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

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Abstract. The work is devoted to the description of the design of the measuring module (ferrosonde magnetic compass) and the creation on its basis of various magnetometric devices.These devices are designed to carry out geomagnetic and special works in various conditions and environments, - as for use in stationary observation points, also working on expeditions.

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1. INTRODUCTION

For a long time IZMIRAN designers and instrument makers of magnetometer equipment have been thinking about creation of a universal, economical and compact measuring device for its use in scientific research in various conditions and environments with the possibility of minor addition to its scheme of additional devices required for specific works. At present, the possibilities of modern techniques and technologies allow us to make real progress in solving this problem. At the same time, as the main element of the device, − magnetometer sensor, it is possible to use small-size ferroprobe sensors (FD), which nowadays the industry has learned to make rather compact, micro-consuming and highly sensitive [Lyubimov, 2024].

FD is a primary magnetomodulation transducer used as a magnetometer to convert magnetic induction into an electrical signal [Afanasiev, 1986]. The action of the PD is based on the modulation of the magnetic state of a ferromagnetic core by means of an auxiliary alternating magnetic field (AMF). Sometimes FD is called a ferromodulation transducer, emphasizing its belonging to magnetomodulation transducers. The classical scheme of a ferro-probe includes a magnetoconductor, an excitation winding (supplied with alternating current) and a measuring winding (see the scheme in Fig. 1*a*).

Fig. 1.

Currently, there are many different designs of magneto-measuring transducers (MMTs), which are based on ferro-probe magnetosensitive sensors (MDS) [Afanasiev, 1986].

As it was mentioned earlier, ferroprobe devices are characterized by small-size and compactness, low power consumption, high sensitivity and accuracy. Modern FDs and devices based on them have low intrinsic noise, which makes it possible to carry out work with high reliability in very weak MFs and in a wide temperature range. The use of devices (magnetometers) on the basis of FD during geomagnetic studies allows (unlike other types of MFDs) to realize the possibility of direct measurement of the components of the magnetic induction vector (MFI), which provides obtaining complete information on the field structure and its sources both at stationary measuring points of observations and on the move, during various kinds of expeditionary and prospecting works.

Both in our country and abroad there is already a large number of MIP developments on the basis of FD, which have analog or digital output of the measured information. Along with certain advantages of all known component FDs (and MIPs based on them), such as compactness and low power consumption, these devices have some disadvantages. These disadvantages include change and increase of measurement error due to change of external ambient temperature (temperature drift), as well as measurement error due to uncontrolled change of their orientation in space during long-term operation. These are the parameters of FDs that should be controlled and taken into account [Lyubimov, 1992; 2017; 2024], especially during long-term stationary measurements both in the conditions of a magnetic observatory (MO) and during expeditionary operations.

The capabilities of modern technology nowadays allow us to realize not only the control of FD parameters, accumulation, processing and correction of the obtained data and their transmission through communication channels over a distance, but also to have the binding and synchronization of the obtained data during field work, for example, with the help of 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 long-term and short-term measurements, having high (at the level of 1 nTL and higher) resolution and made on the basis of a universal measuring module (MM), which can be realized using various designs of ferro-probe CDMs.

2. UNIVERSAL MEASURING MODULE

In early 2009, as a result of experimental and research work with different types of FDs, a team of collaborators under the leadership of A.S. Zverev created the IM design (see Fig. 1*d*) and comprehensively tested a prototype [Zverev and Lyubimov, 2019; Lyubimov, 2021; Lyubimov et al., 2019; Zverev and Lyubimov, 2019]. This IM was a universal six-channel converter of analog geophysical data with the possibility of their subsequent accumulation, transmission over a distance and registration in digital form. The construction scheme of this IM is universal and technological, which allows it to be used as a part of various measurement complexes when carrying out works in different conditions and environments.

IM includes three different independent analog-to-digital converters (see Fig. 1*c*): three-channel MIP, three-channel inclination angle converter - digital inclinometer (DIC) and temperature sensor (TS). The combination of magnetic sensors with inclinometers in the practice of geophysical works is called a platform-free magnetic compass (MC).

The use of component FDs in the IM and complemented by other devices (CI and DT) allows compensating the MF distortions that arise due to various factors, which allows getting rid of part of the additional measurement error, for example, when changing the sensor inclination angle or the influence of the ambient temperature.

The IM is built on the basis of FD and includes three measurement channels (IC) for measuring the VMI components of the Earth field D, H and Z. The functional scheme of the IM is shown in Fig. 1*c* and includes: a three-component FD, inclinometer board (IB), which includes three DICs and DTs, and microcontroller board (MCB), which includes ADC circuits, microcontroller (MC) with serial data channel interface (RS232) and power supply unit (PSU).

When creating the device and searching for the necessary CDMs to use in the design of its MIP, we considered the use of several known domestic and foreign small-size FD designs (see the data of Table 1 in [Lyubimov, 1994; Lyubimov et al., 2019]). As a result of the analysis of characteristics and conducted comparative and evaluative experimental works, the FLC3-70 type FDs of the German company Stefan Mayer Instruments GmbH & Co. (http://www.stefan-mayer.com) were chosen for the basic circuit of the instrument's MIP. These sensors realize the reference measurement accuracy of 1 nTl in the range from 0 to ±70 μTl and the conversion factor of the field– voltage of 35 μTl/V for each IR. In this case, the intrinsic noise of each PD does not exceed the level of 0.1– 0.15 nTl. The general view of the three-component FD used in the device circuit and some variants of IM designs are shown in Fig. 1*d*.

The main criteria for choosing this variant of FD were higher measurement accuracy and low power consumption (6 mA) from the unipolar power supply (PS). Low consumption (low value of compensation current in the measurement windings of the PD) was important for reducing (or eliminating) the effect of mutual influence of the measurement channels on each other in the design of a three-component small-size PD, especially when the IM is used in the process of moving in space.

Analog voltage (±2 V) from the output of each of the three ICs (D, H, and Z) of the IMI is fed to the inputs of the ADC, which is located on the microcontroller board (MCB), which also houses the MC circuits with serial data link interface (RS232) and the PSU. From the ADC output, the data from the IIP goes to the input of the MC and then through the RS232 serial port in digital form to the output of the IM. Through this RS232 serial port is also controlled externally (eg, using a computer) modes of operation of the IIP, accumulation and correction of incoming data.

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. *1b*, *c*). The choice of this chip for the CI was due to its compactness, high accuracy of measurements (see the data of Table 2 in [Lyubimov et al., 2019]), as well as the use of unipolar IP and low power consumption, which is very important when installing the CI near the PD. The main advantage of this CI is its built-in DT, which allows the correction of measured data by both the CI and the FD.

