

## Ground Geophysical Surveys: Measuring Tools

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**Abstract**—The paper considers some original strainmeters and gravitoinertial instruments designed at the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences. The instruments are successfully used for measuring the Earth's gravitational field, tilts, and deformations of the Earth's crust in solving a number of applied and fundamental problems in geophysics and geodynamics, in particular, evaluating and monitoring the stability of environmentally hazardous engineering and construction objects (dams, hydroelectric dams, nuclear power plants, oil and gas pipelines, etc.), searching for the zones of weakness in the Earth's crust, identifying precursors of natural and technological disasters, studying the Earth's global characteristics (lunar–solar tides, irregularity of the Earth's rotation, translational oscillations of the Earth's core, and azimuthal shifts of lithosphere blocks).

**Keywords:** geophysical research, deformation monitoring, gravimeter, microlevel unit, borehole inclinometer, hydrostatic level

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### INTRODUCTION

The solution of many fundamental and applied problems in geophysics, environmental safety, and urban planning is closely related to progress in the development of instruments and improvement of observation methods (Nikolaev et al., 2011). The Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (IPE RAS) has made a significant contribution to the development of non-standard approaches to solving such problems.

This article briefly discusses some IPE RAS hardware developments for ground-based geophysical studies with high metrological characteristics, in particular, a device for high-precision ground-based gravity survey, a microlevel unit for precision leveling, a precision borehole inclinometer, a tilt–strainmeter apparatus with a wide dynamic range, and long-base hydrostatic level unit.

### GAG-3M GRAVIMETER

Ground-based high-precision gravimetric survey is one of the most widely used methods in mineral prospecting, detection of weakened ground crust, and solving many other applied and fundamental geophysics problems. IPE RAS has participated in the development, testing, and launch of manufacture of the GAG-3 geophysical quartz gravimeter. This gravimeter (Fig. 1, Table 1) is a variant of the GAG-3 upgraded at IPE RAS (Dubovskoi et al., 2010a), the main parameters of which surpass domestic and for-

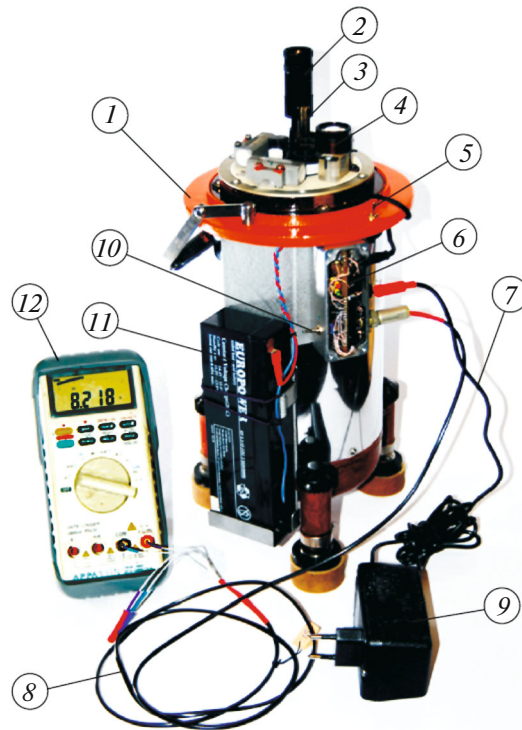
eign analogs. The use of a number of innovations has provided a significant reduction in destabilizing factors. The device uses a compensatory magnetoelectric measurement system with high coercitive magnets, an instantaneous system for active temperature control, a high degree of protection against seismic and acoustic impacts, an automatic horizontal positioning system, and a design that eliminates barometric influence.

The upgraded gravimeter allows measurements in real field conditions at the Brownian noise level and yields qualitative results against a background of significant acoustic and seismic noise.

The GAG-3M gravimeter has been successfully used in geophysical studies in Russia and abroad including studies of the fine structure of the gravitational field on the grounds of the Leningrad nuclear power plant (NPP) and Christ the Savior Cathedral in Moscow; for revealing nontidal variations in the gravitational field in the Leningrad survey area; mapping of cavity inhomogeneities in many crucial facilities in Moscow; high-precision determination of the vertical gravitational acceleration gradient; mineral prospecting in Western Siberia and in the Vrancea area in Romania; etc.

