to the internet to receive the RTK correction from the base station. Additionally, a 15cm circular base plate was attached with the U-blox ANN-MB GNSS antenna using screw bolts to enhance its signal stability and mitigate multipath effects.

At each test location, the rover was configured to operate in both RTK and non RTK mode. The GNSS antenna was placed in the middle of the control point as shown in the fig. 3. Both RTK Fixed and non RTK static data were recorded for a duration of 15 minutes using the u-center software [15].

The collected data from the rover was post-processed, and the deviations from the known geodetic control points were calculated. The resulting positioning solutions were analyzed to assess the accuracy of the RTK GNSS system. The Root Mean Square Error was calculated for both the horizontal and vertical components to quantify the deviation from the reference control points.

Fig. 3. U-blox ANN-MB GNSS antenna mounted on a 15cm circular ground plane and placed on top of the geodetic control point which is connected to the GNSS survey grade receiver (Ardusimple simpleRTK2B Budget).

IV. Result and Discussion

This section presents the results from the Precise Point Positioning analysis and the evaluation of the system's relative and absolute positional accuracy. The u-center software's analysis of the static position data showed an average horizontal accuracy of 0.0148 meters and a 3D accuracy of 0.0252 meters, based on 978 data points collected. This high-precision performance demonstrates the effectiveness of the RTK GNSS system in achieving centimeter-level accuracy for both horizontal and vertical positioning.

A. Precise Point Positioning Result

The base station's position was determined through PPP analysis [11]. The estimated coordinates based on 24 hours of static data are latitude 24° 34' 52.07391" N, longitude 90° 22' 29.2210" E, and ellipsoidal height -23.349 m. The corresponding standard deviations are 0.002 m for latitude, 0.002 m for longitude, and 0.008 m for ellipsoidal height. The figure 4 shows the latitude, longitude, and ellipsoidal height along with the phase ambiguity status. These parameters were set as the known point for the base station.

B. Evaluating the Deviation Between Rover Measurements and Geodetic Control Points

Two geodetic control points, GPS 5344 and GPS 5346, were chosen to evaluate this experimental setup. The control point information was purchased through the SOB Online Data Service [2]. Geodetic control point is a well-defined, permanent physical marker or object whose precise geographic location (latitude, longitude, and height) is known. The deviations between the rover-based RTK positioning and the known geodetic control points were calculated for both horizontal and vertical components.

The tables I and II summarize the RTK-based and non-RTK positioning results at the test locations, respectively. The

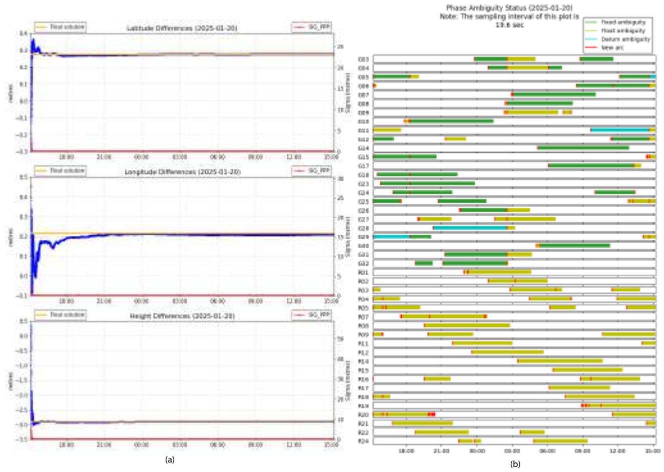

Fig. 4. Latitude, Longitude, Height Difference with the final solution and phase ambiguity status from PPP analysis plot provided by the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) service

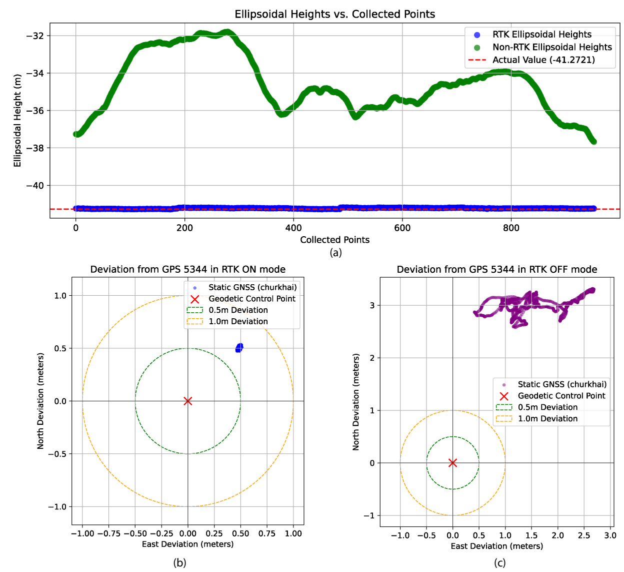

Fig. 5. The GNSS positioning performance was evaluated in comparison to the geodetic control point GPS 5344, with and without RTK correction: (a) Comparison of ellipsoidal heights for RTK-assisted and non-RTK data points. (b) Analysis of deviation in static GNSS measurements when operating in RTK mode. (c) Analysis of deviation in static GNSS measurements without RTK correction.

