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#### ИССЛЕДОВАНИЕ РАБОТЫ АНИЗОТРОПНОГО ОПТИКОТЕРМОЭЛЕМЕНТА С БОКОВЫМ ТЕРМОСТАТИРОВАНИЕМ

Решено неоднородное уравнение теплопроводности с учетом закона Бугера для продольного сечения круглого цилиндра с термоэлектрически-анизотропного материала. Получены выражения для поперечной термоЭДС и характеристик радиационного анизотропного оптикотермоэлемента (АОТЭ), что позволяет контролировать величину потока энергии в области оптической прозрачности материала, из которого он изготовлен. Описана конструкция прибора на основе радиационного АОТЭ с боковым термостатированием.

**Ключевые слова:** радиационный анизотропный оптикотермоэлемент (АОТЭ), распределение температуры, АОТЭ с боковым термостатированием.

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# ANALYSIS OF MODERN GRAVIMETERS OF THE AVIATION GRAVIMETRIC SYSTEM

*Обґрунтовано доцільність використання авіаційних гравіметричних систем для проведення гравіметричних вимірювань та отримання інформації про гравітаційне поле Землі. Проведено аналіз існуючих сьогодні гравіметрів авіаційних гравіметричних систем, визначено їх переваги та недоліки. Розглянуто сучасні перспективні розробки у галузі створення авіаційних гравіметрів нового типу із вищою точністю та швидкодією у порівнянні з відомими на сьогодні аналогами.*

**Ключові слова:** *чутливий елемент, гравіметр, прискорення сили тяжіння, гравітаційне поле Землі.*

## 1. Introduction

Research of parameters of the gravitational field of the Earth (gravitational acceleration (GA) g and its anomalies $\Delta g$) is necessary in:

– seismology, (earthquake prediction);
– aviation and space technology (correction of systems of inertial navigation of rockets, aircraft, orbits of spacecraft);
– for research of geodynamic phenomena;

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– for implementation of the tasks of engineering geology, geophysics, archeology, cartography, oceanology, etc.

Gravimetric measurements were carried out on the surface of the Earth, on a submarine, on a surface ship and on an aircraft.

Ground measurements provide the highest accuracy (0.01 mGal). However, they are carried out slowly. The regions of the poles, the equator, and the oceans are not available for such measurements.

Marine measurements have accuracy less than ground measurements (0.1–0.5 mGal). However, marine measurements are impossible in the mountainous and remote regions of the oceans [1].

Measurements on the aircraft make it possible to measure $\Delta g$ in hard-to-reach regions of the Earth at a rate much greater than ground ones. Also, measurements can be made in places that were previously inaccessible (sea hollows, mountain peaks, areas of poles, etc.). For these purposes, use aviation gravimetric systems (AGS), the sensing element of which is the gravimeter.

The study of new types of gravimeters, recommendations for their manufacture and modern research in this industry is the first and the main stage in the development of a new device. Therefore, conducting a comparative analysis of modern gravimeters is an urgent task. After all, this information will greatly help and orient the developer.

## 2. The object of research and its technological audit

*The object of research* is gravimeters of aviation gravimetric systems.

AGS gravimeters inherent such significant disadvantages:

1) insufficiently high measurement accuracy (3–10 mGal);

2) mandatory need to apply the filtration procedure for the output signal of the AGS gravimeter;

3) instability of the static transfer coefficient of the AGS gravimeter caused by changes in the properties of structural elements;

4) low speed and lack of ability to process information quickly, and others.

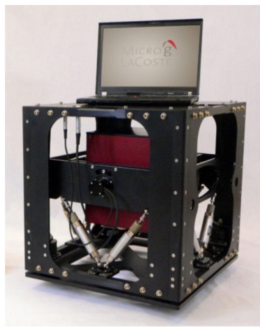
These and other [2, 3] gravimeters are given in a comparative Table 1.

