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A model of the response of the MGS-6 gravity sensor to tilting

Krzysztof Pyrchla [a,*], Małgorzata Pająk [b], Julia Gołyga [b], Jerzy Pyrchla [b]

[a] Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, Gdańsk, Poland
[b] Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland

A R T I C L E I N F O

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A B S T R A C T

The reliable interpretation of the measurements made by the Micro-g marine gravimetric system (MGS-6) depends on how the temporary changes of the scale coefficients such as gravimeter scale factor, vertical cross-coupling (VCC) effect, tiltmeter cross and tiltmeter long are compensated for during the signal analysis. The listed coefficients cannot be determined from readings during the measurements or by analysing the final data. The method presented here can be used to periodically check individual scale factors before starting shipborne measurements. This article focuses on determining the scale coefficients of the gravimeter: VCC effect, tiltmeter cross and tiltmeter long based on the MGS-6 gravity sensor's response to tilt. An unique non-linear model of Lacoste & Romberg gravimeter response to tilt was developed. In this paper, the measurement of the tilt angle of the object based on the photogrammetric elaboration of metric photographs is presented, using the principles of one-image photogrammetry.

1. Introduction

Shipborne (dynamic) gravimetry is an essential method to measure the gravity field of the Earth in oceanic regions, primarily due to the development of global navigation satellite system (GNSS) technologies.

The largest share of gravity values in offshore and coastal areas are measured by spring-based relative gravimeters mounted on stabilised platforms. Gravimetric sensor technology has constantly improved, and spring-based systems are comparatively old [1,2].

Ships act as platforms and are a source of signal disturbances in raw measurements [3]. Those signal disturbances are mainly concentrated in the high frequencies. In such cases, the only reasonable solution is to remove both the gravity signal and the noise signal by applying an appropriate low-pass filter. The situation is better for the lowest frequencies, where the main gravity signal is concentrated. It is possible to filter out the noisy, low-frequency components and extract the entire gravity signal. In particular, this approach works well with LaCoste & Romberg gravimeters due to their good drift properties [4,5]. When gravimeters are used for geodetic purposes [6], careful analysis of the measurement uncertainty of the gravimeter is necessary to meet the strict accuracy [6–8]. The distinction of relative gravimeters types should be made here since there is an important difference between them. Some sensors working principle employs mass on the spring (e.g. CG-6), but others use the probe mass mounted on the beam, which can rotate under gravitational force (e.g. MGS-6). Since the system of spring is used for balancing torque acting on a beam, gravimeters of this kind are also known as spring gravimeters.

The gravimeters in which probe mass is not mounted on the beam are particularly sensitive for sided accelerations. Therefore even a slight tilt of the sensor causes disturbances in the raw measurements [9,10]. The standard procedure in marine gravimetry, where beam-type spring gravimeters are used almost exclusively, assumes that the cross-coupling correction (CC-correction) can be neglected in shipborne gravimetry, and attention should be paid to optimising the frequency filtering of the signal.

This feature of the beam gravimeter poses a problem only for analysing signals in airborne gravimetry [11,12]. In response to this problem, strapdown airborne gravimetry was developed [13]. For shipborne gravity measurements, however, it is assumed that when the velocity is low and the wave motion is relatively regular, the application of the Eötvös correction and appropriately selected filter characteristics reduces the ambient noise to a sufficiently low level, and, simultaneously, the influence of the correction on the vertical cross-coupling (VCC) effect becomes negligible. From our investigations, we also find that this assumption is incorrect. Accounting for the phenomenon of cross-coupling in the analysis of shipborne gravimetric data significantly

* Corresponding author at: Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, Gdansk, Poland.
E-mail addresses: krzpyrch@student.pg.gda.pl (K. Pyrchla), malpajak@pg.edu.pl (M. Pająk), s182244@student.pg.edu.pl (J. Gołyga), jerpyrch@pg.edu.pl (J. Pyrchla).

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reduces the influence of environmental factors on the measurements and decreases the error of the gravity measurement [5].

The presented method was inspired by situations when unforeseen weather deterioration took place during the measurements at sea. In such cases, the gravimetric system worked under extreme conditions. After such campaigns, there were doubts about the credibility of further sensor indications, mainly because of a possible change in scale factors. It isn't easy to submit it to the manufacturer for inspection. Therefore, it was about carrying out the verification in a more straightforward way. The solution in such a situation is the proposed method. Therefore, when developing the technique, particular emphasis was placed on the simplicity of the solution, which will allow each measurement team to use the proposed method. Furthermore, it is a non-invasive method, so the risk of damaging the sensor is minimal.

Our research considers only empirical models as the most accurate and easiest to apply in practice. However, the use of such models requires knowledge of the following scale factors of the gravimeter: the VCC effect, tiltmeter cross and tiltmeter long. In other words, the calibration of the device must be known [9]. Taking these considerations into account, the main challenge of applying the VCC correction to the processing of gravity signals recoded at sea is knowledge of the model coefficients. Therefore, in our research, we focused on the most accurate modelling of the impact of the horizontal acceleration on the sensor.