### NI-3MICROLEVEL

High-precision leveling is the main method for monitoring deformation processes of buildings and structures. Application of this method is complicated by errors associated with refraction and the need for



**Fig. 1.** GAG-3M gravimeter: (1) housing; (2) eyepiece; (3) measuring screw; (4) readout; (5) light switch; (6) electronics; (7) power cable; (8) data cable; (9) power supply; (10) electronics switch; (11) 12 V accumulator, 2.3 A h; (12) APPA 109 N multimeter.

direct visibility, which is often absent, e.g., due to temporary buildings, transport, and adverse weather conditions.

IPE RAS has developed an alternative monitoring system free of the above drawbacks but with comparable accuracy. This system is a microlevel unit with a digital readout and resolution of  $2.5 \times 10^{-6}$  rad (Table 2), which in relation to the standard step of level measurements (10 m) corresponds to an uncertainty of 0.02 mm (Dubovskoi et al., 2010b). The rapidity in obtaining information makes it possible to solve the problem of mass monitoring deformation of critical structures in Moscow at yearly intervals. The advantages of microlevel measurements are: the information obtained with this instrument is easily recalculated to the stress state of the studied structure; there is no need for direct sighting of marks; there are no errors associated with refraction; and the rapidity of the method. In various modifications, the device can measure inclinations in both the vertical and horizontal directions.

The proposed microlevel is a promising tool for determining the stress state of various structures, including deformations of building bases, wall-in-soil curvature, and changes in the inclination of load-bearing structures (columns, slatted foundations, etc.). Various modifications of this microlevel device have been used in deformation monitoring of the most

important buildings in Moscow: the Manezhnaya ploshchad' broadcasting company, Croatian House, Italian House, etc. The comparison of building shrinkage measured with the Ni-007 level and NI-3 microlevel showed their good coincidence.

## NI-2 BOREHOLE INCLINOMETER

IPE RAS has developed a special measurement method and created an original design to determine the planned position of a borehole at different horizons with an error no greater than 1 mm, which makes it possible to solve a wide range of problems in monitoring geomass displacement and deformation of building structures. These ideas have been implemented in the NI-2 two-axis borehole inclinometer (Dubovskoi et al., 2010c). This device determines the angles of a borehole relative to the vertical line, uses a technique that eliminates the instrument errors of the sensor, and calculates the true zenith angles in borehole inclination measurements and the zero angle position of the inclination sensors.

At each measurement point, all errors due to imperfections in the balance of the measuring device are excluded by means of  $180^\circ$  rotation of the measuring system using rods, which are rigid in respect to twisting deformation. The measurements are discrete with gradual lowering of the device at a fixed distance

of 2 m. The increase in the measurement accuracy is achieved owing to constancy of azimuthal orientation of the sensing element during the operation and the possibility of installing the device at the same horizons for repeat measurements. The device allows measurements in boreholes of different diameter. The schematic diagram of measurement is shown in Fig. 2; the technical characteristics of NI-2 inclinometer are given in Table 3.

Figure 3 shows the results of two-year measurements with NI-2 borehole inclinometer on the creeping slope at Kolomenskii Park National Reserve Museum, Moscow. The plots clearly reveal the size, horizon of the slip surface of the landslide slope, and the dynamics of the process.

### TILT-STRAINMETER APPARATUS

The tilt-strainmeter apparatus was developed for geophysical measurements in a wide dynamic range (Bashilov et al., 1995). The noise of its sensors in the long-term spectral region was significantly reduced owing to a unique capacitive frequency converter for small mechanical displacements with self-drift auto-compensation. This converter has been used as a unified unit in a large number of primary information sensors. The devices of the developed apparatus are characterized by high sensitivity and long-term stability, a wide operating range, simplicity, and reliability.

Tilt-strainmeter apparatus includes the following devices: an NMD-S two-coordinate borehole tiltmeter, a KDC quartz deformometer, a GN hydrostatic level, liquid level meter in boreholes, and sensors for meteorological parameters: atmospheric pressure and temperature. All devices are equipped with a unified capacitive frequency converter with self-drift auto-compensation; their main characteristics are given in Table 4. The high resolution and low self-drift of the equipment have made it possible to solve problems in identifying individual blocks of Earth's crust, earthquake prediction, and geodynamics problems.