RMSE height deviation averaged 0.0502 m for GPS 5344 and 0.0466 m for GPS 5346, while the RMSE horizontal deviation averaged 0.702 m for GPS 5344 and 0.684 m for GPS 5346, based on 978 and 954 data points collected at 1 Hz, respectively. In contrast, when the rover operated in non-RTK mode, a significant increase in the deviations was observed, with height deviations of 6.8439 m for GPS 5344 and 2.6392 m for GPS 5346, and horizontal deviations of 3.407 m for GPS 5344 and 2.859 m for GPS 5346. The height and horizontal deviation differences between the control point and the rover measurements, with a comparison to the non-RTK measurements, are shown in Figures 5 and 6.

The results demonstrate the significantly improved accuracy of the RTK-based positioning compared to the non-RTK approach.

TABLE I
HEIGHT DEVIATION FROM TRUE ELLIPSOIDAL HEIGHT (RTK VS NON-RTK)

Point ID	Deviation Measurement	RTK Fixed (meters)	RTK Off (meters)
GPS 5344	Average Deviation (RMSE)	0.0502	6.8439
	Minimum	0.0001	3.5931
	Maximum	0.0931	3.3222
GPS 5346	Average Deviation (RMSE)	0.0466	2.6392
	Minimum	0.0022	0.8542
	Maximum	0.1372	3.3222

C. Geodetic Point reference for the base station

The positional accuracy of the rover is heavily dependent on the absolute position accuracy of the base station. Using the Precise Point Positioning method, we found a significant deviation from the geodetic control point. However, the relative accuracy was at the centimeter level, typically less than 0.02 m for horizontal accuracy and less than 0.03 m for

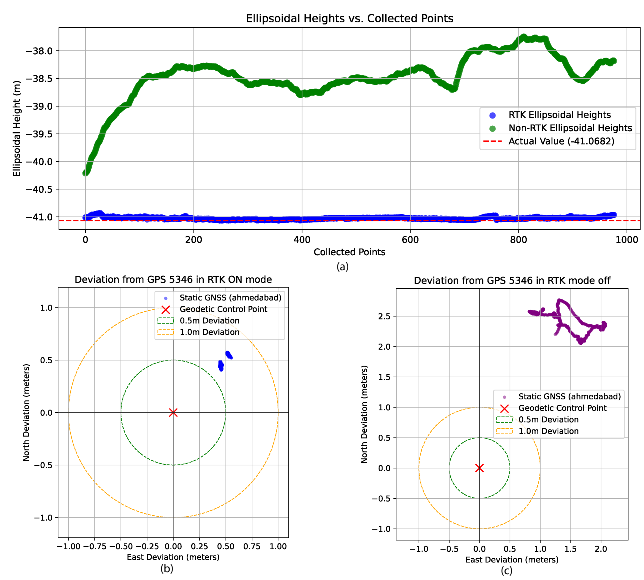

Fig. 6. The GNSS positioning performance was evaluated in comparison to the geodetic control point GPS 5346, with and without RTK correction: (a) Comparison of ellipsoidal heights for RTK-assisted and non-RTK data points. (b) Analysis of deviation in static GNSS measurements when operating in RTK mode. (c) Analysis of deviation in static GNSS measurements without RTK correction.

TABLE II
HORIZONTAL GNSS DEVIATION FROM STATIC GEODETIC CONTROL POINT (RTK VS NON-RTK)

Point ID	Deviation Measurement	RTK Fixed (meters)	RTK Off (meters)
GPS 5344	Average Deviation (RMSE)	0.702	3.407
	Minimum	0.664	2.835
	Maximum	0.735	4.258
GPS 5346	Average Deviation (RMSE)	0.684	2.859
	Minimum	0.610	2.527
	Maximum	0.774	3.153

vertical accuracy. This phenomenon raises questions about the reliability of the PPP method, particularly in areas without operating CORS networks.

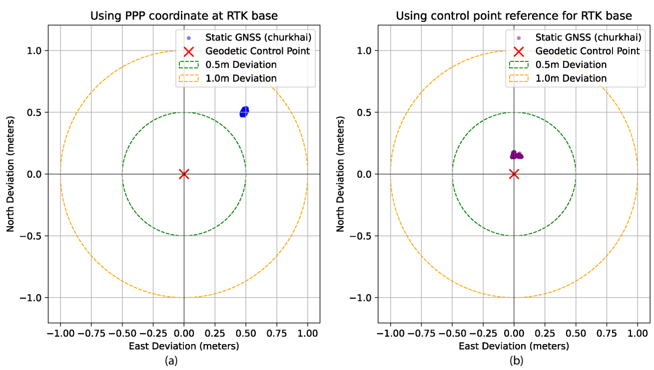

Fig. 7. Comparison of GNSS deviation using different RTK base reference approaches. (a) Deviation plot of the rover using the base coordinate from PPP analysis. (b) Deviation plot of the rover using a geodetic control point as the base reference.

