FLUXGATE MAGNETOMETERS FOR GEOPHYSICAL AND SPECIAL STUDIES, CREATED ON THE BASIS OF A UNIVERSAL MEASURING MODULE (REVIEW OF DEVELOPMENTS)

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This work is devoted to describing the design of a measuring module (fluxgate magnetic compass) and the creation of various magnetometric devices based on it. These devices are designed for conducting geomagnetic and special works in various conditions and environments, both for use in stationary observation points and for work in expedition conditions.

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1. INTRODUCTION

For a long time, the minds of instrument engineers of magnetometric equipment at IZMIRAN have been occupied with the idea of creating a universal, economical, and compact measuring device for use in scientific research in various conditions and environments, with the possibility of minor additions to its circuit of additional devices necessary for specific works. Currently, the capabilities of modern technology allow for real progress towards solving this problem. As the main element of the device - the magnetometric sensor - it became possible to use small-sized fluxgate sensors (FS), which industry has now learned to manufacture quite compact, with micropower consumption and high sensitivity [Lyubimov, 2024].

FS is a primary magnetic-modulation converter used as a magnetometer to convert magnetic induction into an electrical signal [Afanasiev, 1986]. The operation of FS is based on the modulation of the magnetic state of a ferromagnetic core using an auxiliary alternating magnetic field (MF). Sometimes FS is called a ferromodulation converter, emphasizing its belonging to magnetic-modulation converters. The classical fluxgate scheme includes a magnetic core, an excitation winding (powered by alternating current), and a measuring winding (see diagram in Fig. 1 *a*). Fig. 1.

Currently, there are many different designs of magnetometric transducers (MMT), which are based on fluxgate magnetic sensitive sensors (MSS) [Afanasyev, 1986].

As mentioned earlier, fluxgate devices are characterized by small size and compactness, low power consumption, high sensitivity and accuracy. Modern fluxgate sensors (FS) and devices based on them have low intrinsic noise, which allows for highly reliable work in very weak magnetic fields and across a wide temperature range. The use of devices (magnetometers) based on FS in geomagnetic research allows (unlike other types of MSS) the ability to directly measure the components of the magnetic induction vector (MIV), which provides complete information about the field structure and its sources both at stationary measurement observation points and in motion, when conducting various kinds of expedition and exploration work.

Both in our country and abroad, there is already a large number of MMT developments based on FS, which have analog or digital output of measured information. Along with certain advantages of all known component FS (and MMT based on them), such as compactness and low power consumption, these devices have some disadvantages. These disadvantages include changes and increases in measurement errors due to changes in external ambient temperature (temperature drift), as well as measurement errors due to uncontrolled changes in their orientation in space during long-term operation. These parameters of FS need to be monitored and taken into account [Lyubimov, 1992; 2017; 2024], especially when conducting long-term stationary measurements both in magnetic observatory (MO) conditions and during expedition work.

The capabilities of modern technology now allow not only to control FS parameters, accumulate, process and correct the obtained data and transmit them via communication channels over a distance, but also to have reference and synchronization of the obtained data when conducting field work, for example, using the GPS system.

This review presents some projects and designs of magnetometers [Zverev and Lyubimov, 2019; Lyubimov, 1994; 2004; 2018; 2019a, b, c; 2020a; 2024; Lyubimov et al., 2019; Zverev and Lyubimov, 2019] for conducting long-term and short-term measurements with high (at the level of 1 nT and above) resolution, based on a universal measurement module (MM), which can be implemented using various designs of fluxgate magnetic field sensors.

2. UNIVERSAL MEASUREMENT MODULE

In early 2009 . , as a result of experimental and research work with various types of fluxgate sensors, a team of researchers led by A.S. Zverev created the design of the MM (see Fig.1 *g*) and comprehensively tested a prototype [Zverev and Lyubimov, 2019; Lyubimov, 2021; Lyubimov et al., 2019; Zverev and Lyubimov, 2019]. This MM was a universal six-channel converter of analog geophysical data with the possibility of their subsequent accumulation, transmission over a distance, and digital registration. The construction scheme of this MM is universal and technologically efficient, which allows it to be used as part of various measuring complexes when working in different conditions and environments.

The MM includes three different independent analog-to-digital converters (see Fig.1 *c*): a three-channel magnetic field converter, a three-channel tilt angle converter - digital inclinometer (DI), and a temperature sensor (TS). The combination of magnetic sensors with inclinometers in the practice of geophysical work is called a strapdown magnetic compass (MC).

The use of component fluxgate sensors in the MM, complemented by other devices (DI and TS), allows for the compensation of magnetic field distortions that arise due to various factors, which helps eliminate some additional measurement errors, for example, when changing the sensor tilt angle or due to the influence of ambient temperature.

The MIP is built on the basis of the FD and includes three measurement channels (MC) for measuring the components of the Earth's VMI field D, H and Z. The functional diagram of the IM is shown in Fig.1 *c* and includes: a three-component FD, an inclinometer board (IB), which includes three DI and TS, as well as a microcontroller board (MCB), which includes ADC circuits, a microcontroller (MC) with a serial data transmission interface (RS232) and a power supply unit (PSU).

When creating the device and searching for the necessary MFD to use in the design of its MIP, options for using several known domestic and foreign small-sized FD designs were considered (see data in Table 1 in [Lyubimov, 1994; Lyubimov et al., 2019]). As a result of analyzing the characteristics and conducting comparative and evaluative experimental work, FD type FLC3-70 from the German company Stefan Mayer Instruments GmbH & Co. (http://www.stefan-mayer.com) was selected for the basic MIP scheme of the device. These sensors implement a counting accuracy of 1 nT in the range from 0 to ±70 μT and a field-to-voltage conversion coefficient of 35 μT/V for each MC. At the same time, the intrinsic noise of each FD does not exceed the level of 0.1−0.15 nT. The general view of the three-component FD used in the device scheme and some variants of the IM designs are shown in Fig. 1 d.

The main criteria for choosing this FD variant were higher measurement accuracy and low power consumption (6 mA) from a unipolar power source (PS). Low consumption (small value of compensation current in the measuring windings of the FD) was important to reduce (or eliminate) the effect of mutual influence of measurement channels on each other in the design of a three-component small-sized FD, especially when the IM is used during movement in space.

Analog voltage (±2 V) from the output of each of the three SCs (D, H, and Z) of the MIP is fed to the ADC inputs, which is located on the microcontroller board (MCB), where the MC circuits with a serial data transmission interface (RS232) and the PS are also located. From the ADC output, data from the MIP is fed to the MC input and then through the RS232 serial port in digital form to the MM output. Through this RS232 serial port, external control (for example, using a computer) of the MIP operating modes, accumulation, and correction of incoming data is also carried out.

