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# DEVELOPMENT, TESTING, AND IMPLEMENTATION OF AN LC GNSS RECEIVER

The article presents an extended analytical review of the current state, historical development, technical characteristics, experimental results, application areas, and prospects of low-cost GNSS receivers (LC GNSS). Single-frequency (SF-LC), dual-frequency (DF-LC), and multi-frequency (MF-LC) models are considered with an analysis of positioning accuracy, stability, multi-path effects, antenna, and software compatibility. The paper demonstrates advantages and limitations of LC GNSS receivers in geodesy, navigation, structural health monitoring, agriculture, and atmospheric studies. It also represents the results of the development, design features, and experimental testing of the multi-system LC GNSS receiver "BASE-970". For testing reasons, the receiver was applied for geodynamic monitoring in the 2025 Ukrainian Antarctic Expedition to the Akademik Vernadskyi Station, as well as for deformation monitoring of hydraulic engineering structures in Ukraine. Constructions and functional schemes of various receiver modifications are described. Experimental studies of positioning accuracy in static and kinematic modes using Precise Point Positioning (PPP) and differential positioning methods were carried out. The results demonstrate that in static mode, the positioning accuracy reaches 2–4 mm for horizontal coordinates and 3–6 mm for height, comparable to the performance of professional receivers of leading global manufacturers. In kinematic mode, the horizontal coordinates are determined with a standard deviation of 25 mm, and the vertical component of 44 mm. The developed receiver is characterized by low cost, high reliability, and broad functional capabilities, which ensures its effective use in scientific research and practical tasks for deformation monitoring of engineering structures and geodynamic phenomena.

*Key words:* LC GNSS, DF-LC, MF-LC, RTK, PPP, GNSS monitoring, positioning, precision agriculture, multi-path mitigation, GNSS receiver development, GNSS boards.

## Introduction

Over the past decades, Global Navigation Satellite Systems (GNSS) have become a fundamental technology for real-time spatial positioning. High accuracy, global coverage, and the ability to integrate with other sensor platforms have enabled the widespread use of GNSS in monitoring geodynamic phenomena, landslides, structural oscillations of engineering facilities, as well as in precision agriculture, transportation, and telecommunications.

The evolution of GNSS receivers has moved toward reduced size, power consumption, and cost while maintaining accuracy and reliability. This has made it possible to create compact and affordable devices for tasks that previously required bulky and expensive geodetic systems. In modern conditions, GNSS is considered not only as a technology but also as a broadly applicable infrastructure service. The development of receivers adapted to specialized satellite signals for monitoring dynamic processes requires consideration of several factors:

Support for multi-frequency reception and multi-constellation capability; resistance to multi-path effects and interference; provision of high-precision real-time positioning; compatibility with field antennas and data acquisition / processing systems.

This article presents the results of development, laboratory and field testing, and experience in practical implementation of our GNSS receiver, based on the Trimble BD970 board. This board is used in multifunctional professional and relatively expensive receivers.

## Aim

The aim is to create a reliable, economically accessible, and technically adaptive solution based on a high-precision professional-grade GNSS board to monitor dynamic geophysical and technogenic processes.

## Application of low-cost GNSS receivers (LC GNSS), current state and prospects

The demand for precise positioning is growing worldwide. The development of satellite navigation technologies, particularly GNSS, has made it possible to create inexpensive yet functional devices – low-cost GNSS receivers (LC GNSS). They provide users with access to high-precision navigation and measurements without purchasing expensive geodetic systems.

The history of GNSS receivers began with military applications, but since the 1980s, GPS signals have become available for civilian use. In the 1980s, the first geodetic GPS receivers were single-channel, bulky, and expensive. They provided only static positioning with long observation times and were primarily used in research projects. In the 1990s, multi-channel dual-frequency receivers emerged, supporting both code and phase measurements. At that time, real-time kinematics (RTK) technologies were actively implemented, device sizes were decreasing, and autonomy was increasing. The use of GLONASS satellites was introduced, making receivers dual-constellation.

In the 2000s, full implementation of Continuously Operating Reference Station (CORS) networks began, along with expanded support for additional satellite systems (Galileo, BeiDou). Domestic production of satellite navigation systems was also launched in Ukraine in the early 2000s, which is related to the activities of the state-owned enterprise "Orion-Navigation". According to [Vodyanykh A., 2005], by the early 2000s, the enterprise carried out full-cycle development of geodetic GNSS complexes, including receivers, antennas, data loggers, and software. The result of this work was the Geodetic Complex SRNS SN-3603, designed to determine the coordinates of points and terrain objects using GPS and GLONASS satellites. Key tasks were solved during the development of this complex:

- development of a dual-frequency GNSS receiver;
- development of the G102 geodetic antenna considering phase center calibration;
- accumulation and processing of raw data in BINR, BINR 68, and RINEX formats;
- provision of RTK and static positioning modes.