### HYDROSTATIC LEVEL

Development of a long-range (with a base of more than 1 km) hydrostatic level (Manukin et al., 2013) is of special importance. The device consists of a connector tube and two or more measuring vessels to measure the change in the liquid level upon their relative vertical displacements (Fig. 4). A significant increase in the linear base in order to increase the representativeness of measurements and extend the dynamic range while maintaining high sensitivity is achieved by the following features:

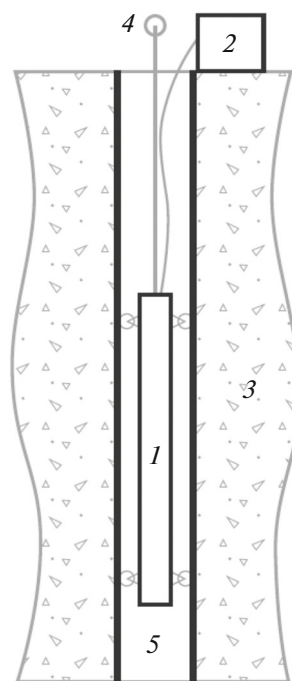
(1) the measuring vessel has no moving parts—the measuring element is a cylindrical capacitor, the capacitance of which changes when the dielectric liquid inside it moves;

**Table 1.** Technical data of GAG-3M gravimeter

Δg measurement range with help of micro-screw, mGal	
without tuning	90
with tuning	6000
Δg measurement ranges with electric counting (two ranges), mGal	100 and 10
Reference setting time	≤3 min
Zero-point offset at 40°C thermostating per day, mGal	≤0.3
Thermostating temperature, °C	30 and 41
Thermostating coefficient	≤10 <sup>-3</sup>
Resolution of electric reading device, μGal	
for Δg measurement range of 100 mGal	0.67
for Δg measurement range of 10 mGal	0.07
Thermostat build-up time, h	≤24
dc power supply, V	11–14
Operating threshold of accumulator discharge indicator, V	11 ± 0.2
Operating temperature range, °C	–20...+40
Gravimeter power consumption, W	≤2
Gravimeter weight with battery, kg	≤5

**Table 2.** Technical characteristics of NI-3 microlevel

Measurement base, m	1.5
Range of measured tilt angle, arcsec	±4000 ( $2 \times 10^{-2}$ rad)
Resolution, arcsec	±0.5 ( $2.5 \times 10^{-6}$ rad)
Scale factor, arcsec/V	500
Nonlinearity, %	0.01
Temperature coefficient, arcsec/°C	0.2–0.5
Power, V	±9
Consumption, W	0.2
Dimensions, m	$1.5 \times 0.08 \times 0.04$
Weight, kg	2.7



**Fig. 2.** Schematic diagram of measurement with NI-2 inclinometer: (1) inclinometer; (2) digital recorder; (3) studied object; (4) rod; (5) borehole.

**Table 3.** Main technical characteristics of NI-2 inclinometer

Measurement range of Zenith angles	$\pm 15^\circ$
Measurement accuracy:	
Angles, arcsec	1–2
Horizontal displacement, mm	$\pm 0.1$
Scale factor, arcsec/V	10000
Nonlinearity, %	0.01
Temperature coefficient, arcsec/ $^\circ\text{C}$	0.1–0.2
Temperature measurement range, $^\circ\text{C}$	0–40
Temperature measurement accuracy, $^\circ\text{C}$	$\pm 0.02^\circ$
Measurement depth, m	to 100
Depth measurement step, m	2
Accuracy of azimuth fixation, arcsec	60
Power supply of inclinometer, V	$\pm 12$
Consumption, W	0.1–0.2
Size:	
Diameter, mm	70
Height, m	2
Weight, kg	3
Borehole diameter, mm	75–120

(2) in the measuring vessel there is a second, reference measuring element used to compensate for the effect of temperature changes—the level of liquid in the reference element does not change when the vessel moves vertically;

(3) the device's design allows measurement of relative vertical displacement of the measuring vessels on the order of tens of centimeters with a resolution of fractions of a micron, which makes it possible to increase the linear base of the level to several kilometers.

