Evaluation of Self-Developed Low-Cost GNSS Receivers for Cadastral Surveying Using RTK Techniques

Khai Cong Pham

Hanoi University of Mining and Geology, No.18 Vien Street – Dong Ngac Ward - Ha Noi city
Email: *khaingocthuy2002[at]gmail.com*

Abstract: ***This study evaluates the performance of a self-developed low-cost Global Navigation Satellite System receiver for cadastral surveying using real-time kinematic techniques. The receiver is based on U-blox hardware and operates with a single continuously operating reference station over short baselines. Field experiments were conducted to compare positioning accuracy with a commercial geodetic receiver. Results indicate that the developed receiver achieves centimeter-level accuracy, with a maximum coordinate difference of 9.8 cm over a baseline of 8.74 km. The findings demonstrate that low-cost GNSS receivers can provide reliable positioning performance for cadastral applications, offering a cost-effective alternative to conventional systems.***

Keywords: GNSS; CORS; RTK techniques; Low-cost GNSS Receivers; Positioning accuracy evaluation; Cadastral surveying

1. Introduction

In recent years, the Global Navigation Satellite System (GNSS) has been widely utilized in topographic and cadastral surveying. GNSS-based positioning on the Earth's surface is implemented through the establishment of continuously operating reference station (CORS) networks. Consequently, real-time kinematic (RTK) positioning techniques have been extensively adopted in geodetic surveying. The integration of RTK techniques with CORS networks has significantly improved operational efficiency, reducing both survey time and associated costs. The key advantages of GNSS technology include the provision of real-time three-dimensional (3D) data, continuous operation under all weather conditions, and high-precision real-time positioning.

In Vietnam, a network of continuously operating reference stations (VNGEONET) has been established, enabling users to access an expanding range of positioning applications. Within this framework, GNSS/CORS/RTK positioning is typically performed using dual-frequency GNSS receivers to achieve high accuracy and precision. In recent years, increasing attention has been directed toward the development of low-cost GNSS receivers with high positioning performance. For example, the study presented in [1] developed a low-cost single-frequency GPS receiver with a single antenna and demonstrated its applicability for RTK positioning. In addition, the development of positioning devices based on high-sensitivity sensors for operation under unfavorable measurement conditions has been successfully reported in [2]. Furthermore, the integration of GPS with inertial navigation system (INS) sensors for precise RTK positioning over long baselines has been investigated in [3].

A study presented in [4] successfully developed a GPS-RTK receiver in terms of both hardware and software, integrated within a smartphone platform. The system provides wireless communication and supports data transmission via the NTRIP protocol. Performance evaluation of the developed GNSS receiver demonstrated that RTK positioning accuracy at the centimeter level can be achieved at a sampling rate of 20 Hz. Furthermore, optimization methods for integrating GPS-RTK with accelerometer sensors have been developed in [5] to determine structural displacements. The study presented in [6] focused on comparing different positioning methods based on the open-source RTKLIB software using a GNSS receiver developed from the u-blox LEA-6T GNSS module. The study in [7] analyzed the effectiveness of the Network Real-Time Kinematic (NRTK) positioning method was analyzed using a low-cost RTK positioning board for the Arduino platform, open-source software running on the Android environment of a smartphone, and correction data acquired from CORS services. A study presented in [8] successfully developed a GNSS receiver capable of RTK positioning using CORS networks at a reasonable cost.

The development of a GNSS receiver based on a u-blox's satellite signal reception board, with an approximate cost of a few hundred U.S. dollars and capable of tracking the L1 frequency of the GPS system and the B1 frequency of the BeiDou system, was reported in [9]. A comparison with high-end GPS receivers supporting L1+L2 frequencies, typically costing several thousand U.S. dollars, indicated that low-cost GNSS receivers can achieve positioning performance comparable to that of more expensive systems [10], [11]. The study in [12] developed two types of low-cost GNSS receivers, namely the u-blox LEA-6T and NEO-7P modules. The performance evaluation of these receivers was conducted in accordance with established international standards. Experimental results indicated that both receivers are capable of achieving centimeter-level positioning accuracy.