In this paper, we discuss the method of verifying the scale factors: the VCC effect, tiltmeter cross, tiltmeter long and the gravimeter scale factor. The method is crucial in processing the signal read from the spring-based gravimeter. Moreover, we present the instrument layout for the tilt calibration of the dynamic gravimeter sensor. This layout allows for the correction of the gravimeter signal readings from an inclined platform. It has been shown that such an approach provides data on the spring gravimeter's behaviour, thus allowing identification and correction of disturbances [14]. This issue is especially significant for the geodetic use of the acquired data [15,16]. The objective nature of the data from our system is emphasised because no correction procedures are included in the obtained data. The results related to simultaneous tilting in two axes are also presented. Unfiltered gravity estimates were found to be a good tool for identifying changes in the recorded values resulting from problems maintaining the sensor verticality. Filter-optimised scale factors are introduced to obtain the corrected response of the gravimetric sensor arm. The analysed system was shown to map the coefficients with an accuracy of 0.29 mGal.

The scale factor is most frequently determined in gravimeters without a feedback loop using vertical or horizontal calibration lines [17–19]. A general problem is the possibility of unknown temporal fluctuations of gravity at individual stations (e.g. due to changes in the groundwater level). In addition, internal sensor parameters such as drift or thermal drift can distort the difference in gravity between stations. This issue is relatively insignificant in the case of land gravimeters intended for fieldwork. It is a larger problem for gravimeters adapted to work in the set thermal conditions of the interior of the carrying platform (such as MGS-6). This is a fundamental dilemma in relative calibration procedures using calibration lines. Tilt measurements enable quick and easy determination of nonlinearity and cyclic errors by comparing the constant displacements of the test bolts with the corresponding angles at different positions. The calibration problem shifts to the determination of the calibration function, which can be described with a linear relation between relative gravity g and the angle of inclination.

The article presents the possibility of calibrating the sensor of a dynamic gravimeter using an optical bench with a controlled tilt along with a parallel photogrammetric registration of the tilt. In the second section, we briefly describe the measurement layout and all the test stand instruments used in the experiments and the measurements. The results for the calibration factor (and its uncertainty) using various correction procedures between the tiltmeter and photogrammetric readings are given in Section 3, and a sensitivity analysis is performed in Chapter 4. In conclusion, a comparison of the scale factors of the gravimeter determined in this way with the values assigned in the documentation is presented.

2. Materials and methods

Determining the scale factors and VCC of the gravimeter requires high standards for measuring and subsequent processing of the recorded signals. Relative gravimeters operate at the accuracy level of 10^{-8} m/s and record changes in their environment with high sensitivity [16,20]. The manufacturer shielded the sensor against interference, but very often, this protection does not work well, which has been confirmed by numerous laboratory tests [21,22]. Therefore, to achieve high measurement accuracy, efforts were made to eliminate the causes of disturbances. In principle, gravity is most sensitive to nearby mass changes. It is responsive to hydrogeological changes, which have a strong seasonal effect and may significantly affect the measurement of relative gravity [22,23]. To eliminate this effect, all measurements were made under the same hydrological conditions.

The location was selected to guarantee the best-quality gravity measurements. A site was chosen at a sufficient distance from artificial disruptive effects (e.g. large cities, railways, and highways) and mass changes such as dams, mines and rivers. The laboratory was located at a low altitude to avoid the scale factor and significant meteorological changes. During the measurements, the measuring station had constant temperature and humidity, which ensured protection against wind and sunlight and minimised changes in the drift. The identical orientation of the instrument minimised the influence of the magnetic field. A sufficiently long stabilisation time reduced the mechanical hysteresis of the sensor.

In Fig. 1, the three essential parts for the dynamic gravimeter sensor tilting procedure are presented. Fig. 1 *I* shows a platform designed for holding the sensor and providing an accurate and repatriable way of performing tilting. Fig. 1 *II* shows the boards used as a reference target for photogrammetric measurements. Fig. 1 *III* shows the computer screen with the dedicated Piper Pro app running to collect the data from the sensor. The construction presented in Fig. 1 *I* consist of the optical bench (1) supported by three submicrometric adjustment screws(2), allowing for precision setting up the tilt. The gravimeter sensor is connected with the optical bench by the custom-designed holder (3), allowing for stable montage in 4 positions (rotations by 90 degrees). Finally, the optical bench is connected with one of the reference target (4), which was called the 'B' reference target during analysis. The important factor which affects the final data quality is the placement of the reference targets, thus it was shown on Fig. 1 *II*. The raw results which are displayed on the computers screen (Fig. 1 *II*) represents typical readout during each tilting step.

The device designed for the tilting calibration of the dynamic gravimeter sensor (Fig. 1) and virtual testing of the scope of its work was patented in the Patent Office of the Republic of Poland [No. IWIPO ST 10/C PL43z667]. A physical measuring stand was built by: (1) setting the camera on a stable tripod; (2) illuminating the measuring boards with a diffused light of appropriate intensity and location such that there were no shadows on the measuring boards; and (3) mounting the measuring boards (chessboard bar) on the optical bench, which was centrally located in relation to the camera axis.