To control the spatial orientation of the FD, a three-component inclinometer is used, which is based on the ADIS16209 chip (https://www.analog.com/media/en/technical-documentation/data-sheets/ADIS16209.pdf) and contains two devices (two chips) for measuring tilt angles (see Fig.1 *b* , *c*). The selection of this chip for the DI was due to its compactness, high measurement accuracy (see data in Table 2 in [Lyubimov et al., 2019]), as well as the use of a unipolar PS and low power consumption, which is very important when installing the DI near the FD. The main advantage of this DI is the presence of a built-in TS, which allows for the correction of measured data from both the DI and FD.

Inclinometers X, Y measure deviations in the horizontal plane, and inclinometer R measures the tilt angle of the FD in the vertical plane. The DIs are rigidly fixed (see Fig.1 *d*) relative to the FD on the inclinometer board (IB) and are located at a distance of 55 mm from them (to exclude influence on the FD measurement results). With the help of inclinometers (simultaneously and synchronously with the measurement of EMI components), the measurement and control of three angles of deviation of the FD measuring axes are carried out, and the accuracy of these measurements is ± 0.1º.

To ensure a favorable temperature operating regime for the FD, the entire MM circuit is placed in a non-magnetic housing-container (see **.** Fig.1 *d*), which, depending on the application conditions, can be made of duralumin or plastic with a minimum internal diameter of 50 mm and a length of 250-300 mm.

The IM created on the basis of a three-component FD is a functionally complete device design, which has sufficiently high measurement accuracy characteristics and low power consumption (no more than 30 mA), which allows it to be used as a universal element for many geophysical measurement systems. For example, the proposed scheme and design of the IM was used in the development of marine magnetometers and gradiometers [Zverev and Lyubimov, 2019; Lyubimov, 2019a, c; 2020a; Lyubimov et al., 2019], and was also used in the creation of field search devices [Lyubimov, 2020b] and magnetovariational stations (MVS) [Lyubimov, 2021; 2024]. It should be noted that depending on the method of IM application (when solving various geophysical and special tasks), its weight characteristics (mass) can be changed in the range from 0.3 to 5 kg.

Below we will focus on new solutions and designs of created devices and on promising projects for implementing devices and special instruments based on IM.

3. MAGNETOVARIATIONAL STATION

Based on the universal IM, a new magnetometric device has been developed – a fluxgate MVS, which allows measurements and scientific research to be carried out both in MO conditions and in expedition conditions, in the field [Lyubimov, 2021; Lyubimov, 2021b]. At the same time, the use of DI makes it possible to set the FD arbitrarily during the research process, measure the components of the VMI and calculate its modulus.

Fig. 2.

The proposed design of the IM (and the MVS based on it) suggests two main options for using the station, which are shown in Fig. 2 *a* . The first option for using the MVS is designed for the operation of the device in MO conditions or a stationary observation point, where the IM is installed on a non-magnetic pedestal equipped with three screw legs for leveling the container with the MIP in the horizontal plane (see Fig. 2 *b*). When the MVS is operating in field conditions, a second option is provided - installing a container with an IM in a pit dug in the ground, which is located below ground level (see Fig. 2 *a*).

As noted earlier, the basic IM (induction magnetometer) circuit (in a specific application case) is additionally equipped with a digital temperature sensor (DT) connected to the microcontroller (MC) via a communication line (RS232). This sensor is installed (see Fig. 2) inside the IM housing and located close to the FD (flux-gate detector), which allows monitoring the temperature near the FD with an accuracy of 0 . 1°C. The DT is implemented using an LM35D type chip, has a plastic housing design and consumes current not exceeding 60 μA, which eliminates its electromagnetic influence on the FD measurement results.

To ensure favorable temperature conditions for the FD operation, the entire IM circuit is placed in a non-magnetic housing-container made of duralumin or plastic (PVC or fiberglass-epoxy tube) with dimensions Ø150x300 mm. Inside the housing, there is an insulating foam insert 20 mm thick (not shown in Fig. 2 *a*), behind which there is a screen made of double-sided foil-clad fiberglass (1 mm thick), which simultaneously serves as an electrostatic screen for the FD. Inside this screen, a heating element (HE) is fixed (soldered), which is based on a small-sized ceramic self-regulating PTC heater (PN) type ST6-1B-1 [Lyubimov, 2017].

The PN is powered by DC or AC voltage (exceeding by approximately an order of magnitude the FD excitation frequency) from the power supply (PS) circuit. Temperature control is carried out by the DT and regulated by the MC.

The functional diagram of the MMS (magnetic measuring system, built on the IM base) is shown in Fig. 2 *b* . The external view of one of the created MMS variants for magnetic observatory (MO) is also presented here. The MMS circuit includes: IM and measuring unit (MU), which are connected by a cable for supplying power voltage from the power supply, exchanging data and control signals between the units according to the RS232 standard at a distance of up to 25 m.

The MU includes the following functional units: MC, control circuit (CC), graphic display (GD), rechargeable battery (RB), power supply (PS), as well as a GPS receiver and data transmission modules Bluetooth (BT) and GPRS with antennas A2, A1 and A3 respectively.

The GPS module is equipped with a time strobe output. The Bluetooth module has data transmission range options: class 2 module - up to 30 m, class 1 module - up to 100 - 200 m, and class 1 module with an external antenna - up to 300 - 400 m. The GSM module design features a replaceable SIM card.

The IB circuit also includes a real-time clock (with non-volatile power supply) and "buffer" non-volatile memory (NVM) - internal data storage (IDS) with a capacity of 8 MB.

Before starting operations, the MVS measurement cycle is set using an external personal computer (PC) and special software (SW). The general view of the data obtained by MVS in digital form on the PC display is shown in Fig. 2 *b* . The software also allows obtaining data in graphical form, calculating and visualizing the GMF module (Bt) based on the measured GMF components, as well as correcting the obtained magnetometric data based on DI data and built-in temperature sensors.

An external removable digital file storage (RFS) with a capacity of up to 4 GB is used as the external storage, which connects to the IB and allows accumulating measured data in autonomous operation mode, without connecting to a PC.

The MVS allows accumulating and storing data during operations in the internal NVM, as well as transmitting the accumulated data via available GPRS and BT channels to a remote receiving point (computer).

The total consumption of the IM circuit in this design (without NE) is no more than 25 mA, and the total consumption of the entire device in data transmission mode via the communication channel is 250 mA. The MVS can be powered either from a rechargeable battery with a voltage of 7-24 V or from 220V (50 Hz) AC mains using a power adapter (PA) with a voltage of 12-24 V.

4. MULTICHANNEL MAGNETOMETER-GRADIOMETER

The multichannel MG (MMG) [Lyubimov, 2020b] is a universal device that allows conducting component (or modular) geomagnetic studies for terrain mapping and searching for local magnetic anomalies. MMG is used to search for local ferromagnetic objects located in the thickness of a non-magnetic medium (in soil or water). The measurement technique involves simultaneous parallel movement of MFDs, which are located at a specific and adjustable distance (IB) from each other, in space with simultaneous measurements and calculations of VMI elements. In this version, the device is constructed using five MIPs. Such design of the measuring part of the device allows exploring a fairly large area in width in one pass, which can be variable and wider than in known modern special devices [Zvezhinsky and Parfentsev, 2009a, b].

