Quality Assessment of the New Gravity Control in Poland: First Estimate

P. Dykowski and J. Krynski

Abstract

The new gravity control in Poland is based on absolute gravity measurements. It consists of 28 fundamental stations and 168 base stations. Fundamental stations are located in laboratories; they are to be surveyed in 2014 with the FG5-230 gravimeter. Base stations are monumented field stations; they were surveyed in 2012 and 2013 with the A10-020 gravimeter. The part of the new gravity control consisting of base stations is the subject of the quality assessment.

Besides absolute gravity measurements the vertical gravity gradient was determined at all 168 base stations. Nearly 350 single absolute gravity measurement setups and vertical gravity gradient determinations performed provide valuable and comprehensive material to evaluate the quality of the established gravity control. Alongside the establishment of the base stations of the gravity control, multiple additional activities were performed to assure and provide a reliable gravity reference level. These activities concerned regular gravity measurements on monthly basis with the A10-020 on the test network at Borowa Gora Geodetic–Geophysical Observatory, calibrations of metrological parameters of the A10-020 gravimeter and scale factor calibrations of LCR gravimeters, participation with the A10-020 in the international (ECAG2011, ICAG2013) and regional comparison campaigns of absolute gravimeters.

Careful analysis of the data gathered throughout the project resulted in the estimation of the Total Uncertainty budget for the A10-020 gravimeter on each of 168 base stations. It provides a reliable quality assessment of the new gravity control in Poland.

Keywords

A10 absolute gravimeter • Gravity control • Uncertainty

1 Introduction

The technical project for the modernization of gravity control in Poland was developed at the end of 2011 (Krynski et al. 2013). The new gravity control in Poland (PBOG14) is based in principle on absolute gravity measurements. The PBOG14 consists of 28 fundamental stations located in laboratories and 168 base stations (1 in 1,850 km^2) which are monumented field stations. Fundamental stations are to be surveyed in 2014 with the FG5-230 of the Warsaw University of Technology. Base stations were surveyed in 2012 and 2013 with the A10-020 absolute gravimeter of the Institute of Geodesy and Cartography (IGiK), Warsaw. They consist of 57 ASG-EUPOS (active GNSS network) eccentric stations, 78 POGK98 (previous gravity control) stations, 4 EUVN (European Vertical Reference Network) stations, 22 POLREF (densification of European Reference Network) stations, and 7 new stations (Fig. 1).

P. Dykowski (✉) • J. Krynski
Institute of Geodesy and Cartography, 27 Modzelewskiego St, 02-679 Warsaw, Poland
e-mail: przemyslaw.dykowski@igik.edu.pl

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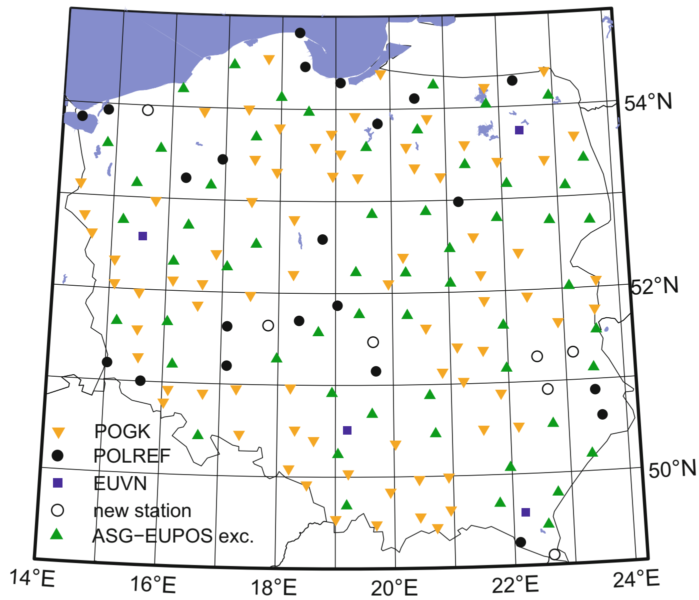

Fig. 1 PBOG14 stations

Surveys at the base stations (absolute gravity and vertical gravity gradient) were carried out from July 2012 till December 2013. Absolute gravity was determined with the A10-020 in six campaigns. Also in six campaigns vertical gravity gradient with LaCoste&Romberg (LCR) gravimeters was determined. Each campaign lasted no longer than 2 weeks. The acquired data has been processed by April 2014 and the performance of the A10-020 gravimeter has initially been analyzed.

