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Research and Development of Real-time High-precision GNSS Receivers: A Feasible Application for Surveying and Mapping in Vietnam

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Abstract. In recent years, the Global Navigation Satellite System (GNSS) has been widely applied in surveying and mapping. Currently, in Vietnam, dual-frequency GNSS receivers are quite extensively applied with the real-time kinematic (RTK) measurement technique using a continuously operating reference station network. However, high-accuracy GNSS receivers are often expensive, sometimes not meeting the needs of users for specific applications. This research develops two types of low-cost high-precision GNSS receivers for RTK positioning for different purposes. First, the millimeter precision GNSS receiver used in real-time displacement monitoring is based on Trimble's BD970 mainboard technology and some other modules. These components are interconnected according to a standard design scheme and assembled in an enclosure to form a GNSS receiver. In addition, a GNSS data transmission in the National Marine Electronics Association standard format by Networked Transport of Radio Technical Commission for Maritime Services via Internet Protocol (NTRIP) has been designed and developed. The GNSS receiver after development is loaded with program code written in the C# programming language, using the Arduino programming tool. Second, the GNSS receivers have the centimeter accuracy for RTK positioning used in surveying and mapping based on U-blox's mainboard technology and some other modules. These modules are also connected together according to a standard design scheme and assembled in an enclosure to form a complete GNSS receiver. The evaluation results show that the designed and developed GNSS receivers completely meet the requirements of surveying and mapping in coal mines in Vietnam, such as real-time monitoring of landslides, surveying and topographical mapping and other surveying works to serve the mining process.

Keywords: GNSS/CORS, Low-cost high-precision GNSS receivers, Real-time high-precision GNSS receivers, NTRIP, BD970 Trimble, ZED-F9P

1. Introduction

Nowadays, the Global Navigation Satellite System (GNSS) is widely used in surveying and mapping. With GNSS technology, positioning on the ground is conducted by establishing a continuously operating reference station (CORS) network. Then RTK positioning is widely applied in surveying. The application of the RTK positioning technique using CORSs has brought great efficiency in surveying, reducing time and low cost. The advantage of GNSS technology is providing 3D data in real time, working continuously in all weather conditions, positioning in real time and high accuracy.

Currently, a network of CORSs has been built in Vietnam (VNGEONET), based on which users will be provided with many more applications. The GNSS/CORS/RTK positioning technique is then performed by dual-frequency GNSS receivers to achieve highly accurate and precise results. In recent times, there has been an increasing interest in low-cost high-precision GNSS receivers. For example, in [1], the authors developed a low-cost single-frequency Global Positioning System (GPS) receiver and concluded that this GPS receiver can be used for RTK positioning. The research and development of a high-sensitivity sensor locator in unfavorable measuring conditions has been successfully carried out by Trajkovski et al. (2010) [2]. The integration of GPS positioning with inertial navigation system (INS) sensors has been performed by Lee (2010) [3] to accurate RTK positioning with long baselines. A study by Hwang et al. (2012) [4] has successfully developed GPS-RTK receivers in both hardware and software, which are installed in a smartphone. It provides wireless communication, transmission data over the Networked Transport of RTCM via Internet Protocol (NTRIP). Performance evaluation of the developed GNSS receiver showed that the RTK positioning accuracy is a few centimeters at 20 Hz. The optimal methods integrating GPS-RTK with an accelerometer have been developed by Hwang et al. (2012) [5] to determine the displacement of the structures.

The study by Wisniewski et al. (2013) [6] compared different positioning methods based on the open-source software called RTKLIB with GNSS receivers developed based on the U-blox's GNSS LEA-6T satellite signal receive module. The effect of the Network Real Time Kinematic (NRTK) positioning method with the use of a low-cost RTK navigation board for Arduino environment, an open-source software application that runs in the Android operating system of smartphones and receives correction data from the CORS service was analyzed by Pepe (2018) [7]. A recent study by Manurung et al. (2019) [8] has researched and developed a GNSS receiver with reasonable cost, RTK positioning using CORS stations. The development of a GNSS receiver based on Ublox's satellite receiver board costing just a few hundred dollars that captures the L1 GPS frequency and the B1 Beidou frequency has been carried out by Parluhutan et al. (2019) [9]. A comparison of the results measured with a GPS receiver with the L1+L2 frequency, which costs several thousand dollars, showed that the low-cost GNSS receiver has the same positioning performance as the high-cost GNSS receiver [10, 11].

The tests and evaluations of the developed GNSS receiver based on the U-blox's NEO-P7 module and the low-cost Tallysman TW2410 antenna showed that RTK positioning is of the centimeter accuracy [12]. In [13], the authors have developed two types of low-cost receivers; U-blox's LEA-6T and NEO-7P. The quality assessment of the two types of receivers was carried out within the framework of published standards of the International Organization. The test results showed that the two types of receivers achieve centimeter accuracy. The accuracy of low-cost GNSS receivers is also of concern. A study was performed with two types of GNSS receivers, which are a Leica GS10 GNSS receiver with AS10 antenna and the low-cost receivers based on U-blox's NEO-M8P board [14]. The results of the assessment of the accuracy of the two types of GNSS receivers showed that, for the Leica GS10 GNSS receiver, the horizontal error is ±2.5 mm and the vertical error is ±4.5 mm, and the U-blox's NEO-M8P receivers have a horizontal error of ±5.5 mm and a vertical error of ±11 mm.