Two photogrammetric reference targets with 1200 dpi printing resolution were developed and made for the described measurements. The measuring boards were flat-surface and passive. In the nodes of the black and white chessboard, measurement points were marked on the boards. Due to the photogrammetric geometry, the aim was to photograph the reference targets in the maximum area of the recorded image. One background board was 1250 mm × 1800 mm, and the printed chessboard image contained 3600 black and white fields (25 mm × 25 mm). The second board is a 30 mm × 1000 mm strip, and the printed image of the chessboard contains 1200 black and white fields (5 mm × 5 mm).

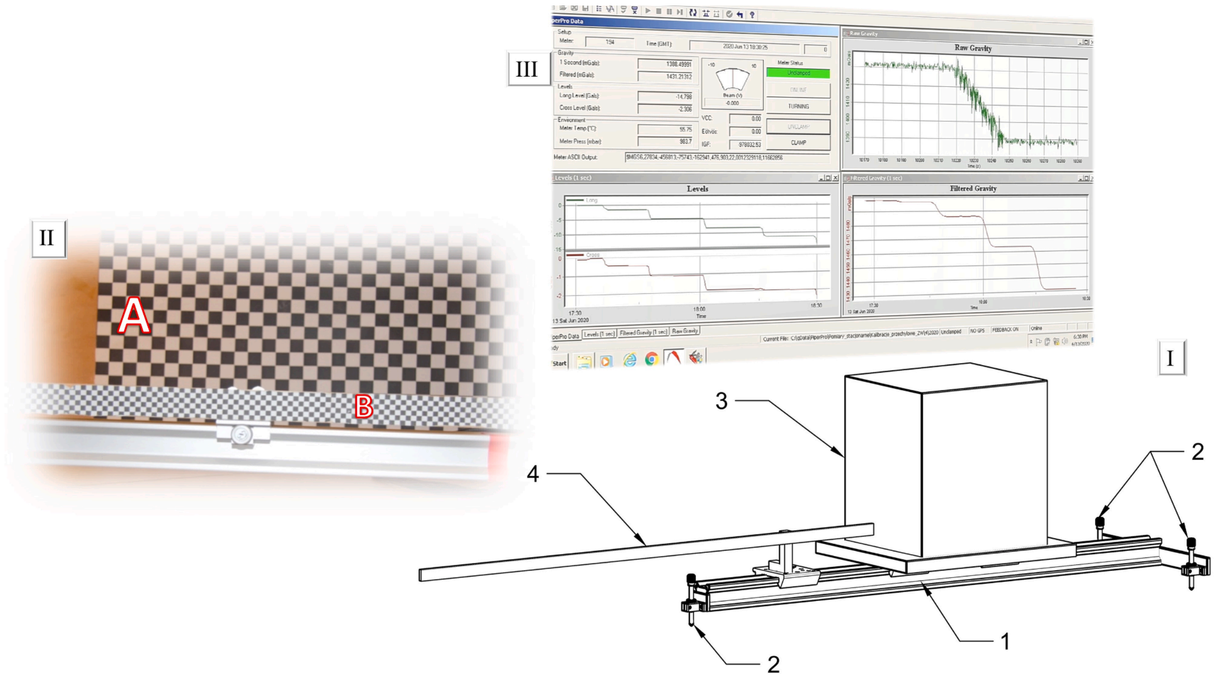

Fig. 1. The basic experimental setup used during calibration of the dynamic gravimeter sensor: I – a platform designed for tilting the sensor, consisting of (1- optical bench, 2 – submicrometric screws, 3- gravimeters sensor holder, 4- reference target mounted on the optical bench), II – the placement of the reference targets A and B, III – the computer printScreen showing the application controlling the MGS-6 system during data registration.

The board arrangement enables the identification of 1176 and 276 regularly arranged measurement points, respectively.

The location of the boards relative to each other is shown on the left side of Fig. 1 III.

The measurement phases consisted of adjusting a screw, which tilted the optical bench. The gravimeter sensor installed on the bench recorded the values of the gravitational acceleration, and the tiltmeters recorded the angles of tilt. After each change in angle, the bench was held in that position for a 15 min period to let the gravimeter stabilise. Compering the constant displacement of the measuring bolts with the corresponding angles at different gravimeter positions (Fig. 2) provided the data for determining the scale coefficients.

In order to determine the values of interest for the coefficients, let us consider how the gravimeter reading will change during the controlled tilt. This can be done by reversing the normal process of correcting the measurement. The value of the VCC effect is added to the value of gravity at the calibration point, and the decrease in the value of the projection of the gravitational force on the sensor axis is considered. In the first approximation, the VCC effect depends linearly on the product of the acceleration in the long direction and the deflection of the gravimeter arm [24]. The sensor has a global calibration constant C, which is also taken into account. For a fixed test stand and short time intervals, and after subtracting tidal effects, the gravity can be considered constant (within the accuracy of spring-based gravimeters). For this reason, it only appears as a parameter in Equation (1).