**Table 1**

Comparative characteristics of the latest existing gravimeters of aircraft gravity systems

| Type | Name | Image | Features |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| quartz | CG-5 AutoGrav (Russian Federation) |  | Automatic compensation and correction, no influence of temperature, pressure, magnetic field, automatic noise reduction, seismic noise suppression, low residual drift<br>Accuracy: 0.01*mGal<br>Zero point offset:<br><0.02 mGal/day |
| String with liquid damping | Гравитон-М (Russian Federation) |  | Low weight and sensitivity to shocks, a large measuring range and convenient digital recording system, consists of three string gravimeters placed in special assemblies and a control unit for gravimeters<br>Accuracy: 0.01*mGal<br>Zero point offset:<br><0.02 mGal/day |
| Magnetic | GT-2A (РФ) |  | Mounted on a tri-axial gyrovertical platform, the mass of the gravimeter is made in the form of a flat two-winding coil in the gap of the differential magnetic system, (of four heat-compensating magnets)<br>Accuracy: 0.01*mGal |

**Continuation of Table 1**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| Quartz | ЧЕКАН-АМ (Russian Federation) |  | The software allows to carry out the full processing of the survey results onboard with the estimation of accuracy and the construction of gravity maps<br>Accuracy: 0.01*mGal<br>Zero point offset:<br><0.1 mGal/day |
| Spring-type | TAGS-6 (Canada) |  | Combines the latest GPS technology and data acquisition with the solid foundation of the Lacoste dynamic gravimeter. The system includes a spring-type converter with a low level of drift mounted on a gyrostabilized cardan platform<br>Accuracy: 0.01*mGal<br>Zero point offset:<br><3 mGal/day |

**Note**: The accuracy of 0.01 mGal on the Earth's surface (absolute measurements) is indicated by the enterprises, but there is no specific data on aviation gravimetric studies with these gravimeters. Under real conditions, the error is much higher – in the range 2–8 mGal [1, 4].

Table 1 shows that even the most modern aircraft gravimeters have the following disadvantages:

- a large time constant;
- insufficient speed;
- low sensitivity;
- hardly predictable drift of elastic properties of a spring-type element;
- instability of the magnetic properties of a permanent magnet;
- instability of elastic properties of a string; The possibility of resonances;
- high cost price;
- complexity of the design.

## 3. The aim and objectives of research

*The aim of research* is analysis of the gravimeters of the aviation gravimetric system that exist today, to determine their advantages and disadvantages.

To achieve the formulated aim, the following tasks are set:

1. To conduct a comparative analysis of the gravimeters of aviation gravimetric systems that exist today.
2. To consider modern perspective developments in the field of creation of aviation gravimeters.
3. To propose ways to improve the accuracy of gravimeters.

## 4. Research of existing solutions of the problem

AGS efficiency is largely ensured by the choice of the sensing element of the system – the gravimeter. The leading technical universities of Russia, the USA, Japan, Germany and other leading countries are engaged in development of new models of AGS gravimeters and increase of their accuracy.

Gravimeter ГИ 1/1 (developed by JSC Ramensky Instrument-Making Plant, Russia) is designed to determine the GA from mobile objects for the purpose of geological exploration of oil and gas bearing structures and other minerals beyond the Δg of the Earth. The main area of application of the gravimeter is an airplane and helicopter geophysical complexes that carry out high-performance mineral prospecting, especially in hard-to-reach areas of the Earth and in marine geophysical complexes.

The accuracy of GA measurement, without taking into account the error of the external information for averaging interval of 100 s [1, 5]:

- from marine carriers (4.3–5.5) mGal;
- from ground carriers (4.2–5.3) mGal;
- from air carriers 6.0 mGal.

Gravimeter «*Чекан-АМ*» (developed by JSC Concern «Central Research Institute «Electropribor», Russia) is designed for conducting air and marine gravimetric survey of the surface. The gravimeter consists of a gravimetric sensor and a gyrostabilizer with an integrated control system on microcontrollers. The gravimetric sensor is based on a double quartz elastic system with an optoelectronic linear converter. The measurement accuracy is 6 mGal [6].

Gravimetric complex «*ГРІН-2000/М*» consists of two quartz sensors with liquid damping, covered by boosting feedback that provides strong interference suppression and wide bandwidth for a useful signal [7]. Accuracy in operating conditions on marine vessels 1 mGal, for aircraft –5 mGal.

Magnetic gravimeters МАГ-1М, GT-1A, GT-2A are developed in JSC «Gravimetric technologies», Russia. In them, the sensing element consists of an inertial mass, looks like a flat coil in the gap of the differential magnetic system. The method of compensation of the pendulum moment in such gravimeters occurs by rotating a permanent magnet relative to the pendulum rotor around the initial axis of the

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device. In this case, the radial magnetic field is formed by two permanent magnets of a symmetrical design, interacting with the control current passing through the coil of the sensing element. The AGS study based on the listed magnetic gravimeters showed an accuracy of 5 mGal [8].