The results of numerous test measurements with the A10-020 absolute gravimeter in laboratory as well as in various field conditions conducted since 2008 on the test network at Borowa Gora Geodetic–Geophysical Observatory (Krynski and Sekowski 2010; Sekowski and Krynski 2010; Dykowski et al. 2012) were fundamental for the specification of the project objectives as well as the measurement methodology. Important role played also the results from the survey of the Finnish First Order Gravity Control in 2009–2010 (Mäkinen et al. 2010) and tests with a group of LCR gravimeters equipped with modern feedback systems (Dykowski 2012). All the activities described above before and during the project including calibrations and absolute gravity comparison campaigns were to provide the most reliable gravimetric level yet in Poland.

Although the A10 absolute gravimeters are widely used for more than a decade, no study on the Total Uncertainty (T.U.) budget estimation for any A10 gravimeter was reported and published. Total Uncertainty budget estimated for A10 gravimeters when processing data from ICAG (International Comparison of Absolute Gravimeters) and ECAG (European Comparison of Absolute Gravimeters) absolute gravity comparison campaigns was incomplete; moreover it was in most cases based on the Micro-g LaCoste Inc. provided values. For the first time an experimental T.U. value was presented for the A10-020 gravimeter for ICAG2013. It was based on the results of a previous research (Dykowski et al. 2013). The material collected during the project on the modernization of gravity control in Poland is a unique source of information on the performance of the A10-020 gravimeter. It makes possible to provide a complete and reliable estimation of T.U. budget.

2 Supplementary Activities During the Establishment of PBOG14

The basic activities during the establishment of the new gravity control concerned absolute gravity determinations with the A10-020 gravimeter, and vertical gravity gradient measurements with the LCR gravimeters needed for reducing the measured gravity values to a benchmark level. Multiple additional activities were carried out throughout the project to ensure accuracy and reliability of the determined gravity values. They concerned calibrations of the laser and frequency standards of the A10-020 gravimeter, calibrations of the LCR gravimeters used, regular repeatable measurements with the A10-020 at Borowa Gora Observatory, and the most crucial for the gravity reference level estimation: the participation in international, regional and local comparison campaigns of absolute gravimeters.

2.1 Calibrations of the A10-020 Laser and Frequency Standards

The calibrations of the components of the A10-020 gravimeter were planned to cover all absolute gravity surveys to be conducted within the project, i.e. those on PBOG14 stations,

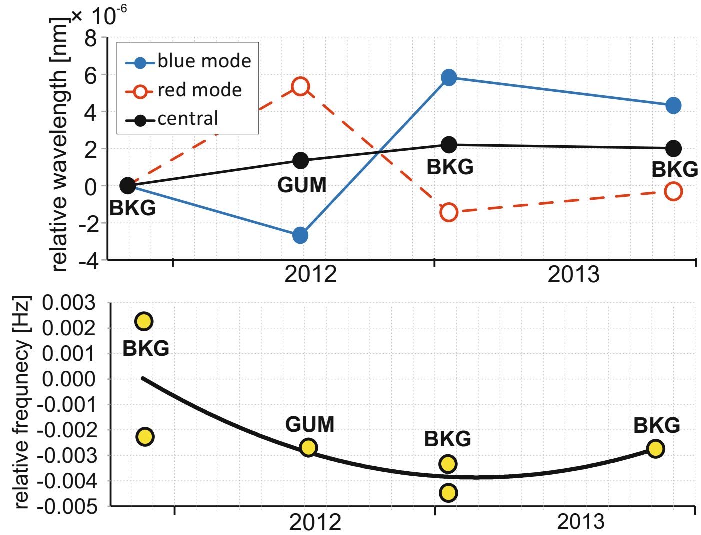

Fig. 2 Laser (*top*) and frequency standard (*bottom*) calibration data throughout the establishment of PBOG14

those during AG comparison campaigns, and those during regular A10 gravimeter surveys at Borowa Gora Observatory.