An alternative approach is to temporary configure the base station on a geodetic control point and then establish a permanent base from that temporary base. To address this, a temporary base station was set up at the control point GPS 5344 to determine the permanent base station, which showed a significant improvement relative to the control point, as shown in Figure 7. The results indicate an RMSE deviation of 0.150 m, with a minimum of 0.135 m and a maximum of 0.180 m. However, the limited availability of control points make this method unreliable.

V. CONCLUSION

This research demonstrated the feasibility of establishing a low-cost GNSS RTK reference station and evaluating the performance of a centimeter-level accuracy RTK GNSS system. It achieved high precision for both horizontal and vertical accuracies, relative to the base station on a average 10 km base line. For positional accuracy, using geodetic control point as for base station reference have demonstrated significantly less deviation compared to the PPP solution. CORS networks can be utilized across a variety of fields, including surveying, mapping, precision agriculture, navigation, geodetic monitoring, atmospheric monitoring, and Earth surface monitoring. Maintaining an uninterrupted connection between the base and rover stations is crucial, which requires highly reliable internet connection for both base and rover unit. In the future, more geodetic control point observations and more accurate base station position will provide a better understanding of this system, and dynamic movement rover scenarios can also be evaluated.

Supporting Materials: GNSS RTK Reference Station - asljkkniu.com/gnss-rtk-reference-station/

REFERENCES

[1] S. Bisnath and Y. Gao, "Current state of precise point positioning and future prospects and limitations," in *Observing our changing earth*, pp. 615–623, Springer, 2009.

[2] Survay Of Bangladesh, "Sob continuously operating reference station (cors)." https://sob.gov.bd/site/view/important_links, 2025. Accessed: Feb. 12, 2025.

[3] V. Hamza, B. Stopar, O. Sterle, and P. Pavlovčič-Prešeren, "Recent advances and applications of low-cost gnss receivers: a review," *GPS solutions*, vol. 29, no. 1, pp. 1–17, 2025.

[4] F. Ehrlich-Sommer, F. Hoenigsberger, C. Gollob, A. Nothdurft, K. Stampfer, and A. Holzinger, "Sensors for digital transformation in smart forestry," *Sensors*, vol. 24, no. 3, p. 798, 2024.

[5] M. E. Hodgson, "On the accuracy of low-cost dual-frequency gnss network receivers and reference data," *GIScience & Remote Sensing*, vol. 57, no. 7, pp. 907–923, 2020.

[6] M. Chen, L. Zhao, W. Zhai, Y. Lv, and S. Jin, "Assessment of the real-time and rapid precise point positioning performance using geodetic and low-cost gnss receivers," *Remote Sensing*, vol. 16, no. 8, p. 1434, 2024.

[7] N. Van Nguyen, W. Cho, and K. Hayashi, "Performance evaluation of a typical low-cost multi-frequency multi-gnss device for positioning and navigation in agriculture–part 1: Static testing," *Smart Agricultural Technology*, vol. 1, p. 100004, 2021.

[8] M. S. Steckler, M. H. Jaman, C. J. Grall, S. L. Goodbred, C. A. Wilson, and B. Oryan, "Contribution of campaign gnss toward parsing subsidence rates by time and depth in coastal bangladesh," *Frontiers in Earth Science*, vol. 12, p. 1354686, 2024.

[9] S. Madry *et al.*, *Global navigation satellite systems and their applications*. Springer, 2015.

[10] B. Akpınar and N. O. Aykut, "Determining the coordinates of control points in hydrographic surveying by the precise point positioning method," *The journal of navigation*, vol. 70, no. 6, pp. 1241–1252, 2017.

[11] Natural Resources Canada's Canadian Geodetic Survey, "Csrs-ppp." https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php, 2025. Accessed: Feb. 12, 2025.

[12] T. Banković, M. Dubrović, A. Banko, and M. Pavasović, "Detail explanation of coordinate transformation procedures used in geodesy and geoinformatics on the example of the territory of the republic of croatia," *Applied Sciences*, vol. 14, no. 3, 2024.

[13] JKKNIU-ASL, "Mount point of the refernce station." http://www.rtk2go.com:2101/SNIP::STATUS, 2025. Accessed: Feb. 12, 2025.

[14] RTKLIB, "Rtklib: An open source program package for gnss positioning." https://www.rtklib.com/, 2025. Accessed: Feb. 12, 2025.

[15] u blox, "Gnss evaluation software for windows." https://www.u-blox.com/en/product/u-center, 2025. Accessed: Feb. 12, 2025.