Testing the Suitability of the A10-020 Absolute Gravimeter for the Establishment of New Gravity Control in Poland

P. Dykowski, J. Krynski, and M. Sekowski

Abstract

The A10 absolute gravimeter is the first fully operational equipment to perform absolute gravity determinations in field conditions. A long time series of gravity determinations with the A10-020 performed since 2008 on a monthly basis on three stations in Borowa Gora Observatory provides an invaluable data source for quality estimation of the meter and its performance. Data from regular metrological calibrations of both, linear-polarized and stabilized laser and rubidium oscillator of the A10-020 are a complementary material for the analysis of the gravimeter performance. In May 2012 a measurement campaign at nearly 15 points was conducted to test and verify the developed methodology of absolute gravity survey with the A10 for establishing a new gravity control in Poland. Measurements were performed at absolute gravity stations of current Polish gravity control and their eccentric points. The obtained results were analyzed considering different types of station monumentation. At five laboratory stations the A10-020 results were compared with the recent FG5-230 determinations. The comparison included unification of vertical gravity gradient determinations as well as metrological parameters. At all occupied stations the vertical gravity gradient had been determined with two LaCoste & Romberg gravimeters with the use of a special stand made in the Institute of Geodesy and Cartography. The importance of vertical gravity gradient determination for the establishment of the new gravity control is discussed. The experience with the A10-020, including its suitability for modernization and re-measurement of gravity control in Finland, Sweden, Norway, and Denmark proves its high efficiency and accuracy. Furthermore it allows to develop a complete methodology for the establishment of a new type of gravity control.

Keywords

A10 absolute gravimeter • Gravity control • Relative gravimetry • Metrology

1 Introduction

The currently existing gravity control in Poland (POGK) is based on nearly 350 points. Since the end of the twentieth century nearly 100 of them were destroyed, making it impossible to re-measure completely the entire network. Following the suggestions of scientific community in Poland (Krynski 2009) the Head Office of Geodesy and Cartography initiated in 2011 the activity towards the modernization of the existing gravity network. As the technology of gravity determinations has significantly improved during the last 20 years it is possible to set a new type of gravity control (Krynski et al. 2012). The major tool to be used to determine gravity at the sites of gravity control could be the A10 gravimeter manufactured for over 10 years by the Micro-g LaCoste (Micro-g Lacoste Inc. 2008a) that ensures sufficient accuracy and efficiency

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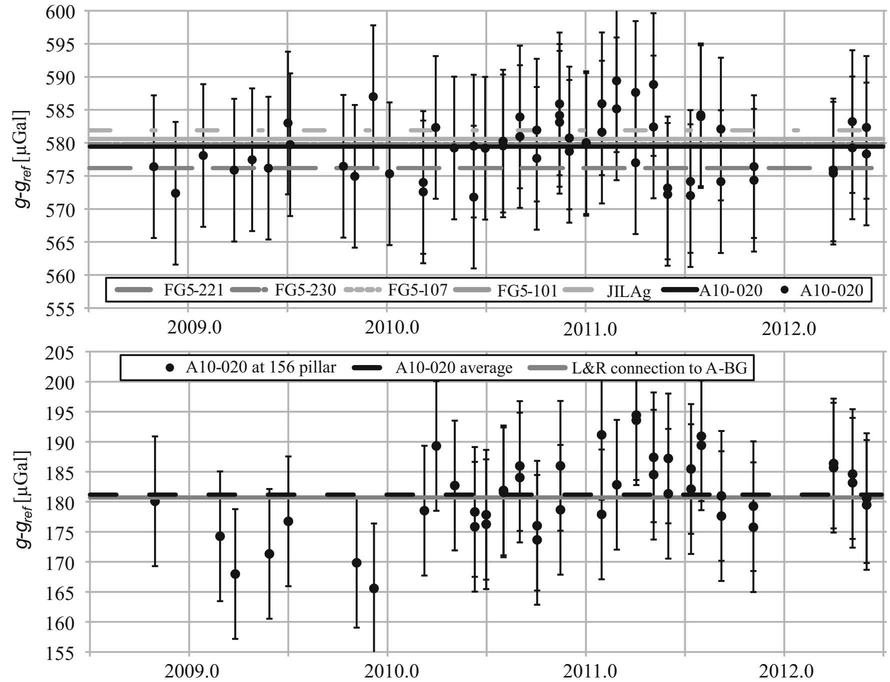