The ML-1 laser of the A10-020 gravimeter was calibrated four times during the course of the measurement part of the project: three times at the Bundesamt für Kartographie und Geodäsie (BKG) which is in close cooperation with IGiK in terms of absolute gravity determinations, and once at the Central Office of Measures (GUM) – Polish metrological institute. The results of laser calibrations are shown in Fig. 2 (top) with distinction to the red, blue mode and the central frequency. The central frequency of the laser drifted slightly in the course of the project, resulting in ~3.3 µGal change in the observed gravity value. This value was considered significant enough to be included into the calculations of gravity values determined with the A10-020. Laser wavelengths were linearly interpolated between consecutive calibration data for each day of absolute gravity surveys.

The frequency standard of the A10-020 gravimeter was also calibrated four times: three times at BGK and once at GUM (Fig. 2 – bottom). The total frequency variation in the course of the project results in less than 0.005 Hz (~1.0 µGal in terms of gravity variation). For the calculation of gravity determinations with the A10-020 these calibration data were interpolated with second degree polynomial for each day of absolute gravity surveys.

2.2 Calibrations of LCR Gravimeters

Three LCR gravimeters with modern feedback systems were used for the vertical gravity gradient determinations on all PBOG14 stations. They were calibrated twice on the Central Gravimetric Calibration Baseline in Poland, i.e. in June 2012 and July 2013. Each calibration was performed on at least three spans of the baseline of minimum 30 mGal gravity difference. As the vertical gravity gradient determination requires a measurement range of no more than 400 µGal the scale factor was determined with far greater accuracy than needed. The effect of LCR calibration on the vertical gravity gradient determined was found negligible.

2.3 Regular Absolute Gravity Measurements with the A10-020 at Borowa Gora Observatory

In the course of the project, gravity was regularly determined with the A10-020 on monthly basis on three stations at Borowa Gora Geodetic-Geophysical Observatory: two laboratory stations A-BG and BG-G2, and the field station, 156. The measurements were performed with the same methodology as on PBOG14 stations. The results obtained were used for quality assessment of the A10-020 absolute gravimeter performance during the project. Figure 3 presents the results of each single setup of absolute determinations of gravity on the laboratory station A-BG and the field station 156. The standard deviation of the determined gravity on the field station equals 5.1 µGal. The value was used as the representative "system model" uncertainty of the A10-020 in field conditions for the T.U. estimates on PBOG14 stations. This value was further used as "System Model" uncertainty instead of 10 µGal suggested by the manufacturer (Micro-g Inc. 2008). The scattering shows also the variability of the determined gravity at a station when no correction due to local hydrology is applied. Statistics of the results on the test network are presented in Table 1.

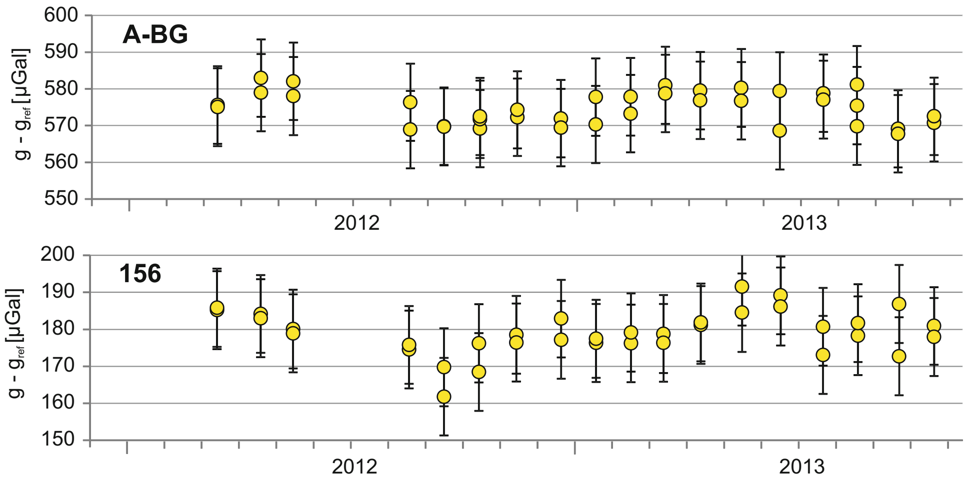

Fig. 3 Results of gravity survey with the A10-020 at Borowa Gora Observatory test network; $g_{\text{ref}} = 981{,}250{,}000\ \mu$Gal