State tests of the SN-3603 complex in 2003 demonstrated that its positioning accuracy in static phase measurements was comparable to foreign samples (e. g., Trimble 4600 LS Surveyor, Ashtech ProMark2). The internal data storage capacity of the domestic development was 32 MB, providing data storage for a 32-hour observation session at a 1 Hz frequency [Vodyanykh A., 2005]. Notably, the development included proprietary software – SaturnPro, FlashMan, and RiCo – designed for code and phase processing, format conversion, coordinate calculation, and quality control. This indicates that the company possessed not only production but also full-fledged research and development capabilities.

During these years, the development of Ukrainian GNSS technologies began. National post-processing services appeared in Ukraine, particularly ZakPOS. Multi-frequency GNSS receivers were actively introduced. The first LC receivers with RTK functions (u-blox NEO-M8P) appeared, accompanied by a mass transition to integrated GNSS+INS solutions and reduced size and power consumption.

Regarding the GNSS infrastructure in Ukraine, five separate real-time correction services have been established over the past decade (ZakPOS, SKNZU, TNT-TPI, System-net, Geoterrace). Each uses specialized software from companies such as Leica, Trimble, and Topcon, along with ground-based GNSS stations. Several hundred permanent GNSS stations have been deployed throughout Ukraine. The ZakPOS and System-net networks are fully automated. It automatically provides users with calculated coordinates in national or other systems, ellipsoidal or standard heights in RTCM messages. According to studies [Savchuk, 2009; Zademleniuk, 2010], under favorable conditions, the ZakPOS service allows coordinates to be determined within a few seconds with an accuracy of 5–10 cm at distances of up to 100 km from the reference stations. In the work of [Vivat, 2011] at the Berezhany National Geodetic Test Site, it was found that RTK coordinate accuracy is within 5 cm using the ZakPOS base station network and virtual reference station technology. The work of [Baran, 2005] investigated the possibility of achieving coordinate accuracy of 2 mm using GNSS methods. In the 2020s, DF-LC (ZED-F9P) and MF-LC (Mosaic-X5) receivers supporting L5/E5/B3 frequencies and PPP-RTK were introduced to the market. Open-source systems (RTKLIB, SNIP, STRSVR) have been expanded. GNSS technology has been integrated into mobile platforms, agricultural machinery, hydraulic structure monitoring, UAVs, and the Internet of Things. Initially, the market was dominated by only a few manufacturers of high-precision receivers and boards:

- Trimble Navigation – a well-known developer of geodetic GNSS receivers and OEM boards;

- Ashtech – a well-known manufacturer of multi-channel GPS solutions;
- NovAtel – a leader in high-precision OEM board development [Ziebart, 2001];
- Javad Positioning Systems – the first company to integrate multi-constellation GPS+GLONASS solutions [Hofmann-Wellenhof et al., 2008].

In the 2020s, the low-cost GNSS receiver (LC GNSS) segment has been actively developed. Several factors contributed to this trend:

- Demand for affordable positioning: In many sectors (agriculture, public transportation, infrastructure monitoring), there emerged a need for accurate positioning without the necessity of investing in expensive geodetic systems.
- Miniaturization of microelectronics: The reduction of size and power consumption of electronic components enabled the integration of receivers into portable devices.
- Development of satellite systems: With the launch of Galileo, BeiDou, the expansion of GLONASS, and the modernization of GPS, the number of available satellites significantly increased, allowing LC receivers to operate more reliably even in challenging conditions.
- Openness of protocols and open-source software development: Solutions such as RTKLIB, GNSS-SDR, GNSS-Logger, SNIP, and others have made it possible to process raw LC GNSS data without purchasing expensive proprietary software.
- Market competition: Mass consumer demand for GNSS (smartphones, navigation devices, drones) has reduced GNSS microchips' price, and the emergence of universal modules.

The use of LC GNSS receivers is particularly relevant in Ukraine, where there is a growing need for rapid deployment of inexpensive, mobile, and accurate positioning systems. This demand is driven by: the necessity of monitoring critical infrastructure (dams, bridges, roads); the widespread use of precision agriculture in an agrarian country; the implementation of open data and digital solutions within state digital transformation policy; limited funding for the purchase of expensive geodetic equipment in both public and private sectors; military and post-war recovery efforts, where mobile geodetic tools play a key role in surveying and reconstruction.

Compared to well-known geodetic brands (Trimble, Leica, Topcon, Septentrio), LC GNSS receivers offer the following advantages and unique features:

- Cost: LC GNSS receivers are 10–20 times cheaper than geodetic-grade alternatives, enabling their broad adoption in educational institutions, small farms, and research projects.
- Mobility and energy efficiency: Compact size, low weight, and USB or battery power make them suitable for UAVs, field campaigns, and autonomous monitoring stations.
- Rapid development: Thanks to competition among manufacturers (u-blox, Emlid, SparkFun), new LC GNSS models are released more frequently than in the premium segment.
- Integration with IoT: LC GNSS receivers can easily be integrated with platforms such as Arduino, Raspberry Pi, LoRa, and other devices, making them highly suitable for sensor networks, smart farming, and monitoring systems.
- Research potential: Researchers can experiment with signal reception parameters, positioning algorithms, and new RTK/PPP methods without the restrictions imposed by commercial software and APIs.

