# Three-Coordinate Gravimeter with Exhibition of Axis Sensitivity Based on Digital Videoimages

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## ABSTRACT
The paper presents a new design of a three-axis gravimeter of aviation gravimetric system, which provides compensation for errors caused by influence of mobile base vertical accelerations and in the result of measurement of full gravity acceleration vector. Angle of inclination of a mark that is applied to a gravimeter body and coincides with vertical sensitive axis direction is determined by linear approximation in digital video images. These data are used to point sensitive axes and improve gravimeter accuracy.

## CCS Concepts
**• Information systems → Information systems applications → Spatial-temporal systems → Geographic information systems • Information systems → Information systems applications → Process control systems**

## Keywords
three-axis gravimeter; pointing of sensitive axis; digital video image; linear approximation

## 1. INTRODUCTION
Operation of a gravimeter as a part of aviation gravimetric system (AGS) is characterized by complex conditions. Accuracy of gravity acceleration measurements is substantially influenced by vertical accelerations of the mobile basis and inaccuracy of spatial orientation of gravimeter sensitive axis with respect to direction of full gravity acceleration vector [1].


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The most famous are aviation gravimeters such as string gravimeter (GS), quartz gravimeter (GAL-S), magnetic gravimeter (Bell BGM-2) and gyroscopic gravimeter (PIGA-16,25). Actually achieved accuracy of such gravimeters is (6 ... 10) mGal. But at the present time such accuracy is not sufficient to solve the applied problems of geodesy, geology, navigation of aerospace objects [2-4].

Developments of new, more accurate gravimeters have been recently appeared. They are based on modern technologies of MEMS accelerometers (microelectromechanical accelerometers), piezoelectric and atomic sensors, and magnetic levitation with superconducting materials [5-10].

However, a sensitive element of such gravimeters measures only gravity acceleration $g_z$ along the vertical axis $O_z$. Therefore, elements of gravity acceleration $g_x$ and $g_y$ along the axes $O_x$ and $O_y$ are considered equal to zero due to their small absolute value. However, in order to achieve the accuracy of measuring gravity acceleration of above 1 mGal, the above elements must be taken into account. This can be solved by building a three-axis gravimeter operating as a part of AGS. Known solutions in the field of three-axis accelerometers and gravimeters, for example [11, 12], are not adapted to operate in conditions that are typical of the aviation gravimetric system.

When using three-axis gravimeters, there are difficulties in determining direction of full gravity acceleration vector in space [13, 14]. Existing solutions for measuring local variations of gravity accelerations require direct location of a measuring device with one sensitive axis over a site on the Earth's surface under study [15, 16].

Thus, determination of module and direction of full gravity acceleration vector by aviation gravimetric system requires using a gravimeter for which a previous pointing of sensitive axes is carried out [17].

The purpose of the research is to improve accuracy of measurement of full gravity acceleration vector by a three-axis gravimeter due to: high-precision pointing of its sensitive axes based on linear approximation of digital video image of the mark that is applied to a gravimeter body and coincides with vertical sensitive axis direction; pointing of two sensitive elements in the direction of each sensitive axes for vertical acceleration effect compensation.

## 2. SCHEMATIC STRUCTURE OF THE THREE-AXIS GRAVIMETER

The developed three-axis gravimeter (fig. 1) provides measurement of a module of full gravity acceleration vector by determining projections of the vector on three coordinate axes, along which measurements are carried out. Also, the effect of vertical accelerations is compensated by pointing of two sensitive elements (for example, piezoelectric plates with inertial mass) in direction of each sensitive axis of a three-axis gravimeter.