Each MIP represents an IC and is based on an IM and PD, for which a device of the FLC3-70 type is used. The resolution of each IC is 1 nT. The use of DI in this device design allows measuring the magnetic field gradient and VMI components during movement with accuracy no worse than 1-5 nT.

Fig. 3.

The block diagram of the MMG is shown in Fig. 3 *a* . Fig. 3 *b* and Fig. 3 *c* show respectively the layout of the main functional units of the device when measuring the horizontal gradient (HG) and vertical gradient (VG) of the magnetic field and possible applications of the device.

Fig. 3 *a* presents a detailed functional diagram of the MMG, which implements the basic idea of the VMI gradient measurement method both on land and in aquatic environments. When using the device in an aquatic environment, a long special cable and hydrostatic pressure sensors (HPS), which are mounted in the housing of each MIP, are additionally used. Fig. 3 *b* shows the layout of the main units of the device during the research process and possible variants of its use when measuring HG and VG of the magnetic field.

Fig. 3 *c* presents possible methods of conducting research using the device in pedestrian, automobile, or marine versions.

The functional diagram of MMG (see Fig. 3 *a*) includes five MIPs, which are located on their mounting device (UKIM) at a certain (specified or dependent on the width of the research area and the size of UKIM) distance from each other. Each MIP is connected via RS232 data transmission channel to the IB. The IB includes the following functional units: MC, control circuit (CC), graphic display (GD), AB, IP, DT, as well as a GPS receiver and data transmission modules Bluetooth (BT) and GPRS with antennas A1 - A3.

The MMG data transmission system, which includes a GPS receiver and data transmission modules BT and GPRS with antennas, as well as the VND circuit, are similar to those used in the MVS design and described above.

MMG allows accumulating and storing data during operation in the internal EP, as well as transmitting accumulated data via available GPRS and BT channels to a remote receiving point (computer). The total consumption of one MIP is not more than 15 mA, and the total consumption of the entire device in data transmission mode via the communication channel is 250 mA.

MMG can be successfully used in pedestrian mode, as well as when moving with it being towed as a trailer to a vehicle on the earth's surface or on a raft - on water. The device allows simultaneous recording of data from each MIP and field gradients between them.

The uniqueness of the MMG design is that when measuring VG or HG of the magnetic field, there is no need to adjust the measuring axes of the MCS relative to each other (as is done in most manufactured devices [Zvezhinsky and Parfentsev, 2009a, b]) with high accuracy. This work is performed by the CI and MC, which during the measurement process make corrections and calculate the real values , measured by the MCS.

The use of component measurements, – simultaneous synchronous measurement of HG and VG components of VMI during magnetic survey, – increase the accuracy and informativeness of the conducted research. This is especially important when searching for and determining local anomalies, which is much more difficult to do when using modular magnetometers or single-component gradiometers.

5. GRADIOMETER FOR HYDROMAGNETIC SURVEYS

The marine component gradiometer (MCG) was developed on the basis of a fluxgate IM [Zverev and Lyubimov, 2019; Lyubimov et al., 2019; Zverev and Lyubimov, 2019]. The created device is intended for relative measurements of the MF in space at points and the gradient between them in marine conditions during hydromagnetic survey (HMS), including it can be effectively used to search for ferromagnetic objects and objects.

The device consists of two main parts connected by a towing cable: outboard and onboard. The functional diagram of the MCG is presented in Fig.1 in the work [Zverev and Lyubimov, 2019].

The onboard part of the device includes a power supply unit (PSU) and a personal computer (PC) and is installed on board the tugboat. The offboard part of the device includes two towing cables (TC) and two submersible gondolas (PG), which are towed at a distance (to eliminate the influence of the magnetic mass of the vessel) of at least three lengths of the tugboats hull from its stern.

The towing speed of the PG is limited within the range from 3 to 10 knots with an acceptable sea state amplitude of no more than 5 points. The general appearance of individual parts of the device and the diagram of its use during the GMS are shown in Fig. 4, respectively. *a* and Fig. 4 *b* . The SG is designed to be capable of towing at horizons and depths up to 130 m. The depth of each SG is recorded using a built-in hydrostatic pressure sensor (HPS), which provides information about the course and depth of the SG with an accuracy not worse than 0.2 m.

Fig. 4.

The block diagram of the measuring part of the MCG (measuring module - MM) of the device, which is located in each of the PG, includes the MK board, the DI board and the MCD. The measurement of the components of the VMI in the device and the gradient between them is carried out using two analog three-component PDs of the FLC3-70 type. Analog signals that come from each of the three IRs of both PDs, corresponding to the components of the VMI, are converted into a digital code using a 24-bit ADC.

To control the spatial orientation of the FD, a two-component digital signaling system is used, which contains two devices for measuring the angle of inclination. The inclinometer X, Y measures deviations from the horizontal plane passing through the axial line of the gondola and perpendicular to the "vertical" of the gondola, while the inclinometer R measures the angle of inclination (rotation) of the gondola in the plane perpendicular to the axial line. The position of the DC relative to the PD in the PG is shown in Fig.1 *b* . The inclinometers are used to measure the roll and pitch angles of the PG, with a measurement accuracy of ± 0.1°. As shown above, a digital DGD is used to control the depth of the PG, which is located inside the PG at the maximum distance from the MCH. The sensitive element of the DGD is connected to the external environment (water) through a channel.

Information from each PG is transmitted via a serial RS422 interface through a cable to the ship. Passing through the onboard interface converter (IC), which is part of the PS, the data is converted to the RS232 standard and sent to the PC. The software is used for data accumulation, processing, and visualization in various forms on the PC screen. For precise time reference of current measurements, a GPS receiver is connected to the computer's COM port.

A non-magnetic Kevlar-based cable with increased breaking strength of about 1500 kg is used as the TC. This cable (see Fig. 4 *a*) has an external diameter of 12 mm and includes two conductive wires for power supply, two twisted pairs for digital information transmission, and a shield. The length of the TC connecting the nearest BG to the onboard part of the device is 380 m. For GG measurement during HMS at different IBs, the MKG kit includes two similar cables with lengths of 100 m and 20 m.

The assembled PG design [Lyubimov et al., 2019] consists of a non-magnetic housing with removable stabilizer and weight attached to it. The stabilizer is designed to increase the stability of the PG during towing, and the weight is necessary to reduce gondola oscillations around the longitudinal axis and to fix the position of its vertical plane. The BG nearest to the ship's hull has two cable inputs, while the farther BG has one.