The principle of the action of string gravimeters is based on the property of the string to change the frequency of natural oscillations when its tension changes. GA measurement is reduced to measuring the frequency of string oscillation.

To date, the gravimetric complex ГРАВІТОН–М is a well-known and widely used gravimetric complex (developed by SRL of Geophysics, GNPP «Aerogeophysika» and Bauman Moscow State Technical University), which includes a measuring block of three string gravimeters, a gyro-inertial platform, two-frequency indicators of the receivers of the GPS satellite navigation system, the registration and data processing unit with the corresponding software package.

The complex is tested on helicopters and on airplanes. Helicopter surveys over the sea showed an accuracy of 5 mGal [9].

The currently known gyroscopic gravimeters containing a gyroscopic pendulum are connected to the frame by means of a horizontal axial support perpendicular to the axis of gyroscope rotation, which are one of the most accurate AGS gravimeters [4, 10].

PIGA-type gravimeters, developed by the Massachusetts Institute of Technology (USA), have a relatively high sensitivity and are used as AGS gravimeters and elements of navigation systems (accuracy 3 mGal) [2]. However, such gravimeter has one axis of sensitivity parallel to the axis of gyroscope rotation relative to the platform and measures the projection of g on this axis. To determine the direction of the gravitational vertical, a very precise stabilization of the axis of gravimeter sensitivity in the direction of the gravitational field of the Earth is needed. In addition, the rotation of the gyroscope around the axis of the outer frame causes the appearance of instrumental PIGA errors.

There are many modern theoretical developments of AGS gravimeters: quartz [11], string with liquid damping [9], magnetic [8, 12], quartz [6], spring-type [12], the principle of operation is based on various physical phenomena [10]. They have both advantages and disadvantages. Almost all known gravimeters measure the error of vertical acceleration [14, 15], which is tens of times higher than the useful signal [16]. Complicated by auxiliary systems (global positioning system (GPS)) [17]. It will require a long, thorough calibration [18] and adjustment [19], which greatly complicates the work. The current developments relate to submarine [20, 21] and ground [18] measurement methods, which are not used in aviation gravimetry.

Carrying out high-precision aviation measurements remains a necessary task. Therefore, it would be advisable to carry out a comparative analysis of the existing AGS gravimeters and consider current promising developments in this field.

## 5. Methods of research

To date, as shown by the analysis of AGS gravimeters, the achievable accuracy of aviation gravimetric measurements is (3–10) mGal. However, the aerogravimetric survey for solving the problems of search gravity requires a significant increase in the accuracy and speed of aviation gravimetric measurements [22]. This is primarily due to the need to improve the gravimeter accuracy, development of methods for automatic compensation of measurement errors Δg, with the improvement of the mathematical model of AGS, solving the problems of filtering disturbing effects in the output signal of the AGS gravimeter [1, 23].

Developments that would satisfy all modern requirements are only theoretical.

So, at the department of instrumentation of NTUU «KPI» (Kyiv, Ukraine) together with ZHSTU (Zhitomir, Ukraine) new types of AGS gravimeters are developed and investigated:

– gyroscopic gravimeters based on a dynamically tuned gyroscope (DTG) (Fig. 1);
– ballistic laser gravimeters (BLG) with a two-dimensional video image (Fig. 2) [24];
– two-gyroscope (Fig. 3) [25];
– piezoelectric (Fig. 4) [26];
– capacitive and string [27] (Fig. 5) gravimeters.

The accuracy of the developed gravimeters is (0.1–2.0) mGal.