Inclinometers X, Y measure deviations in the horizontal plane, and inclinometer R measures the angle of inclination of the PD in the vertical plane. The DICs are rigidly fixed (see Fig. 1*d*) relative to the PD on the inclinometers board (PI) and removed from them at a distance of 55 mm (to eliminate the influence on the measurement results of the PD). With the help of inclinometers (simultaneously and synchronously with the measurement of VMI components), the measurement and control of three angles of deviation of the measuring axes of the PD, and the accuracy of these measurements is ± 0.1°.

To ensure a favorable temperature regime of the FD operation, the whole IM circuit is placed in a non-magnetic housing-container (see Fig. 1*d*), which, depending on the application conditions, can be made of dural or plastic with a minimum inner diameter of 50 mm and a length of 250− 300 mm.

The created IM based on the three-component FD is a functionally complete design of the device, which has sufficiently high characteristics in terms of measurement accuracy and low power consumption (not more than 30 mA), which allows its use 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 gradientometers [Zverev and Lyubimov, 2019; Lyubimov, 2019a, c; 2020a; Lyubimov et al., 2019], as well as used in the creation of search field devices [Lyubimov, 2020b] and magnetovariation stations (MVS) [Lyubimov, 2021; 2024]. It should be noted that depending on the way of IM application (in 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 dwell on new solutions and constructions of the created devices and on perspective projects of realization of devices and special devices on the basis of IM.

3. MAGNETOVARIATION STATION

On the basis of the universal IM, a new magnetometric device, the ferro-probe MVS, has been developed, which makes it possible to carry out measurements and scientific research both in the conditions of MO and in the conditions of expedition, in the field [Lyubimov, 2021; Lyubimov, 2021b]. At the same time, the use of CI allows to set the FD arbitrarily during the research process, measure the VMI components and calculate its modulus.

Fig. 2.

The proposed design of the IM (and MBS based on it) assumes two main variants of station utilization, which are shown in Fig. 2*a*. The first variant of the MBS use is intended for operation of the instrument in the conditions of the MO or stationary observation point, where the IM is installed on a non-magnetic pedestal equipped with three legs-screws for leveling the container with MIM in the horizontal plane (see Fig. 2*b*). When operating the IMU in the field, the second option− is provided for installation of the container with the IM in a hole dug in the ground, which is located below ground level (see Fig. 2*a*).

As noted earlier, the basic IM circuit (in a particular application case) is additionally equipped with a digital DT connected to the MC via a communication line (RS232). This sensor is installed (see Fig. 2) inside the IM case and is located close to the PD, which allows to control the temperature near the PD with an accuracy of 0.1°C. DT is made with the use of LM35D type microcircuit, has a plastic case and consumes current not more than 60 μA, which allows to exclude its electromagnetic influence on the PD measurement results.

To ensure a favorable temperature mode of operation of the FD, the whole IM circuit is placed in a non-magnetic housing-container, which is made of dural or plastic (PVC or glass-epoxy pipe) with dimensions Ø150 x 300 mm. Inside the case there is an insulation insert made of foam plastic of 20 mm thickness (not shown in Fig. 2*a*), behind which there is a screen made of foiled double-sided fiberglass-textolite (1 mm thick), which is simultaneously an electrostatic screen for FD. Inside this screen is fixed (soldered) heating element (HE), which is made on the basis of a small-size ceramic self-regulating posistor heater (PN) of ST6-1B-1 type [Lyubimov, 2017].

The heater is supplied with DC or AC voltage (exceeding the PD excitation frequency by about an order of magnitude) from the PSU circuit. At the same time, the temperature control is carried out by DT and regulated by means of MC.

The functional scheme of the MVS (based on the IM) is shown in Fig. 2*b*. Here is also presented the appearance of one of the created variants of MBS for MO. The scheme of MVS includes: IM and measuring unit (MU), which are connected with each other by a cable, for supplying the supply voltage from the IP, data exchange and control signals between the blocks via RS232 standard at a distance of up to 25 meters.

The IB consists of the following functional units: MCU, control circuitry (CC), graphic display (PGI), battery (AB), power supply (PS), as well as 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 on the output. Bluetooth module has options of data transmission range: Class 2 module - up to 30 m, Class 1 module - up to 100 − 200 m, and Class 1 module with remote antenna - up to 300 − 400 m. The GSM module is designed with a replaceable SIM card.

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

Before starting the work, the MBS measurement cycle is set up using an external personal computer (PC) and special software (SW). The general view of the data obtained by IBS in digital form on the PC display is presented in Fig. *2b*. The software also allows to obtain data in graphical form, to calculate and visualize the VMI modulus (W) using the measured VMI components, as well as to correct the obtained magnetometric data on the basis of DSC and built-in DT data.

As an external removable digital file data storage device (DFSD) an ES drive of up to 4 Gb is used, which is connected to the IS and allows accumulating the measured data in the autonomous operation mode without PC connection.

The MMS allows accumulating and storing data in the internal ES during operation, 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 EE) is not more than 25 mA, and the total consumption of the whole device in the mode of data transmission through the communication channel is 250 mA. The MBS can be powered either from 7− 24 V AB or from 220 V (50 Hz) AC mains using a 12− 24 V power adapter (CA).

4. MULTICHANNEL MAGNETOMETER-GRADIOMETER

Multichannel MG (MMG) [Lyubimov, 2020b] is a universal instrument that allows to conduct component (or modular) geomagnetic surveys for the purpose of mapping the terrain, searching for local magnetic anomalies. The MMG is used to search for local ferromagnetic objects that are located in the thickness of a nonmagnetic medium (in soil or water). The method of measurements assumes simultaneous parallel movement of the MMG, which are located at a certain and set distance (IS) from each other, in space with simultaneous measurements and calculations of the VMI elements. In this variant the device design is built with the use of five ISIs. Such a design of the measuring part of the device allows for a single pass to investigate a sufficiently large area in width, which can be variable and wider than in known modern special devices [Zvezhinsky and Parfentsev, 2009a, b].

Each MIP is an IR and is made on the basis of an IM and a FD, which is an FLC3-70 type device. The resolution of each of the CIs is 1 nTl. The use of DIC in this instrument design allows to provide measurement of the MF gradient and VMI components during motion not worse than 1− 5 nTl.

Fig. 3.

The structural diagram of the MMG is presented in Fig. 3a. In Fig. 3*b* and Fig. 3*c* show, respectively, the layout of the main functional units of the device when carrying out works on measuring the horizontal gradient (HG) and vertical gradient (VG) of the MF and possible applications of the device.