Based on the aforementioned studies, it can be observed that GNSS/CORS technology is increasingly being applied in surveying, leading to a growing demand for GNSS receivers. Therefore, this study focuses on the design and development of a low-cost GNSS receiver for cadastral surveying applications.

2. RTK positioning using with low-cost GNSS receivers based on a single CORS station with a short baseline

The use of self-developed, low-cost GNSS receivers for real-time applications has become increasingly prevalent for several reasons, particularly their low cost, compact size, and ease of use. These receivers are typically configured with external antennas (comprising a separate receiver and a patch antenna) and are capable of tracking not only GPS satellites but also other constellations such as GLONASS, BeiDou, and Galileo. Furthermore, these receivers can be employed for RTK positioning using a single CORS station with a short baseline [13].

The short-baseline RTK positioning technique can achieve real-time positioning accuracy at the centimeter level, or even at the millimeter level. The double-difference (DD) model is also applied in RTK positioning based on a single CORS station with a short baseline. The DD model can effectively eliminate satellite- and receiver-related errors, such as satellite and receiver clock errors, initial phase biases, and hardware delays of both satellites and receivers, among others [14]. Furthermore, ionospheric and tropospheric delays are negligible for short baselines.

The RTK positioning technique based on a single CORS station with a short baseline employs one CORS reference station and one rover station (Figure 1). In this approach, the CORS station has precisely known coordinates, while the rover station determines its position by receiving DGNSS corrections from the CORS station, provided that both receivers track more than four common satellites. The position of the CORS reference station is used to compute corrections for the rover based on the DGNSS principle using pseudorange measurements. These corrections are then transmitted to the rover via the NTRIP protocol over 4G (or 5G) telecommunication networks to derive precise coordinates.

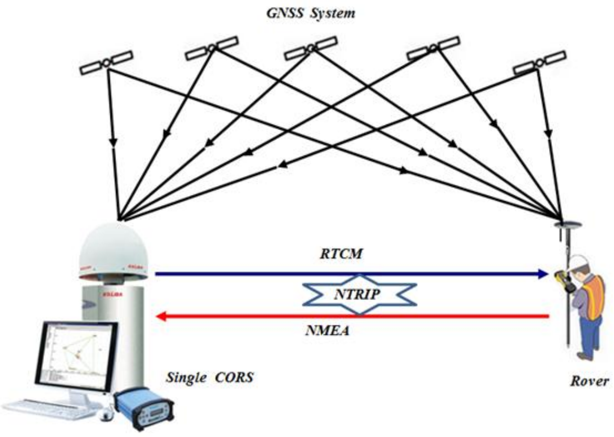

Figure 1: Principle of RTK positioning using a single CORS station

The pseudorange correction from the CORS station to the j-th satellite is computed using equation (1)

$$\delta\rho^j(t) = \rho^j(t) - R^j(t) \quad (1)$$

Where:

-$\rho^j(t)$ is the geometric distance from the CORS station to the j-th satellite, computed from the satellite coordinates $X^j(t)$, $Y^j(t)$, $Z^j(t)$ at time t and the known coordinates X_{CORS}, Y_{CORS}, Z_{CORS} of the CORS station.

-$R^j(t)$ is the measured distance from the CORS station to the satellite determined at time t at the CORS station.

In this case, the corrections $\delta\rho^j(t)$ are encoded in the RTCM standard format and are immediately transmitted to the rover via the NTRIP (Networked Transport of RTCM via Internet Protocol) protocol through 4G or 5G telecommunication networks.

At the rover station, the receiver measures the pseudoranges to the satellites. These pseudoranges are further corrected by the term $\delta\rho^j(t)$. Consequently, the receiver and processing software at the rover perform absolute positioning computations based on the corrected pseudoranges.