The MCG has measuring ranges for all components of the EMF for each of the magnetometric measuring channels from 0 to ±70 μT, with the basic measurement error not exceeding 5 nT, and the counting accuracy implemented using ADC is 0.1 nT. The registration range of the gradient between MSS in PH for each of the measuring magnetometric channels lies within the limits from 0 to ±10 μT. The registration range of the immersion depth of BH is from 0 to 130 m, with the accuracy of course depth and immersion registration being 0.2 m.

Information from the measuring channels of magnetometers in binary code is output through the RS422 serial interface via the communication line (two cores of the towing cable) to the onboard recording device at a speed of 115200 baud.

During the marine survey (MS), the device power supply (when using marine vessels) is provided from an AC power network with a voltage of 220±22 V and a frequency of 50±5 Hz, with the power consumption not exceeding 50 VA. For operations performed using various types of small "floating crafts", there is a possibility to power the MCG from a rechargeable battery with a voltage of 10−15 V.

The housings of both PHs, made based on a polyurethane non-magnetic tube (housing wall thickness 18 mm), have overall dimensions: 70 mm in diameter and 1000 mm in length. The weight of the PH, including the IM and MSS located inside it, does not exceed 10 kg, and the total weight of the BC used in the device in various application options does not exceed 100 kg. The onboard part of the MCG, the power supply unit (sized 120 x 50 x 200 mm) and the PC weigh no more than 5 kg.

6. MARINE MAGNETOMETER-GRADIOMETER

To implement the MS method proposed in [Lyubimov, 2019c], a new design of a marine component magnetometer (MCM) based on IM was proposed. This method of measuring the magnetic field gradient in an aquatic environment is used in MS, which allows increasing measurement accuracy by eliminating errors associated with variable towing conditions of the underwater gondola (UG) such as: instability of the towing body, "yawing" and varying depths of the UG [Lyubimov, 2019a, c]. Using only one towed UG significantly simplifies the methodology of operations (especially launching and recovery), as well as work related to deploying two or more UGs during towing, for example, when measuring the horizontal gradient of the Earth's magnetic field, at the same horizon. In this case, an acoustic channel is used as the main element of synchronization (and metrological tool for implementing accuracy) of all measurement processes of the magnetometric equipment, which includes a controlled pulse pneumatic emitter (PE) installed on the towing vessel, and a piezoelectric pressure receiver (PPR) installed in the towed UG. This channel forms a pulse of ultrasonic energy (echo signal of an acoustic wave), which propagates in the aquatic environment at a certain speed   Vsound.

Fig. 5.

Figure 5 shows a block diagram of the device that implements the main idea of the method for measuring the Earth's magnetic field gradient at sea. This device contains a non-magnetic towed UG, inside which IM and various sensors are located. The IM contains a microcontroller (MC1), ADC, power converter (PC) and an interface for data transmission and operation control (RS422). The photodetectors (three measuring channels X, Y, Z) of the magnetometer, two inclinometers (measuring channels X, Y and R), a hydrostatic pressure sensor (HPS) and PPR are connected to this IM (via ADC).

The UG is towed using a cable of arbitrary length behind the ship. Typically, the length of the towing cable is chosen after practical determination of the magnetic moment of the towing vessel and should not be less than 2-3 lengths of its hull. Also, when choosing the length of the towing cable, the size of the water area where MS is performed and its depth are important.

The ship accommodates a measurement unit (MU) with connected personal computer (PC), GPS receiver, probing pulse generator (PPG), and pneumatic radiator (PR). The MU, which is the main synchronization element of the entire system, includes a microcontroller (MC2), interface conversion unit (ICU), and power supply unit (PSU).

MC1, located in the PG, synchronizes and controls data acquisition from sensors in digital form and transmits it via RS422 interface to the ship. MC2 provides complete synchronization of all data with world time and positioning using the GPS system, and also controls the acoustic channel for synchronizing measured data using PPG and PR. Two variants of PR usage can be implemented, either rigidly fixed to the ship's hull or towed behind its stern.

The measurement accuracy of IB in the proposed device when measuring the horizontal gradient of the MPF is determined by the parameters of the ultrasonic energy pulse emitted by the PR and allows for a resolution in HMS conditions of about 1-10 cm. The depth gauge sensor used is a sensor with digital output (MS5541B chip), which allows monitoring the towing depth of the PG with an accuracy of up to 20 cm.

The measurement accuracy of MCM components of the MPF is determined by the parameters of the PD used in the magnetometer (in this design, a PD type FLC-70 is used, having non-orthogonality of axes of ±1º), as well as the accuracy parameters of the DI. Both inclinometers are based on the digital chip ADIS16209, which is currently the most accurate integrated measuring instrument. This ensures measurement accuracy of angles during PG towing of about 0.1º (angular degree) with a resolution of 0.025º.

Experience in using DI (and, in particular, this model) in creating marine magnetometers with towed PGs provides measurement of VMI components during MS with accuracy not worse than 1-5 nT [Lyubimov, 2019c, 2020a; Lyubimov et al., 2019].

7. POSSIBLE APPLICATIONS OF MAGNETOMETRIC SYSTEMS BASED ON IM

The created IM design based on three-component PDs can find its application in various spheres of scientific, research, medical activities [Gurfinkel' et al., 1995a, b; Lyubimov, 2021a]. Including – for electromagnetic monitoring of the environment and special research, for example, in the radio engineering industry, as well as for military purposes [Afanasiev, 1986; Lyubimov, 1994; 2004; 2018; 2019b; 2024]. At the same time, the created IM design is compact, has high sensitivity (at the level of units of nT) and low energy consumption.

Based on the conducted research and gained experience, the use of several IMs in medical wards, magnetic chambers, and industrial work areas is proposed for electromagnetic monitoring of the environment. With the necessary software, it is possible to build maps of the magnetic environment in the studied rooms and work areas in real-time [Lyubimov, 2004; 2018; 2019b; 2024].

Fig. 6.

When using the measurement scheme shown in Fig. 6 *a* , it becomes possible to study (using several IMs) the magnetic moment (MM) of various products in a room, for example, large scientific and other devices, satellites, various special equipment. This creates the possibility of multi-channel measurements of both MM (when rotating the test object in separate planes and directions) and conducting three-component gradient measurements (including the VMI module - Bt).

When organizing a similar (as in Fig. 6 *a*) multi-channel measurement scheme (4 or more IMs) in field conditions, there is an opportunity for special work, for example, studying the MM of tanks, special vehicles, armored vehicles, various weapons. Thus, when installing several IMs in an aquatic environment (in river beds and channels or on rafts), it is possible to study the MM of both various watercraft and ships and submarines (see Fig. 6 *b*).

This device solution based on IM is quite applicable for high-precision security activities and protection of maritime and land borders (see Fig. 6 *b*). It can be used on non-magnetic drifting (including weather balloons and high-flying) aerostats [Lyubimov, 2024] when conducting special scientific gradiometric studies with a large "measurement base" (see Fig. 6 *d*).