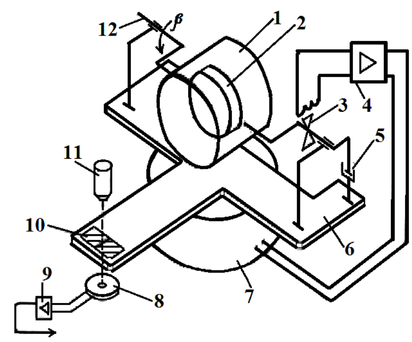


**Fig. 1.** The integrating gyroscopic gravimeter

The main elements shown in Fig. 1: gyromotor 1 with beryllium rotor 2. The latter is mounted on the axis 12 of the internal support so that a pendulum is created. The center of mass of the gyromotor is located on the axis of rotation of the outer frame. The outer frame is a rotary platform 6, on which there are columns with bearing assemblies for fixing the axis of the internal gyromotor support. The rotor of the gyromotor angle β sensor 3 is fixed on the axle 12 of the gyromotor internal support and the stator of the sensor 3 is fixed to the platform 6. To attenuate the angular vibrations of the gyromotor 1, a liquid damper 5 is provided around the axis of the gyromotor inner support 12. By selecting a working gap between the blade and the box of the liquid damper, an increase in the coefficient of viscous friction to $f_1$=2.3·10$^{-3}$ kg·m$^2$/s is provided. The signal from the sensor 3 is amplified and directed to the torque sensor, in which the servomotor 7 operates, which applies a torque to the turntable, which is proportional to the signal from the sensor 3 of the angle β. The rotatable platform 6 is provided with a radially offset light-impermeable membrane 10 from a gap above which there is a source 11 of narrowly directed light. At each turn of the platform, the light beam passes above the photodetector 8. A short pulse informs about the complete rotation around the axis of rotation by the platform 6. The accuracy of the count is 5 microradians. This pulse (the signal output of the gyro-gravimeter) is routed through the amplifier 9 to the circuit of the electronic meter unit. The device is enclosed in an aluminum protective cylinder (magnetic protection) [25].

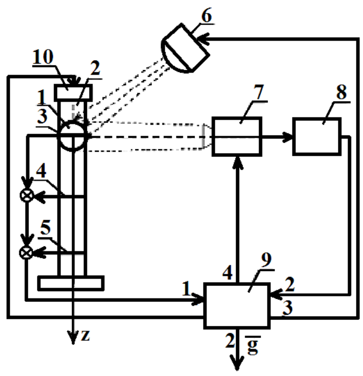

**Fig. 2.** Ballistic laser gravimeter with a two-dimensional video image

The test body 1 is fixed in the electromagnet 10 (Fig. 2). From the first output of the digital computer 9 to the input of the electromagnet 10, a signal is sent along which the electromagnet releases the test body 1. It starts to move down the transparent tube 2 in a fixed base under GA action. Since the test body 1 is made in the form of a ball with magnetic properties, when it passes by the coils 4, 5, 6, an EMF is induced in them. From the outputs of the coils 4, 5, 6 to the first input of the digital computer, an electrical signal is produced consisting of three voltage pulses, each of which is caused by the occurrence of EMF in the coils 4, 5, 6. The time delays $\hat{\tau}_1, \hat{\tau}_2, \hat{\tau}_3$ of each of the pulses relative to the moment of the beginning of the motion of the test body 1 are proportional to the absolute GA value g and the distances $x_1$, $x_2$, $x_3$ from the electromagnet 10 to the coils 4, 5, 6.

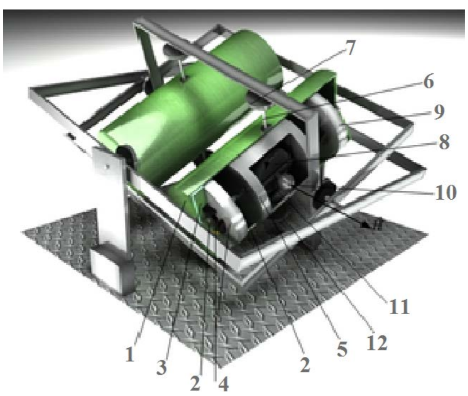

**Fig. 3.** Two-gyro gravimeter

Gravimeter in Fig. 3 consists of a rotor 8 of a gyromotor with an internal stator located in a cylindrical float 5. The stationary axis of the gyromotor is fixed in the float bar 11 of the float 5. The longitudinal axis of support of the float 5 is aligned with the longitudinal axis of the body 1 of the device. The float has trunnions (made of high-strength steels with a diameter of 0.4...1.0 mm), by means of which a gyroscopic sensor is fixed in support stones 2 (sapphire, corundum, ruby). They perceive the uncompensated weight of the float and the forces that arise when the device is operated on a mobile basis. The clearance (0.1-0.15 mm) between the outer cylindrical surface of the float 5 and the inner surface of the body 1 is filled with liquid (ПМС-1000), which creates a damping moment with respect to the gyroscope axis x and isolates the support stone from impacts and vibrations.