The advantage of this technique is that the corrections received by the rover from the CORS station typically exhibit minimal variation, as the CORS station is installed in a highly stable environment. However, this approach is limited by the distance between the CORS station and the rover. As the distance between them increases, positioning accuracy degrades due to the differing effects of tropospheric and ionospheric delays on satellite signals over longer baselines. Therefore, in relative positioning, it is necessary to minimize errors caused by tropospheric and ionospheric delays. These errors exhibit spatial correlation with baseline length; consequently, to mitigate their impact on RTK positioning, the baseline length should generally not exceed 10 to 15 km in cadastral surveying.

3. Methods

3.1 Hardware system design of GNSS receivers

Nowadays, dual-frequency GNSS receivers widely applied for surveying and mapping, because they can fully receive satellite signals at frequencies L1 and L2, which gives the dual-frequency receivers a wide operating range and higher accuracy than single frequency receivers. The components of a dual-frequency GNSS receiver include the main modules shown in Figure 2 [15].

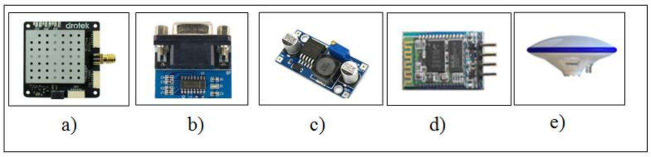

Figure 2: Modules for developing a GNSS receiver

3.1.1. GNSS positioning module

The GNSS positioning module used to design the receiver is the U-blox's ZED-F9P shown in Figure 2a. This is a module that receives signals from GPS, GLONASS, GALILEO, Beidou satellite systems. The U-blox's ZED-F9P module has a compact size, small power consumption, and supported formats of correction messages are RTCM, so it is suitable for developing GNSS receivers used in RTK positioning. U-blox's ZED-F9P positioning module has a horizontal error of 10mm and a vertical error is 15mm [16].

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3.1.2. RS232 to TTL Module

The RS232 to TTL module shown in Figure 2b is uses the MAX232 chip to transfer data level between standard RS232 and TTL. It helps to communicate with the microcontroller without any additional peripherals.

3.1.3. LM2596 Module

The LM2596 module shown in Figure 2c to a range of 1.23 V to 30 V. It is used in voltage converter circuits or circuits that need to reduce voltage.

3.1.4. Bluetooth Module

Bluetooth is a wireless communication standard for exchanging data over short distances. This communication standard uses radio waves (UHF radio) in the Industrial Scientific Medical (ISM) frequency, ranging from 2.4 to 2.485 GHz. The data transmission distance of the Bluetooth module is about 10 m. The HC-05 Bluetooth module was used to develop the GNSS RTK receiver in this study shown in Figure 2d.

3.1.5. GNSS antenna

The antenna used for the GNSS receivers with model GN-GGB0710 shown in Figure 2e has a low cost (only a few tens of dollars). It can provide comprehensive GNSS tracking of satellite systems are: GPS: L1/L2/L5; Glonass: G1/G2; Beidou: B1/B2/B3: Galileo: L1/L6/E1/E2/E5/E6 and QZSS: L1, L2, L5.

The modules are assembled in a housing designed using specialized software and printed with a 3D printer. This GNSS receiver has model KX20-R as shown in figure 3.

a) Incomplete b) completed

Figure 3: Developed GNSS receivers - KX20-R

3.2 Design and build software for GNSS receivers

We have developed software called RTK KX Rover shown in Figure 4 to control the operation of GNSS receivers. It is written in C# programming language in the Android environment and set up on smartphones. The function of the software is to manage measurement jobs, input coordinates, convert parameters, set up parameters of CORS station, manage measurement data files among other functions.