A unique feature of the long-range level is that it can be used to solve not only applied, but also important fundamental problems to determine the parameters characterizing the Earth as a whole. These fundamental tasks include the following:

(1) measurement of the unevenness of the Earth's rotation within one day: if the sensitivity with respect to relative vertical displacement of the liquid in the vessel is  $z = 1 \mu\text{m}$ , a hydrostatic level with a base of 1 km can measure the relative change in the Earth's angular velocity of  $\Delta\omega/\omega = 5 \times 10^{-8}$  over a time of  $\Delta T = 10^3 \text{ s}$ ;

(2) measurement of torsional movements of lithosphere blocks: a change of  $z = 1 \mu\text{m}$  corresponds to a change of  $10^{-7} \text{ rad}$  in the angle of rotation of the lithosphere block during 1 day;

(3) measurement of translational vibrations of the inner core of the Earth: for a level unit with the base of 1 km, the displacement of the inner core of the Earth at 1 m would increase relative levels by  $0.25 \mu\text{m}$ , which is 400 times larger than the resolution of the device determined by thermal noise.

## CONCLUSIONS

We have considered original instruments for gravity and strain measurements developed at IPE RAS. In recent years, these instruments have been widely used in the territory of Moscow and many other places both in Russia and abroad. Observations with these instruments have contributed significantly to the environmental safety of studied objects.

The main advantages of the developed instruments are as follows:

(1) the GAG-3M gravimeter has unprecedented interference immunity;

(2) NI-3 microlevel unit has no analogs in this class of devices;

(3) the borehole inclinometer allows high-precision measurements of the spatial position of a borehole of any size and requires no specialized boreholes;