Fig. 3*a* presents the unfolded functional scheme of the MMG, which realizes the basic idea of the method of measuring the VMI gradient both on land and in the aquatic environment. When the instrument is used in an aquatic environment, a long special cable and hydrostatic pressure transducers (HPTs) are additionally used, which are mounted in the housing of each MMG. Fig. 3*b* shows the layout of the main assemblies of the instrument in the process of research and possible variants of its use in measuring the HG and HV magnetic field.

Fig. 3*c* shows possible ways of conducting studies using the instrument in pedestrian, automobile or marine versions.

The functional scheme of the MMG (see Fig. 3*a*) includes five IPIs, which are located on the device for their mounting (UCIM) at a certain (specified or, depending on the width of the research site and dimensions of UCIM) distance from each other. Each IPI is connected via RS232 data channel to the IS. The IB includes the following functional units: MC, control circuitry (CC), graphic indicator (GI), AB, IP, DT, as well as GPS receiver and Bluetooth (BT) and GPRS data transmission modules with antennas A1 - A3.

The MMG data transmission system including a GPS receiver and BT and GPRS data transmission modules with antennas, as well as the GND scheme, are similar to those used in the design of the MBS and described above.

The MMG allows data to be accumulated and stored during operations into the internal ES, and the accumulated data to be transmitted via the available GPRS and BT channels to a remote receiving site (computer). The total consumption of one MMG is not more than 15 mA, and the total consumption of the whole device in the mode of data transmission through the communication channel is 250 mA.

MMG can be successfully used in pedestrian mode, as well as when moving with its towing as a trailer to a vehicle on the ground surface or on a raft - on water. The device allows simultaneous recording of data from each of the MMGs and field gradients between them.

The uniqueness of the MMG design is that when measuring the VG or GG magnetic field, there is no need to align the measuring axes of the MFDs relative to each other (as is done in most manufactured instruments [Zvezhinsky and Parfentsev, 2009a, b]) with high accuracy. This work is taken over by the CI and MC, which in the process of measurements make corrections and calculate the real values measured by the CDM.

The use of component measurements, − simultaneous synchronous measurement of the GG and VG components of the VMI in the process of magnetic survey, − increase the accuracy and informativeness of the conducted surveys. This is especially important when searching for and identifying local anomalies, which is much more difficult to do when using modular magnetometers or single-component gradient meters.

5. GRADIOMETER FOR HYDROMAGNETIC SURVEYS

The marine component gradientometer (MCG) was developed on the basis of the ferroprobe IM [Zverev and Lyubimov, 2019; Lyubimov et al., 2019; Zverev and Lyubimov, 2019]. The developed instrument is designed for relative measurements of MF in space at points and the gradient between them in marine conditions during hydromagnetic survey (HMS), including can be effectively used for searching ferromagnetic objects and subjects.

The instrument includes two main parts connected by a tow cable, − outboard and set. The functional scheme of the ICG is presented in Fig.1 in [Zverev and Lyubimov, 2019].

The inboard part of the instrument includes a power supply unit (PSU) and a personal computer (PC) and is installed on board the towing vessel. The intake part of the device includes two towing cables (BCs) and two submerged gondolas (SGs), which are towed at a distance (to exclude the influence of the vessel's magnetic mass) of at least three hull lengths of the towing vessel from its stern.

The towing speed of the HG towing is limited within 3 to 10 knots with the permissible amplitude of sea waves not more than 5 points. The general view of individual parts of the device and the scheme of its use during the HMS are shown in Fig. 4*a* and Fig. 4*b*. The SG is designed so as to be able to be towed at horizons and depths up to 130 m. The depth of immersion of each of the SGs is recorded by means of a built-in hydrostatic pressure sensor (HPS), allowing to have information on the progress and depth of the SG towing 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 instrument, which is located in each of the PGs, includes the MC board, the DIC board and the CDM.

Measurement of VMI components in the instrument and the gradient between them is performed by two analog three-component FDs of FLC3-70 type. The analog signals that come from each of the three IRs of both FDs corresponding to the VMI components are converted into a digital code using a 24-bit ADC.

To control the spatial orientation of the FDs, a two-component CI is used, which contains two inclinometer devices. Inclinometer X, Y measures deviations from the horizontal plane passing through the centerline of the nacelle and perpendicular to the "vertical" of the nacelle, inclinometer R measures the angle of inclination (rotation) of the nacelle in the plane perpendicular to the centerline. The location of the CI relative to the FD in the PG is shown in Fig. 1*b*. The inclinometers are used to measure the roll and trim angles of the SG, and the accuracy of these measurements is ± 0.1°. As it was shown above, for controlling the depth of the PG stroke is used digital DGD, which is located inside the PG at the maximum distance from the CDM. The sensing element of the DGD is connected to the external environment (water) using a channel.

Information from each DGD is transmitted via RS422 serial interface via cable to the ship's board. Passing through a dial interface converter (DIC), which is part of the PSU, the data is converted to RS232 standard and sent to a PC. The software is used to accumulate and process the data and visualize them in one form or another on the PC screen. For precise time reference of current measurements, a GPS receiver is connected to the COM port of the PC.

A non-magnetic cable based on Kevlar with increased breaking force of about 1500 kg is used as a BC. This cable (see Fig. 4*a*) has an outer diameter of 12 mm and includes two conductive cores for supplying the supply voltage, two twisted pairs for transmitting digital information, and a shield. The length of the BC connecting the near-GH to the set part of the instrument is 380 m. Two similar cables with lengths of 100 m and 20 m are included in the ICG set to measure the GH at GMCs at different IBs.

The design of the GH assembly [Lyubimov et al., 2019] consists of a non-magnetic body with removable stabilizer and weight fixed on it. The stabilizer is designed to increase the stability of the GHG during towing, and the cargo is necessary to reduce the oscillations of the nacelle around the longitudinal axis and to fix the position of its vertical plane. The near hull CG has two cable glands, and the far CG, − one.

The ICG has measuring ranges for all VMI components for each of the magnetometric IRs from 0 to ±70 μTl, with the basic measurement error of no more than 5 nTl, and the accuracy of reference realized by means of ADC is 0.1 nTl. The range of registration of the gradient between CDM in the PG on each of the measuring magnetometric channels is from 0 to ±10 μTl. The range of registration of the depth of immersion of the BG is from 0 to 130 m, and the accuracy of registration of the depth of travel and immersion is 0.2 m.

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

In the process of marine survey (MS) the power supply of the device (when using marine vessels) is carried out from the AC network with voltage 220 ± 22 V and frequency 50 ± 5 Hz, and the power consumption is not more than 50 VA. For works carried out with the use of various types of small "floating means", there is a possibility of MCG power supply from AB with voltage 10− 15 V.