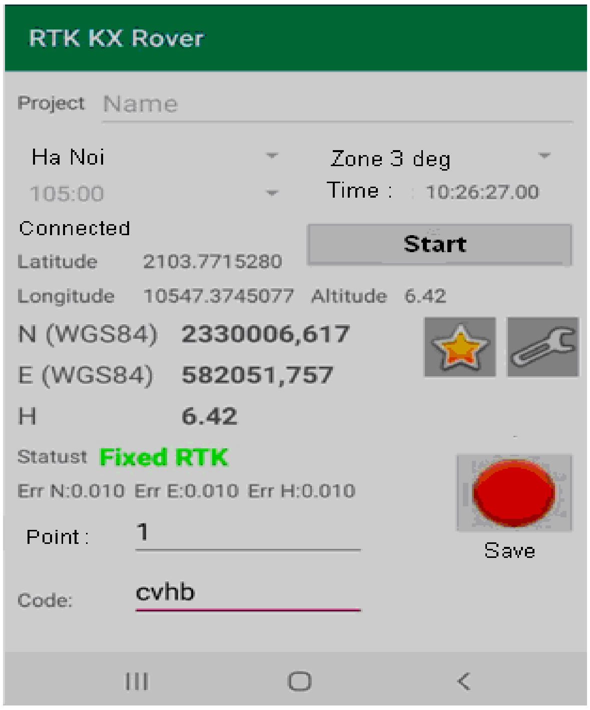

Figure 4: Interface of RTK KX Rover software installed in a smartphone

4. Accuracy evaluation of developed GNSS receivers.

A method to evaluate the accuracy of coordinates measured by the RTK KX20-R GNSS receiver is developed by using two GNSS receivers set up at the same point of a control network with exact coordinates as shown in figure 5.

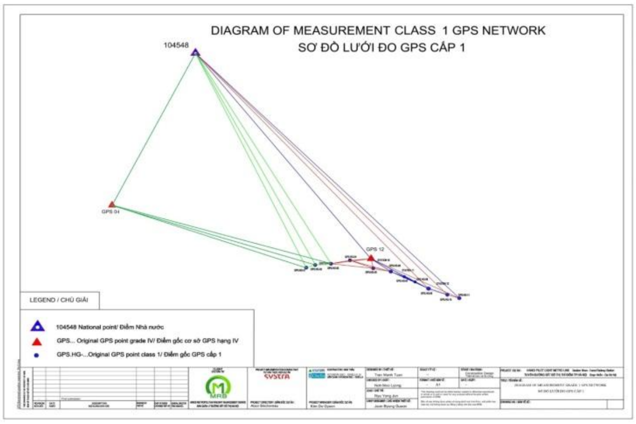

Figure 5: Diagram of control network

The control network used for accuracy evaluation is established by GPS technology and adjusted by the Trimble Business Control (TBC) 3.5 software. In this work, the KX20-R GNSS receiver, which is developed in this study, and a South's GNSS S82 receiver are used. The S82 receiver is a dualfrequency GNSS receiver that can receive 220 channels of the GPS, GLONASS, Compass systems. The RTK positioning errors are 10 mm ±1 ppm in the horizontal component and 15 mm ±1 ppm in the vertical component. The communication is carried out via USB, Bluetooth, RS-232 serial ports. Thus, the S82 receiver is quite similar to the KX20-R receiver. When conducting the experiment, the two E-Servey E600 and KX20-R receivers are used and set up at the points of the control network. A Leica's CORS station (Figure 6) is used to correct the positions for the receivers.

a) CORS Station b) GNSS receivers

Figure 6: Locations of the CORS station and the GNSS receivers.