$$g_r(A_L, A_c, B) = \frac{1}{C}\left(\sqrt{g_o^2 - A_L^2 - A_C^2} - g_o + A_L B C_{VCC}\right) + g_{off} \tag{1}$$

where:

g_r- acceleration recorded by the gravimeter

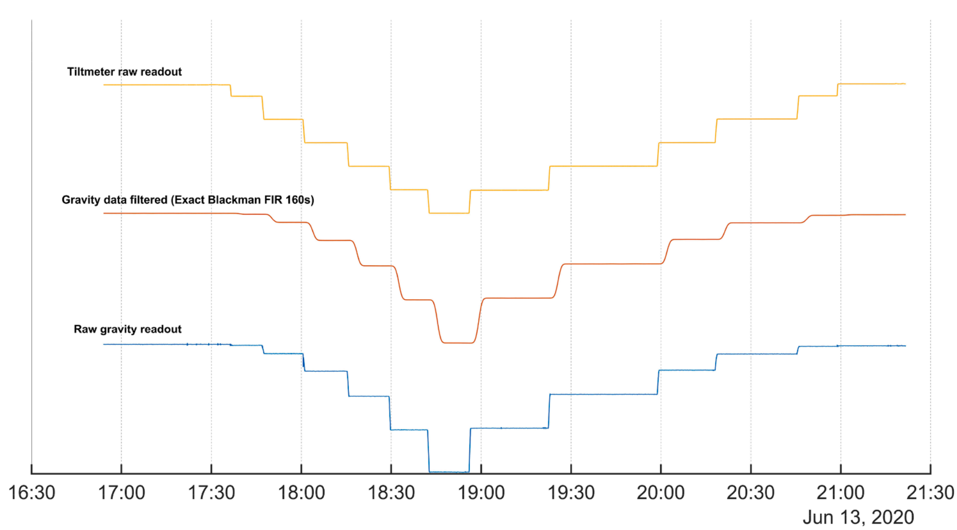

Fig. 2. The plot comparing records from the tiltmeter and gravimeter recoded during the tilting procedure.

A_L- acceleration in the direction of the long axis
A_C - acceleration in the direction of the cross axis
C - scale factor of the gravimeter
B - beam position
C_{VCC} - scale factor of the VCC effect
g_o - absolute gravitational acceleration at the measurement site
g_{off} - offset of the relative gravimeter

By approximating to first order, we can transform Equation (1) to Equation (2).

$$g_r(A_L, A_c, B) = \frac{1}{C}\left(A_L B C_{VCC} - \frac{A_L^2 + A_C^2}{2g_o}\right) + g_{off} \tag{2}$$

Consequently,

$$\lim_{A_L \to 0, A_c \to 0} g_r(A_L, A_c, B) = g_{off} \tag{3}$$

Under real conditions, A_L nor A_C are both unknown. However, we can assume that the response of the tiltmeters is linear. However, we can assume that the response of the tiltmeters is linear. It should be written explicitly that this assumption is not applied to the raw signal from the tiltmeter (the analogy signal generated by the electronic tiltmeter) but to the digital values returned by the device. These values are already pre-processed by the measuring systems provided by the manufacturer and (in the case of MGS-6) are displayed in Gal's of the horizontal acceleration. Thus, there was assumed that real horizontal acceleration is close to the value returned by the gravimetric system, and constants C_{AC} and C_{LC} are not equal to 1 only because of the imperfection of the measurement unit (they are playing the same role as the global scale factor in gravimeter). A similar solution was presented in [15].

In this case, the relationship between the horizontal accelerations and the readings from the tiltmeters is expressed in Equation (4).

$$\begin{cases} A_C = C_{AC}A_{CR} + O_{AC} \\ A_L = C_{AL}A_{LR} + O_{AL} \end{cases} \tag{4}$$

$$\begin{cases} -C_{AC}A_{CR} = O_{AC} \\ -C_{AL}A_{LR} = O_{AL} \end{cases} \text{for } A_c = 0, A_L = 0$$

where:

A_{CR}– acceleration recorded by the tiltmeter cross,
A_{LR}– acceleration recorded by the tiltmeter long,
C_{AC}– scale factor of the tiltmeter cross,
C_{AL}– scale factor of the tiltmeter long,
O_{AC}– the offset of the tiltmeter cross,
O_{AL}– offset of the tiltmeter long

The calibration coefficients can be derived from Equations (2) and (3), but first, we need to check the tiltmeter calibration. Due to the linear nature of Equation (4), this is conceptually straightforward. The tilt angle of the sensor should be measured regardless of the operation of the tiltmeters. The absolute value of the measured angle is not essential, but only the amount by which it has changed. Consequently, it is not necessary to align the zero of the photogrammetric system with the axis of the gravimeter sensor. To find the value of the potential offset of the tiltmeter, a well-known phenomenon occurring in relative gravimeters is used: the indication of gravity has a maximum when the sensor is perfectly levelled. As shown by Equations (2) and (3), the position of this point is independent of the sensor calibration constants, and therefore it can be used as a reference when calculating the values of the O_{AC} and O_{AL} of the tiltmeters. Given reliable acceleration values for both axes of the system, we can use the non-linear least-square method to adjust Equation (1) to the data collected during the calibration measurements and determine the parameters C, g_o, C_{VCC} and g_{off}.