Table 1 Statistics of absolute gravity determinations with the A10-020 at Borowa Gora Observatory test network ($g_{\text{ref}} = 981{,}250{,}000\ \mu$Gal) ($\mu$Gal)

Station	$g-g_{\text{ref}}$	Std dev.	Max–Min
A-BG	574.8	3.7	12.1
BG-G2	439.8	5.9	19.8
156	179.0	5.1	22.1

2.4 Absolute Gravimeter Comparison Campaigns

An essential part of the establishment of the gravity control concerned the participation of the A10-020 gravimeter in local, regional and international absolute gravimeter comparison campaigns. All comparisons were planned in a way that would allow repeated control of the gravity reference level provided with the A10-020 for the project of the modernization of the gravity control. The A10-020 participated in one regional AG comparison at Wettzell Observatory in January 2013 organized by BKG. Besides A10-020 four FG5 gravimeters participated in the comparison. The resulting offset for the A10-020 was determined as −7.0 µGal. The A10-020 also participated in ECAG2011 (Francis et al. 2013) and ICAG2013, both carried out in Walferdange, Luxemburg, in November 2011, and 2013, respectively. The observed offsets were −5.8 µGal (ECAG2011) and −4.7 µGal (ICAG2013). For the establishment of the gravity reference level for the PBOG14 a single offset value was calculated, based on international comparison campaigns as a weighted average with the weights proportional to the number of AG participating in the comparison campaign. The value used is −5.0 µGal with the standard deviation of 1.1 µGal.

The A10-020 also participated in two local comparison campaigns with the FG5-230 of Warsaw University of Technology. The campaigns were carried out at the gravimetric laboratory at Borowa Gora Observatory in December 2012 and May 2013 giving offsets for the A10-020 of +9.6 and +7.0 µGal, respectively. In the ECAG2011 the FG5-230 had an unusual offset of −11.9 µGal and the A10-020 had a −5.8 µGal offset (Francis et al. 2013), therefore the local campaign results are consistent within a few µGal. Yet as the FG5-230 did not participate in ICAG2013 and because of the unusual offset during ECAG2011 it was decided not to include these comparisons in the final gravity control data processing.

3 Vertical Gravity Gradient Determinations with LCR Gravimeters

Test measurements with LCR gravimeters conducted in the framework of the independent project in May 2012 (Dykowski et al. 2012) were used to check the methodology for the determination of vertical gravity gradient specified in the technical project. For nearly 330 measurements (2 on each station) performed on all PBOG14 stations the estimated measurement error for a single survey (Fig. 4a) was below 10.0 µGal (assumed in the technical project) with the average of 4.0 µGal and the standard deviation of 2.1 µGal. It was calculated as a standard deviation of LCR readings on repeated measurement levels. The difference between gravity reductions to a benchmark level from two independent vertical gravity gradient determinations (Fig. 4b) were smaller than 10.0 µGal (assumed in the technical project) with the average of 4.3 µGal. Reductions of the gravity to a benchmark level were calculated using a second degree polynomial approximation at the measurement height. Vertical gravity gradient values determined on PBOG14 stations using linear approximation vary from −3.68 to −2.75 µGal/cm with the average of −3.09 µGal/cm.

The uncertainty of the determined vertical gravity gradient at the station was estimated as the half of the difference

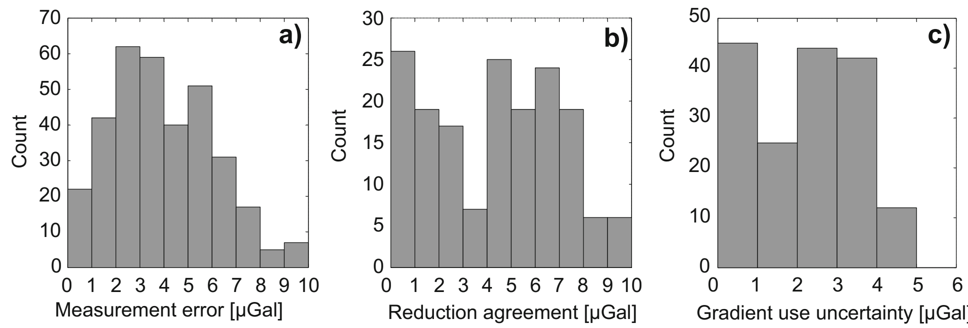

Fig. 4 Histograms of vertical gravity gradient determinations: (**a**) measurement errors, (**b**) reduction agreement, (**c**) vertical gravity gradient uncertainty