Fig. 1 Results of repeated gravity measurements at A-BG (*top*) and 156 (*bottom*) stations at Borowa Gora Observatory ($g_{ref} = 981{,}250{,}000$ µGal)

of gravity determination. Its performance investigated by a number of research teams (Pujol 2005; Schmerge and Francis 2006; Sousa and Santos 2010; Falk et al. 2012) indicates the potential usefulness of the A10 in the establishment of the gravity control. As each A10 gravimeter is handmade, it needs, to be tested in various measurement conditions, especially those characteristic for the country, in order to verify its suitability for the establishment of the new gravity control. The A10 gravimeters had already been used for the modernization of existing gravity control, e.g. in France (Duquenne et al. 2005), Spain (Pujol 2005), and Germany (Falk et al. 2012). Throughout the last couple of years the A10-020 operated by the team of the Institute of Geodesy and Cartography, Warsaw (IGiK) had been used in the field work on the gravity control in Scandinavia: Finland (Mäkinen et al. 2010), Norway (Pettersen et al. 2012), Sweden and Denmark.

The paper presents the results obtained in the process of extensive investigations and test survey with the A10-020 on some absolute stations and their eccentric sites of the POGK. The discussion concerns stability and reliability of the A10-020 with special attention to the monumentation of sites, metrology and vertical gravity gradient determination.

2 Stability and Reliability of the A10-020

Since 2008 quasi regular monthly gravity measurements were performed with the A10-020 at three pillars (two laboratory and one field station) of the Borowa Gora Geodetic-Geophysical Observatory (BG) of IGiK. Figure 1 (top) presents the results at A-BG absolute gravity station (laboratory station) in the Observatory at which numerous absolute gravity determinations were performed since 1978 by a number of teams, while Fig. 1 (bottom)—the results at the field station 156. The reference gravity at the 156 pillar was obtained by transferring to it the average gravity value at the A-BG pillar with a group of LaCoste & Romberg (LCR) gravimeters. Results at A-BG and 156 pillars reduced to the benchmark level show a very good agreement with previous precise gravity determinations.

All shown gravity determinations performed at the BG Observatory sites since 2008 were re-calculated with the use of new vertical gravity gradient ($\Delta g/\Delta h$) determinations performed in 2011 (Dykowski 2012) as well as with the use of calibration data of the ML-1 HeNe laser of