The limitations of LC receivers compared to branded models mainly relate to operational stability under complex conditions, accuracy without external post-processing, the lack of calibrated antennas, and limited technical support. However, LC GNSS can become an effective alternative for many functions with appropriate application. When using LC GNSS, new opportunities emerge compared to high-end receivers:

- Ease of integration into multi-sensor platforms: LC GNSS receivers can be embedded into custom drone designs, robotic systems, and hydrographic platforms without expensive licenses or SDKs.
- Scalability and deployment in remote areas: Their low price allows for deploying dense monitoring networks for subsidence, seismic activity, and deformation monitoring with minimal investment.
- Rapid technology updates: New features (support for L5, B3, Galileo HAS, PPP-RTK) appear faster in the LC than in the premium segment. For example, PPP-RTK in ZED-F9P or Mosaic-X5 became available earlier than in some Trimble or Leica models.

- Use in education and GNSS promotion: In academic institutions, LC GNSS allows students to conduct full-fledged GNSS experiments, learn RTK/PPP processing, work with open-source code, and experiment with various antennas.

Considering the above, it can be stated that LC GNSS receivers are not only a technological alternative but also a strategic instrument for developing Ukraine's geospatial infrastructure. LC GNSS receivers have emerged as a result of the combination of technological progress, economic feasibility, and societal demand for accurate positioning for a broad user base.

The u-blox company pioneered the creation of mass-market GNSS modules [Tsakiri, M., 2017]. Single-frequency LC modules such as NEO-M8P [Cina, A., 2015] enabled positioning with accuracies up to 2 cm under favorable conditions. A further breakthrough occurred with the appearance of DF-LC (ZED-F9P) and MF-LC (Mosaic-X5) models. LC GNSS receivers can be divided into three groups: SF-LC (Single-Frequency Low-Cost), DF-LC (Dual-Frequency Low-Cost), and MF-LC (Multi-Frequency Low-Cost).

- **SF-LC (Single-Frequency Low-Cost).** These are the most affordable GNSS devices, designed for simple positioning tasks. They typically support only one frequency (L1 GPS, sometimes B1 BeiDou) and lack a built-in RTK module. Typical models include u-blox NEO-M8P, M8T, and NEO-7P. Their main advantage is low cost (€ 50–150) and energy efficiency. However, without RTK modules, they require external software (e. g., RTKLIB) to achieve 1–2 cm accuracy in static conditions. Their limitations include short baselines (5–10 km), high sensitivity to multipath, long RTK initialization times, and the need for external software. These receivers are suitable for educational purposes, agro-monitoring, basic UAV positioning, or preliminary field data collection. They typically support only L1 (GPS) and B1 (BeiDou) frequencies.
- **DF-LC (Dual-Frequency Low-Cost).** These receivers support simultaneous reception on L1 and L2 (GPS), E1/E5a (Galileo), B1/B2 (BeiDou), and L1/L2 GLONASS frequencies. The primary model is u-blox ZED-F9P, available in Ardusimple, simpleRTK2B, and Emlid Reach M2/M+ formats. They include a built-in RTK module that provides initialization in under 10 seconds and 1–3 cm accuracy in RTK mode. DF-LC represents the optimal standard among LC solutions, suitable for geodesy, monitoring, precision agriculture, UAV navigation, and field campaigns. DF-LC receivers can receive L1 and L2 signals, Galileo E1/E5, and BeiDou B1/B2. They are equipped with built-in RTK modules, providing 1–3 cm accuracy in RTK and 2–5 cm in PPP-RTK. Examples include ZED-F9P and Emlid Reach M2/M+.
- **MF-LC (Multi-Frequency Low-Cost) [4],** This is the newest class, capable of receiving signals on three or more frequencies simultaneously (L1/L2/L5 GPS, E1/E5 Galileo, B1/B2/B3 BeiDou), enabling full static and kinematic PPP positioning with millimeter-level accuracy. The most notable examples are Mosaic-X5 (Septentrio) and SparkFun Mosaic Board. MF-LC receivers are considered viable alternatives to geodetic receivers for projects requiring high stability, such as monitoring, CORS networks, scientific research, including crustal movement studies, seismology, and hydraulic structure monitoring. Latest generation models receive L1, L2, L5, B3, and Galileo E5a/b signals. Their key competitive advantages include high PPP accuracy and low phase noise, compared to branded receivers such as Mosaic-X5 and Trimble Alloy [Vidal, B., 2024]. In terms of accuracy and observation quality, LC receivers demonstrate certain advantages compared to professional-grade receivers. The $C/N_0$ ratio and phase noise [Stopar, B., 2024] are typically lower for LC receivers compared to well-known geodetic receivers.