In order to calibrate the tiltmeters, equipment for the photogrammetric measurement of the tilt was prepared. The apparatus was designed to carry out relative measurements. The components of the apparatus were appropriately positioned on the optical bench (chessboard bar) and in the background of the object (chessboard board). The essence of our method of photogrammetric measurements is the measurement of the tilt of the optical bench represented by the measuring board. The photogrammetric measurement is performed by collecting a sequence of images during the tilting of the optical bench with the reading of the gravimeter sensor recorded in successive time steps, as shown in Fig. 2.

This method of determining the angle of inclination of the optical bench was implemented based on the principles of single-image photogrammetry and is based on the point cloud analysis procedure, with additional conditions imposed during the measurement and computation process. This method of developing photogrammetric data is described, among others, by [2526]. In our measurements, a calibrated camera was used to record the position of the measuring board relative to the background board. Based on photogrammetric analysis of the photographs, we determined the point clouds in the local coordinate systems of individual measurement targets: the reference target (A) and the target (B). In order to increase the accuracy of the measurement, the condition that the measurement points are located on a single plane (the condition of co-planar measurement points [27]) is used in the calculation procedure. In the second computational stage, using the known mathematical formulas [28,29] and the results from the first stage, the cloud of target points is broken down into a set of straight lines intersecting the points forming the lines of the measurement targets (A) and (B). On this basis, the angle of rotation of board (B) relative to board (A) is determined for each photo. The origin of the Cartesian coordinate system of the measuring board A is in the upper left corner of the "chessboard" grid, the x-axis points downwards (along the grid columns), and the y-axis points to the right (along the grid rows).

Despite the actions taken, there may be slight constant biases between the series, for example, a bias due to the clamping of the sensor during its configuration on the tilting bench. In order to remove this possibility, the data were subjected to an additional pre-processing stage. Each data series was pre-fitted with Equation (2) using a non-linear least-squares method to determine the g_{off} parameter that was subtracted from the data series before combining them.

In order not to unbalance the statistics with a large number of measurement points recorded for small tilt values (i.e. when the sensor is levelled), only the data from the range between the beginning of the first and the end of the last tilt with an interval equal to the longest time step for which the sensor was withheld from tilt to either side was analysed.

3. Results

The gravimetric reaction to deviations from the vertical sensor was analysed, focusing on the correction of the gravimeter signal reading. Such a procedure provides data on the behaviour of the spring-based gravimeter, allowing for the identification and correction of disturbances. Notably, it is a crucial issue in the geodetic use of the acquired data [30,31]. The platform's tiltmeters are part of a feedback loop that keeps the platform close to vertical during the survey. However, the tiltmeter output is also recorded for use in calculating the tilt corrections. We aim to define the scale factors in order to translate them into acceleration units. The results from platform tiltmeters can theoretically be calculated from the horizontal kinematic accelerations to which the platform has been subjected [32].

Using the linear tiltmeter model (Equation (4)) and the data collected during the photogrammetric recordings, the tiltmeter cross and long scale factors and their offsets were calculated. The analysis began by examining the dependence of the tilt indicated by the tiltmeter and measured with the photogrammetric method. The horizontal acceleration recorded by the tiltmeters was converted into an angle with the assumption that it is a projection of the actual acceleration of the gravitational force onto the direction perpendicular to the axis of the instrument. The normal acceleration at the measuring point was assumed as the acceleration of the gravity force. Using the principles of error transfer, it can be shown that the influence of gravity disturbances in the vicinity of the measurement site is negligible at such slight tilt angles.

The angle calculated by the photogrammetric method is the angle of the intersection of the series of straight lines defined by the points of reference target A with the analogous lines of reference target B. The given value of the angle is the average value for all straight lines. The errors calculated as the standard deviation of the mean angle between the lines in reference target A and B do not exceed $\pm$ 48″ for the long tilt and $\pm$ 32″ for the cross tilt. As expected, linear relationships were obtained, as shown in Fig. 3. The linear proportionality coefficient of these parameters was estimated using the least-squares method. Assuming the form of a linear fit equation, f (x) = a $\cdot$ x + b, the parameter a corresponds to the constants C_{AC} and C_{AL} from Equation (4). The above analysis allowed us to determine the values of $C_{AC} = 1.14$ and $C_{AL} = 1.018$. The coefficients b of such an adjustment are not easily interpreted because they depend on the angle between the zero of the tiltmeter and the direction determined by Table A, which was not defined as being of fundamental importance in this experiment.

Therefore, further analysis was performed to determine the tiltmeter offset. This analysis made use of the fact that the value of the gravitational force indicated by the relative gravimeter will be highest when the axis of the instrument coincides with the direction of the force of gravity. In this case, the exceptional cases of Equation (3) and Equation (4) can be used, which express the relationship mentioned above numerically. The problem of determining these offsets comes down to selecting the relative coordinates of the maximum g in the 2-dimensional indication space of the long and cross tiltmeters. Data collected during all the instrumental tilting sessions performed during the experiment were used to determine this point. The raw gravimetric data was filtered with an exact Blackman window with a length of 120 s. For the data from the individual series of experiments to be comparable, the drift was removed from each data series using the Chebyshev polynomial of degree 5. In addition, the residual effect of solid-earth tides was also subtracted. Tidal values were calculated using Tsoft software [33].