In Vietnam in recent years, there have been a few research and projects working on GNSS receivers used in real-time displacement monitoring deformation [15, 16, 17]. The design and development of GNSS positioning equipment with centimeter-level accuracy were also carried out by the International Collaboration Centre for R&D on Satellite Navigation Technology in South East Asia of Hanoi University of Science and Technology [18]. The Ho Chi Minh City University of Technology in collaboration with Dai Nam Company has researched and developed high-precision dual-frequency P2 Elite GNSS receivers used in surveying for mapping. Vietnam Aitogy Infrastructure Technology Joint Stock Company has developed Ainav-RTK-R receivers used for RTK positioning according to CORS station technology with centimeter-level accuracy. However, the Ainav-RTK-R receivers are still under design and manufacture separately between the antenna and the GNSS receiver.

With the above assessment, it can be seen that GNSS/CORS technology is increasingly widely applied. Currently, in Vietnam's coal mines, CORS/RTK positioning techniques are applied, so the demand for GNSS receivers is increasing. But currently, GNSS receivers on the Vietnamese market are mainly purchased from large global corporations such as Trimble, Leica, Topcon that are of high cost, thereby reducing the applicability of this technology. Therefore, the development of real-time high-precision GNSS receivers and low-cost that meets user requirements is of great economic and technical significance. In this study, two real-time high-precision GNSS receivers were developed; the first receiver for real-time displacement monitoring, the second receiver for surveying and mapping.

2. Development of GNSS receivers for real-time displacement monitoring systems

2.1. Components of a real-time displacement monitoring system

A real-time displacement monitoring system is designed based on GNSS/CORS/RTK technology and consists of two main parts: a) The CORS System and b) Continuously Monitoring Station System (CMSS) [19]. The CORS system includes CORS GNSS antennas (1), data transmission cables (2), CORS GNSS Receivers (3), Wi-Fi modem and internet connection (4), host computers with specialized software (5), and electricity supply (6). The CMSS system includes GNSS antennas (7), GNSS receivers (8), data transmitters (9), Uninterruptible Power Supply (UPS) (10), power converters (11), solar panels (12), warning equipment (13). The components of the real-time displacement monitoring system are shown in Fig. 1.

The operating principle of the real-time displacement monitoring system is built based on the operating principle of the GNSS/CORS system. CORS is responsible for data processing to determine the correction for the monitoring station according to the standard of the Radio Technical Commission for

Maritime Services (RTCM). The monitoring station that receives the correction from the CORS will determine the exact coordinates. The monitoring data is received according to the National Marine Electronics Association-0183 (NMEA-0183) standard. The correction data from the CORS is sent to the monitoring station and the monitoring data sent to the server is performed by the NTRIP.

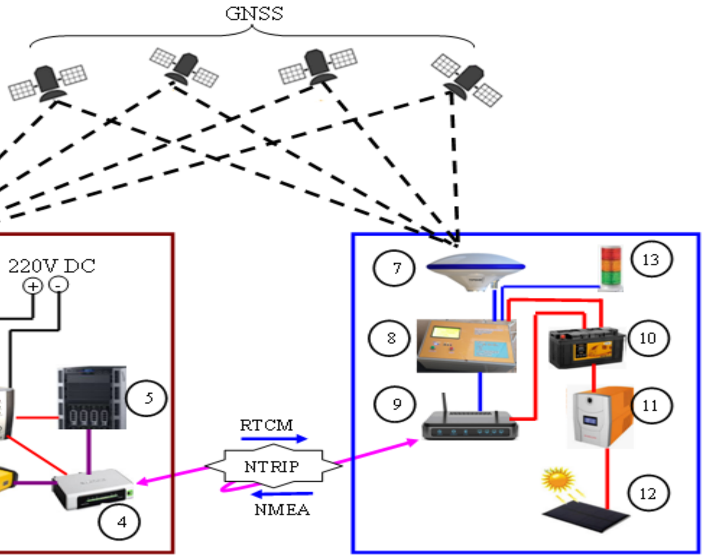
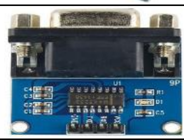
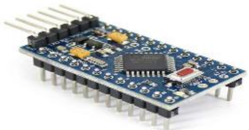
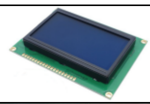
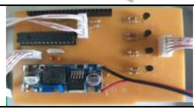


Fig. 1. Components of a real-time displacement monitoring system: CORS (left) and CMSS (right).

2.2. Development of GNSS receivers for monitoring station

Receiving data from the monitoring station and transmitting it to the CORS must ensure continuous operation and provide the 3D position of the monitoring station in real-time. The GNSS receiver and data transmission are designed and developed, including the main modules described shown in Table 1.

Tab. 1. Main modules for developing GNSS receivers for monitoring station.

No	Module name	Description	Module image
1	Trimble BD970	Receive 220 channels of constellation including GPS L2C/ L5, Global Navigation Satellite System, GLONASS L1/L2, BeiDou B1/B2, Galileo L1/E5A/E5B/E5C1	
2	LM2596	This module is used to lower the output voltage from 1.23V to 30V. It is used in voltage converter circuits or circuits that need to reduce voltage.	
3	RS232 to TTL	This module uses Chip MAX232 to transfer data between standard RS232 and transistor-transistor logic (TTL). It helps to communicate with the microcontroller without any additional peripherals.	
4	Atmega328P	This is the central control module. It is responsible for controlling other modules to operate. All codes are loaded directly into the ATmega 328 microprocessor. In the signal transmission protocols, the ATmega328 module is responsible for receiving calculation data and returning it to other modules.	
5	Display screen LCD12864	It is used to display information, message lines about the status of the GNSS receiver	
6	Warning	This module is our self-developed for the monitoring station to warn by sound and light when the displacement occurs beyond the limit.	