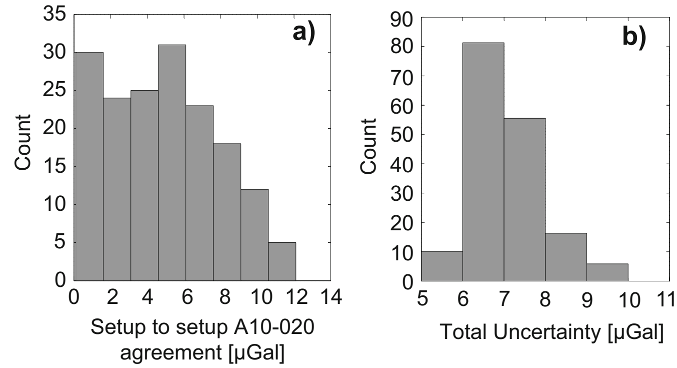

Fig. 5 Histograms of absolute gravity determinations: (**a**) setup to setup agreement on PBOG14 stations, (**b**) Total Uncertainty values on PBOG14 stations

between two reductions of gravity from the level of determination with the A10-020 to a benchmark level with the use of a second-degree polynomial. Values of the estimated uncertainty are presented in Fig. 4. They are all smaller than 5.0 µGal (Fig. 4c) and their average is 2.2 µGal (Fig. 4c).

4 Absolute Gravity Measurements with the A10-020

At least two independent setups of the A10-020 absolute gravimeter were performed at each PBOG14 station accordingly to the measurement methodology applied (Krynski et al. 2013). A total number of nearly 350 single setups were performed on 168 PBOG14 stations. Setup to setup agreement at PBOG14 stations is presented in Fig. 5a. Its values vary from 0.2 to 12.0 µGal with the average of 5.0 and 3.0 µGal standard deviation. On five stations the setup to setup agreement exceeded 10 µGal (assumed as a limit in the technical project) yet these station were accepted as correct as their T.U. values were good.

5 Total Uncertainty Budget Estimation

A crucial part of the project concerned a reliable estimation of the A10-020 Total Uncertainty budget for a complete evaluation of the quality of PBOG14 gravity control. Total Uncertainty has been expressed by three main terms: σ_{stat} – statistical uncertainty (function of set scatter), σ_{sys} – measurement system uncertainty, and σ_{model} – correction/reduction models uncertainty.

$$\text{T.U.} = \sqrt{\sigma_{stat}^2 + \sigma_{sys}^2 + \sigma_{model}^2}$$

The values of those terms and their components used for the estimation of the T.U. budget for gravity determination with the A10-020 on PBOG14 stations are presented below. All the values used were estimated based either on the absolute gravity measurements and gravity gradient determinations or on supplementary activities carried out during the project. For example, calibrations became a valuable source of information used for the estimation of the components of the T.U. budget for the A10-020 gravimeter allowing studies on its long and short term stability. At the same time, introducing the results of calibrations reduced the uncertainty estimates for the laser wavelength and frequency of the clock. For the laser the uncertainty was estimated as single calibration uncertainty as the laser frequency values for each measurement were calculated from linear interpolation. For the rubidium clock the uncertainty was calculated from the residual fit of a second degree polynomial to the calibration data. The values contributing to the T.U. estimate are as follows:

- σ_{stat} – statistical uncertainty (function of set scatter) (sr);
- σ_{sys} – measurement system uncertainty;
  - setup (0.1–6.0 µGal – half of setup-to-setup agreement) (sr);
  - system model (5.1 µGal based on Borowa Gora outdoor station results) (ss);