From the data prepared in this way, the area for $A_{CR} < 2Gal$ and $A_{CL} < 2Gal$, was selected, and a parabolic surface was fitted to the points in this range, with the coordinates (g_r, A_{CR}, A_{CL}). According to Equation (4), the coordinates of the maximum of such a function were taken as the desired offsets, O_{AC} and O_{AL}.

After calibrating the tiltmeters, the remaining parameters of the sensor were determined. The data series (filtered, corrected for drift and offset, and corrected with the values of the tiltmeter inclinations) were divided into measurement points. The measurement point was found by averaging the tiltmeter indications, the beam position and the measured gravity from 240 s after the tilt change and to 240 s before following tilt change. This procedure allowed the exclusion of filtration artefacts. The prepared data was matched to the surface defined by Equation (2) using the non-linear least-squares method [34]. The results are shown graphically in Fig. 3.

The obtained values of the gravimeter coefficients are C = 1.0454, $C_{VCC} = 0.2348$ 1/V, $g_{off} = 0.05$ mGal, and $g_0 = 981399.99$ mGal. The value of the calibration constant of the gravimeter calculated using measurements on the calibration line was 1.04538 $\pm$ 0.003. An independent LaCoste team performed this measurement, and the results were provided in the documentation for the gravimeter.

The tilt of the gravimeter in the cross and long directions changes over time. The course of changes of both components does not show any

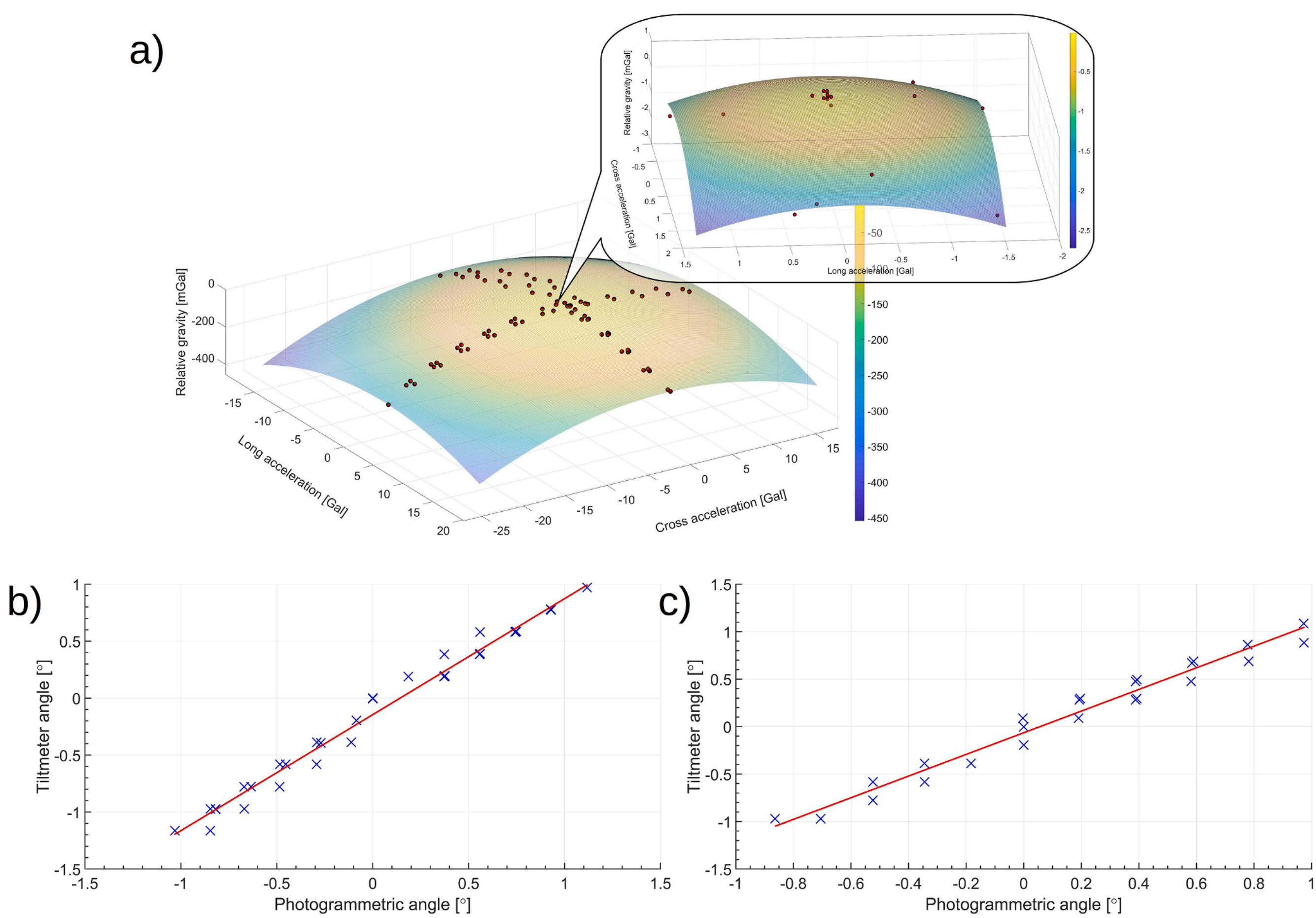

Fig. 3. The results of tiltmeters calibration: a) The parabolic surface fitted to the data in order to find where its maximum is located, the 2 Gal zone around maximum is magnified b) the calibration of the scale factor of long tiltmeter c) the calibration of the scale factor of cross tiltmeter.