The modules of the GNSS receiver for the real-time displacement monitoring station are connected to each other according to the diagram as shown in Figure 2. According to the connection diagram in Figure 2, the assembly process is as follows:

- Module BD970 is assembled with a circuit board connected by male-female pins.
- The input of the LM2596 module is connected to a 12V power supply. The output of the LM2596

module is connected to the input of the connecting board.

- The RS232 to TTL module is connected to the Com1 port of the connecting board.
- The Atmega328P module is connected to the RS232 to TTL module.
- The Atmega328P module is connected to the alarm module.
- The alert module is connected to the display.

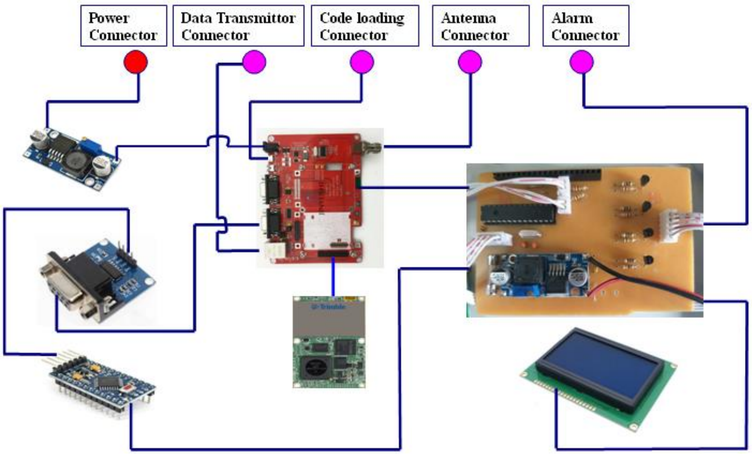


Fig. 2. Connection diagram of GNSS receiver components.

The modules are connected and assembled in a standard design enclosure and form a complete GNSS receiver as shown in Figure 3.

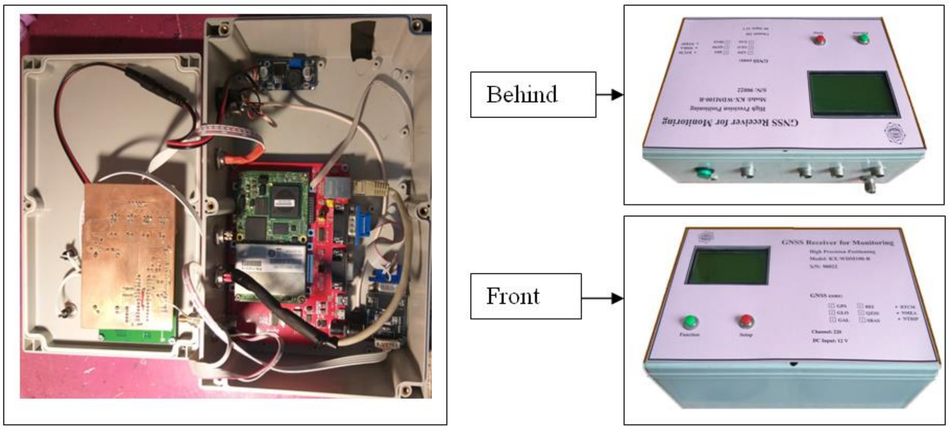


Fig. 3. GNSS receiver: incomplete (left) and complete (right)

After the GNSS receiver is assembled completely, the software controls operation in our self-developed system. The software written in the NMEA's standard data format using the Arduino programming tool and the C# programming language is shown as Figure 4.

Fig. 4. Program source code that controls operation of the GNSS receiver.

When software source code has been written and checked for errors, it is loaded into the GNSS receiver via the USB connector to the computer by Arduino's programming tool. Software controls GNSS data acquisition and transmission functions as follows: The satellite signal collected from receivers in the NMEA standard format is directly transmitted to Arduino via an RS232 port. The received Arduino signals are divided into two types $GPGGA, $GNGGA and other NMEA signals. The $GNGGA signals are transmitted to the server according to the NTRIP server protocol and other NMEA signals are simultaneously transmitted to Ethernet W5100 and stored in an SD memory card, which is integrated into Ethernet W5100 in the text file format. $GNGGA signals are processed then the results are sent to the software in the server to provide instant location. These data are automatically processed by our self-developed software called GNSS CORS WDM (GNSS CORS Works Deformation Monitoring) and deformation and displacement quantities are determined with high accuracy.

2.3. Development of the GNSS data transmitter for monitoring station

The transmission of RTCM correction data and monitoring data in accordance with the NMEA format is carried out over the internet according to the NTRIP [20] protocol using a developed data transmitter (Fig. 4). The GNSS data transmitter is developed based on TP-Link's mainboard with high power, using Qualcomm's chip to receive, decode and process incoming and outgoing signals, broadcast Wi-Fi, transmit port signals LAN, the antenna receives and transmits the signal. The mainboard is also integrated with USB Dcom 4G to used telecommunications services. The data transmitter uses a 12V electricity supply with the voltage change module LM2596 when the input voltage is greater than 12V.

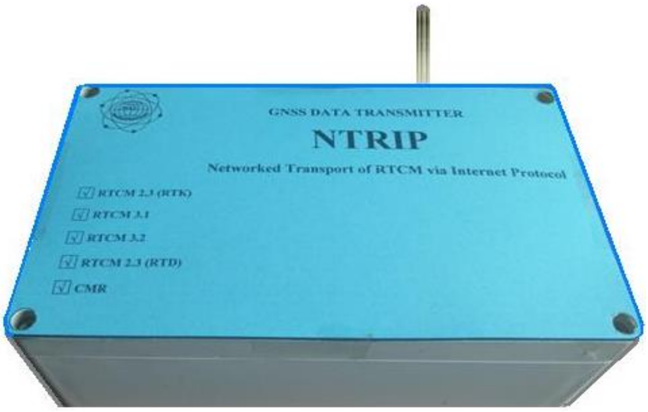


Fig. 4. GNSS data transmitter by NTRIP.

