Capacities of TEC measurements by the low-cost GNSS receiver based on the u-blox ZED-F9P for ionospheric research

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Abstract. A prototype of a low-cost GNSS receiver assembled on the u-blox ZED-F9P module is described in the paper. The original low-cost GNSS receiver (OGNSS-R) allows the parallel registration of 184 channels in the entire frequency range (1176 ÷ 1610 MHz) of the main GNSS (GPS, GLONASS, Galileo, Beidou) and recording raw data of carrier-phase, pseudorange (code) and signal strength measurements. The obtained data processing allows to calculate the slant total electron content (TEC), TEC variations and other most popular TEC-based indices of ionospheric activity. The comparative studies of these parameters and similar parameters obtained by simultaneous measurements on the professional geodetic GNSS receiver Trimble Alloy (KZN2 station of the IGS network) were performed. The analysis showed the median value of the signal strength at the L1 frequency for the KZN2 station are 8% higher than that at the low-cost GNSS receiver based on the u-blox ZED-F9P module (KZN2–48.75 dBHz; OGNSS-R – 45 dBHz). For the L2 frequency that difference is less than 2% (KZN2–49.4 dBHz; OGNSS-R – 48.5 dBHz). The median levels of relative slant TEC and TEC-based indexes of the ionospheric activity obtained by the Trimble Alloy receiver at KZN2 station are 25–50% lower than for the u-blox ZED-F9P receiver. Thus, the using of starter kits such as the simpleRTK2b debug board based on the u-blox ZED-F9P module described in the paper, is really actual for creating a permanent network of GNSS-stations and/or for carrying out field measurements in experimental campaigns.

1. Introduction
The field of aerial and ground unmanned vehicles, which is now actively developing, is becoming a leading part of the development of high-precision positioning. The peculiarity of this industry imposes additional requirements on most of the devices that provide such accuracy: small size, energy efficiency, and low cost relative to professional geodetic solutions. For scientific researchers, this state of affairs in the industry opens up new opportunities in monitoring the upper atmosphere with GNSS signals. To ensure high positioning accuracy, the devices described above can parallel receive multi-channel navigation signals from the main global navigation satellite systems (GNSS such as GPS, GLONASS, Galileo, Beidou), which allows calculating the total electron content (TEC) based on dual frequencies carrier-phase and pseudorange (code)
measurement of GNSS signals and restoring ionospheric and tropospheric delays. It is worth noting here that GNSS TEC method has widely used the method of remote sensing of the ionosphere by GNSS signals in the last thirty years to study various phenomena occurring in the ionosphere [1–6].

One of the first devices in this class was the ZED-F9P GNSS module with a built-in RTK unit from company u-blox. This navigation chip allows parallel reception of signals in the entire frequency range (1176-1610 MHz) of the main GNSS systems, has 184 operating channels, low power consumption, and temporal resolution of GNSS receiver output data can reach up to 20 Hz. The low cost of debugging boards based on the ZED-F9P module ($200÷250) opens up wide opportunities for the development of low-cost mobile GNSS receivers that provide monitoring of the ionosphere using TEC and other most popular TEC-based ionospheric activity indices.

Now there are other models with similar characteristics on the market. Chips with the possibility of parallel reception in two bands (L1 + L2 or L1 + L5 \(^1\)) include OpenRTK330 from Aceinna; LC79D and LG69T from Quectel; BCM47765 and BCM47755 from Broadcom; PX1122R from Skytraq and others. Ready-made solutions presented as debugging boards and starter kits that allow getting raw GNSS measurements with the possibility of subsequent conversion to RINEX to include simpleRTK2B from Ardusimple; PX1122R-EVB from Skytraq; C099-F9P application board from u-blox; SparkFun GPS-RTK2 Board and others. All the solutions listed above belong to the mass market and have a cost below $250.

The current density and uneven distribution of base GNSS stations on the territory of the Russian Federation do not fully provide the possibility of continuous monitoring of near-Earth space by GNSS TEC methods. And this is despite a significant increase in the number of permanent GNSS stations in the last decade. According to the last data, the official website of the federal service for state registration, cadaster and cartography (ROSREESTR) contains information about 551 GNSS stations of regional and commercial operators of high-precision positioning networks in the territory of the Russian Federation. Therefore, the data of TEC, TEC variations, the TEC and ROTI maps, and other ionospheric activity indices TEC-based, such as ROTI, DROT1, AATR, DIX, and DIXSG [7–10] for most of the territory of the Russian Federation have a low spatial-temporal resolution. An additional limitation, especially in scientific research, is that the operators of existing GNSS networks provide data for a paid subscription while storing archived GNSS data on their servers for a limited time, usually only half of a year.

Thus, developing a low-cost GNSS receiver that has characteristics of registration of TEC data that is comparable to professional geodetic solutions, but has a lower cost, is significant and relevant, now.