Currently, the use of magnetometric equipment based on FD is becoming relevant for conducting scientific research and search operations from low-flying devices over land or water surfaces, any type of UAV (drones) with a payload of 2-5 kg.

Fig. 7.

The proposed design of a multi-channel magnetometer-gradiometer for drones (MGD), created on the basis of IM and shown in Fig. 7 *a* , is designed for areal surveys when ground pedestrian and automobile surveys are not possible. MGD can be used for high-resolution surveys to detect small objects in the ground, such as mines, bombs and unexploded ordnance, as well as for archaeological investigations.

The use of special software provides accumulation of measured data in the internal memory or data transmission in real-time, as implemented in MMG. The use of low-power compact MFSs in the device circuit makes it quite economical and allows for longer usage time from the battery during the survey. It also significantly reduces the total weight of the UKIM. Options for suspending various UKIM designs to a drone are shown in Fig. 7 *b* .

An example of detecting magnetic objects during research using MGD is presented in Fig. 7 *c* , which shows maps of the anomalous magnetic field and its gradient during search operations at one of the test sites.

8. CONCLUSION

This review presents several designs of magnetometric devices for long-term and short-term measurements based on fluxgate magnetometers, having high (at the level of 1 nT and above) resolution and allowing for both scientific and geophysical research, as well as special work in various directions. The main focus of the developments was on the compactness of the created devices and their cost-effectiveness using the most advanced foreign component base.

Currently, there is an urgent need in domestic instrument engineering to focus on the use of our own instrument manufacturing products and component base. For example, Russian three-component magnetic field sensors NVO391.5-20/3, NVO391.5-35/3 or NV0302 transducers (of various modifications) produced by LLC "Magnetic Devices" can be quite successfully used as fluxgate sensors for new fluxgate magnetometer developments (www.magnetic.spb.ru) **.** The main technical characteristics of these magnetic field sensors do not differ very significantly from the best foreign samples of fluxgate sensors currently available [Zvezhinsky and Parfentsev, 2009a, b; Lyubimov et al., 2019].

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Figure Captions

Fig. 1. Block diagram of a single-channel fluxgate MIP (*a*), arrangement diagram of FD and DI (*b*), functional diagram of IM (*c*), and IM design (*d*).

Fig. 2. General view of two IM design variants: desktop version for work in MO and expedition version (*a*) and functional diagram of MVS with data registration on PC (*b*).

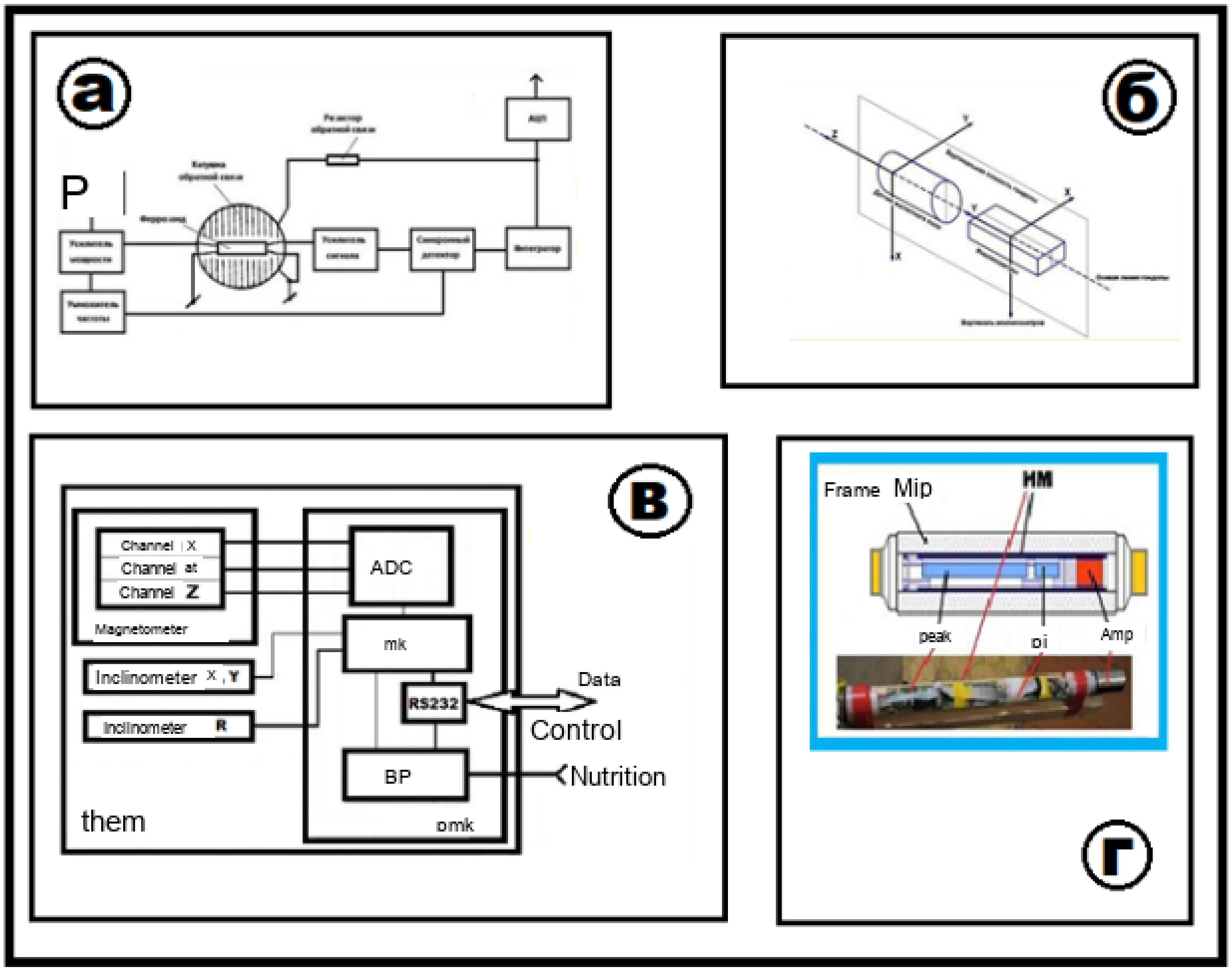
Fig. 3. Functional diagram of the device (*a*), arrangement diagram of the main functional units of the device when measuring HG and VG (*b*) and possible applications of the device (*c*).

Fig. 4. General view of onboard and towed parts of MKG (*a*) and towing diagram of the device (*b*).

Fig. 5. Block diagram of MKM for measuring the horizontal gradient of MPF in aquatic environment.

Fig. 6. Schemes of conducting research using IM: for studying MM of the product (*a*) and conducting multi-channel gradiometric measurements in aquatic environment (*b* , *d*), on land (*c*) and in air (*e*).