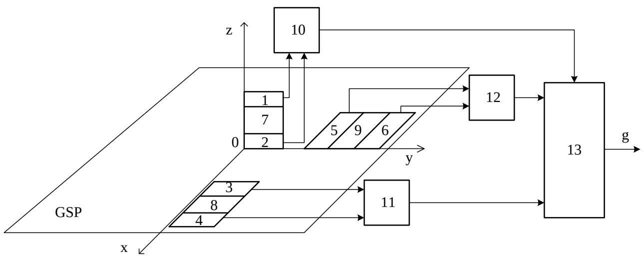


**Figure 1. Three-axis gravimeter of aviation gravimetric system: 1 ... 6 - piezoelements in the form of plates, which are installed pairwise along each sensitive axis; 7 ... 9 - inertial masses attached to piezoplates; 10 ... 12 - operational amplifiers (OP); 13 – an onboard computer; GSP is a gyrostabilized platform**

Sensitive elements $A_z$, $A_x$, $A_y$ are installed along each axis of measurement $O_z$, $O_x$ and $O_y$ on the gyrostabilized platform in the three-axis gravimeter of the aviation gravimetric system. Each of the sensitive elements contains two piezoelements in the form of identical plates. Frequency of oscillations of the plates is equal to frequency spectrum of gravity acceleration useful signal and signal of main disturbance of mobile base vertical acceleration (spectral densities at this frequency have equal numerical values). Inertial masses 7, 8, and 9 are attached to the bottom of piezosplates 1, 3 and 5 respectively and at the same time to the top of piezoplates 2, 4 and 6. Electrical signals of outputs of piezosplates of each of the three sensitive elements are fed to inputs of operational amplifiers 10, 11 and 12, which perform the function of adders and amplifiers of these signals. The result of signal processing comes to the onboard computer.
Digital computer makes calculations to determine the value of a full vector $\vec{g} = \vec{g}_x + \vec{g}_y + \vec{g}_z$ and a gravity acceleration module $|g| = \sqrt{g_x^2 + g_y^2 + g_z^2}$ . Thus, improvement of accuracy of gravity measurements is ensured due to the use of three sensitive elements.
Influence of mobile base vertical acceleration on gravimeter readings in the three-axis gravimeter developed is eliminated in two ways: 1 - by setting the frequency of piezoplate oscillations equal to frequency spectrum of gravity acceleration useful signal and signal of main disturbance of mobile base vertical acceleration [ 1-3, 9]; 2 - by using two piezoplates in each of the three sensitive elements $A_z$, $A_x$, $A_y$ and inertial mass between them, as well as operational amplifier that summarizes signals of two piezoplates.
Both piezoelements are affected by gravity acceleration either $g_x$ or $g_y$ or $g_z$, depending on coordinate axis, by vertical acceleration $\Delta\ddot{z}$ of the moving base and by instrumental errors $\Delta i$ caused by influence of residual non-identity of designs of piezoplates and inertial masses, and influence of changes in temperature, humidity and ambient pressure.
If we project all these actions on gravimeter measurement axis Oz and take into account that one piezoelement is involved in compression, and another in extension, then we obtain [9]:

$$u_1 = k\left(mg_z + m\Delta\ddot{z} + \Delta i\right),$$

$$u_2 = k\left(mg_z - m\Delta\ddot{z} - \Delta i\right),$$

where $u_1$ and $u_2$ are the output electrical signals of two piezoelements; $m$ is the inertial mass value; $k$ is the piezoelectric constant.

Output electrical signals $u_1$ and $u_2$ received in accordance with formulas (1) and (2) are amplified and summed up by an operational amplifier:

$$u_\Sigma = u_1 + u_2 = 2kmg_z\,,$$

where $u_\Sigma$ is the output signal of operational amplifier.

Resulting useful electrical signal (3) is proportional to double gravity acceleration signal. Consequently, this guarantees absence in a three-axis gravimeter output signal of errors caused by influence of vertical accelerations of the mobile basis and residual non-identity of designs of piezoplates and inertial masses, and influence of changes in temperature, humidity and ambient pressure (instrumental errors) that can be considerable.