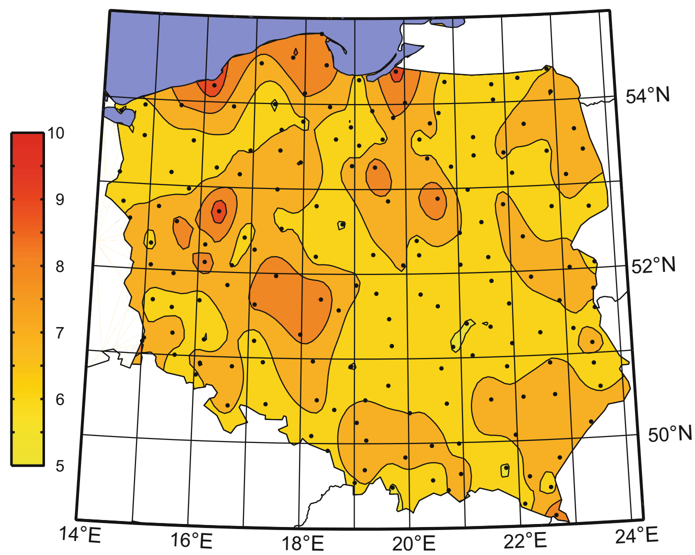

Fig. 6 Distribution of the total uncertainty of the A10-020 from T.U. values on 168 PBOG14 stations (μGal)

- laser wavelength (0.7 μGal) and rubidium frequency (0.2 μGal) (ss);
- Self Attraction Correction (SAC) (0.3 μGal) (ss) – Jiang et al. (2012);
- Diffraction Correction (DC) (0.6 μGal) (ss) – Jiang et al. (2012);
- std dev. of A10-020 offset determination (1.1 μGal) (ss);

• σ_{model} – correction/reduction models uncertainty;
- gradient use (0.0–5.0 μGal) (sr);
- tide and ocean loading (1.5 μGal) – Dykowski and Sekowski (2014) (ss);
- polar motion (0.05 μGal) (ss);
- barometric (1.0 μGal) (ss).

The presented uncertainties can be assigned into two groups: systematic ones (marked as "ss") and site related (marked as "sr"). Systematic uncertainties in total give a value of 5.5 μGal and the site related uncertainties vary from 1.6 to 8.4 μGal. For each PBOG14 station T.U. had been estimated based on the root of the sum of the squared values listed above. Values of T.U. estimated for the PBOG14 stations range from 5.7 to 10.0 μGal with the average of 7.1 μGal and a standard deviation of 0.8 μGal. The histogram of T.U values is presented in Fig. 5b. Distribution of estimated T.U. values on PBOG14 stations is presented in Fig. 6. Considering that T.U. values should not exceed 10 μGal (assumed in the technical project) the T.U. values estimated for PBOG14 stations prove to be satisfying as they were larger than 10 μGal only on four stations. At almost 85% PBOG14 stations T.U. values do not exceed 8 μGal. Reliable evaluation of the T.U. for the A10-020 gravimeter is an indication of good quality of the newly established gravity control in Poland. The correctness of the T.U. estimation was visible during the ICAG2013 campaign; even though it was almost twice smaller than the uncertainty specified by the manufacturer, it proved to be slightly larger than the offset estimated during the campaign. A more detailed study on the T.U. value for the A10-020 can be found in Dykowski et al. (2013).

6 Conclusions

Supplementary activities performed during the establishment of the modernized gravity control in Poland (PBOG14), i.e. calibrations of the laser and frequency standard of the A10-020 gravimeter, calibrations of the LCR gravimeters used, repeatable measurements with the A10-020 on the test network, and participation in comparison campaigns of absolute gravimeters were essential for ensuring the proper quality of its gravity reference level. Good stability of the components of the A10-020 gravimeter (laser wavelengths, clock frequency) during the project was confirmed, showing, however, a need to perform calibrations on regular basis. Regularly repeated gravity measurements with the A10-020 gravimeter carried on the test network at Borowa Gora Observatory confirmed the stable performance of the A10-020 throughout the realization of the project proving the A10-020 as a trustworthy tool to establish and maintain the gravimetric reference level. The participation of the A10-020 in absolute gravimeter comparison campaigns provided a correction to the established gravimetric reference level of +5.0 μGal for PBOG14 stations. The final stage of the PBOG14 evaluation was the T.U. estimation for each of the absolute gravity station. T.U. of the A10-020 gravimeter estimated during the project is smaller by 20–30% than the one based on the suggestions of the manufacturer. It proofs potentiality of the A10 gravimeter to provide high accuracy gravity determinations in field conditions. A thorough and complete evaluation of the T.U. budget proved that the quality of the PBOG14 established is as good as planned in the technical project.