Fig. 7. Design of a multi-channel magnetometer-gradiometer for installation on low-flying drones of different designs (*a*), variants of suspension of various UKIM designs (*b*) and an example of conducting search operations when detecting magnetic objects (*c*).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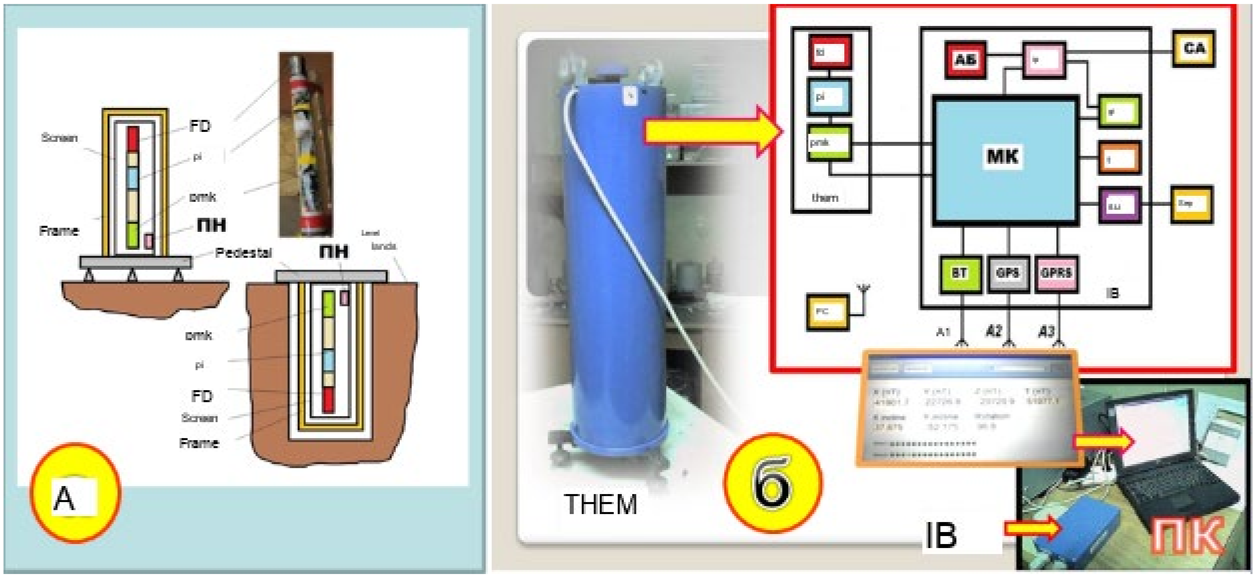
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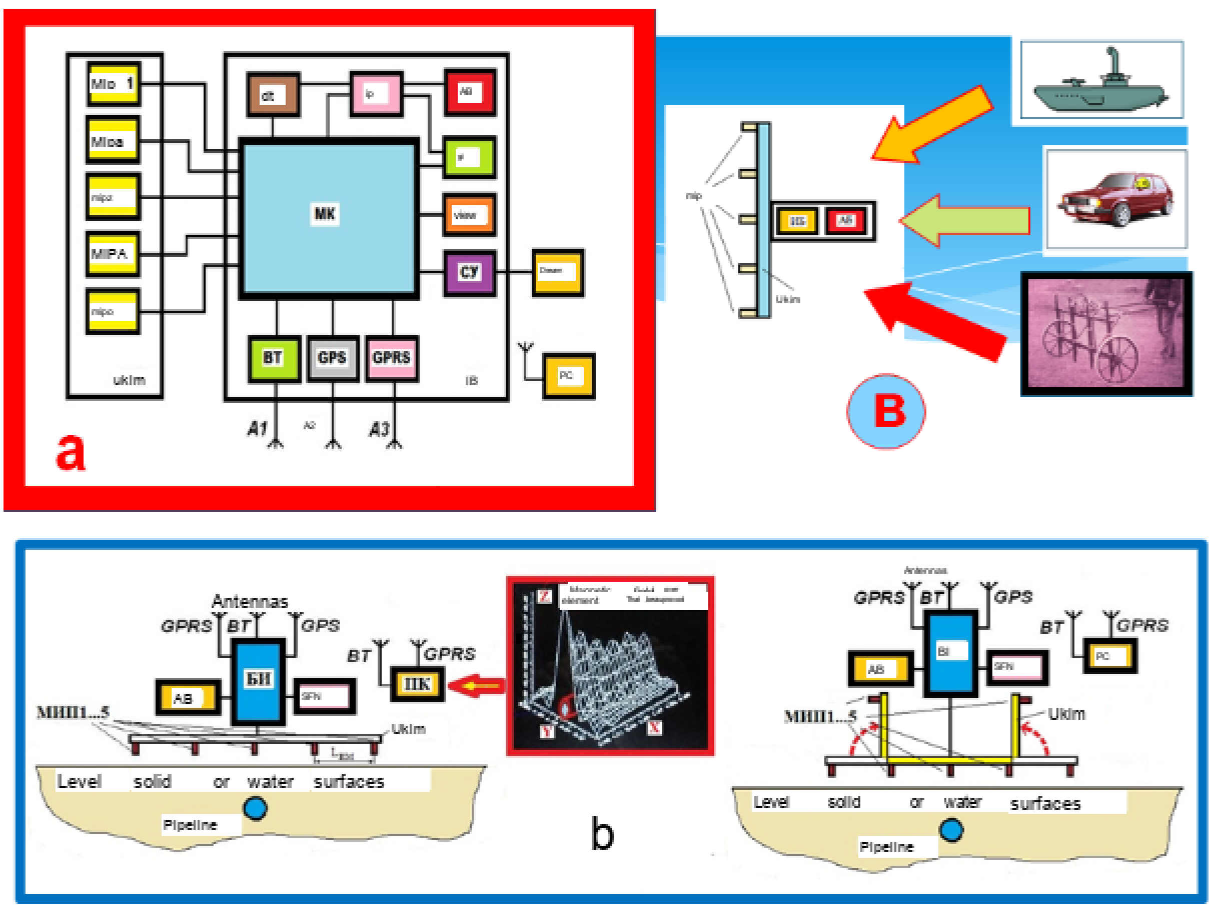
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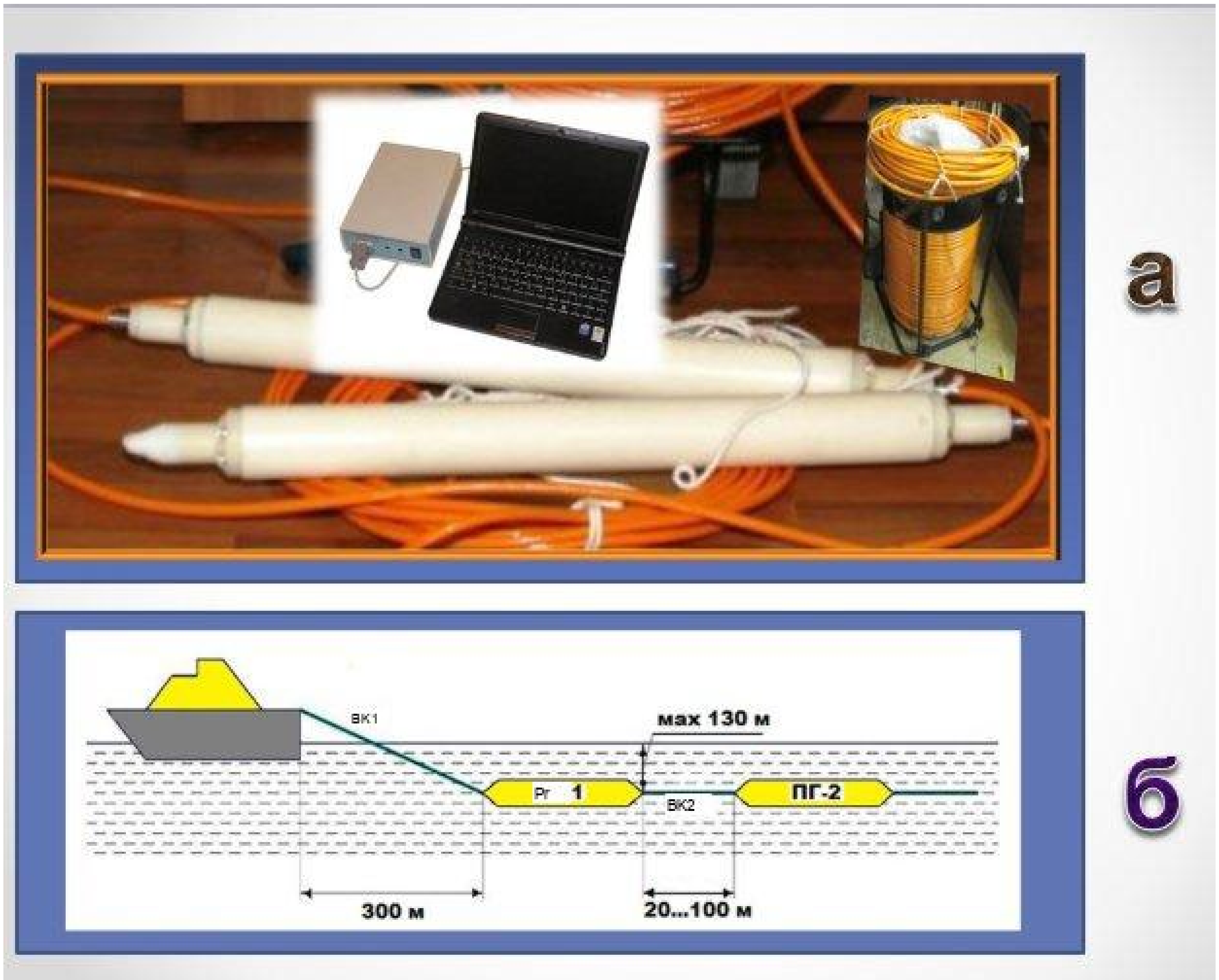
Fig. 3.