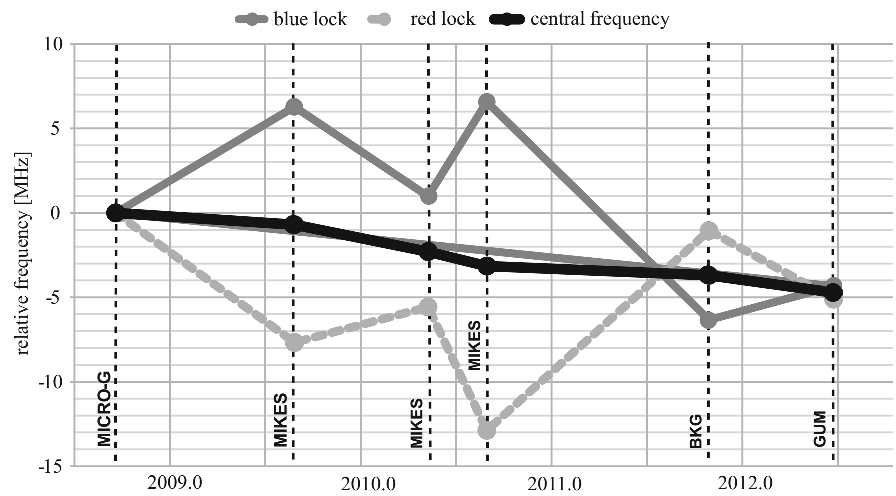

Fig. 2 Calibration data of the ML-1 laser of the A10-020

Table 1 Comparison of relative gravity determinations and A10-020 results between stations in the Borowa Gora Observatory [μGal]

Span	LCR_{2012}	A10 new $\Delta g/\Delta h$	A10 old $\Delta g/\Delta h$
A-BG—BG-G2	135.0 ± 2.2	136.8 ± 4.6	140.6 ± 4.6
A-BG—156	398.7 ± 1.9	399.0 ± 4.6	418.6 ± 4.6
BG-G2—156	263.6 ± 2.6	262.2 ± 5.5	278.0 ± 5.5

Table 2 Statistics at BG stations

Pillar	No of determinations	Std [μGal]	Max-Min [μGal]
A-BG	56	4.6	17.6
BG-G2	84	4.6	22.4
156	44	6.2	28.9

the A10-020 (Fig. 2). Both, metrological data and new $\Delta g/\Delta h$ data substantially contributed to the improvement of the results shown in Fig. 1. Particular attention has been paid to the quality of $\Delta g/\Delta h$ data. The effect of replacing "old" $\Delta g/\Delta h$ determined at two heights (1 m apart) (Sas-Uhrynowski 2002) with "new" $\Delta g/\Delta h$ determined in 2011 with the use of precise multiple-height strategy and special stand (Dykowski 2012) is shown in Table 1. Long term averages of gravity determined with the A10-020 at the BG Observatory sites were compared with the precise relative survey performed in April 2012. The results obtained show much better agreement of the A10 results with the use of currently determined $\Delta g/\Delta h$ than with those determined in the past (Krynski and Sękowski 2010).

Table 2 presents the basic statistics of the results at all three BG pillars. The observed standard deviations are much smaller than 10 μGal uncertainty suggested by the manufacturer (Micro-g Lacoste Inc. 2008a) while the differences between the maximum and the minimum value at each station exceed double of that uncertainty. These discrepancies are most probably due to environmental or geophysical phenomena. The trend observed in the results of gravity determinations (Fig. 1) is consistent with water table level recordings in the Observatory, which varies within 2 m. Unfortunately those recordings, due to short and not continuous time series, are still insufficient to apply a hydrological correction. More thorough analysis of time series of gravity determinations in the BG Observatory include metrological and environmental effects (Dykowski et al. 2012; Sekowski et al. 2012a).

Laser calibrations clearly prove the importance of the measurement traceability, assured by a correct application of metrological specifications, to the reprocessing of absolute gravity measurements with the A10-020. The observed change in the central frequency reaches 5 MHz (Fig. 2) which corresponds to a nearly 10 μGal shift in determined gravity (Niebauer et al. 1995). The trend observed in the laser calibration parameters shows a steady decrease in the central frequency with the red and blue mode experiencing much more significant variations.

The rubidium oscillator being the frequency standard of the A10-020 gravimeter is for the last 4 years stable within 5×10^{-3} Hz specified by the manufacturer. A contribution of such stability to the uncertainty of gravity determined is below 1 μGal, it corresponds well to the uncertainty specification suggested by the manufacturer. Since it is much lower than the total uncertainty of gravity measurement with the A10, there is no need to the correction to the gravity determinations for this effect. Metrological issues concerning the A10-020 have been more widely described in previous works of the authors (Dykowski et al. 2012; Sekowski et al. 2012a, b).