The sensing element of the piezoelectric gravimeter (PG) consists of a piezoelectric element (PE) 5, working on compression-expansion deformations, insulators 7 at the ends of the PE and inertial mass (IM) 6. In order to increase the reliability and strength of the structure, the sensor is elastically pressed against the base 8 by the screw 10. The PG is connected to the operational amplifier by means of a cable 11. The piezoelectric element 5 is a multilayer structure (piezo package) consisting of layers of crystalline lithium niobate.

Under the action of the gravity acceleration g, a gravitational force arises, as a result of which the IM moves by an amount x. Such motion of the IM causes compression or stretching of the PE and the appearance of the electric charge Q on its surface (the phenomenon of the direct piezoelectric effect), which is directly proportional to g [26].

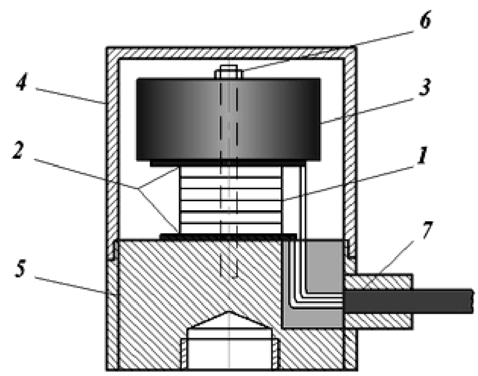

**Fig. 4.** Design of the piezoelectric gravimeter: 1 – piezoelectric elements; 2 – insulators; 3 – inertial mass; 4 – base; 5 – hermetic case; 6 – screw; 7 – pin cable

In the new piezoelectric gravimetric (PG) of automated AGS, the problem of filtering the output signal is solved by establishing the frequency of the natural oscillations of the PG equal to the frequency of intersection of the spectral densities of the useful signal of gravity acceleration and the signal of the main noise of the vertical acceleration of the aircraft. This ensures that there is no influence of the main noise – vertical acceleration of the aircraft and significantly increases the accuracy of the measurement.

The sensor element of the capacitance gravimeter CG is located in a sealed box. It is made in the form of upper and lower metal plates separated by a dielectric. Moreover, the upper metal plate is connected to the hermetic case, and the lower metal plate with an elastic membrane to which the seismic mass is attached through insulators [27]. The upper and lower metallic plates of the CG sensor element, separated by a dielectric, form a capacitor with variable gap δ and capacitance C. During the action of gravity acceleration $g_z$ on the seismic mass, an attractive force arises that causes its movement. As a result of this movement, the elastic membrane begins to bend, which changes the gap δ between the upper and lower metal plates separated by the dielectric, and hence the capacitance C, which is inversely proportional to the acceleration $g_z$

The parameters of the CG sensing element are chosen so that its frequency of natural oscillations is equal to the highest frequency of gravitational accelerations that can be measured against a background of interference [28]. That is, the gravimeter sensing element also performs the functions of the low-pass filter. This eliminates the influence of the errors on the output CG readings, whose

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frequency is greater than the frequency of CG natural oscillations, and will increase the accuracy of measuring the acceleration due to gravity.

The string gravimeter (SG) (Fig. 5) has a sensor element made in the form of two identical string gravimeters, the strings of which are made of a strain-sensing material. They are placed in a sealed enclosure and electrically connected by a bridge circuit to the two opposite shoulders of the bridge. The output of the bridge is connected to the device for calculating the output signal of the gravimeter.

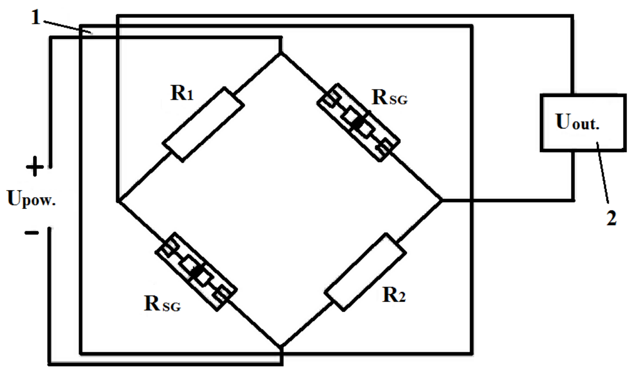


Fig. 5. String gravimeter

This CG design ensures a linear dependence of the output signal on g, which makes it possible to significantly increase the measurement accuracy g. The output signal of the investigated SG will not depend on changes in temperature, pressure, humidity, since they affect the frequencies of both strings of two identical string gravimeters in the same way, but with opposite signs. This also ensures an increase in the accuracy of measurements of g in the investigated SG as compared to the known ones [29].