When developing LC GNSS receivers, particular attention must be paid to the GNSS antenna, as its quality directly affects positioning accuracy. Low-cost segment antennas (e. g., patch antennas or embedded modules) are characterized by high multipath effects and instability in phase measurements. To achieve geodetic-level accuracy, it is recommended to use antennas with known Phase Center Offset (PCO) and Phase Center Variation (PCV) parameters, such as: Tallysman TW2410 and TW3870 – circular antennas with precision characteristics; u-blox ANN-MB – compact entrylevel antenna; and survey-grade antennas such as AS-ANT2BCAL, LEIAR10, and Trimble Zephyr 2 – calibrated solutions with multi-frequency support [Harxon Corporation, 2025].

Studies have shown that using calibrated antennas can reduce residual phase errors by 30–40 %, with vertical component errors limited to a few millimeters [Krietemeyer, S., 2022]. In contrast, the absence of calibration may lead to systematic vertical errors of 1–2 cm. Patch antennas exhibit high multipath levels, and positioning accuracy significantly decreases under complex conditions (urban areas, forests). Geodetic antennas reduce phase noise to 3 mm.

As with traditional receivers, the positioning accuracy of LC receivers depends on the positioning mode [Calian GNSS, 2025]. The main disadvantages of LC receivers are instability in kinematic measurement mode, antenna quality issues (absence of PCO/PCV), and high susceptibility to interference.

The most promising directions for further development include mass deployment of MF-LC receivers for CORS networks, creation of specialized machine learning-based software for multipath mitigation, development of domestic MF-LC modules for geospatial monitoring needs in Ukraine, and inclusion of LC GNSS receivers into university curricula in geodesy, agronomy, and meteorology.

Modern LC GNSS receivers are capable of delivering sub-decimeter accuracy for many applied tasks. DF-LC receivers remain the most promising due to their versatility and cost, while MF-LC receivers offer strong potential for PPP positioning and long-term stability. In Ukraine, their active implementation may enable large-scale industrial infrastructure monitoring, expand capabilities for farming enterprises, optimize navigation, and support research programs related to climate change.

The application areas of LC GNSS receivers are rapidly expanding. LC GNSS is actively used for cadastral surveys, topographic mapping, and construction control. This is due to the fact that RTK connection via NTRIP, combined with a quality antenna, ensures stable accuracy in open terrain. LC GNSS receivers are widely applied in monitoring dams, bridges, landslides, and cultural heritage sites. For example, at the Laze landslide (Slovenia), DF-LC receivers successfully recorded daily displacements of up to 3 cm [Hamza, V., 2025].

LC GNSS enables automated fieldwork, seeding control, and machine navigation in precision agriculture. DF-LC receivers are successfully used to determine atmospheric parameters such as TEC, ZTD, and IWV. Networks like MPG-NET are actively utilized in climatology [Robustelli, U., 2023]. GNSS-R and GNSS-IR Earth monitoring allow the study of snow depth, water levels, glacier movement, and sea height with an accuracy of up to 0.4 cm. Table 1 presents the comparative characteristics of the three main classes of LC GNSS receivers.

*Table 1*

**Comparative characteristics of the three main classes of LC GNSS receivers**

| Characteristic | SF-LC | DF-LC | MF-LC |
|---|---|---|---|
| Frequencies | L1 | L1, L2 | L1, L2, L5 |
| Satellite Systems | GPS, BeiDou | GPS, GLONASS, Galileo, BDS | GPS, GLONASS, Galileo, BDS |
| RTK | Limited (via external software) | Built-in RTK module | RTK + PPP-RTK |
| PPP | – | 2–5 cm | 3–4 mm |
| RTK Accuracy | ~1–2 cm | 1–3 cm | 1–2 cm |
| RTK Initialization Time | >30 s | <10 s | <10 s |
| Cost, € | 50–150 | 150–300 | 500–1000 |
| Typical Models | NEO-M8P, M8T | ZED-F9P, Emlid Reach M2 | Mosaic-X5, SparkFun Mosaic |
| Applications | UAV, education | Geodesy, agriculture, monitoring | CORS, science, high-precision research |

### *General Description of the LC GNSS Receiver "BASE-970"*

During 2023–2024, specialists of the Institute of Geodesy at Lviv Polytechnic National University, based on the Educational and Scientific Laboratory of Satellite Measurements Processing and drawing on many years of experience in GNSS receiver operation, developed a communication board, designed the receiver housing, and constructed an interface fully tailored to the needs of the geodetic field. This receiver is actively used to replace outdated and malfunctioning receivers at permanent GNSS stations of the "Geoterrace" network. It is also applied for conducting static GNSS measurements in solving geodynamic monitoring tasks and calculating transformation fields at sites studied by the specialists of the Institute of Geodesy (Fig. 1).

The BASE-970 receiver was successfully tested during the 2025 seasonal Ukrainian Antarctic Expedition (UAE) at the Ukrainian Antarctic Station "Akademik Vernadsky" (Fig. 1, *a*) for monitoring the geodynamic processes of the tectonic fault in the Penola Strait of the Argentine Islands Archipelago, as well as for deformation monitoring of the Kremenchuk, Kyiv, and Kaniv HPP dams (Fig. 2, *b*). At the time of publication, dozens of such receivers have been manufactured. They reliably operate as permanent station receivers within the "Geoterrace" network (Fig. 2, *c*).