## 3. SUBSYSTEM OF SENSITIVE AXES POINTING

Sensitive element of a gravimeter measures projection of a full acceleration vector on its own sensitive axis, which has a certain position in space. Sensitive axis can deviate from direction of full gravity acceleration vector measured, under the action of destabilizing factors. Herewith, projection length is less than length of full gravity acceleration vector. As a result, there is a considerable error in measurement results. Therefore, it is necessary to determine direction of this axis in space and introduce an appropriate correction to the measurement results. Direction (angular position) of a sensitive axis is determined by an instrument system using a straight line mark applied to the surface of the sensitive element body.
A sensitive axis shall be pointed with an error of not more than 5 arc minutes to ensure a gravity acceleration measurement error of 1 mGal and not more than 1.6 arc minutes for an error of 0.1 mGal [3].
In real operation conditions, a sensitive axis of gravimeter deviates at some angle from direction of full gravity acceleration vector. Therefore, due to this deviation, gravimeter measures projection of full gravity acceleration vector on sensitive axis rather than its true value.
Sensitive axis pointing errors which cannot be technologically eliminated can arise while installing accelerometers on a gyrostabilized platform. Magnitude of these errors reaches (1 ... 5) arc minutes [3, 17]. Sensitive axis of a gravimeter is pointed by orientation of its axis in three-dimensional space as intended for error compensation. The developed subsystem (fig. 2) contains a platform on which a sensitive element of gravimetric system is fixed, and a digital computer the input of which is connected to the output of the sensitive element, and the output to the input of platform spatial position control.

Improvement of accuracy of determining an angular position and pointing a sensitive axis of a sensitive element is ensured by applying to its body a straight line mark, direction of which coincides with direction of sensitive axis. The computer contains now a video camera, input of which is optically linked to the mark, and a computer for linear approximation of mark video image, input of which is connected to output of the video camera and output is connected to additional input of a digital computer [18].

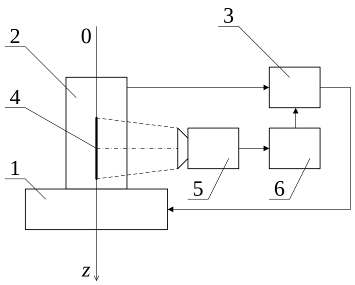


**Figure 2. Schematic structure of the subsystem for determining angular position and pointing sensitive axis of a gravimeter: 1 – a platform; 2 – a gravimeter; 3 – a digital computer; 4 – a straight line mark; 5 – a video camera; 6 – a computer for linear approximation of a mark video image**

Video camera and computer for linear approximation of mark video image provide a precise determination of angular position of gravimeter sensitive axis in a vertical plane. This is due to properties of the procedure of mark video image linear approximation [19, 20]. According to angular position measurement the digital computer calculates and sends control signals to the platform in such a way that direction of gravimeter sensitive axis determined on the basis of mark video image coincides with direction of full gravity acceleration vector measured.

The subsystem of pointing sensitive axes (fig. 3) contains a gravimeter, a digital computer, a mark, a video camera, a linear

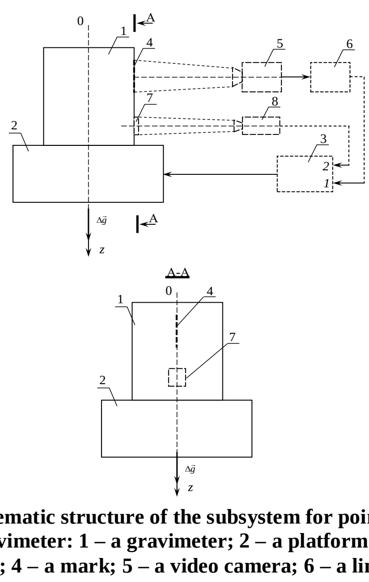


**Figure 3. Schematic structure of the subsystem for pointing sensitive axis of a gravimeter: 1 – a gravimeter; 2 – a platform; 3 – a digital computer; 4 – a mark; 5 – a video camera; 6 – a linear mark approximation processor; 7 – a reflective element; 8 – a photoelectric autocollimator**

mark approximation processor, a reflective element and a photoelectric autocollimator. A straight line mark direction of which coincides with sensitive axis direction is applied to the gravimetric body.