2. Short description of the hardware and software parts of the GNSS receiver

The hardware part of the device comprises three key elements: the simpleRTK2B debugging board from the company Ardusimple with the u-blox ZED-F9P GNSS module, the Raspberry Pi 4 single-board computer, and the BEITIAN BT-290 circular polarized antenna shown in figure 1. The simpleRTK2B board connectors with the Raspberry Pi 4 GPIO is carried out through a specialized adapter. Software communication between the Raspberry Pi 4 and simpleRTK2B is carried out using a serial Com-Port.

Various debugging and device management scenarios depending on the hardware configuration. It is possible to connect the simpleRTK2B debugging board directly to a PC running Windows OS (Vista and older) via the USB interface and use the U-center program to perform configuration, testing, and visualization of GNSS data in real-time. Unfortunately, the U-center program is not supporting on Linux. Therefore, to configure, debug, and control

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1 The L band is the IEEE designation for the range of frequencies in the radio spectrum from 1÷2 GHz.
the receiver using a Raspberry Pi 4 with Raspberry Pi OS, the original software was written in Python.

![Image of components](image1)

**Figure 1.** The main components of the low-cost GNSS receiver: a) simpleRTK2B debugging board; b) Raspberry Pi 4 single-board computer; c) GNSS antenna BEITIAN BT-290.

Management of the GNSS receiver in the Linux OS is implemented in two ways. The first – “classic” is a connection to the receiver using the keyboard, mouse, and monitor. This method is well suited for debugging software, including data visualization, thanks to the use of all the functionality of the graphical shell of Raspberry Pi OS or any other Linux OS. The second way is using the SSH protocol. Since the Raspberry Pi 4 has several network interfaces for transmitting information, such as Wi-Fi, Ethernet, and a USB modem (optional); you can control the device from an ordinary smartphone, the key thing is that Secure Shell Protocol (SSH) client is included. It is possible to connect to the device via the remote desktop protocol (RDP).

The result of the GNSS receiver is the formation of raw GNSS measurements, with the simpleRTK2B board, presented in the UBX binary format. However, for storing and exchanging raw GNSS measurements, it is much more convenient to use the accepted Receiver Independent Exchange Format (RINEX). To convert the UBX data to RINEX, the RTKLIB library was used. It showed the general algorithm of the GNSS receiver operation is shown in figure 2.

![Algorithm Diagram](image2)

**Figure 2.** General block diagram of the GNSS receiver operation algorithm.

For convenient transportation and rapid deployment at the site of the experiment, the GNSS receiver body was developed in the Autodesk Fusion 360 program, followed by printing the test model on a 3D printer. The general view of the finished device is shown in figure 3. To power the device, you can use either the main charger or any other power source that has 5 V and 2 ÷ 3 A.
3. The results of comparative data analysis

To estimate the quality of technical characteristics of the low-cost GNSS receiver u-blox ZED-F9P, a comparative analysis of the raw GNSS data recorded at u-blox ZED-F9P was carried out with the data synchronously recorded at the KZN2 station, which is part of the International GNSS Service (IGS). It was equipped with a professional Trimble Alloy GNSS receiver with a Trimble TRM 59800 antenna. Given the prime requirements applied to the stations included the IGS network and the long series of continuous measurements, the data received at the KZN2 station were used as a reference data. The data used in the comparative analysis were recorded on 30.04.2020 with a temporal resolution of GNSS receiver output data 1 Hz. At the time of recording, the developed GNSS receiver was located approximately 148 meters from the station of the KZN2 station (Geodetic coordinates: 55°79′N, 49°11′E).

In all figures 4–6 left panels – data from the Trimble Alloy GNSS receiver IGS KZN2 station; right panels – data from the low-cost GNSS receiver u-blox ZED-F9P. For comparison, 24 satellites were selected: GPS (G08, G10, G18, G26, G27, G32), GLONASS (R03, R04, R05, R09, R18, R19, R20), Galileo (E04, E05, E09, E11, E15, E30, E36), Beidou (C09, C11, C12, C13), whose data was recorded in the time 15:30-19:00 UTC. The time in all figures 4–6 is in UTC.

Figure 4 shows the results of a comparative analysis of the carrier-phase measurements recorded by a low-cost GNSS receiver based on the u-blox ZED-F9P module with similar synchronously recorded data by a professional geodetic GNSS receiver Trimble Alloy with a Trimble TRM 59800 antenna (KZN2 station of the IGS network). According to the results presented in [11], the optimal dual carrier-phase and pseudorange (code) combination for GPS signals is the navigation signals L1, L2C and L5 in terms of sensitivity and observation noise. Data of signal strength (carrier to noise ratio) at frequencies L1 and L2 for the same GNSS receivers are presented in figure 5. We should note that the signal strength on the u-blox ZED-F9 was written only in integer form, and it was impossible to allocate a larger number of bits for storing data for this parameter.