2.4. GNSS antenna

The antenna used for the monitoring station system with model GN-GGB0710 has a low cost (only a few tens of dollars). It can provide comprehensive GNSS tracking of satellite systems, which are GPS (L1/L2/L5), GLONASS (G1/G2), Beidou (B1/B2/B3), Galileo (L1/L6/E1/E2/E5/E6) and QZSS (L1, L2, and L5). The GNSS antenna is shown in Figure 5.

Fig. 5. GNSS antenna GN-GGB0710.

The GNSS data receiver and transmitter together with the GNSS antenna and other ancillary equipment form a complete monitoring station system. The GNSS receivers have been developed with the product code KX-WDM100-R.

3. Development of RTK GNSS receivers

3.1. Hardware system design

Nowadays, dual-frequency GNSS receivers are widely applied for surveying and mapping because they can fully receive satellite signals at the L1 and L2 frequencies, 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 6.

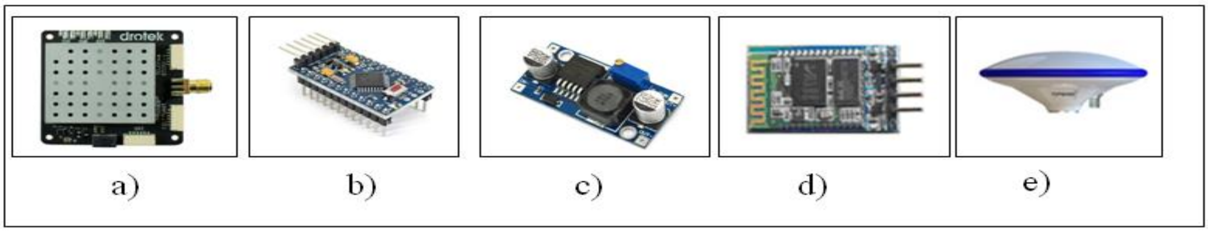


Fig. 6. Modules for developing a GNSS RTK receiver.

3.1.1. GNSS positioning module

The GNSS positioning module used to design the receiver is the U-blox's ZED-F9P (Fig. 6a). This is a module that receives signals of 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. The U-blox's ZED-F9P positioning module has a horizontal error of 10 mm and a vertical error of 15 mm [21].

3.1.2. Atmega328P Module

The Atmega328P module (Fig. 6b) used to design the GNSS RTK receiver is the same type as the module used for the GNSS receiver of the monitoring station as shown in Table 1.

3.1.3. LM2596 Module

The LM2596 module (Fig. 6c) is used to lower the output voltage of the GNSS RTK receiver to 1.23V ÷ 30V. It is the same type as the module used for the GNSS receiver of the monitoring station as shown in Table 1.

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 (Fig. 6d).

3.1.5. GNSS antenna

The antenna used to design the GNSS RTK receivers is of the same type as the antenna used in the monitoring station system as shown in Table 1. The modules are assembled in housing designed using specialized software and printed with a 3D printer. This GNSS receiver has model KX20-R as shown in Figure 7.

Fig. 7. Developed GNSS RTK receivers KX20-R: incomplete (left) and completed (right)

3.2. Design and build software for GNSS RTK receivers

We have developed software called RTK KX Rover (Fig. 8) 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.

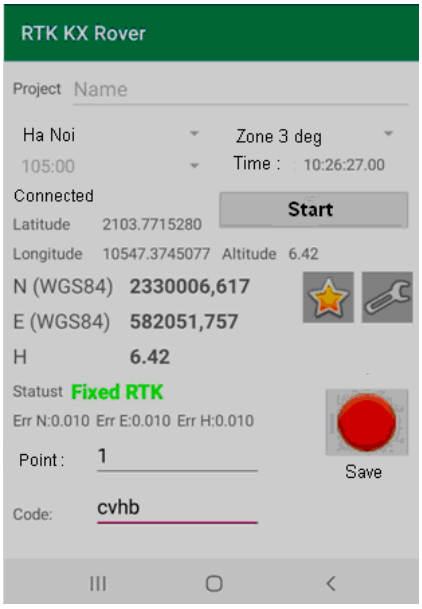


Fig. 8. Interface of RTK KX Rover software installed in a smartphone.

4. Evaluation of the performance of the two developed GNSS receivers

4.1. Evaluation of the performance of the KX-WDM100-R GNSS receiver for monitoring station

To evaluate the performance of the KX-WDM100-R GNSS receiver, an experiment was performed on 09-06-2021 at 04:37:13.00 (UTC time) i.e., at 11:37:13.00 (Hanoi time). A Leica's single CORS station was established at the main campus of the Hanoi University of Mining and Geology and the KX-WDM100-R GNSS receiver was set up on the roof of the apartment building 184 in Hoang Quoc Viet street. The distance from the CORS station to the KX-WDM100-R GNSS receiver is about 2.836 km (Fig. 9).