## 6. Research results

As a result of the most complete analysis of AGS gravimeters, it is found that there are still many unresolved problems in aerogravimetry. Among them the main are:

– inadequate speed and lack of the ability to quickly process information;
– hardly predictable drift of elastic properties of a spring element;
– instability of the magnetic properties of a permanent magnet;
– instability of elastic properties of a string; the possibility of resonances;
– insufficiently high measurement accuracy;
– mandatory necessity of application of filtration procedure of output signal of AGS gravimeter;
– complexity of the design.

In the future, it is planned to study in more detail the foreign market and scientific prototypes of aerogravimetry. Especially, compare with countries such as China, Japan and Korea.

All the latest developments that could completely or partially solve the above-described deficiencies exist mainly in the form of scientific prototypes [30]. And aerogravimetric survey for solving the problems of search gravity requires a significant increase in the accuracy and speed of aviation gravity measurements. Therefore, the study of this issue remains a promising problem.

## 7. SWOT analysis of research results

*Strengths*. An analysis of the current aircraft gravimeters and their comparisons makes it possible to determine their main advantages and disadvantages. This greatly helps in the development of new devices. Based on this analysis, the methods have been proposed to improve the accuracy of aircraft gravimeters.

*Weaknesses*. There are still many unresolved problems in aerogravimetry. Among them the main ones are: insufficient performance and accuracy; instability of characteristics of used materials; complexity of the design.

*Opportunities*. In the future it is planned to study in more detail the foreign market and scientific prototypes of aircraft gravimeters. Particularly, compare with countries such as China, Japan and Korea.

*Threats*. In Ukraine, very few enterprises and scientific schools deal with gravity issues. This, of course, does not contribute to the development of this industry. Foreign analogues are rapidly occupying the first positions in the market. While Ukrainian production only improves existing devices, without resorting to the latest developments.

## 8. Conclusions

1. A comparative analysis of modern aircraft gravimeters and scientific prototypes is carried out. Their main disadvantages are revealed: low accuracy of measurement (3–10 mGal) mandatory necessity of application of filtration procedure of output signal of AGS gravimeter; instability of the static transfer coefficient of the AGS gravimeter; low speed.

2. Modern advanced developments in the field of aircraft gravimeters are considered: gyroscopic, ballistic, piezoelectric, capacitive, string gravimeters. They are distinguished by high accuracy (1–2 mGal) and speed. This is achieved by choosing the intrinsic frequency of the gravimeter at the point of intersection of the spectral densities of the useful GA signal and the main noise of the vertical acceleration. This frequency is 0.1 $s^{-1}$. Then the gravimeter serves as a filter for the main perturbing vibration accelerations, whose frequency is greater than 0.1 $s^{-1}$.

3. It is proposed to use a two-channel (differential) method for GA measurement in all gravimeter designs. Then the useful signal is doubled 2g, and the signals of the main disturbing vertical acceleration, instrumental errors from the influence of changes in temperature, pressure and other environmental factors are canceled.

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### АНАЛИЗ СОВРЕМЕННЫХ ГРАВИМЕТРОВ АВИАЦИОННОЙ ГРАВИМЕТРИЧЕСКОЙ СИСТЕМЫ

Обоснована целесообразность использования авиационных гравиметрических систем для проведения гравиметрических измерений и получения информации о гравитационном поле Земли. Проведен анализ существующих сегодня гравиметров авиационных гравиметрических систем, определены их преимущества и недостатки. Рассмотрены современные перспективные разработки в области конструирования авиационных гравиметров нового типа с высокой точностью и быстродействием в сравнении с известными на сегодня аналогами.

**Ключевые слова:** чувствительный элемент, гравиметр, ускорение силы тяжести, гравитационное поле Земли.

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