significant tendency. Therefore, it is essential to confirm that the changes are not due to measurement errors or undetected gravity variations. Under the condition that the scale factor function remains constant over time, the measurements may also be used to determine the scale factor VCC. This applies to the non-linear component in particular, while the determination of the linear component can be systematically influenced by the inelastic behaviour of the spring. Fig. 4 shows the results obtained when testing different bolt positions. The data fit well with the trend of the calibration results of the scale factors, VCC effect, tiltmeter cross, tiltmeter long and gravimeter scale factor, obtained over the whole series. Using the complete measuring cycle, it is possible to check the external indications of the tiltmeters. These indications can be used to calibrate the gravimeter scale factors and the VCC effect.

In order to validate the achieved fitting, the residual analysis was conducted. For each measurement point, the residual value was calculated. The residual value is understood as a measured value minus the value computed from the model. The histogram of the residuals is presented in Fig. 4b. The qualitative analysis of this histogram shows that residuals are clustered in in the range of [-0.2,0.2]mGal, and their numbers are almost symmetrical, falling to zero for values 0.8 mGal. This suggests that there is no significant bias in the model and the achieved fitting is proper since the MGS-6 is incapable of measuring signals with amplitude lower than 0.05 mGal. To quantitatively prove that the residuals form the realisation of the random process, the chi2 test was applied. The results show that we can treat the fitting residuals as a realisation of a random process with a 0.05 level of confidence.

To maintain consistency with the results of the nonlinearity test, the data obtained on the laboratory test bench should be used. In this way, the significance of the temporal irregularities of the scale factors can be determined. The impact of gravimeter calibration on the readout is most clear in the case of the global scale factor. In the presented case, the global scale factor was 1.0454, so by omitting it and treating it as 1 the relative bias of the measurements is nearly 5%. In other words, the 20 mGal anomaly will be biased by 1 mGal what is an unacceptable high difference in modern marine surveys. Hoverer, the scale factor for the MGS-6 system in the experiment, proved to be quite stable since it didn't change more than 0.003 from the last estimation 3 years ago. Although, without a doubt, a good practice is to check its value and prove that results collected by the device during the campaign will not be biased.

The impact of error from the VCC factor is not so straightforward. The simplest model for VCC effect, recommended by the user manual of MGS-6 m, assumes that this effect is proportional to the product of beam position and Long acceleration. The factor describing this proportion is the VCC effect coefficient, as was written in Equations (1) and (2). In this experiment, the factor was estimated to be 0.2348. Taking this coefficient as 1 leads to an overestimation of the effect nearly 4 times. However, the impact on gravity also depends on the mentioned product of beam position and Long acceleration. Unfortunately, this value is highly dependant on the environmental conditions under which the data was collected. The reliable data about the beam position and Long acceleration during different gravimetric campaignings are not publicly available, so the authors have to base our experience. Our Baltic sea