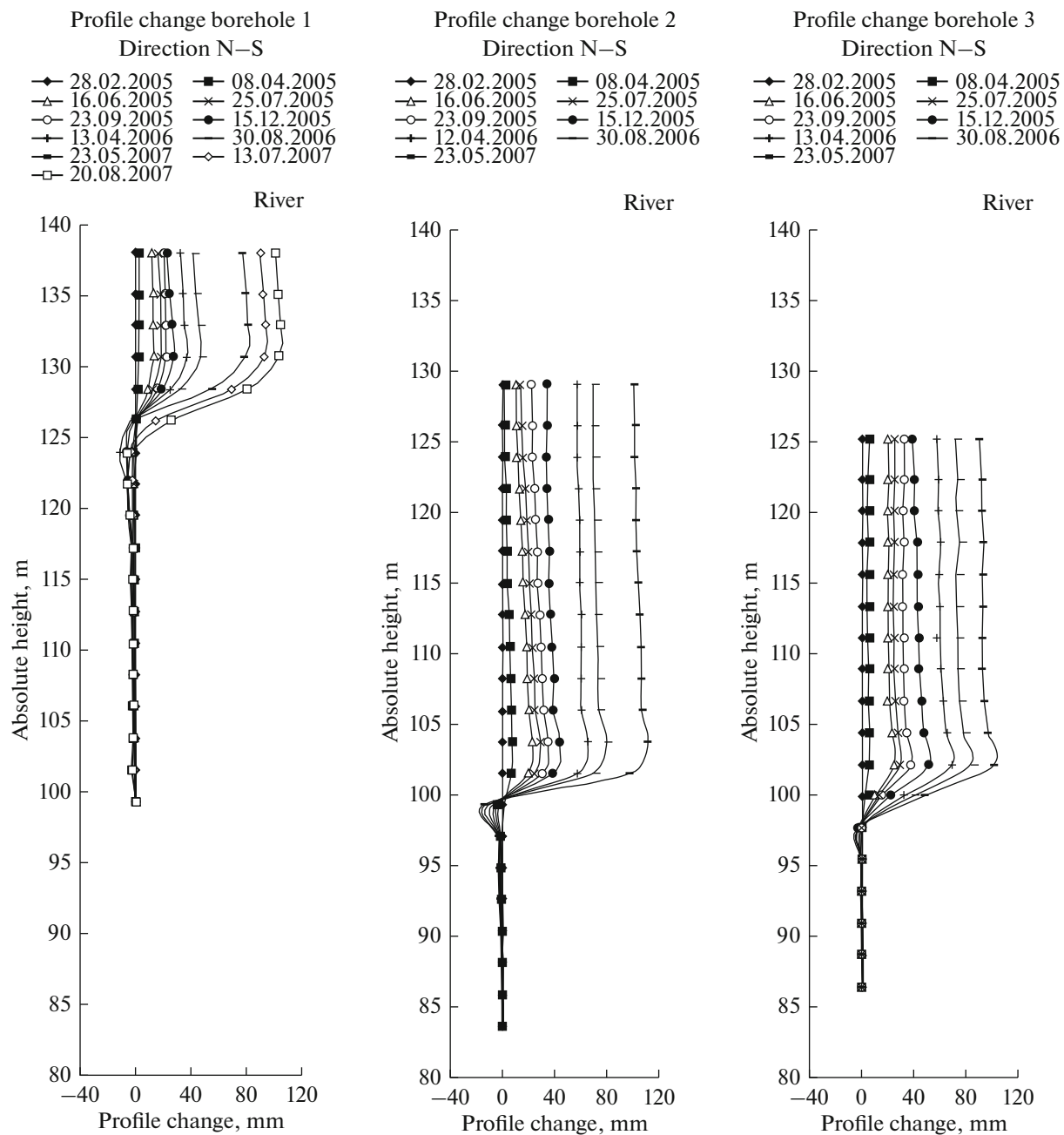


Fig. 3. Results of two-year measurements using NI-2 borehole inclinometer on creeping slope at Kolomenskii Park National Reserve Museum, Moscow.

Table 4. Devices of apparatus and their main characteristics

NMD-Sh two-axis pendulum borehole tiltmeter	
Sensitivity	0.1 marcsec
Range	$\pm 5$ arcmin
KDC frequency quartz deformometer	
Sensitivity of absolute displacements	$\Delta x = 10^{-10} - 10^{-11}$ m
Range (for linear base $L = 1$ m, it corresponds to relative deformations of $10 \times 10^{-10}$ to $10 \times 10^{-11}$ m)	$5 \times 10^{-4} - 5 \times 10^{-5}$ m
GN hydrostatic level	
Relative vertical displacement sensitivity of measuring vessels $5 \times 10^{-3}$ $\mu$ m in range of $\pm 5$ mm	
Meter of fluid level variation in borehole	
Sensitivity of 0.1 mm in range of $\pm 5$ mm	
Sensors of meteorological parameters (atmospheric pressure and temperature)	

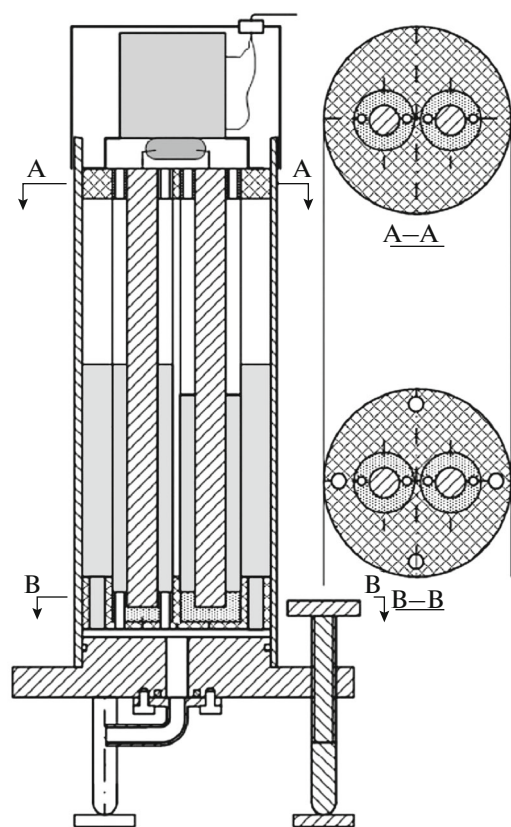


Fig. 4. Sketch of measuring vessel of level.

(4) the use of the devices of tilt-strainmeter apparatus for mass measurements on large areas increases the representativeness of the results and reduces the impact of local interference;

(5) the long-base hydrostatic level makes it possible to solve a wide range problems of not only applied but also of fundamental interest.

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