The ability of the A10-020 to provide reliable, high quality gravity has been proved in multiple gravity survey projects (nearly 180 stations in Scandinavia). In 2012 first 50 stations of the new gravity control in Poland were surveyed with the A10-020 within the 2 years project. The gravimeter took part in the ICAG2009 and ECAG2011 campaigns and

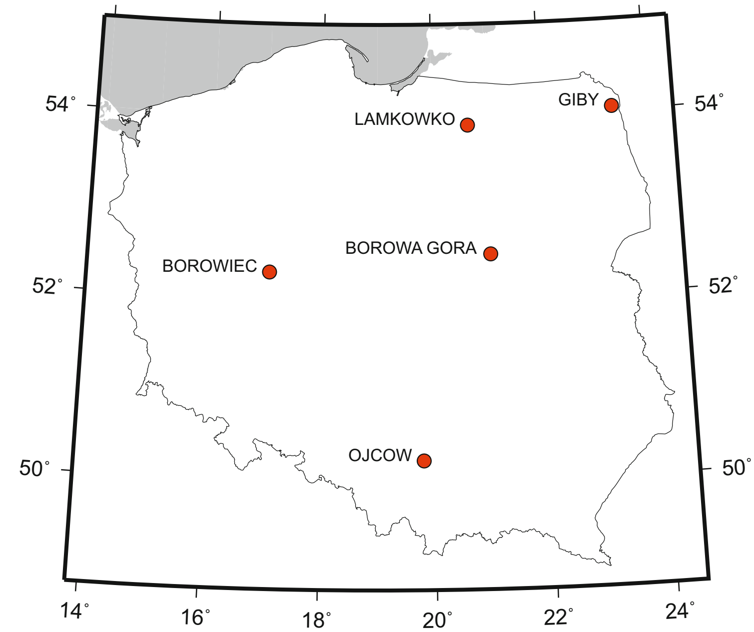

Fig. 3 Fundamental gravity sites selected for the test survey

has proven itself to provide reliable gravity values (Jiang et al. 2012; Francis et al. 2012).

3 Test Measurements with the A10-020 on the Sites of the Polish Gravity Network

Before the works on the modernization of the current gravity control in Poland could begin, a decision to perform a test survey at selected stations of the existing POGK network was made. Five fundamental gravity stations of the current Polish gravity network: Borowa Gora, Borowiec, Giby, Lamkowko, and Ojcow (Fig. 3) were selected for test measurements. Back in the 1990s absolute gravity measurements on the gravity network were performed with a few types of gravimeters by different teams (Sas-Uhrynowski 2002). At most of the mentioned sites the measurements with the A10-020 gravimeter were performed also at the eccentric points for the fundamental stations. At all points surveyed a new vertical gravity gradient was determined with two LCR gravimeters using a special stand (Dykowski 2012) and following a measurement schedule developed at IGiK.

The idea of test measurements was to generate and verify a strict and consequent methodology to obtain a good quality gravity value at any surveyed station. Measurements with the A10-020 were performed using a procedure tested multiple times by the IGiK team (Krynski and Sękowski 2010; Mäkinen et al. 2010). It includes two separate gravimeter setups consisting of eight sets each. In each set 120 drops are performed with 1 s drop interval. The agreement between two setups was verified at the spot. The difference between both setups below 10 μGal is considered acceptable. In case of larger difference third or consecutive setup was performed. Further discrepancies not explained by any geophysical phenomena (earthquakes, manmade seismic noise) or setup errors, indicate instability of the site what disqualifies it from the measurements as there is no possibility to determine gravity value with proper accuracy.