The bodies of both PGs, made on the basis of polyurethane non-magnetic pipe (body wall thickness 18 mm), have overall dimensions: diameter 70 mm and length 1000 mm. The mass of the PG, including the IM and CDM located inside it, is not more than 10 kg, and the total mass of the BC used in the device in various variants of use is not more than 100 kg. The set part of the ICG, BP (size 120 x 50 x 200 mm) and PC has a mass not more than 5 kg.

6. MARINE MAGNETOMETER-GRADIENTOMETER

To realize the MS method, which is proposed in [Lyubimov, 2019c], a new design of a marine component magnetometer (MCM) made on the basis of the IM was proposed. This method of measuring the MF gradient in aqueous medium is used during MS, which allows increasing the measurement accuracy by eliminating the errors associated with the variable conditions of towed SGs such as: instability of the IB, "yawing" and different deepening of SGs [Lyubimov, 2019a, c]. The use of only one towed GHG significantly simplifies the methodology of operations (especially descent and ascent operations), as well as operations related to the output of two or several GHGs during towing, for example, when measuring the GHG of the MPZ, to one horizon. In this case, as the main element of synchronization (and metrological tool for realizing accuracy) of all measuring processes of the magnetometer equipment, an acoustic channel is used, which includes a controlled pulse pneumatic emitter (PI) installed on the towing vessel and a piezo pressure receiver (PPR) installed in the towed PG. This channel generates a pulse of ultrasonic energy (acoustic wave echo signal), which propagates in the water medium with some velocity V_{zv}.

Fig. 5.

Fig. 5 shows the structural diagram of the device that realizes the main idea of the method of measuring the MPZ gradient at sea. This device contains a non-magnetic towed PG, inside which the IM and various sensors are located. The IM contains a microcontroller (MK1), an ADC, a power converter (PC) and an interface for data transmission and operation control (RS422). A FD (three measurement channels X, Y, Z) of a magnetometer, two inclinometers (measurement channels X, Y and R), a hydrostatic pressure transducer (HPT) and a PG are connected to this IM (via ADC).

The PG is towed by a cable of arbitrary length behind the ship. As a rule, the length of the tow cable is selected after practical determination of the magnetic moment of the towing ship and should not be less than 2− 3 lengths of its hull. Also, the size of the water area where the MS is performed and its depth are of importance when selecting the length of the tow cable.

The measurement unit (BI) with a personal computer (PC), GPS receiver, sounding pulse generator (SPG) and pneumatic emitter (PI) connected to it are located on the ship. The BI, which is the main element for synchronizing the operation of the whole system, includes a microcontroller (MK2), an interface conversion unit (ICU), and a power supply unit (PSU).

MK1, located in the PG, synchronizes and controls the receipt of data from sensors in digital form and transmits them via RS422 interface to the shipboard. MK2 performs full synchronization of all data with the world time and their positioning with the help of GPS system, and also controls the acoustic channel of measured data synchronization with the help of GZI and PI. At the same time, two variants of using the PI can be realized, which can be rigidly fixed on the ship's hull or towed behind its stern.

The accuracy of IB measurement in the proposed device when measuring the horizontal MPZ gradient is determined by the parameters of the ultrasonic energy pulse emitted by the PI and allows to have a resolution in HMS conditions of about 1− 10 cm. A sensor with a digital output (MS5541B chip) is used as a DGD, which allows controlling the depth of PG towing with an accuracy of up to 20 cm.

The accuracy of the MCM measurement of the MFZ components is determined by the parameters of the FDs used in the magnetometer (in this design, the FLC-70 type FD with axis non-orthogonality of ±1º is used), as well as by the accuracy parameters of the DIC. Both inclinometers are based on the ADIS16209 digital chip, which is currently the most accurate integrated measurement tool. This allows to ensure the accuracy of angle measurement during PG towing in the order of 0.1º (angular degrees) with a resolution of 0.025º.

The experience of using CI (and, in particular, this model) in the development of marine magnetometers with towed PGs provides the measurement of VMI components during MS no worse than 1− 5 nTL [Lyubimov, 2019c, 2020a; Lyubimov et al., 2019].

7. POSSIBLE APPLICATIONS OF MAGNITOMETRIC SYSTEMS BASED ON IMS

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

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

Fig. 6.

When using the measurement scheme shown in Fig. 6*a*, it becomes possible to investigate (using several IMs) in the room the magnetic moment (MM) of various products, e.g., large scientific and other devices, satellites, various special equipment. At the same time, it becomes possible to carry out multichannel measurements of both MM (when rotating the test object in separate planes and directions) and three-component gradient measurements (including the VMI-W modulus).

When organizing a similar (as in Fig. 6*a*) measuring multichannel scheme (4 or more IMs) in the field conditions, it becomes possible to carry out special works, for example, the study of MM in tanks, special vehicles, armored vehicles, various weapons. Thus, when installing several IMs in water environment (in river and canal beds or on rafts) it is possible to investigate MM of various watercrafts, ships and submarines (see Fig. 6*b*).

This IM-based device solution is quite applicable for security high-precision activities and for maritime and land border defense (see Fig. 6*c*). It can be used on non-magnetic drifting (including meteosondes and high-flying) aerostats [Lyubimov, 2024] for scientific special gradientometric studies with a large "measurement base" (see Fig. 6*d*).

Nowadays, the application of FD-based magnetometer equipment becomes relevant for scientific research and prospecting works from low-flying over the earth or water surface vehicles, any type of UAVs (drones) with a payload of 2− 5 kg.

Fig. 7.

The proposed design of a multichannel drone magnetometer-gradientometer (MGD) based on IM and shown in Fig. 7*a*, is designed for area surveys when ground-based pedestrian and vehicular surveys are not feasible. MHD 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 surveys.

The use of specialized software enables the accumulation of measured data into an internal ES or real-time data transmission, as is done with the MMG. Application of low-consuming small-sized CDM in the device circuit makes it quite economical and allows longer time of its use from AB in the process of surveying. And also significantly reduce the total weight of the UCIM. The variants of suspension of different designs of UCIM to the drone are shown in Fig. 7*b*.

An example of magnetic object detection during the survey process using MHD is shown in Fig. 7*c*, which shows maps of the anomalous MF and its gradient during prospecting at one of the polygons.

8. CONCLUSION

This review shows several designs of magnetometer devices for long-term and short-term measurements on the basis of IM, which have high (at the level of 1 nTL and above) resolution and allow to carry out both scientific and geophysical studies and special works in various directions. At the same time, the main direction of developments was aimed at compactness of the created devices and their economy with the use of the most advanced foreign element base.