Photoelectric autocollimator estimates deviation of reflective element surface plane from the position, when it is perpendicular to the optical axis of the autocollimator. The signal, proportional to deviation degree, comes to the computer. The computer controls spatial position of the platform in such a way as to eliminate the deviation.

Gravimeter sensitive axis is consequently located in a vertical plane which is perpendicular to optical axis of the photoelectric autocollimator and in which direction of local vertical is located. However, sensitive axis can be located in the specified vertical plane but deviate at some angle from direction of the local vertical. The deviation can be determined using a mark, a video camera and a linear mark approximation processor. A digital computer controlling a platform spatial position can eliminate the deviation. As a result, this allows determining of spatial orientation of the full gravity acceleration vector with respect to the previous gravimeter settings.

## 4. ANALYTICAL RESEARCH

Let's consider the problem of linear approximation of mark contour on the video image, which corresponds to the mark on gravimeter body surface. Linear approximation is performed for a plurality of points belonging to a mark contour straight-line area on a digital video image. The area is in the form of a straight line which is described by analytic dependence [19, 20]:

$$y = \hat{a}_k + b_k (x - x_c), \quad \hat{x}_c = \delta_x n_c,$$

$$\hat{n}_c = \frac{1}{L}\sum_{j=1}^{L} n_j^*, \quad \hat{a}_k = y_c = \delta_y \hat{m}_c, \quad \hat{m}_c = \frac{1}{L}\sum_{j=1}^{L} m_j^* \tag{4}$$

where $(n_j^*, m_j^*)$ are the measured coordinates of the $j$-th point of mark contour on the digital video image, $L$ is the number of contour points used in the linear approximation procedure. Coefficient $b_k$ determines angular position of the mark and, accordingly, of the sensitive axis: $\alpha = arctg(b_k)$; and values $\hat{x}_c, a_k = \hat{y}_c$ are the coordinates of the middle mark point.

Let's determine angular position of the mark based on the least square method. Coefficient estimate $b_k$ [19] is a variance unbiased estimate

$$\hat{b}_k = \sum_{j=1}^{L} m_j^* (n_j - \hat{n}_c) \Bigg/ \sum_{j=1}^{L} (n_j - n_c)^2 \tag{5}$$

is unshielded with dispersion

$$\sigma_{\hat{b}k}^2 = \frac{\sigma_{m^*}^2}{\sum_{j=1}^{L} (n_j - \hat{n}_c)^2},$$

where $n_j$ is the exact coordinate values of mark points, $\sigma_{m^*}^2$ is the variance of coordinate $m_j^*$ measurement error.

Result of determining the mark angular position:

$$\hat{\alpha} = \mathrm{arctg}\left(\hat{b}_k\right), \quad \sigma_{\hat{\alpha}}^2 = \left(\frac{\partial \hat{\alpha}}{\partial \hat{b}_k}\right)^2 \cdot \sigma_{\hat{b}k}^2 = \frac{\sigma_{\hat{b}k}^2}{(1 + b_k^2)^2}. \tag{7}$$

From a mathematical standpoint, application of the least square method requires fulfilment of certain conditions [21, 22] and precise value of linear function argument (coordinates $n_j$). When measuring coordinates of mark points, the coordinates $n_j^*$ are measured on a video image with an error that has a variance of