Based on the coordinates determined by the E-Servey E600 and KX20-R GNSS receivers and their known coordinates, the deviations in horizontal coordinates of the two receivers are calculated using the formula (2) and as shown in Figure 7.

$$\left.\begin{aligned} \delta X_{KX20\text{-}R} &= X_{KX20\text{-}R} - X_{Kn} \;;\; \delta X_{E600} = X_{E600} - X_{Kn} \\ \delta Y_{KX20\text{-}R} &= Y_{KX20\text{-}R} - Y_{Kn} \;;\; \delta Y_{E600} = Y_{E600} - Y_{Kn} \end{aligned}\right\} \quad (2)$$

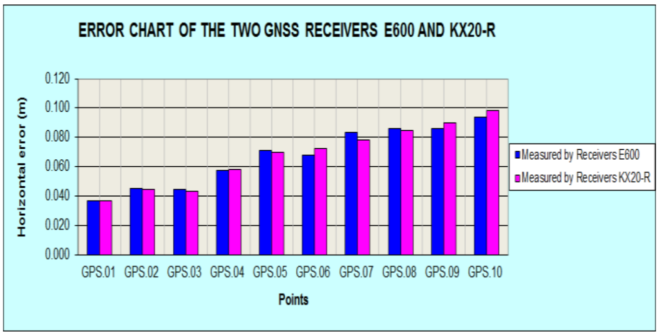

Figure 7: Comparison of horizontal coordinate accuracy of the E600 and KX20-R receivers

It can be seen from Figure 6 that the horizontal errors of points measured by the two receivers KX20-R and E600 are approximately the same and both increase as the distance from the CORS station to the receivers increases. The maximum error at point GPS.10 measured by the E600 receiver is 0.094 m and by the KX20-R receivers is 0.098 m. Thus, the KX20-R GNSS receivers, which is designed and developed in this study, meets the accuracy requirements for cadastral surveying and mapping.

5. Field Experiment and Survey Results

To obtain research results, a field experiment was conducted to perform cadastral mapping. The experimental survey area is located in Nghia Tan, Cau Giay District, Hanoi (Figure 8), using the developed receivers with RTK positioning techniques.

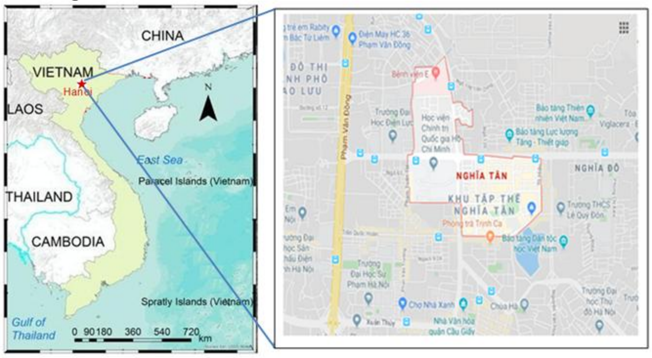

Figure 8: Experimental survey area

The CORS station, established in the campus of the Hanoi University of Mining and Geology, was used to provide correction data for the rover stations. The distance from the CORS station to the experimental survey area is approximately 5 km. The KX20-R receiver is connected to the CORS station through the static IP address: 118.70.171.179 and port 8001 to transmit correction data to receivers in RTCM standard format.

The positions of cadastral points were determined in the WGS84 coordinate system and then transformed into the VN2000 regional coordinate system using the following formulas (3):

$$\left.\begin{aligned} X_{VN2000} &= \Delta X_o + k(X + \varepsilon_o Y - \psi_o Z) \\ Y_{VN2000} &= \Delta Y_o + k(-\varepsilon_o X + Y + \omega_o Z) \\ H_{VN2000} &= \Delta Z_o + k(\psi_o X - \omega_o Y + Z) \end{aligned}\right\} \quad (3)$$

where:

-X_{VN2000}, Y_{VN2000}, H_{VN2000} are the coordinates in the VN2000 system;

-X, Y, Z are the coordinates in the WGS84 system;

and 7 parameters of Helmert transformation, include:

-ΔX_o, ΔY_o, ΔZ_o are the coordinate origin displacement parameters;

-ω_o, ψ_o, ε_o are 3 rotation angles of axes corresponding to X, Y, Z.