At present there is an urgent need in the domestic instrumentation industry to focus on the use of its own instrumentation products and element base. For example, Russian three-component CDMs NVO391.5-20/3, NVO391.5-35/3 or transducers NV0302 (various modifications), produced by the firm LLC "Magnetic Devices" (www.magnetic.spb.ru), can be successfully used as PDs for new IM developments**.** The main technical characteristics of these CDMs do not differ very noticeably from the currently best foreign samples of FDs [Zvezhinsky and Parfentsev, 2009a, b; Lyubimov et al., 2019].

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Figure captions

Fig. 1. Block diagram of the single-channel ferro-probe MIP (*a*), layout of the FD and DIC (*b*), functional diagram of the IM (*c*), and design of the IM (*d*).

Fig. 2. General view of two variants of the IM design: desktop version for operation in the MO and expeditionary version (*a*) and functional scheme of the MIP with data registration on a PC (*b*).

Fig. 3. Functional scheme of the device (*a*), layout diagram of the main functional units of the device during the works on GH and GH measurement (*b*) and possible variants of the device application (*c*).

Fig. 4. General view of the set and towed parts of the ICG (*a*) and the scheme of the instrument towing (*b*).

Fig. 5. Structural diagram of the MCM for measuring the horizontal MPZ gradient in aqueous medium.

Fig. 6. Schemes of research with the use of MCM: on studying the MM of the product (*a*) and conducting multichannel gradient measurements in aqueous medium (*b*, *d*), on land (*c*) and in the air (*e*).

Fig. 7. Design of multichannel magnetometer-gradientometer for installation on low-flying drones of different designs (*a*), variants of suspension of different UCIM designs (*b*) and an example of search operations in the detection of magnetic objects (*c*).