$\sigma^2_{n*}$ Therefore, it is necessary to switch to the confluent methods of mark contour approximation, taking into account an error in $n^*_j$. Such methods provide estimates $\hat{b}_k$ that converge to $b_k$ with an increase in number $L$ of measured coordinates.
At the stage of pre-setting the three-axis gravimeter, the results of measurement of coordinates $n^*_j$ and $m^*_j$ are known, and variance ratio is $k_D = \sigma^2_{m*} / \sigma^2_{n*} = 1$, as the measurements are performed for the same video image using the same methods. Then the coefficient $b_k$ is determined on the basis of a generalized estimate of orthogonal regression [19]:

$$\hat{b}_k = \lambda_c \pm \sqrt{\lambda_c^2 + k_D}\,, \tag{8}$$

where

$$\lambda_c = \frac{\Sigma_y - k_D \Sigma_x}{2\Sigma_{xy}}, \quad \Sigma_y = \sum_{j=1}^{L} (m^*_j - \hat{m}_c)^2, \quad \Sigma_x = \sum_{j=1}^{L} (n^*_j - \hat{n}_c)^2,$$

$$\Sigma_{xy} = \sum_{j=1}^{L} (n^*_j - \hat{n}_c)(m^*_j - m_c),$$

and the sign in formula (8) is determined taking into account quadrant of contour location on the coordinate plane *xOy*.

The estimate $\hat{b}_k$ is determined given the systematic error and variance:

$$\Delta_{\hat{b}\mathrm{k\ syst}} = \frac{2\sigma^2_{m*} + \hat{b}^2_k \sigma^2_{n*}}{\hat{b}_k \Sigma_x}, \tag{9}$$

$$\sigma^2_{\hat{b}\mathrm{k}} = \frac{\sigma^2_{m*} + \hat{b}^2_{\mathrm{k}} \sigma^2_{n*}}{\Sigma_x}. \tag{10}$$

Another method of mark contour linear approximation which takes into account errors in measurement of coordinates $n^*_j$ is fractional-linear estimates [19]. For values $n_j$ that have a constant pitch $h_x = n_j - n_{(j-1)}$ on a digital video image:

$$\hat{b}_{\mathrm{k}} = \frac{\sum_{j=1}^{L} m^*_j (L + 1 - 2j)}{\sum_{j=1}^{L} n^*_j (L + 1 - 2j)}. \tag{11}$$

This estimate $\hat{b}_k$ contains errors

$$\Delta_{\hat{b}\mathrm{k\ syst}} = \frac{12 \hat{b}_{\mathrm{k}} \sigma^2_{n*}}{h_x^2 L (L^2 - 1)}, \quad \sigma^2_{\hat{b}\mathrm{k}} = \frac{12 \sigma_0^2}{h_x^2 L (L^2 - 1)}, \tag{12}$$

where $\sigma_0^2 = \sigma^2_{m*} + \hat{b}^2_{\mathrm{k}} \sigma^2_{n*}$ is the variance of coordinate errors.

## 5. NUMERICAL EVALUATION OF ACCURACY OF RESULTS

Numerical simulations and experimental study of errors in measuring the mark angular position have been performed (Figures 4 and 5). Size of the video images was 2048x2048 discrete points (d.p.) with a signal-to-noise ratio of 55 dB in numerical simulation and 768x576 d.p. with a signal-to-noise ratio of 40 dB in experimental studies. The value of confidence interval used in determining the measurement errors was 0.95.

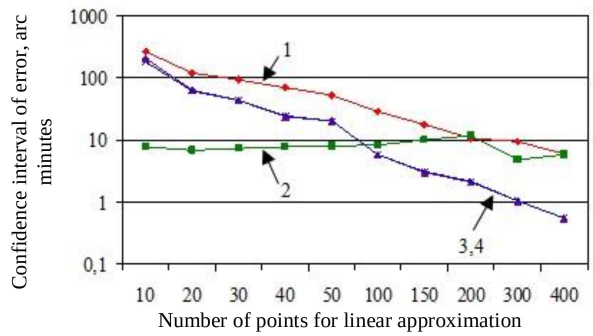


**Figure 4. Errors in determining the mark angular position for the methods of: 1 - 2 selected points; 2 - least squares; 3 - generalized estimate of orthogonal regression; 4 - fractional-linear estimate;**

