On the Estimate of Accuracy and Reliability of the A10 Absolute Gravimeter

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Abstract

The Institute of Geodesy and Cartography in Warsaw, Poland, operates the A10-020 absolute portable gravimeter since November 2008. Numerous gravity measurements with the A10-020 gravimeter, conducted under both laboratory and field conditions, provide a unique material for the estimation of accuracy as well as reliability of the determined gravity. Monthly measurements conducted with the A10-020 at the Borowa Gora Geodetic-Geophysical Observatory, north of Warsaw, provided a 2 year long time series at two laboratory sites and one field station. They have been analysed in terms of their internal consistency and compliance with the previous measurements performed with a few other absolute gravimeters (mainly FG5). The results of a number of calibrations of both, the rubidium oscillator and the polarization-stabilized laser of the A10-020 were considered in the analysis. The effect of applying the frequency standard as well as laser calibration data on the quality of gravity determined was investigated. In addition, the impact of weather conditions as well as variability of metrological parameters on surveyed gravity was taken into consideration when evaluating accuracy and reliability of gravity survey with the A10 gravimeter.

1 Introduction

The A10 absolute gravimeters are used already for more than a decade. Several studies on accuracy and repeatability were performed for a few of A10 gravimeters. Results of gravity measurements conducted over 2 years in field and laboratory conditions with the A10-017 at the Kyoto University campus (Fukuda et al. 2010a) indicated that the accuracy of the A10 gravimeter is in most cases better than 10 μGal specified by the manufacturer (Micro-g LaCoste Inc. 2008). In addition, gravity determined with the A10-017 in a number of test measurements differed by only a few microgals from the one obtained with the FG5-210 (Fukuda et al. 2010b). The authors pointed out the importance of periodic calibration of laser and frequency standard of the A10. Results of tests performed indicated that six to eight sets in a single measurement is sufficient to achieve a reliable gravity value. This corresponds to the strategy developed at the Institute of Geodesy and Cartography (IGiK) in Warsaw (Krynski et al. 2010).

Similar conclusions concerning accuracy and repeatability of the A10 gravimeter were drawn by Schmerge and Francis (2006) from the analysis of the measurements with the A10-008. They pointed out that the quality of tidal model applied to compute tidal correction — the largest correction to gravity measurements — affects the evaluation of repeatability of absolute gravity determinations. On the other hand, analysing the results of calibrations of the rubidium clock and laser, they found no significant effect of the change of calibrated parameters on the determined gravity as long as laser modes drift symmetrically. They

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also investigated the dependence between the gravity value determined and the length of survey comparing the results of survey lasting from 30 min to 24 h. They showed that the gravity value determined is insensitive to the length of the measurements, and therefore the measuring strategy based on drops as frequent as every second can be applied. Such strategy is compatible with the experience in gravity surveys with the A10 in IGiK (Krynski and Roguski 2009; Krynski and Sękowski 2010). Finally, comparisons of gravity determined using the A10-008 with those of FG5-216 showed an offset of only 3 μGal (Schmerge and Francis 2006).

Significant influence of laser and frequency standard parameters of the A10 on gravity determined was observed by Falk et al. (2012) with A10-002 and A10-012 gravimeters. Resulting annual drift was at the level of 4.4 μGal. Repeatability and accuracy was in the range of 6 μGal, with 95 % of measurements within the accuracy specified by the manufacturer.

The A10-020 gravimeter was installed in the Borowa Gora Geodetic-Geophysical (BG) Observatory of IGiK in October 2008. Since then numerous absolute gravity measurements were performed under laboratory conditions at two pillars: A-BG and BG-G2, and at the field point 156 of the Polish Gravity Control Network. Time series analysed in the paper cover the period November 2008–August 2010 for which the calibration data of rubidium oscillator and the polarization-stabilized laser were available.

The A10-020 was used in 2009 and 2010 for re-measurements of the Finnish First Order Gravity Network. Results of those measurements confirmed the usefulness of the A10 absolute gravimeter for the modernization of gravity control networks (Krynski et al. 2010).

2 Data Used

Absolute gravity measurements at the BG Observatory with the A10-020 are performed in regular monthly intervals. In order to avoid or minimize the effects of some unexpected phenomena like earthquakes or rapid temperature changes, which more likely may appear in longer surveys, as well as to unify the data set, all longer measurements were for the following analysis cut down to the first eight sets (120 drops, 1 Hz drop frequency), and all shorter measurements were excluded from the analysis. A small number of measurements (two for A-BG, five for BG-G2 and five for 156) were excluded due to detected gross errors, some technical problems, and other not fully recognized reasons. All excluded measurements substantially differed from long term calculated average value at each point (at least 2σ, where σ = 10 μGal). Gross errors identified were due to gravimeter's out of level (e.g. caused by changing temperature), accidental movement around the meter, meteorological conditions (strong wind, hot/cold weather). No corrections due to local and global hydrology as well other geophysical phenomena were included.