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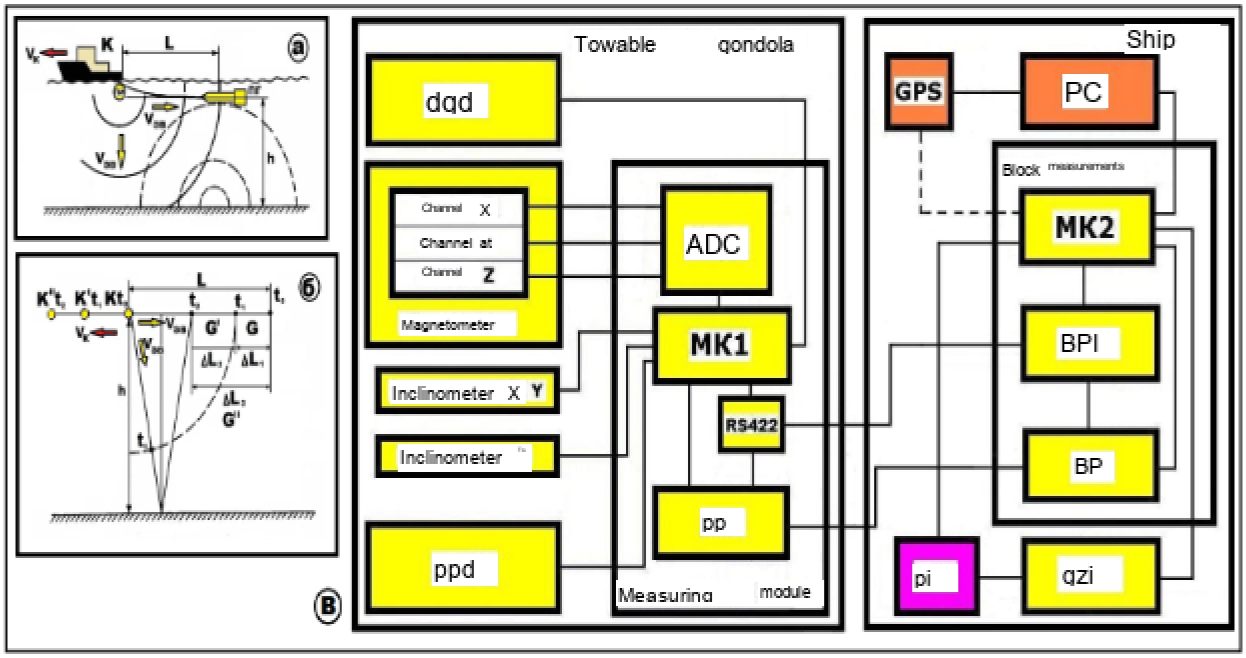

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Fig. 5.