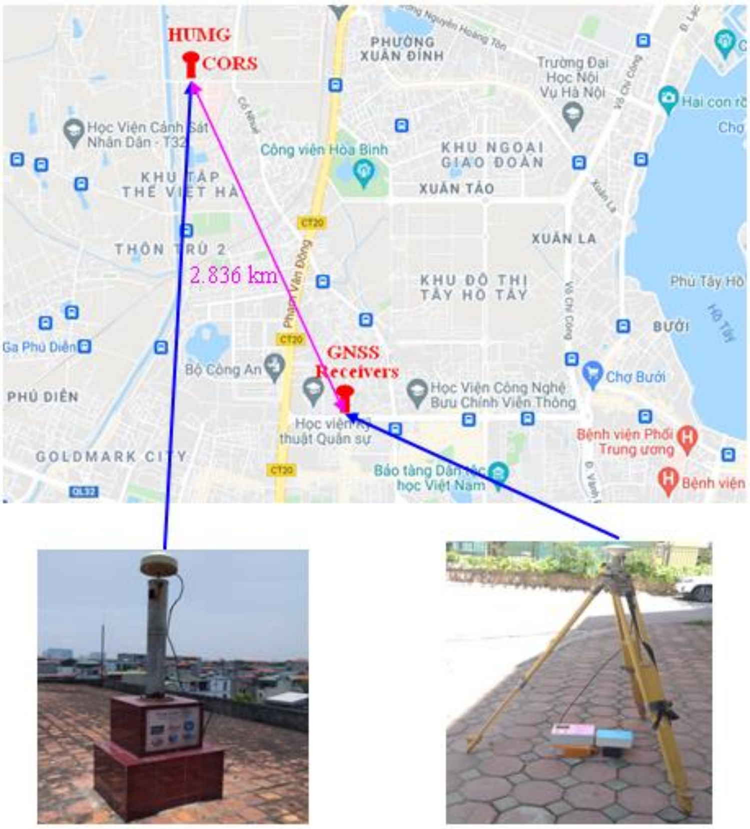


Fig. 9. Locations of the CORS station and the KX-WDM100-R GNSS receiver.

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The KX-WDM100-R GNSS receiver is connected to the CORS station through the static IP address: 118.70.171.179 and port 8001 to transmit correction data to the GNSS receiver in the RTCM standard format. The data at the GNSS receiver are corrected in the NMEA standard format. The evaluation of positioning performance shows that the error in the X-axis is 0.004 m, the error in the Y-axis is 0.003 m, and the error in the altitude component is 0.009 m (Fig. 10). With such errors, the KX-WDM100-R GNSS receiver is suitable for real-time displacement monitoring.

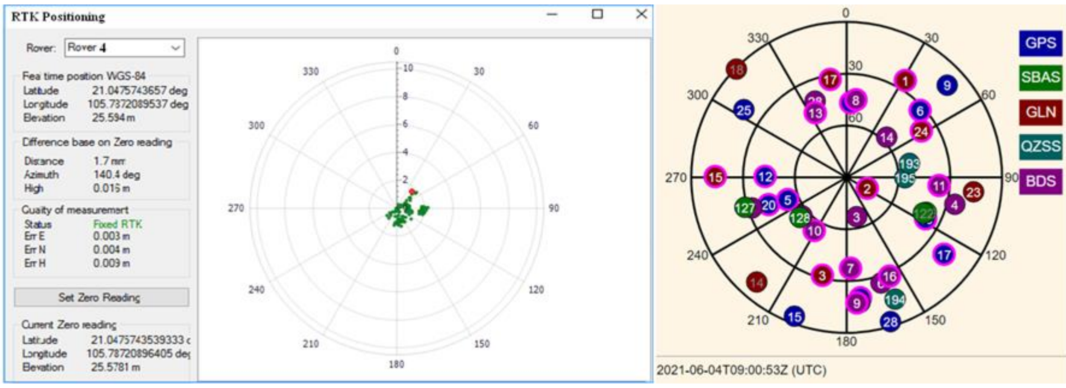

Fig. 10. Positioning performance of GNSS receivers and observable satellite constellation.

Those errors can be obtained by solving the relative position problem in the RTK method as [22] :

$$\mu = \pm\sqrt{\frac{V^T PV}{n - t}} \tag{1}$$

where n is the number of observations, t is the number of unknowns, V is the correction calculated from the system of correction equations in the matrix form using Eq. (2) [23].

$$V = A.X_{XYZ} + B.X_N + L \tag{2}$$

where A is the coefficient matrix of the real unknown of the size $n_t(n_j - 1)$ rows and 3 columns, B is the coefficient matrix of integer unknowns of the size $n_t(n_j - 1)$ rows and $(n_j – 1)$ columns.

$$B = \begin{bmatrix} B_1 \\ B_2 \\ \dots \\ B_{n_t} \end{bmatrix}; \qquad X_N = \begin{bmatrix} N_{A,B}^{j,1} \\ N_{A,B}^{j,2} \\ \dots \\ N_{A,B}^{j,(j-1)} \end{bmatrix}_{(n_j-1)x1}$$

Then, the error components for each coordinate axis are calculated using Eq. (3) :

$$m_i = \mu r_{ii} \tag{3}$$

with i is the i axis, r_{ii} value determined from relative dilution of precision (RDOP).

Data from the KX-WDM100-R GNSS receivers are transmitted to the CORS central server in the standard format NMEA-0183 with the lowest frequency of 1Hz and the highest of 50Hz, depending on the user's requirements. Table 2 shows a segment of data collected in 1 second using KX-WDM100-R GNSS receivers. In this experiment, only GGA, GST, GSV and GSA messages in the NMEA-0183 standard format are collected.

Tab. 2. A segment of NMEA data collected by KX-WDM100-R GNSS receivers.