Various types of sites monumentation were selected for test measurements. All fundamental stations are stabilized with a 1×1 m and at least 1 m high concrete block. It is safe to say that this kind of stabilization is good enough for any type of gravimetric surveys, especially for the A10 gravimeter. A few of the eccentric points also have the same kind of monumentation. Other types of stabilizations are shown in Fig. 4. A mushroom-type block (at the first Lamkowko eccentric point—Fig. 4—right) gave a reliable result. At the EUREF site of the Borowiec second eccentric point (Fig. 4—middle) only one reliable result and several not conclusive results were obtained. The stabilization itself is massive enough but a thin layer of concrete that had been layed on the top of the block created an unstable surface. The last shown monumentation is a tile floor (Fig. 4—left). It showed very high and regular single drop residuals (Fig. 5—top) on which System Response Compensation (SRC) option of the g8 software was used (Micro-g Lacoste Inc. 2008b). Even though high residuals were observed, the single set scatter and set distribution were very good (Fig. 5—bottom).

Fig. 4 The A10-020 absolute gravimeter at sites of various types of monumentation

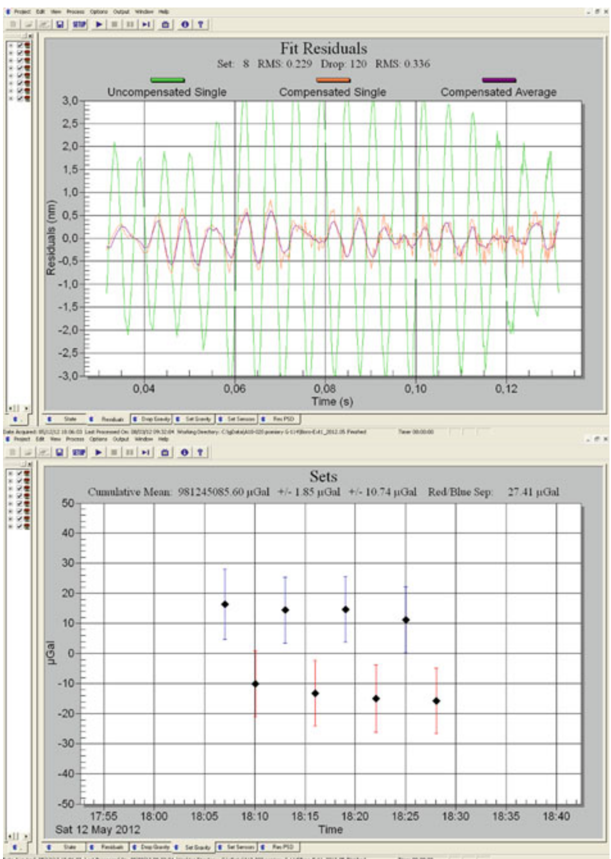

Fig. 5 SRC compensation on Borowiec second eccentric station (Fig. 4—*left*)

4 Analysis of Survey Results

At all sites selected for the test measurements absolute gravity determinations were performed in the past. The most recent were obtained with the FG5-230 of the Warsaw University of Technology (WUT) in 2006, 2007 and 2008 (Barlik 2010; Walo 2010). The other were performed with several different types of absolute gravimeters (FG5, IMGC, JILAg, ZZG) in 1994–1998 within the project of establishing

Table 3 Differences between survey results with the A10-020 on fundamental stations and previous absolute gravity determinations with the FG5-230 [µGal]

Site	$FG5_{2006}$	$FG5_{2007}$	$FG5_{2008}$	$FG5_{2006–2008}$
Borowa Gora	–	+0.9	+1.1	+1.0
Giby	+1.0	+0.4	+0.4	+0.7
Lamkowko	+4.5	−2.6	+4.4	+2.1
Borowiec	−0.4	+0.9	+6.3	+2.3
Ojcow	+1.5	−1.7	−3.4	−1.2

Table 4 Differences between survey results with the A10-020 on fundamental stations and absolute gravity determinations from 1994 to 1998 [µGal]