-k is scale factor;

The coordinate components X, Y, and Z in the WGS84 coordinate system are calculated using the following formulas (4):

$$\left.\begin{aligned} X &= (N+H)\cos B.\cos L \\ Y &= (N+H)\cos B.\sin L \\ Z &= [N(1-e^2)+H].\sin B \end{aligned}\right\} \quad (4)$$

where:

B is the geodetic latitude; L is the geodetic longitude; H is the geodetic altitude

N is the radius of the first vertical circle at the point of consideration:

$$N = \frac{a}{\sqrt{1-e^2\sin^2 B}} \quad (5)$$

where:

e is the first eccentricity of the ellipsoid.

a is the semi-major axis, b is the semi-major axis of the ellipsoid.

The seven parameters of Helmert transformation from WGS84 to VN2000 coordinate system are published by the Ministry of Natural Resources and Environment, Vietnam. The coordinates of several cadastral points, after being transformed into the VN-2000 regional coordinate system as shown in Table 1.

Table 1: Coordinates of several cadastral points measured using the KX20-R receivers.

No	X_{VN2000} (m)	Y_{VN2000} (m)
1	2328243.070	581976.950
2	2328243.080	581971.680
3	2328243.020	581967.590
4	2328242.900	581967.170
5	2328242.480	581966.480
6	2328239.460	581964.610
7	2328235.910	581964.620
8	2328232.440	581964.640
9	2328228.980	581961.180
10	2328224.810	581954.610
11	2328224.800	581953.000
12	2328219.860	581953.050
13	2328219.830	581949.610
14	2328216.320	581949.640
15	2328213.050	581949.670
….	………	……….

The coordinates of the cadastral points, after being transformed into the VN-2000 coordinate system, are saved in a text file (.txt). a specialized software was used in conjunction with this data file to produce the cadastral map. In this study, TOPO software was employed for cadastral mapping (Figure 9)

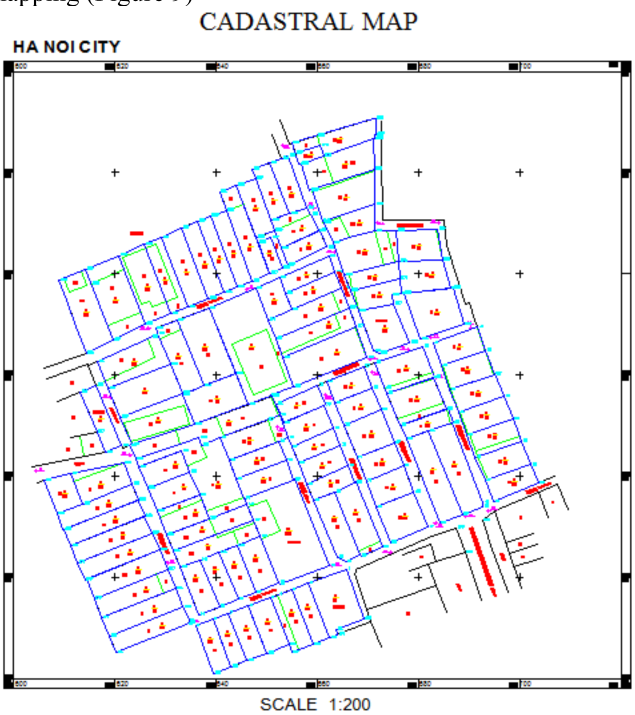

Figure 9: The cadastral map has been produced

6. Conclusion

This study developed and evaluated a low-cost GNSS receiver based on U-blox ZED-F9P technology for cadastral surveying applications. The integration of custom hardware and RTK KX Rover software enabled real-time positioning using CORS correction data. Experimental results demonstrated that the developed receiver achieves centimeter-level accuracy, with performance comparable to a commercial geodetic receiver under short baseline conditions. These findings confirm that low-cost GNSS solutions can serve as reliable and cost-effective tools for cadastral mapping. Future work should focus on performance evaluation under longer baselines and challenging environmental conditions.

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