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References

Dykowski P (2012) Vertical gravity gradient determination for the needs of contemporary absolute gravity measurements – first results. Rep Geod 92(1):23–35

Dykowski P, Sekowski M, Krynski J (2012) Testing the suitability of the A10-020 absolute gravimeter for the establshment of new gravity control in Poland, IAG Symposia, vol 140. Springer

Dykowski P, Krynski J, Sekowski M (2013) Approach to the A10 gravimeter total uncertainty budget estimation, IAG Symposia, vol 143. Springer

Dykowski P, Sekowski M (2014) Tidal investigations at Borowa Gora Geodetic-Geophysical Observatory, EGU General Assembly 2014, held 27 April – 2 May, 2014 in Vienna, Austria

Francis O, Baumann H, Volarik T, Rothleitner C, Klein G, Seil M, Dando N, Tracey R, Ullrich C, Castelein S, Hua H, Kang W, Chongyang S, Songbo X, Hongbo T, Zhengyuan L, Pálinkás V, Kostelecký J, Mäkinen J, Näränen J, Merlet S, Farah T, Guerlin C, Pereira Dos Santos F, Le Moigne N, Champollion C, Deville S, Timmen L, Falk R, Wilmes H, Iacovone D, Baccaro F, Germak A, Biolcati E, Krynski J, Sekowski M, Olszak T, Pachuta A, Agren J, Engfeldt A, Reudink R, Inacio P, McLaughlin D, Shannon G, Eckl M, Wilkins T, van Westrum D, Billson R (2013) The European comparison of absolute gravimeters 2011 (ECAG-2011) in Walferdange, Luxembourg: results and recommendations. Metrologia 50:257–268. doi:10.1088/0026-1394/50/3/257

Jiang Z, Pálinkáš V, Arias FE, Liard J, Merlet S, Wilmes H, Vitushkin L, Robertsson L, Tisserand L, Pereira Dos Santos F, Bodart Q, Falk R, Baumann H, Mizushima S, Mäkinen J, Bilker-Koivula M, Lee C, Choi IM, Karaboce B, Ji W, Wu Q, Ruess D, Ullrich C, Kostelecký J, Schmerge D, Eckl M, Timmen L, Le Moigne N, Bayer R, Olszak T, Ågren J, Del Negro C, Greco F, Diament M, Deroussi S, Bonvalot S, Krynski J, Sekowski M, Hu H, Wang LJ, Svitlov S, Germak A, Francis O, Becker M, Inglis D, Robinson I, (2012) The 8th International Comparison of Absolute Gravimeters 2009: the first Key Comparison (CCM.G-K1) in the field of absolute gravimetry, Metrologia, 49(6): 666–684. doi:10.1088/0026-1394/49/6/666

Krynski J, Olszak T, Barlik M, Dykowski P (2013) New gravity control in Poland – needs, the concept and the design. Geod Cartogr 62(1):3–21. doi:10.2478/geocart-2013-0001

Krynski J, Sekowski M (2010) Surveying with the A10-20 absolute gravimeter for geodesy and geodynamics – first results. Rep Geod 1(88):27–35

Micro-g LaCoste Inc. (2008) g8 user's manual, March 2008, p 48

Mäkinen J, Sekowski M, Krynski J (2010) The use of the A10-020 gravimeter for the modernization of the finnish first order gravity network. Geoinform Issue 2(1):5–17

Sekowski M, Krynski J (2010) Gravity survey with the A10-20 absolute gravimeter – first results, IAG symposium on terrestrial gravimetry: static and mobile measurements (TG-SMM2010), 22–25 June 2010, Saint Petersburg, Russia, pp 78–83