The main advantages of the developed receiver are: multi-system compatibility, low cost, ease of use, reliability and compact design. The technical specifications of the GNSS receiver developed by the Institute fully comply with the key parameters of the professional-grade BD970 board, including: 220 tracking channels; GPS: L1 C/A, L2E, L2C, L5; GLONASS: L1 C/A, L1 P, L2 C/A (GLONASS M only), L2 P; SBAS: L1 C/A, L5; Galileo: L1 BOC, E5A, E5B, 5AltBOC; BeiDou: B1, B2; QZSS: L1 C/A, L1 SAIF, L2C, L5. The receiver has 54 MB of internal memory, which can optionally be activated for data recording. The data can be downloaded via the receiver's web interface and configured for FTP or email transfer in formats T02/T04, Binex, Rinex, and Hatanaka at a specified interval.

In 2025, the BASE-970 GNSS receiver received a Certificate of Verification for legally regulated measuring instruments issued by the Lviv Scientific-Production Center for Standardization, Metrology, and Certification. The external view of the GNSS receiver is shown in Fig. 2.

The device housing consists of three parts:

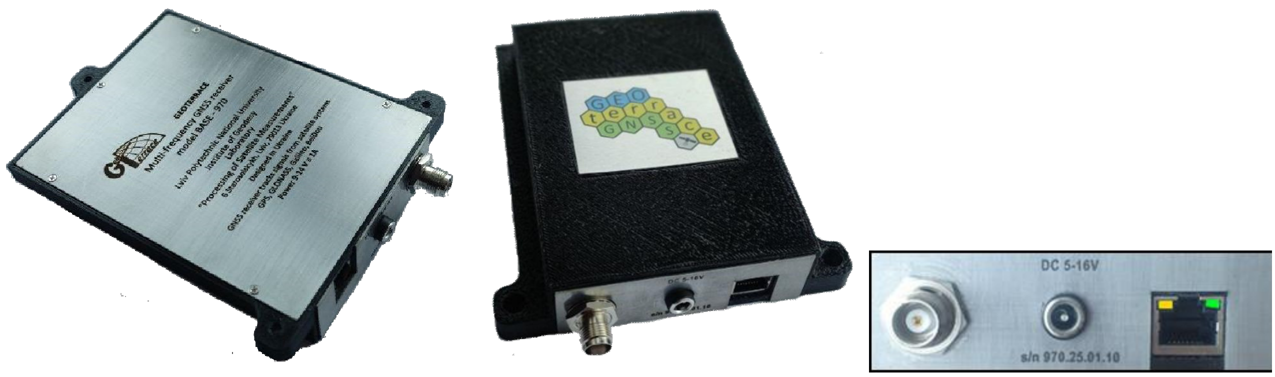
**a.** The main plastic enclosure has built-in nuts for mounting module boards. The housing includes through-holes for the Ethernet and power connectors. Additionally, it contains a groove for installing a sealing ring if necessary.

**b.** The bottom cover is made as a metal plate. In addition to its structural function, this plate serves as a heat sink for the BD970 module. Heat transfer is achieved via a layer of thermally conductive pad attached to the radio module casing.

**c.** The third part is a metal nameplate with printed connector labels and the device serial number.

*a* *б* *c*

*Fig. 1. BASE-970 GNSS receiver*




*a* *b* *c*

*Fig. 2. External view of the BASE-970 GNSS receiver*

The receiver uses two LED indicators on the Ethernet connector to display the operational status:

- Yellow – power indicator;
- Green – receiver status (steady light – initialization; flashing – satellite solutions available; off – no satellite observations).

### *Circuit Design and Construction Features of the LC GNSS Receiver*

The device is implemented as an engineering single-board design, where the BD970 core board (unit U1) with the Ethernet connector X1 is mounted. Since the BD970 board does not have integrated LED support, signals for power (yellow LED) and satellite status (green LED) are routed to the built-in LEDs on the connector. The board is powered by a step-down converter based on the MP2225 microchip (module U3). MP2225 is a high-frequency synchronous buck converter with integrated power MOSFETs. It provides a compact solution that delivers an output current of up to 5 A. MP2225 operates in synchronous mode to achieve high efficiency across a wide load current range. It supports a broad input voltage range from 4.5 V to 18 V, allowing highly flexible power options for the device.

The device supports four configurations:

1. *Base station*: The engineering board only has the BD970 core board (Fig. 3).
2. *Rover*: The engineering board has the BD970 core board and a Bluetooth module HC-08 (or JDY-33) for wireless communication with external devices (Fig. 4).