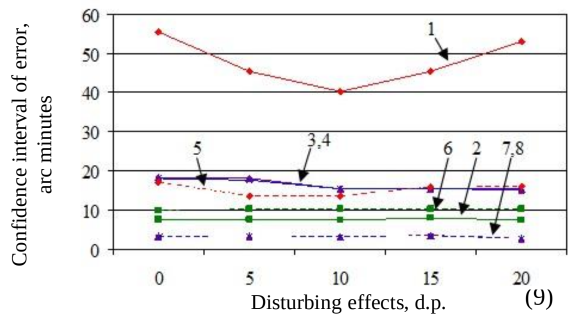


**Figure 5. Errors in determining the mark angular position given disturbing effects: 1,2,3,4 - when using 50 points for linear approximation; 5,6,7,8 – when using 150 points for linear approximation; 1,5 – method of 2 selected points; 2,6 - least square method; 3,7 - generalized estimate of orthogonal regression; 4,8 – fractional-linear estimate.**

Further studies were conducted for 3 ranges of angular measurements: (3…20)′; (0.3…3)°; (3…30)° (fig. 6). Each range used 50 digital video images that were averaged to filter random errors (video noise). Also, estimation and compensation of systematic component of errors in determining the mark angular position was performed. A method of generalized estimate based on orthogonal regression was used.

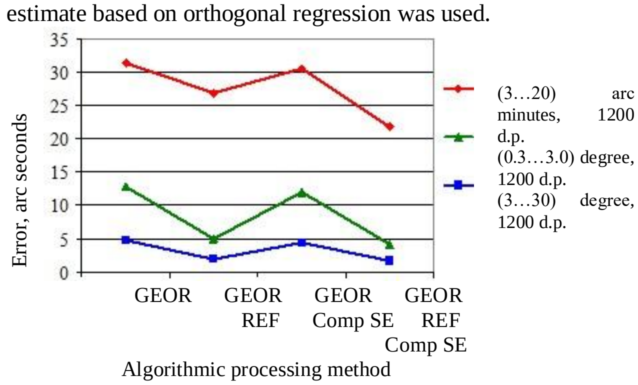


**Figure 6. Accuracy of determining the angular position of gravimeter sensitive axis on video images: GEOR - generalized estimate of orthogonal regression; REF - random error filtration; Comp SE - Compensation of systematic component of error**

Research results were assessed, taking into account that the error of pointing of gravimeter sensitive axis should be ≤5′ to ensure gravimeter output signal error of 1 mGal and ≤1.6′ to ensure gravimeter output signal error of 0.1 mGal [3]. Error in measuring the mark angular position on the basis of generalized estimate of orthogonal regression is (4.7…31.3)′′ depending on measurement range. The error is (1.9…26.8)′′ when applying random error filtration, and (1.7…21.7)′′ when applying random error filtration and algorithmic compensation of systematic component of error. Such an error of measurement of the mark angular position is acceptable to ensure the error of gravimeter output signal of ≤0.1 mGal.

## 6. CONCLUSIONS

A new three-axis gravimeter has been developed for operation in adverse conditions characteristic of aviation gravimetric system. Improvement of accuracy of gravity measurements in a gravimeter is provided by measuring three projections of a full gravity acceleration vector and calculating its module given that direction of the vector does not coincide with direction of vertical sensitive axis of gravimeter.

It has been determined that the error in measuring the mark angular position on the basis of generalized estimate of orthogonal regression is (4,7…31,3)′′, depending on measurement range, provided that random error filtration and algorithmic compensation of systematic component are applied. Such an error is acceptable to ensure that the error of output signal of a three-axis gravimeter is ≤0.1 mGal.

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