The relative slant TEC was calculated a standard technique based on dual carrier-phase combination at frequencies L1 and L2 [2]. To calculate, the rate of TEC (ROT) and the rate of TEC index (ROTI) were used in the equations from the article [7].

Figure 6 shows comparison analysis parameters calculated based on GNSS TEC: 1) variations
Figure 4. Carrier-phase measurements at the L1 (upper panels) and L2 (bottom panels) frequency. Data from the Trimble Alloy GNSS receiver IGS KZN 2 station (a, c); data from the low-cost GNSS receiver u-blox ZED-F9P (b, d).

Figure 5. Signal strength (carrier to noise ratio) at frequencies L1 (upper panels) and L2 (bottom panels) for the 24 satellites. L1, L2 data recorded by the Trimble Alloy GNSS receiver IGS KZN2 station (a, c); L1, L2 data recorded by the u-blox ZED-F9P module (b, d).
in the relative slant TEC (fig. 6a); 2) the rate of TEC (ROT) (fig. 6b); 3) the rate of TEC Index (ROTI) (fig. 6c); 4) Root-mean-square deviation (RMSD) of relative slant TEC in a window of 100 s (RMSTEC) (figure 6d)).

4. Conclusion
Based on the results of measurements of the strength of the navigation signal (carrier to noise ratio) using data from 24 GNSS satellites at frequencies L1 and L2, it is shown that the median signal strength level for the low-cost GNSS receiver based on u-blox ZED-F9P a little lower than for Trimble Alloy. The median value of the signal strength at the L1 frequency for the KZN2 station is 48.75 dBHz, for the developed receiver 45 dBHz. The difference is 8%. The same parameter at the L2 frequency is less than 2% (KZN2–49.4 dBHz; low-cost GNSS receiver based on u-blox ZED-F9P– 48.5 dBHz). From the comparison data analysis of the relative slant TEC and the parameters calculated on its basis presented in fig. 6, the median levels for the data obtained on the Trimble Alloy receiver at KZN2 station are 25÷50% lower than for the u-blox ZED-F9P receiver. Thus, the data obtained using measurements on the low-cost u-blox ZED-F9P has a higher noise level compared to the data of the KZN2 station. It should be noted that the KZN2 station equipped with a professional GNSS receiver Trimble Alloy with a precision GNSS antenna with a stable phase center, unlike a low-cost multiband GNSS antenna (without phase center calibrations) connected to a GNSS receiver with an u-blox ZED-F9P module.

Using starter kits similar to the simpleRTK2b debug board used in the work, is undoubtedly preferable, both for organizing a permanent GNSS station and for carrying out field measurements in experimental campaigns. Since, first, it allows obtaining a continuous series of
code and phase two-frequency measurements in the entire frequency range (1176 ÷ 1610 MHz) of the main GNSS, like GPS, GLONASS, Galileo, BeiDou and calculate long TEC series from them. Now two prototypes of the GNSS receiver based on the simpleRTK2b board with the u-blox ZED-F9P GNSS module work successfully with a temporal resolution of GNSS receiver output data 1 Hz at the Kazan Federal University and the Lobachevsky State University.

The developed low-cost GNSS receiver based on the u-blox ZED-F9P module can provide small scientific groups with mobile and affordable equipment for recording GNSS data. The important advantages of the GNSS receiver are:

- Low cost relative to professional geodetic GNSS receivers. Basic Starter Kit ≈ $250;
- Parallel reception (184 channels) of signals in the entire frequency range (1176 ÷ 1610 MHz) of the main GNSS (GPS L1C/A L2C; GLO L1OF L2OF; GAL E1B/C E5b; BDS B1I B2I; QZSS L1C/A L2C bands);
- Temporal resolution of GNSS receiver output data can reach up to 20 Hz and convert raw GNSS data to RINEX;
- The ability to calculate and visualize the TEC in real-time, as opposed to the retrospective approach;
- The ability to work from independent power sources (solar panel, wind station, etc.) due to low power consumption;
- Automatic data transmission to a remote server via standard telecommunication channels.

For a more detailed assessment of the characteristics of a GNSS receiver developed on a simpleRTK2b board with a u-blox ZED-F9P GNSS module, it is additionally necessary to record raw GNSS measurement for the next cases. SimpleRTK2b board connected to a professional GNSS antenna with a calibrated phase center and parallel connection to several professional GNSS receivers and simpleRTK2b to one GNSS antenna and after to conduct a repeated comparison analysis. This is necessary to exclude the influence of the characteristics of the using GNSS antenna on the registered parameters of navigation signals, and correspondingly measurement relative slant TEC.

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