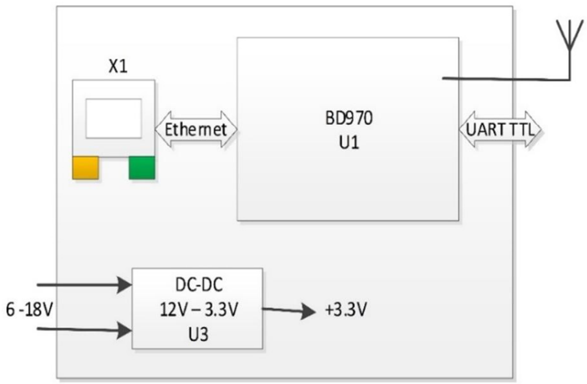



*Fig. 3. Functional diagram of the base GNSS receiver*

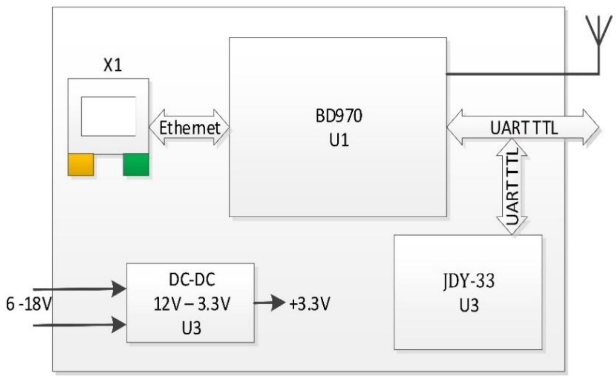



*Fig. 4. Functional diagram of the rover.*

3. *Logger*: The engineering board is equipped with the BD970 core board, STM32F411 module, Bluetooth module HC-08 (or JDY-33), and an SD card connector (Fig. 5).

4. *Wi-Fi rover*: The engineering board is equipped with the BD970 core board and the ESP32 WROOM-32 module (Fig. 6). This extension provides remote contactless access to the receiver's web interface for

full control in field conditions. Communication between the receiver's COM3 port and the ESP module is established via a null-modem interface using Point-to-Point Protocol over Serial (PPPoS). The ESP firmware, where the PPPoS server is running on a Wi-Fi-capable chip, translates the network packets between Wi-Fi and PPPoS interfaces using the Network Address Port Translation (NAPT) software module. The ESP module is configured as a Wi-Fi access point (AP), allowing smartphones, tablets, or portable computers to connect and forward all network traffic to and from the BD970 GNSS receiver.

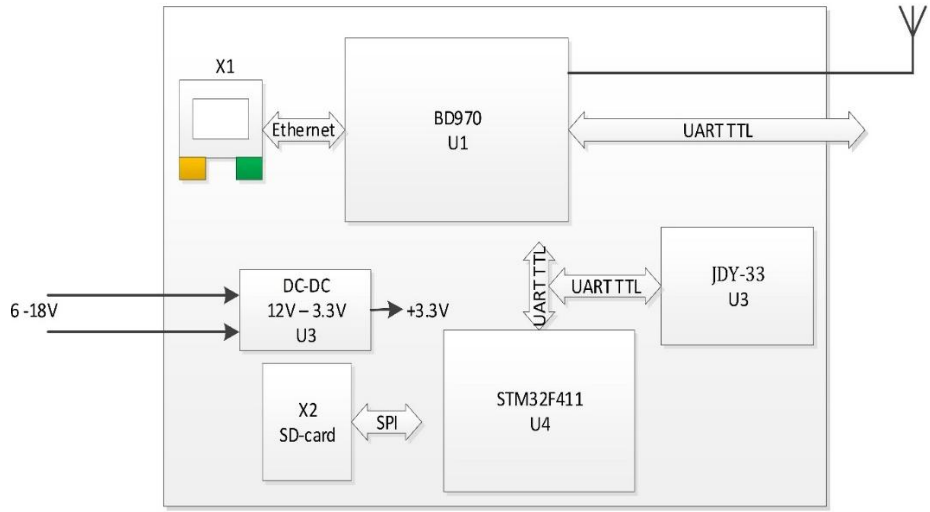



*Fig. 5. Functional diagram of the logger*

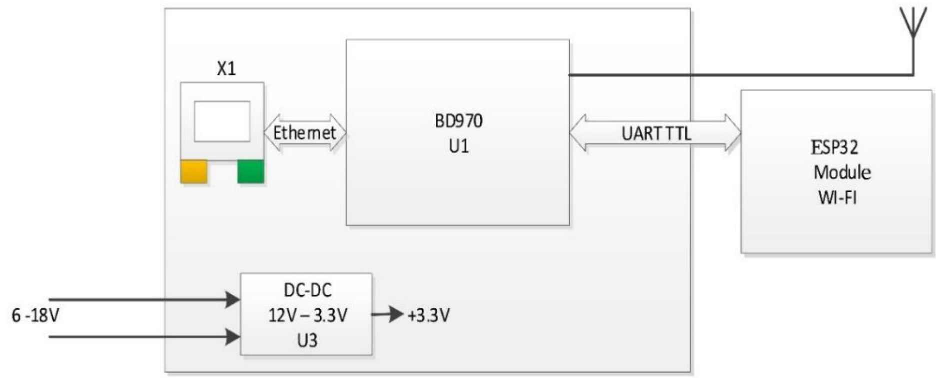



*Fig. 6. Functional diagram of the Wi-Fi rover*

### *Testing of the LC GNSS Receiver "BASE-970"*

Two tests of the developed receivers were conducted in both static and dynamic modes. The static test was performed using a specialized device [Glotov V., 2021], which allows for the displacement of the GNSS receiver antenna along three axes in space with a precision of 0.1 mm within a range of 20 mm. In this study, two GNSS receiver antennas were mounted on the device (Fig. 7, *a*), and GNSS data were recorded simultaneously. During each GNSS session, antenna displacements were applied within a 10 mm range (Table 2). Each session lasted 6 hours with a recording interval of 5 seconds. Data from four GNSS constellations were collected in each session: GPS, GLONASS, Galileo, and BeiDou. During observations, the satellite elevation mask was set to 10°, and the GDOP parameter ranged from 1.3 to 2.1.