$GNGGA,043714.00,2102.85446475,N,10547.23254501,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*4B
$GNGST,043714.00,0.063,0.002,0.001,80.1,0.001,0.002,0.004*74
$GPGSV,11,1,39,30,37,202,46,1,17,036,21,6,45,239,45,17,45,348,45*41
$GPGSV,11,2,39,7,11,170,40,28,61,351,46,14,74,032,46,22,16,050,39*71
$GPGSV,11,3,39,19,36,313,45,3,33,073,42*7C
$GPGSV,11,4,39,40,29,254,33,42,40,114,,41,54,229,47*73

$GLGSV,11,5,39,80,20,161,39,68,8,074,38,69,10,121,43,74,52,322,48*62
$GLGSV,11,6,39,83,13,031,23,85,22,263,46,84,45,332,36,73,70,185,50*5B
$GBGSV,11,7,39,114,10,065,37,116,6,179,,109,11,198,34,105,32,250,37*62
$GBGSV,11,8,39,104,26,104,38,108,88,330,46,102,54,227,42,127,43,299,49*52
$GBGSV,11,9,39,128,43,018,48,103,65,167,44,123,34,167,47,101,40,114,42*52
$GBGSV,11,10,39,107,67,081,45,110,69,359,46,113,68,220,49*6D
$GQGSV,11,11,39,193,22,123,38,195,51,048,44,194,49,138,45*7D
$GNGSA,A,3,17,7,22,14,19,3,28,6,30,,,,1.2,0.7,1.0*19
$GNGSA,A,3,80,84,85,69,73,,,,,,,,1.2,0.7,1.0*2B
$GNGSA,A,3,109,107,110,105,113,101,108,,,,,,1.2,0.7,1.0*19
....

The collected data files are processed by our self-developed software and installed on the central server computer of the CORS station. The data processing is carried out by the following steps:

1. Check the integrity of each message line in the NMEA data file. If these message lines are incomplete, they must be discarded. Inspection of messages is performed by analyzing all characters in the range from $ to * of the NMEA message.

2. Filter the GGA and GST messages to separate the message lines with the most accurate coordinates (minimum position error).

3. Transform the coordinates from the geodetic coordinate system to the VN2000 coordinate system. The transformation of the coordinates from the geodetic coordinate system to the VN2000 coordinate system is carried out by the following steps:

Firstly, the conversion from geodetic coordinates (B, L, H) to Cartesian coordinates (X, Y, Z) in the World Geodetic System 1984 (WGS84) is conducted using Eq. (4) [23].

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

where B is the geodetic latitude, L is the geodetic longitude, H is the ellipsoidal height, and N is the radius of curvature in the prime vertical at the point of consideration:

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

where e is the first eccentricity of the ellipsoid:

$$e = \frac{\sqrt{a^2-b^2}}{a}$$

where a is the semi-major axis and b is the semi-minor axis of the ellipsoid.

Then, Cartesian coordinates are transformed from WGS84 to the VN2000 coordinate system (Vietnam's coordinate system) using Eq. (5):

$$\left.\begin{aligned} X_{VN2000} &= \Delta X_o + k(X + \varepsilon_o Y - \psi_o Z) \\ Y_{VN2000} &= \Delta Y_o + k(-\varepsilon_o X + Y + \omega_o Z) \\ H_{VN2000} &= \Delta Z_o + k(\psi_o X - \omega_o Y + Z) \end{aligned}\right\} \qquad (5)$$

where X_{VN2000}, Y_{VN2000}, H_{VN2000} are the coordinates in the VN2000 reference system, X, Y, and Z are the coordinates in the WGS84 system, and 7 parameters of Helmert transformation includes:

-ΔX_o, ΔY_o, ΔZ_o are the translation.

-ω_o, ψ_o, ε_o are 3 rotation angles about the X, Y and Z axes.

-k is the scale factor.

The seven parameters of Helmert transformation from WGS84 to the VN2000 coordinate system were published by the Ministry of Natural Resources and Environment, Vietnam as shown in Table 3 [24].

Tab. 3. Seven parameters of Helmert coordinate transformation.

No	Parameters	Values of the parameters	Unit
1	ΔXo	-191.90441429	meters
2	ΔYo	-39.30318279	meters
3	ΔZo	-111.45032835	meters
4	ωo	-0.00928836	seconds
5	ψo	0.01975479	seconds
6	εo	-0.00427372	seconds
7	k	1.000000252906278	-

After that, Cartesian coordinates are converted to geodetic coordinates in VN2000.

Secondly, Universal Transverse Mercator (UTM) coordinates (x, y) is computed from geodetic coordinates (B, L) in VN2000 using Eq. (6), [21].

$$\left.\begin{aligned} x &= k_o(X + \frac{1}{2\rho^2}N.t\cos^2B.l^2 + \frac{1}{24\rho^4}N.t(5 - t^5 + 9\eta^2 + 4\eta^4)\cos^4B.l^4 \\ &\quad + \frac{1}{720\rho^6}N.t(61 - 58t^2 + t^4 + 270\eta^2 - 330\eta^2t^2)\cos^6B.l^6 + ...) \\ y &= k_0(\frac{N}{\rho}\cos B.l + \frac{1}{6\rho^3}N(1-t^2-\eta^2)\cos^3B.l^3 + \\ &\quad + \frac{1}{120\rho^5}N(5-18t^2+t^4+14\eta^2-58\eta^2t^2)\cos^5B.l^5 + ... \end{aligned}\right\} \quad (6)$$

where t=tgB, $\eta = e'.\cos B$, $l = \frac{(L-L_o)^{''}}{\rho^{''}}$, k_0=0.9996 corresponds to a 6° projection zone, k_0=0.9999 corresponds to a 3° projection zone, L_0 is the central meridian. In Hanoi, L_0 = 105°00.

From the data in Table 2, the processing and filtering GGA messages with the most accurate coordinate components are shown in Table 4.

Tab. 4. A segment of GGA data according to the NMEA 0183 standard format.