Site	FG5-101	FG5-107	IMGC	JILAg-5	ZZG
Borowa Gora	+2.1	+1.1	–	+1.7	−18.6
Giby	–	–	–	–	−11.7
Lamkowko	–	–	−8.2	–	−28.1
Borowiec	−3.6	–	+0.8	–	−24.2
Ojcow	–	−13.0	–	–	–

POGK (Sas-Uhrynowski 2002). To allow a proper comparison of absolute gravity determination results they all had been unified with the use of the vertical gravity gradient determined in 2012. Unified offsets of gravity determinations with the A10-020 and with respect to the FG5-230 are presented in Table 3. Differences between gravity determined with the A10-020 and the FG5-230 results over 3 years (2006, 2007, 2008) at all surveyed sites are optimistic as the biggest discrepancy does not exceed 6.3 µGal.

Table 4 presents the differences between the A10-020 results and absolute gravity determinations performed in 1994–1998 by different types of absolute gravimeters. Gravity values determined with the A10-020 seem consistent with most FG5 and IMGC determinations but significant discrepancies occur when compared to the results of the ZZG gravimeter.

As the test survey with the A10-020 was also performed at a few eccentric sites of the mentioned fundamental stations, a comparison could be made with the relative measurements performed with LCR gravimeters in 1994–1998 (Sas-Uhrynowski 2002). Differences between those determinations are presented in Table 5. Unfortunately not all eccentric stations survived until 2012, hence the lack of results for some stations.

The first eccentric point of the Borowiec station is a special case (Fig. 4—left). High single drop residuals contaminated the proper gravity determination at that site even though the measurement looks very good in terms of low single set noise, and stable set distribution. In this case SRC option of the g8 software had been used during the reprocessing of the measurements (Micro-g LaCoste Inc. 2008b). For the spans with this site two values are shown in

Table 5 Comparison of A10 survey results on eccentric points with relative determinations [µGal]

Site	$A10_{2012}$	$LCR_{1994–1998}$	Difference
Borowa Gora			
ABS-EX1	136.0	135.0	1.0
ABS-EX2	397.4	398.7	−1.3
EX1-EX2	261.3	263.6	−2.3
Lamkowko			
ABS-EX1	326.6	325.0	1.6
Borowiec			
ABS-EX1	1,056.4	1,061.0	−4.6/*17.8*
ABS-EX2	873.2	873.0	0.2
EX1-EX2	183.2	188.0	−4.8/*18.0*
Ojcow			
ABS-EX1	568.4	566.0	2.4

the "difference" column in Table 5. The left one corresponds to the difference obtained with the use of the SRC option while the right one is a non modified value from the original measurement. This example shows significant improvement in the obtained gravity value coming from the use of SRC option.

Conclusions and Recommendations

No significant problems occurred during the performed test gravity survey. At almost all open field stations a tent was used for protection from wind and other environmental effects. It is recommended to use it for this purpose. As for the suitability of the A10-020 for the establishment of the new Polish gravity control it can be stated that:

- A10-020 gravimeter provides stable results at the reliability level required in the modern gravity control (10 µGal or better);
- described and tested schedule of two independent setups with 8 sets of 120 drops every second is reliable for the detection of gross errors and for assuring a good quality of the determined gravity value at any stable site.

To assure proper gravity determinations several factors need to be taken account:

- point localization—no high and dense settled trees, no heavy traffic, etc. to minimize the noise during the survey;
- proper monumentation—stations planned to be surveyed during the modernization/establishment of the gravity control should be properly stabilized;
- precise and reliable determination of vertical gravity gradients, both the measurement and its reduction including the possible non-linearity of the determined gradient;
- control of metrological standards, especially for the HeNe laser as it seems to be the more "drifting" factor, control of the rubidium frequency standard to verify its long term stability. Such control is recommended every 6 months.

Test absolute gravity determinations with the A10-020 on the Polish gravity control along with the previous gravity network experiences of the IGiK team confirm the suitability of the A10-type gravimeters for the establishment of the gravity control in Poland.

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