The data were processed using two methods – absolute (PPP) and relative (DIF). The following software solutions were used for processing: PRIDE PPPAR [PrideLab, 2025], the online service of the Canadian Geodetic Survey (NRC) [NRC, 2025], Leica Infinity [Leica AG, 2025], and NovAtel GrafNet [NovAtel Inc., 2018]. For the differential mode, the permanent station SULP, located 0.2 km from the test site, was used as the reference station. The data processing utilized precise ephemerides and antenna calibration files. The reference displacement values and the GNSS measurement processing results are presented in Table 2.


*a* *b*

*Fig. 7. Devices used for testing the developed GNSS receiver in static and kinematic modes*

*Table 2*

**Accuracy assessment results of the BASE-970 GNSS receiver in static measurement mode**

| No. of session | No. $R$ | Reference displacements | | | Leica Infinity, DIF | | | GrafNet, DIF | | | PRIDE PPPAR PPP | | | NRC online PPP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta e$, mm | $\Delta n$, mm | $\Delta_U$, mm | $\Delta e$, mm | $\Delta n$, mm | $\Delta_U$, mm | $\Delta e$, mm | $\Delta n$, mm | $\Delta_U$, mm | $\Delta e$, mm | $\Delta n$, mm | $\Delta_U$, mm | $\Delta e$, mm | $\Delta n$, mm | $\Delta_U$, mm |
| 1 | $R_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $R_2$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | $R_1$ | **–10** | 0 | 0 | **–11** | –1 | –2 | **–10** | 1 | –4 | **–9** | –1 | –7 | **–13** | –1 | –13 |
| | $R_2$ | 0 | 0 | 0 | 1 | 0 | 1 | 1 | –3 | –3 | 1 | 0 | –1 | 2 | –6 | 5 |
| 3 | $R_1$ | **6** | 0 | 0 | **6** | 0 | –3 | **4** | –2 | –6 | **6** | –3 | –4 | **5** | –2 | –4 |
| | $R_2$ | 0 | 0 | 0 | –1 | 1 | 1 | 0 | –1 | –2 | 1 | –1 | –12 | 2 | –5 | 3 |
| 4 | $R_1$ | 0 | 0 | 0 | 1 | –1 | –3 | 1 | –1 | –6 | 3 | 0 | –15 | 0 | –2 | –16 |
| | $R_2$ | 0 | **10** | 0 | 0 | **11** | 0 | 5 | **6** | 0 | 2 | **9** | –13 | **3** | 4 | –1 |
| 5 | $R_1$ | 0 | 0 | 0 | –1 | 0 | –2 | –2 | –2 | –6 | –1 | –2 | –5 | –2 | 0 | –12 |
| | $R_2$ | 0 | **–6** | 0 | –1 | **–5** | 1 | 1 | **–11** | –2 | 1 | **–7** | –10 | 2 | **–10** | 3 |
| 6 | $R_1$ | 0 | 0 | **–10** | 0 | 0 | **–19** | 4 | –2 | **–13** | 3 | –2 | **–12** | 3 | –3 | **–21** |
| | $R_2$ | 0 | 0 | 0 | 0 | 0 | –1 | 0 | –3 | –12 | 0 | –1 | –8 | 3 | –2 | 0 |
| $m_e$, $m_n$, $m_u$ | | | | | 0.8 | 0.7 | 3.4 | 2.4 | 2.9 | 5.7 | 1.7 | 1.6 | 9.4 | 2.4 | 3.8 | 9.1 |
| $m_{posn}$ | | | | | 1.1 | | | 3.7 | | | 2.3 | | | 4.4 | | |

Table 2 shows that in a six-hour GNSS observation session, horizontal antenna displacements determined using differential and PPP methods have a standard deviation of 2–4 mm. Vertical displacements determined by the differential method show a standard deviation of 3–6 mm, while the PPP method yields 9–10 mm. The best result was obtained using the Leica Infinity software, with horizontal antenna displacement standard deviations of less than 2 mm and vertical deviations of less than 4 mm. For comparison, the Trimble Alloy GNSS receiver in static mode has a standard deviation of 3 mm +

+ 0.5 ppm for horizontal coordinates and 5 mm + 0.5 ppm for the vertical component [Trimble Inc., 2022]. This indicates that the coordinate accuracy in static mode achieved by the LC GNSS receiver "BASE-970" is on par with leading global brands.