No	GGA Messages according to the NMEA standard format
1	$GNGGA,043713.00,2102.85446474,N,10547.23254501,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*4D
2	$GNGGA,043714.00,2102.85446475,N,10547.23254501,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*4B
3	$GNGGA,043715.00,2102.85446474,N,10547.23254502,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*48
4	$GNGGA,043716.00,2102.85446474,N,10547.23254504,E,4,21,0.7,25.589,M,-28.232,M,1.0,0000*45
5	$GNGGA,043717.00,2102.85446473,N,10547.23254504,E,4,21,0.7,25.589,M,-28.232,M,1.0,0000*43
6	$GNGGA,043718.00,2102.85446474,N,10547.23254505,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*42
7	$GNGGA,043719.00,2102.85446474,N,10547.23254506,E,4,21,0.7,25.590,M,-28.232,M,1.0,0000*40
8	$GNGGA,043720.00,2102.85446474,N,10547.23254509,E,4,21,0.7,25.589,M,-28.232,M,1.0,0000*4D
9	$GNGGA,043721.00,2102.85446474,N,10547.23254507,E,4,21,0.7,25.589,M,-28.232,M,1.0,0000*42
10	$GNGGA,043722.00,2102.85446474,N,10547.23254506,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*49
11	$GNGGA,043723.00,2102.85446474,N,10547.23254505,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*4B
12	$GNGGA,043724.00,2102.85446474,N,10547.23254505,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*4C

13	$GNGGA,043725.00,2102.85446474,N,10547.23254503,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*4B
14	$GNGGA,043726.00,2102.85446473,N,10547.23254502,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*4E
15	$GNGGA,043727.00,2102.85446474,N,10547.23254502,E,4,20,0.7,25.590,M,-28.232,M,1.0,0000*48
16	$GNGGA,043728.00,2102.85446474,N,10547.23254502,E,4,20,0.7,25.589,M,-28.232,M,1.0,0000*4F
17	$GNGGA,043729.00,2102.85446474,N,10547.23254501,E,4,20,0.7,25.589,M,-28.232,M,1.0,0000*4D
18	$GNGGA,043730.00,2102.85446473,N,10547.23254502,E,4,20,0.7,25.589,M,-28.232,M,1.0,0000*41
19	$GNGGA,043731.00,2102.85446473,N,10547.23254505,E,4,20,0.7,25.589,M,-28.232,M,1.0,0000*47
20	$GNGGA,043732.00,2102.85446473,N,10547.23254505,E,4,20,0.7,25.589,M,-28.232,M,1.0,0000*44
…	....

Geodetic coordinates in the WGS84 coordinate system are transformed to those in the VN2000 coordinate system and shown in Table 5.

Tab. 5. Results of coordinate transformaion from WGS84 to VN2000.

No	Experiment times	Latitude (B)	Longitude (L)	Ellipsoid Altitude (H)	X_{VN2000} (meters)	Y_{VN2000} (meters)	h (meters)
1	04:37:13.00 6/9/2021	21 04 51.267884	105 47 13.952701	0.7219	2331412.081	581575.262	25.773
2	04:37:14.00 6/9/2021	21 02 51.267885	105 47 13.952701	0.7229	2327722.718	581593.483	25.711
3	04:37:15.00 6/9/2021	21 02 51.267884	105 47 13.952701	0.7245	2327722.718	581593.483	25.713
4	04:37:16.00 6/9/2021	21 02 51.267884	105 47 13.952702	0.7233	2327722.718	581593.483	25.711
5	04:37:17.00 6/9/2021	21 02 51.267884	105 47 13.952702	0.7226	2327722.718	581593.483	25.711
6	04:37:18.00 6/9/2021	21 02 51.267884	105 47 13.952703	0.7261	2327722.718	581593.483	25.714
7	04:37:19.00 6/9/2021	21 02 51.267884	105 47 13.952704	0.7209	2327722.718	581593.483	25.709
8	04:37:20.00 6/9/2021	21 02 51.267884	105 47 13.952705	0.7241	2327722.718	581593.483	25.712
9	04:37:21.00 6/9/2021	21 02 51.267884	105 47 13.952704	0.7209	2327722.718	581593.483	25.709
10	04:37:22.00 6/9/2021	21 02 51.267884	105 47 13.952704	0.7225	2327722.718	581593.483	25.711
11	04:37:23.00 6/9/2021	21 02 51.267884	105 47 13.952703	0.7278	2327722.718	581593.483	25.716
12	04:37:24.00 6/9/2021	21 02 51.267884	105 47 13.952703	0.7243	2327722.718	581593.483	25.712
13	04:37:25.00 6/9/2021	21 02 51.267884	105 47 13.952702	0.7271	2327722.718	581593.483	25.715
14	04:37:26.00 6/9/2021	21 02 51.267884	105 47 13.952701	0.7202	2327722.718	581593.483	25.708
…	....	…	….	….	…	…	…

4.2. Accuracy evaluation of the RTK KX20-R GNSS receiver used for surveying and mapping

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. 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 dual-frequency 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 S82 and

KX20-R receivers are used and set up at the points of the control network. A Leica's CORS station (Fig. 10) is used to correct the positions for the receivers. Based on the coordinates determined by the S82 and KX20-R GNSS receivers and their known coordinates, the deviations in horizontal coordinates of the two receivers are calculated and shown in Tables 6 and 7.

Tab. 6. Horizontal coordinate deviations of the KX20-R receiver.