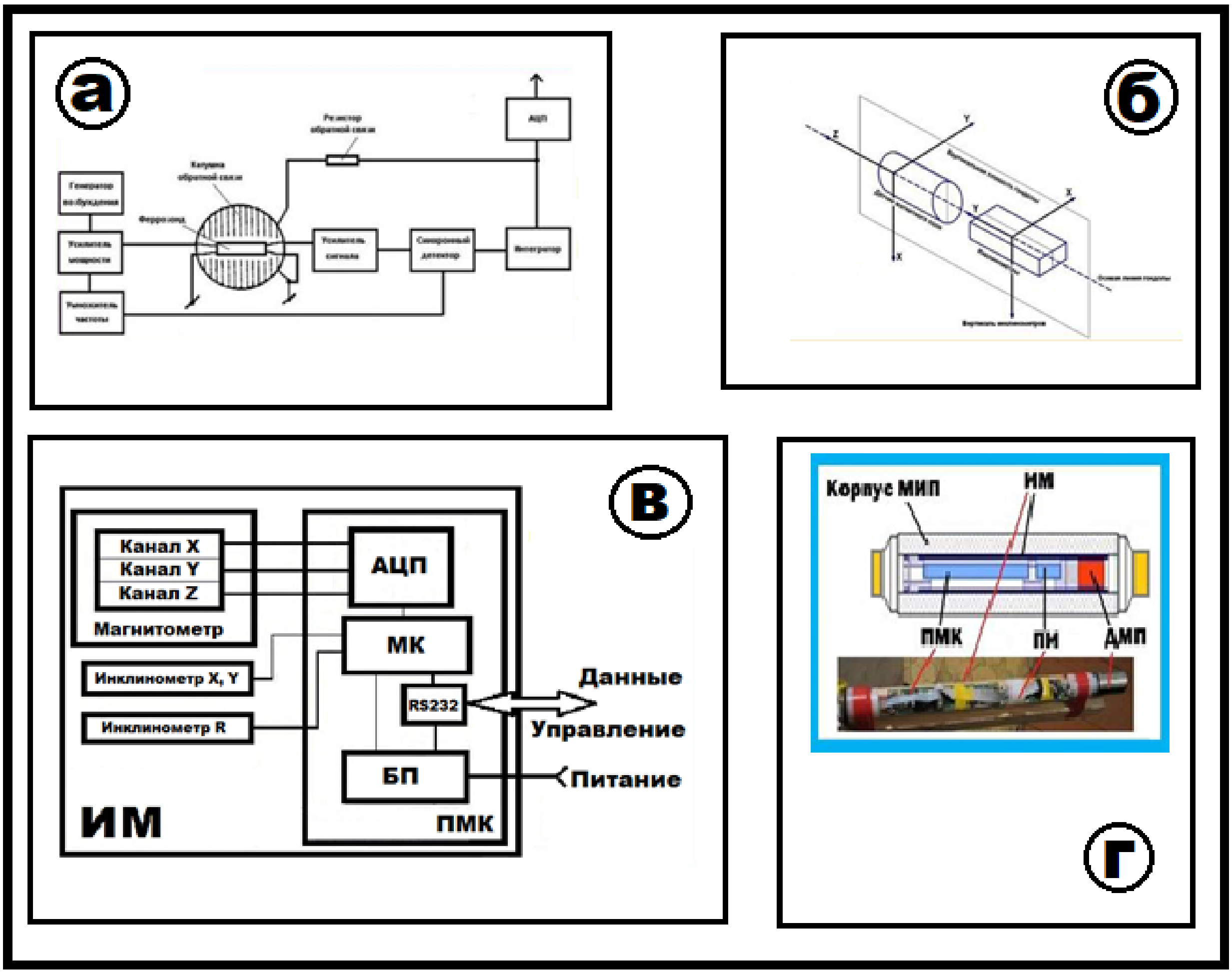

Fig. 1

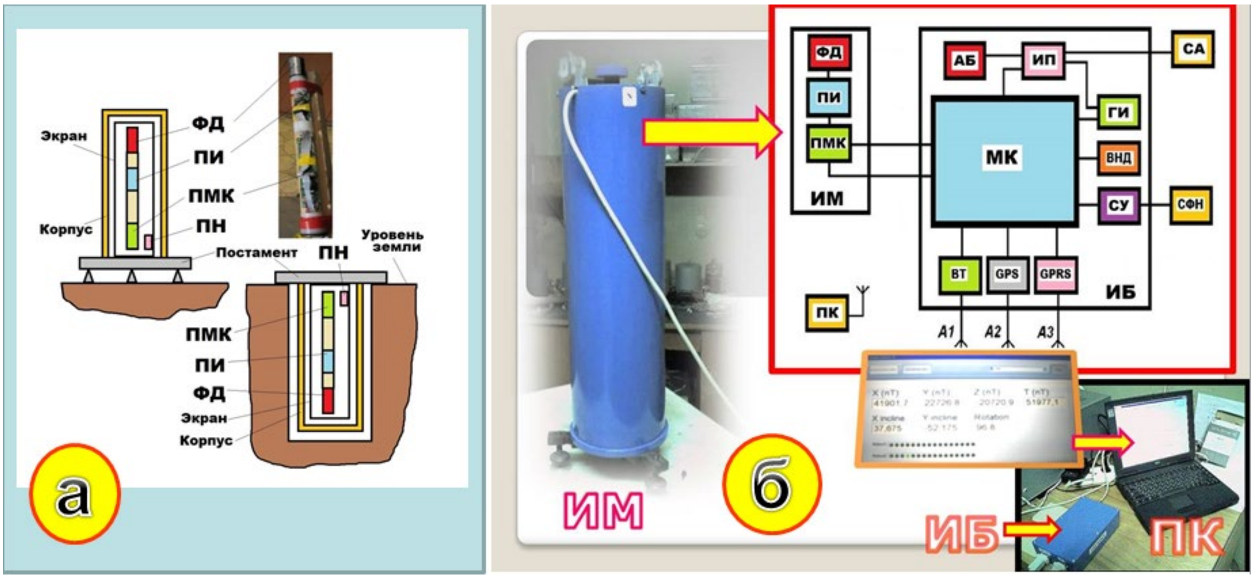
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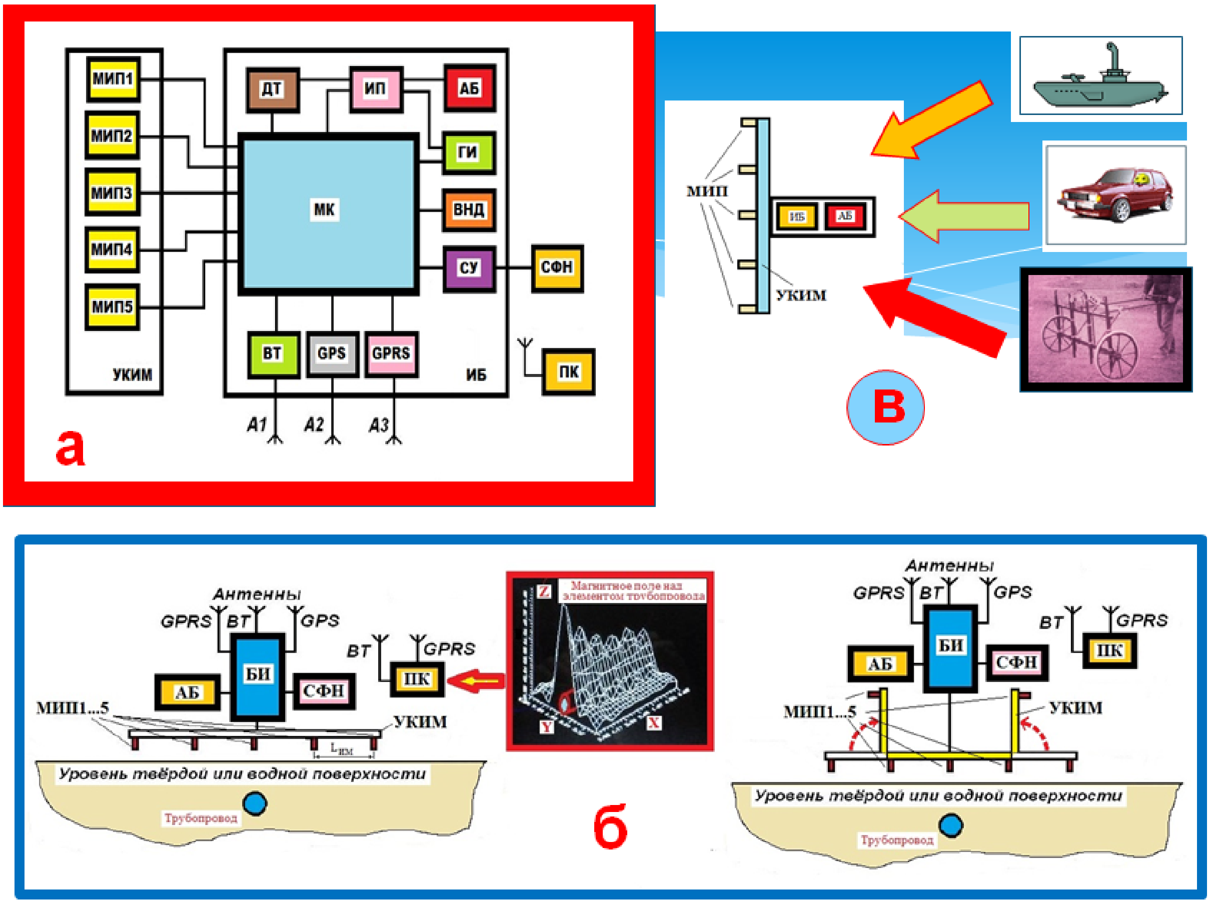
Fig. 2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МИП1...5
УКИМ
Уровень твёрдой или водной поверхности
Трубопровод
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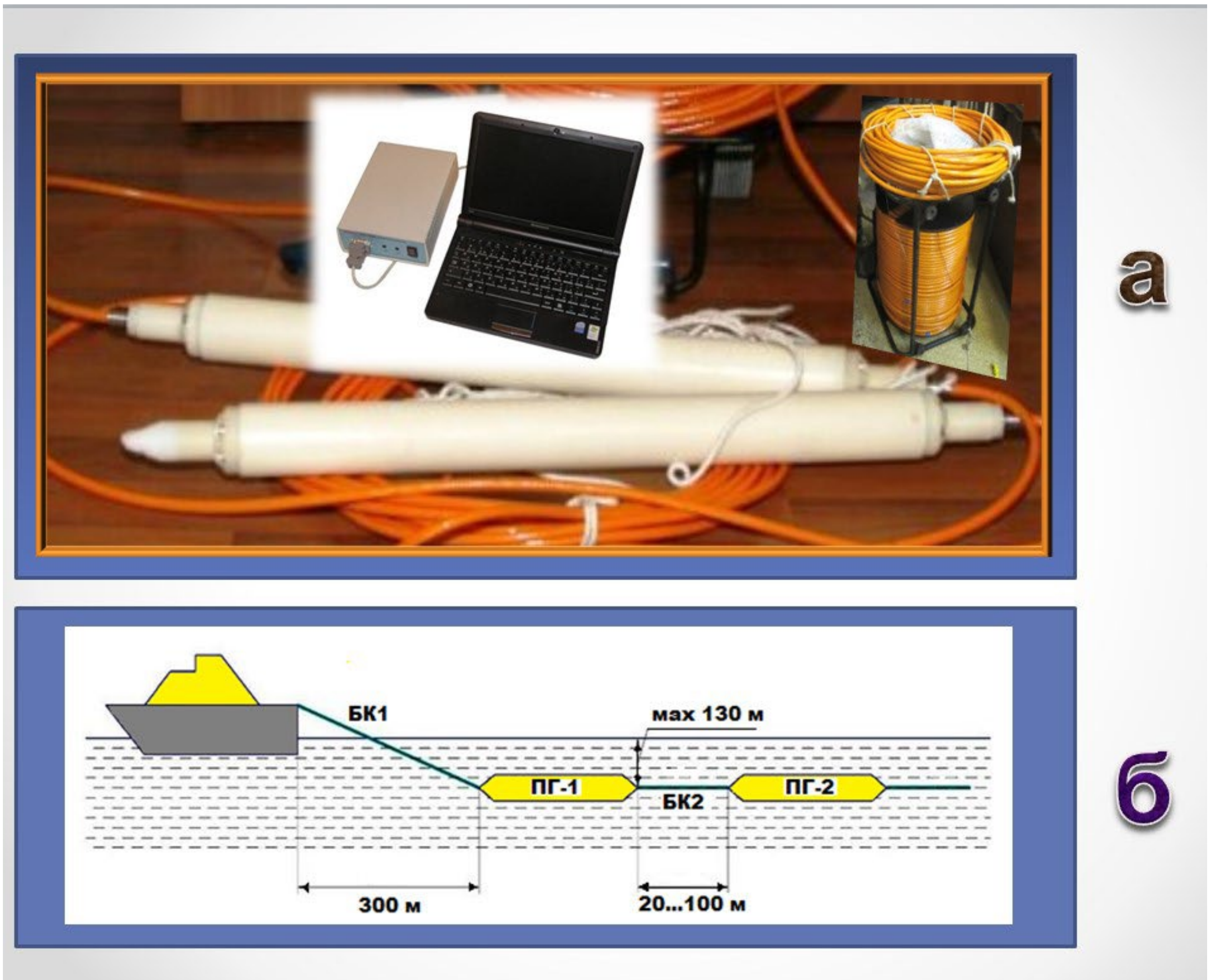
Fig. 3.