Kinematic testing was also performed using a special device [Glotov V., 2021], which allows the GNSS receiver antenna to rotate along a circular path. An additional receiver was used as a base station, simultaneously recording high-frequency GNSS observations (Fig. 7, *b*).

The kinematic measurements lasted 2.5 minutes, with a data recording frequency of 0.1 seconds. Fig. 8 shows the trajectory of the GNSS antenna movement based on the kinematic measurements processing in Novatel GrafNav software. Over 2.5 minutes, at a sampling rate of 0.1 seconds, the system collected 1500 samples. During this time, the GNSS antenna completed 71 turns, covering a distance of approximately 320 meters at an average speed of 2.2 m/s.

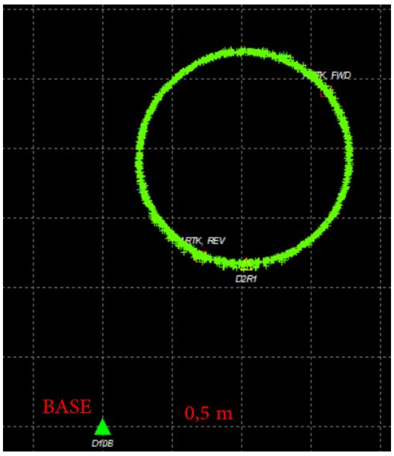



*Fig. 8. Kinematic track of GNSS antenna movement based on processing results in Novatel GrafNav software.*

Based on adjustment results using both differential and PPP methods, approximately identical values were obtained: the calculated circle radii were $r$ = 757 mm and 756 mm, respectively, with a standard deviation of $m_r$ = 1.1 mm, and standard deviations from the circular path of 25 mm and 26 mm. The height component (ellipsoidal height) was determined with a standard deviation of σ = 44 mm. The obtained results fully meet the requirements for conducting the entire scope of work in kinematic mode.

## Conclusions

The developed LC GNSS receiver "BASE-970" has been successfully tested both in the challenging field conditions of Antarctic expeditions and high-precision geodetic monitoring tasks in Ukraine. The conducted tests in static and kinematic modes confirmed its high positioning accuracy comparable to leading global GNSS equipment brands. According to the static measurements, antenna displacements in the horizontal plane determined by differential and PPP methods have a standard deviation of 2–4 mm. Vertical antenna displacements are determined with a standard deviation of 3–6 mm using the differential method and 9–10 mm using the PPP method. In kinematic mode, the horizontal coordinates are determined with a standard deviation of 25 mm, and the vertical component with a standard deviation of $m_u$ = 44 mm. The testing results demonstrate the receiver's suitability for high-precision static measurements and kinematic applications.

The main advantages of the receiver include multi-system compatibility, ease of use, reliability, low cost, and broad configuration flexibility for various tasks, from base stations to rovers with wireless interfaces.

The obtained results confirm that the "BASE-970" GNSS receiver is a competitive solution for precise geodetic measurements and can be successfully used both in scientific research and in practical projects for monitoring engineering structures, hydraulic facilities, and geodynamic processes.

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## РОЗРОБКА, АПРОБАЦІЯ ТА ВПРОВАДЖЕННЯ LC GNSS-ПРИЙМАЧА

У статті наведено розширений аналітичний огляд сучасного стану, історії розвитку, технічних характеристик, експериментальних результатів, сфер застосування та перспектив маловартісних GNSS-приймачів (LC GNSS). Розглянуто одночастотні (SF-LC), двочастотні (DF-LC) і багаточастотні (MF-LC) моделі з аналізом точності, стабільності, мультишляховості, сумісності із антенами та ПЗ. Показано переваги та обмеження LC GNSS у геодезії, навігації, моніторингу інженерних споруд, сільському господарстві та атмосферних дослідженнях. У статті викладено результати розроблення та експериментального випробування багатосистемного LC GNSS-приймача "BASE-970", вказано його конструктивні особливості. Приймач апробовано в умовах Української антарктичної експедиції 2025 р. на станції "Академік Вернадський" для моніторингу геодинамічних процесів, а також у системах моніторингу деформацій гідротехнічних споруд в Україні. Подано опис конструкції та функціональних схем різних модифікацій приймача. Здійснено експериментальні дослідження точності позиціювання приймача у режимах статики та кінематики із застосуванням методів PPP та диференційного позиціювання. Отримані результати демонструють, що точність позиціювання у режимі статики досягає 2–4 мм для планових координат і 3–6 мм для висоти, що є порівнянним із показниками професійних приймачів світових виробників. У кінематичному режимі планові координати визначаються з с.к.п 25 мм, а висотна компонента – 44 мм. Розроблений приймач характеризується низькою собівартістю, високою надійністю та широкими функціональними можливостями, що забезпечує його ефективне застосування у наукових дослідженнях і практичних завданнях моніторингу деформацій інженерних споруд та геодинамічних явищ.

*Ключові слова:* LC GNSS, DF-LC, MF-LC, RTK, PPP, GNSS-моніторинг, позиціювання, точне землеробство, мультипас, розроблення ГНСС-приймачів, ГНСС-плати.

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