No	Points	Known coordinates (m)		Measured coordinates (m)		Coordinate deviation (m)		Horizontal error (m)
		X_{Kn}	Y_{Kn}	X_{KX20-R}	Y_{KX20-R}	δX	δY	
1	KH-1	2331078.161	580952.520	2331078.153	580952.529	-0.008	0.009	0.012
2	KH-4	2328976.440	580430.385	2328976.428	580430.371	-0.012	-0.014	0.018
3	KH-3	2330112.400	581855.510	2330112.386	581855.494	-0.014	-0.016	0.021
4	KH-6	2326970.116	580887.986	2326970.135	580888.008	0.019	0.022	0.029
5	KH-2	2333147.615	582109.681	2333147.640	582109.708	0.025	0.027	0.037
6	KH-5	2327466.300	582693.099	2327466.273	582693.068	-0.027	-0.031	0.041
7	KH-7	2326251.236	582094.451	2326251.208	582094.486	-0.028	0.035	0.045
8	KH-8	2324291.465	581377.192	2324291.429	581377.231	-0.036	0.039	0.053
9	KH-10	2323870.602	579504.400	2323870.559	579504.354	-0.043	-0.046	0.063
10	KH-9	2323643.828	581962.164	2323643.781	581962.213	-0.047	0.049	0.068

Tab. 7. Horizontal coordinate deviations of the S82 receiver.

No	Points	Known coordinates (m)		Measured coordinates (m)		Coordinate deviation (m)		Horizontal error (m)
		X_{Kn}	Y_{Kn}	X_{S82}	Y_{S82}	δX	δY	
1	KH-1	2331078.161	580952.520	2331078.157	580952.526	-0.004	0.006	0.007
2	KH-4	2328976.440	580430.385	2328976.432	580430.376	-0.008	-0.009	0.012
3	KH-3	2330112.400	581855.510	2330112.410	581855.524	0.010	0.014	0.017
4	KH-6	2326970.116	580887.986	2326970.095	580888.008	-0.021	0.022	0.030
5	KH-2	2333147.615	582109.681	2333147.635	582109.702	0.020	0.021	0.029
6	KH-5	2327466.300	582693.099	2327466.278	582693.076	-0.022	-0.023	0.032
7	KH-7	2326251.236	582094.451	2326251.207	582094.480	-0.029	0.029	0.041
8	KH-8	2324291.465	581377.192	2324291.425	581377.235	-0.040	0.043	0.059
9	KH-10	2323870.602	579504.400	2323870.560	579504.356	-0.042	-0.044	0.061
10	KH-9	2323643.828	581962.164	2323643.786	581962.212	-0.042	0.048	0.064

The horizontal errors of points measured from the two GNSS receivers are calculated and shown in Tables 7 and 8, and Fig. 11.

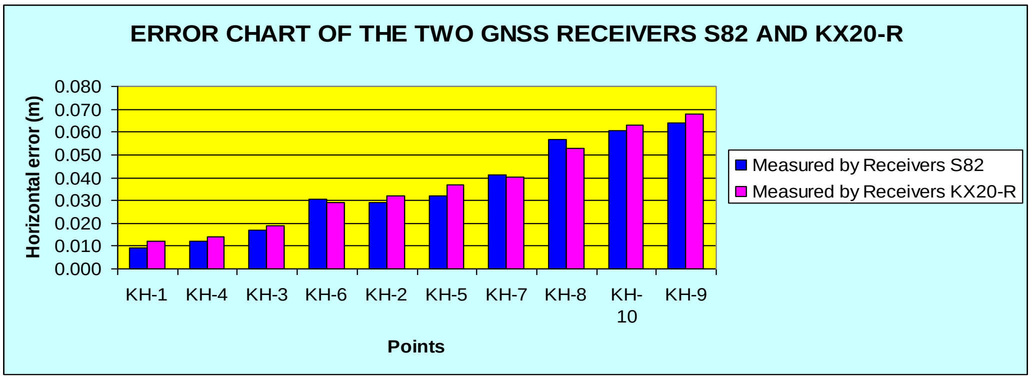

Fig. 11. Comparison of horizontal coordinate accuracy of the S82 and KX20-R receivers.

It can be seen from Fig. 11 that the horizontal errors of points measured by the two receivers KX20-R and S82 are approximately the same and both increase as the distance from the CORS station to the receivers increases. The maximum errors at the KH-9 point measured by the S82 receiver is 0.064 m and by the KX20-R receiver is 0.068 m. Thus, the KX20-R GNSS receiver, which is designed and developed in this study, meets the needs of surveying and mapping in Vietnam.

5. Conclusions

With GNSS/CORS technology, dual-frequency GNSS receivers are widely used for various purposes, especially for real-time high accuracy requirements. This study has developed two types of real-time high-precision GNSS receivers that can be used for geodetic works in Vietnam. The receiver was developed based on Trimble BD970 motherboard technology and several other modules are connected together according to the synchronous design scheme. These modules are assembled according to the design scheme and form a complete GNSS receiver with model GNSS KX-WDM100-R. This receiver could perform high-precision real-time positioning, with errors in the X-axis being 0.004 m, in the Y-axis being 0.003 m and in the altitude component being 0.009 m.

The method of transmitting rectified data in the RTCM format and monitoring data according to the NMEA standard is carried out over the internet according to NTRIP protocol thanks to the data transmitter developed in this study. The experimental measurement results conducted with the developed KX-WDM100-R GNSS receiver connecting to the Leica CORS station showed that positioning data is instantly transmitted to the server of the CORS station with millimeter-level positioning error. Thus, the KX-WDM100-R GNSS receiver developed in this study can be used to monitor real-time landslides in Vietnam.

In addition, in this study, a low-cost GNSS receiver was also developed based on U-blox's ZED-F9P motherboard technology. This receiver, together with the self-developed RTK KX Rover software installed on a smartphone device, has the functions of measuring job management, setting parameters for calculating coordinates and CORS station parameters, and managing the measurement data file to create a complete GNSS receiver. The test results of the RTK method using the S82 and KX20-R GNSS receivers showed that the KX20-R GNSS receiver centimeter accuracy meets the requirements of surveying and mapping in Vietnam.

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