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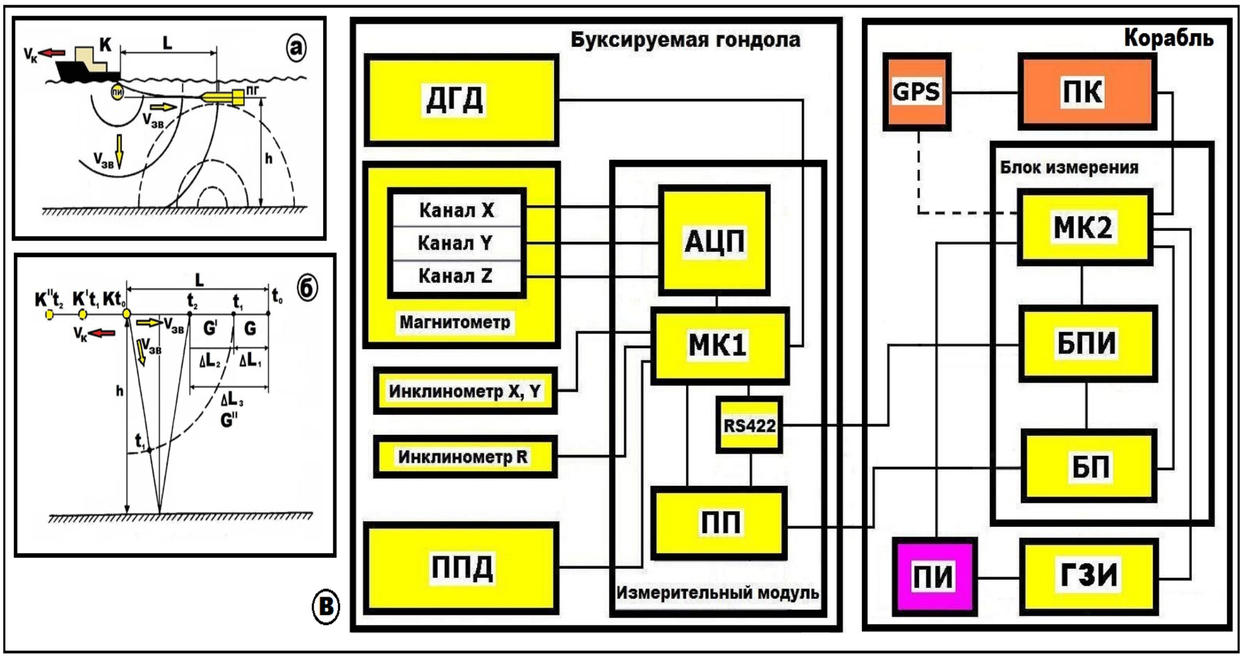
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Магнитометр
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МК1
Инклинометр X, Y
Инклинометр R
RS422
ПП
ППД
Измерительный модуль
Корабль
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Fig. 5.