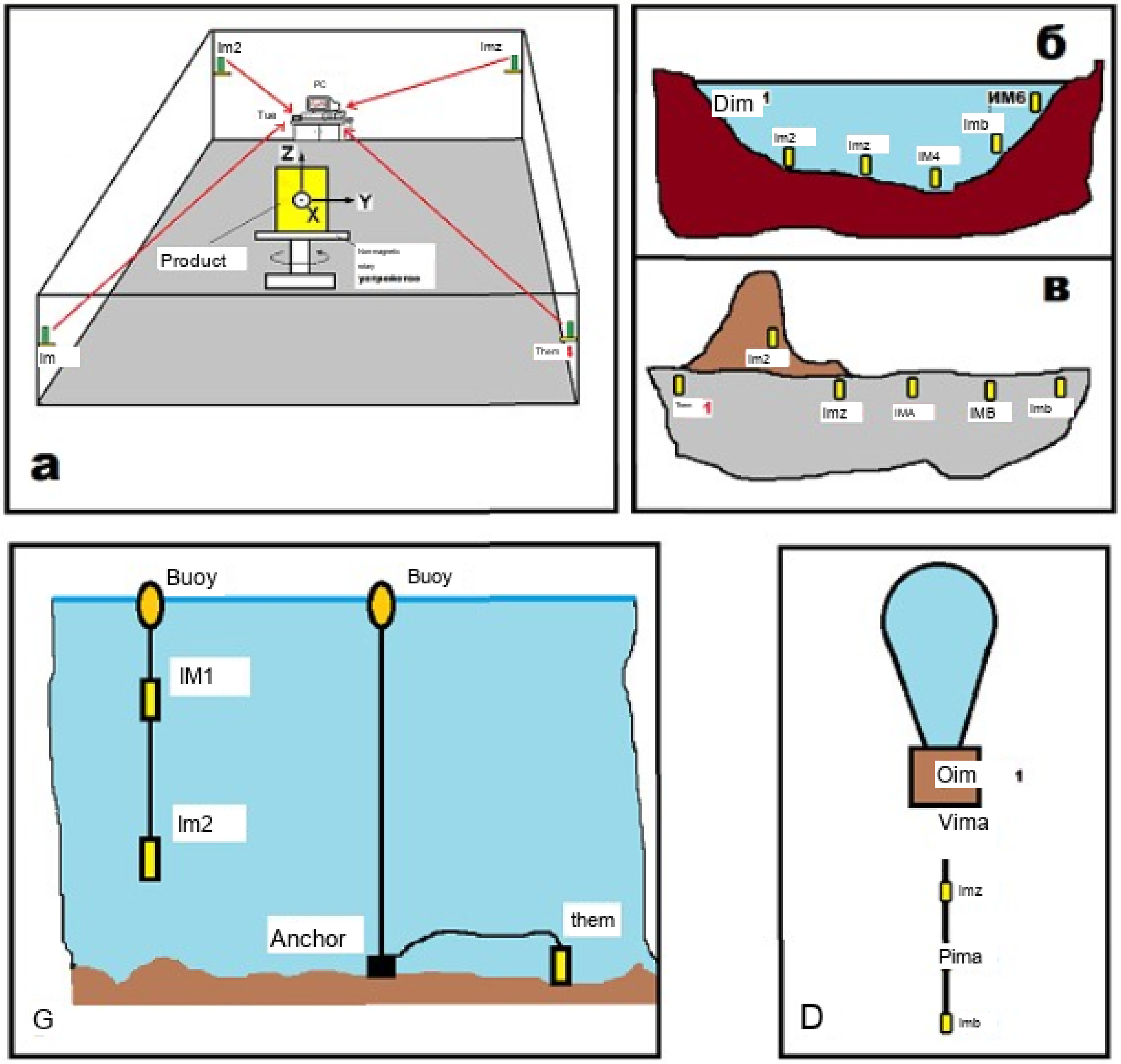
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Fig. 6.

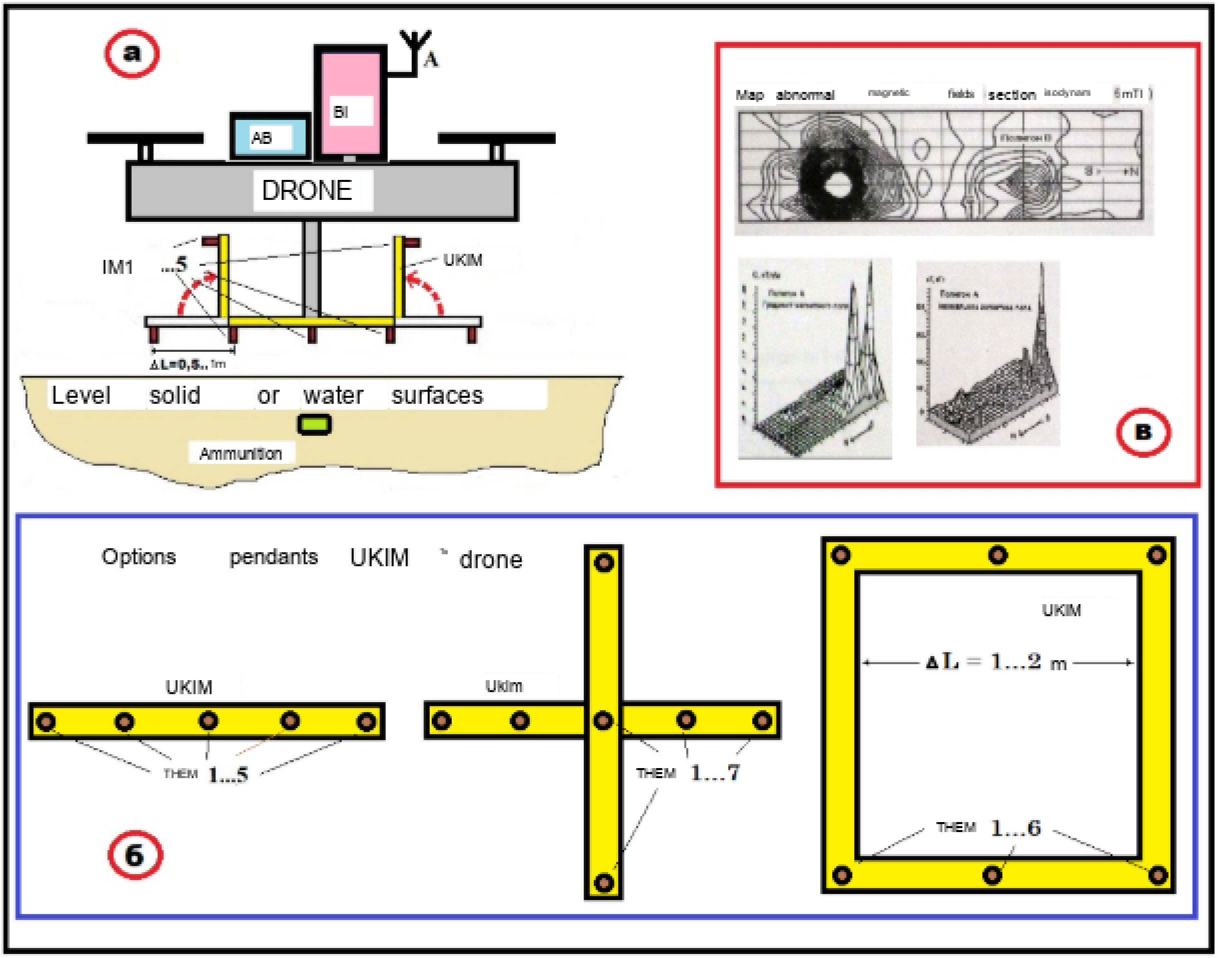
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Fig. 7.