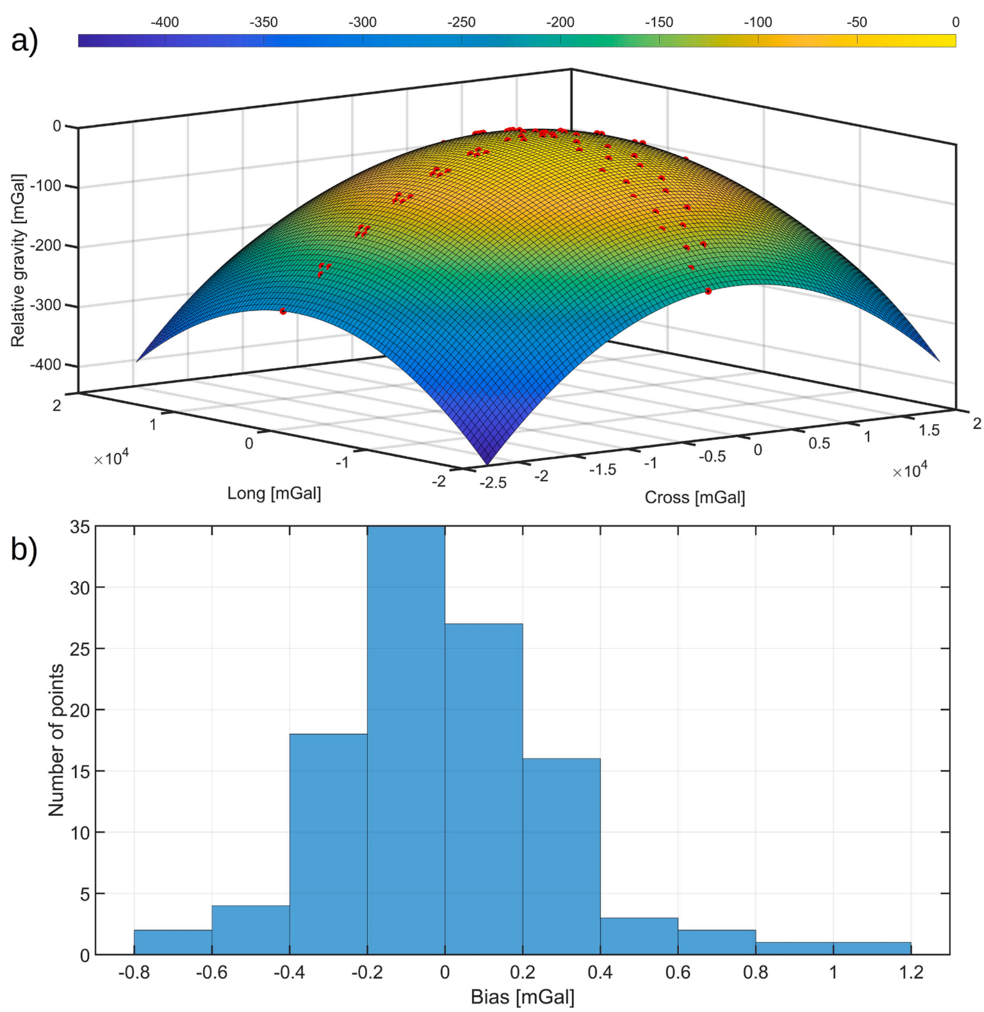

Fig. 4. a) The results of fitting of the model (equation (2)) to the experimental data, after correcting the tiltmeter readout, generated using non-linear least-square method b) The histogram of residuals after model fitting.

campaignings were conducted mainly at favourable conditions: smooth wavelets (2 Douglas scale) and weak wind (3 Beaufort). On our noisiest measurement line, the median value of beam position and Long acceleration product was approximately equal to 4. Roughly estimating this coefficient by 1 we expect to introduce the bias as high as 3.1 mGal. In such a case, omitting the VCC effect, so treating VCC coefficient as equal zero will introduce the error of 0.9 mGal, which is still significant. This clearly shows that this coefficient cannot be neglected during measurements under actual marine conditions to achieve a sub mGal accuracy. These results mean that it is necessary to control the calibration coefficients periodically. They may be controlled by the use of other spring-based gravimeters [9]. Additional measurements are required immediately before and after highly accurate gravimetric measurements.

4. Conclusions

In summary, precision relative gravity measurements for geodetic purposes should consider both environmental factors such as the local terrain conditions and instrumental factors such as the uncertainty of drift and calibration parameters. Our research focused on the estimation of the calibration factors. If the sensor used for data collection is poorly or incompletely calibrated, the errors caused by small tilt can exceed a few mGal, making precise and complete gravimeter calibration essential [35].

Measurements presented in this article were collected to calculate two essential scale factors of marine beam-type gravimeters: global scale factors and the VCC effect scale factor. The applied method requires that both gravimeters have calibrated tiltmeters. For that purpose, we developed the photogrammetric estimation method for the tilt angle of the optical bench and tested it in laboratory conditions. The optical bench was used for controlled tilting of the sensor during measurements. After completing the photogrammetric data analysis, the statistical measurement uncertainty was estimated as $\pm$ 48″ for the long axis and $\pm$ 32″ for the cross axis.

Our results show that the suggested calibration routines should be conducted before each campaign, especially if it is planned to last for a long time (many days spent continuously at sea, without pier binding) or be conducted in challenging weather conditions. During the study, we found that updating the values of the gravimeter global scale factor, VCC effect constant, and the scale factor of the cross or long tiltmeters is possible for beam-type gravimeters with the addition of a tilting optical bench. Such calibration allows the significant increase of the accuracy of the gravimetric signal after data processing since the instability of the scale factors is eliminated. However, each constant is specific to each instrument and cannot be generalised to different sensors of the same type. Each manufactured relative gravimeter is characterised by its unique calibration factors, which can evolve during the exploitation time.

From all the known calibration methods, tilt calibration has the advantage of being non-invasive and easy to automate. The measuring stand with a tilting measuring photogrammetric setup presented here is simple enough to be reproduced by every survey team. Despite its simplicity, the setup allows for measurements of the gravimeter global scale factor with a relative error lower than 0.15%. Based on the residual analysis, the error for the VCC scale coefficient is 0.06. The coefficients calculated using our method have uncertainties low enough to be used during geodetic calculations.

CRediT authorship contribution statement

Krzysztof Pyrchla: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Małgorzata Pająk:** Formal analysis, Investigation, Methodology, Project administration. **Julia Gołyga:** Formal analysis, Investigation. **Jerzy Pyrchla:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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