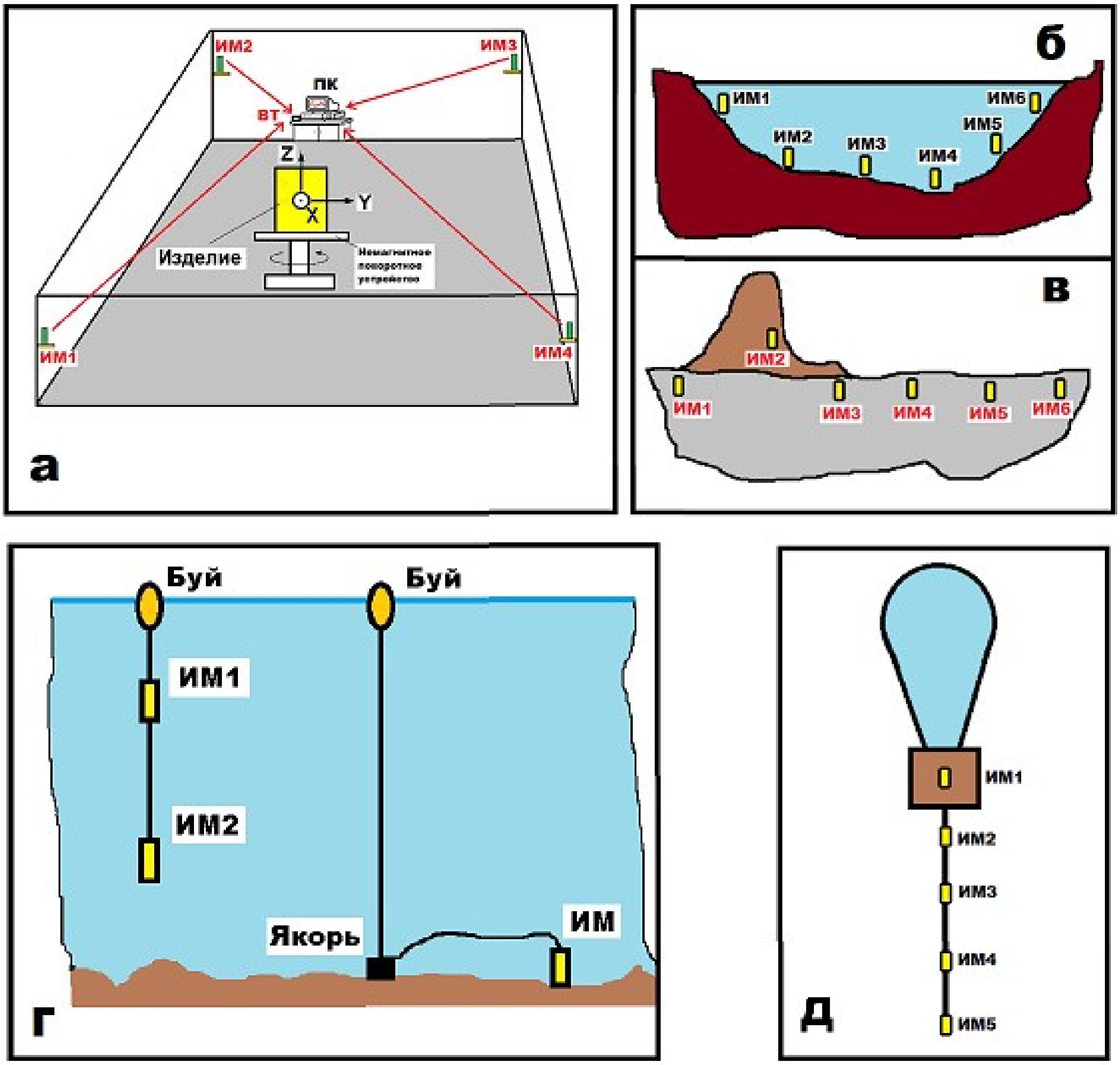
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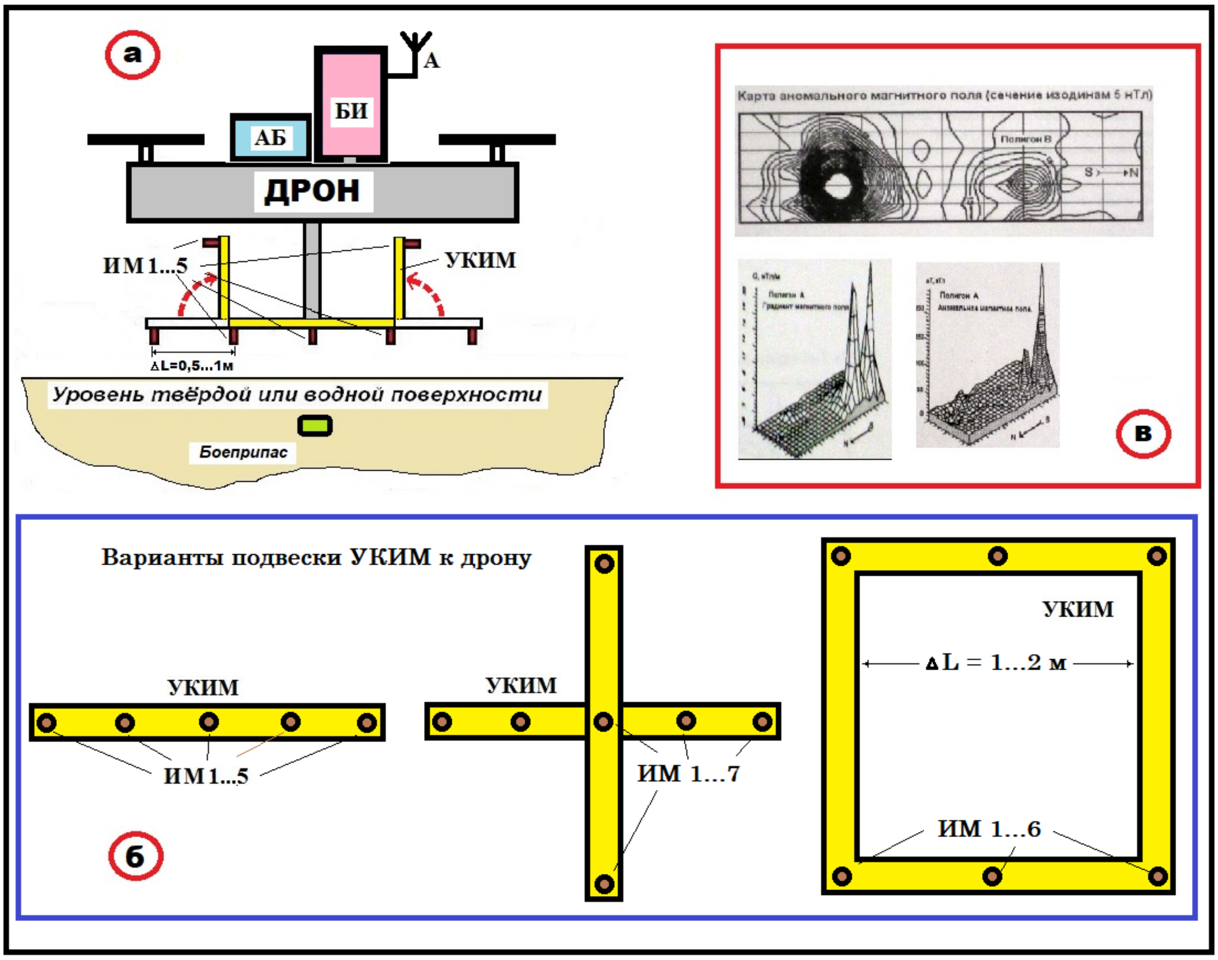
Fig. 6.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ΔL=0,5...1м
Уровень твёрдой или водной поверхности
Боеприпас
Карта аномального магнитного поля (сечение изодинам 5 нТл)
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Полигон А
Полигон А
в
Варианты подвески УКИМ к дрону
УКИМ
ИМ 1...5
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ИМ 1...7
УКИМ
ΔL = 1...2 м
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б

Fig. 7.