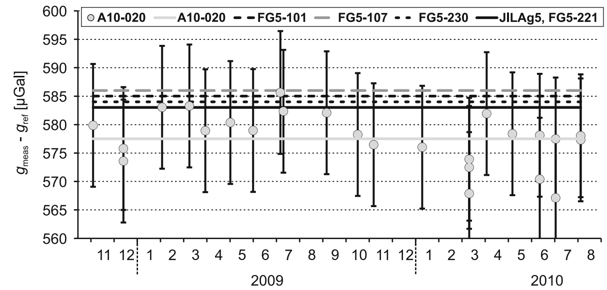

Fig. 1 Absolute gravity determinations at A-BG (g_{ref} = 981,250,000 μGal)

Table 1 Statistics of A10-020 gravity determinations at the BG Observatory (μGal)

Station	No. of observations	Maximum–minimum	Standard deviation
A-BG	26	18.5	4.7
BG-G2	48	13.5	3.5
156	15	18.0	4.6

3 Gravity Values Calculated with Laser and Clock Factory Settings

All gravity measurements with the A10-020 were initially calculated using the factory settings provided by the manufacturer for both, the rubidium oscillator and laser. Results of gravity measurements at A-BG station with the use of factory settings for both laser and clock are shown in Fig. 1 and their statistics including the results at the remaining stations — in Table 1. Additionally, the gravity values determined with the A10-020 at A-BG are compared with previous absolute gravity determinations (mainly with the FG5). The solid grey line indicates long term average value from the surveys with the A10-020. That average value is consistent with all gravity determinations with FG5 gravimeters within 10 μGal even though FG5 measurements were performed in different epochs, reduced with different vertical gravity gradients (by different teams), and no calibration data was applied. Detailed comparison of A10 with FG5 determinations requires specific data unification.

4 Calibration of the Laser and the Rubidium Oscillator

Several calibrations of both, the rubidium oscillator and polarization-stabilized laser of the A10-020 were performed

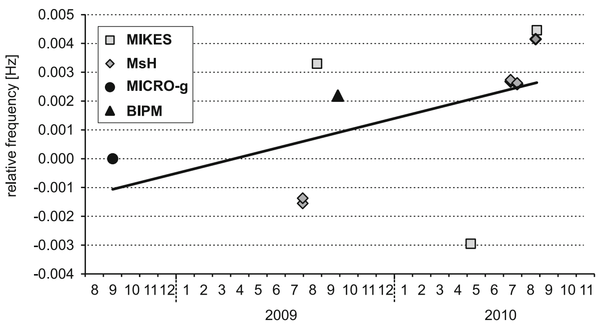

Fig. 2 Rubidium oscillator calibration results

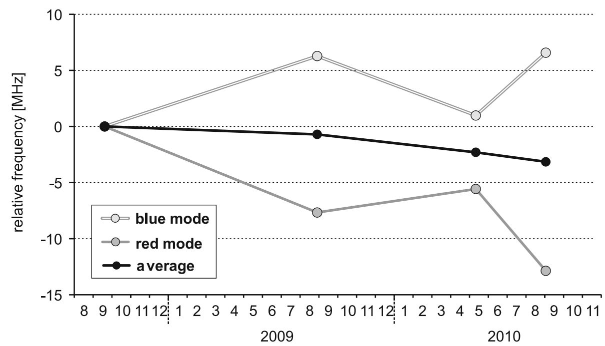

Fig. 3 Laser calibration results

over the period of the analysed time series of gravity determinations. Most of calibrations were performed in Finland in relation to the project of the re-measurement of the Finnish First Order Gravity Network (Krynski et al. 2010; Sękowski et al. 2012).

4.1 Rubidium Oscillator Calibration

The rubidium oscillator Symmetricom X72 of the A10-020 had been initially calibrated at Micro-g LaCoste, Inc., before the delivery of the gravimeter to IGiK. Subsequently it has been calibrated three times at the Finnish Centre for Metrology and Accreditation MIKES (MIKES 2009, 2010a, b) and once at BIPM, Paris, during the ICAG2009 campaign. In addition, four calibrations were performed at the Metsahovi Radio Observatory of the Helsinki University of Technology (MsH). All results are shown in Fig. 2 as offset relative to nominal frequency of 10 MHz.

Since the results of the rubidium oscillator calibration do not exhibit any visible pattern, the linear trend (solid line in Fig. 2) was applied to fit the results. It should be noted that the change of 0.005 Hz in clock frequency corresponds to 1 μGal in measured gravity (increase in rubidium oscillator frequency if not corrected causes the increase in estimated gravity). All measurements were then re-processed using values interpolated from a linear trend model. Changes in clock frequency resulted in linear change of gravity during the analysed period from −0.2 to 0.5 μGal.

4.2 Laser Calibration

The polarization-stabilized laser (ML-1 model) of the A10-020 had been initially calibrated at Micro-g LaCoste, Inc., before the delivery of the gravimeter to IGiK. After that it was calibrated three times at MIKES (MIKES 2009, 2010c, d). The laser is stabilized at two frequencies about 700 MHz apart, usually called red and blue side-lock (or mode). Gravity data are taken alternating between the two side-locks and the average is the final result since the mean of the side-locks is much more stable than any of the side-locks themselves. Consequently, estimated absolute gravity change is the result of a change in centre frequency. Calibration results as offset relative to initial calibration at Micro-g LaCoste, Inc. are presented in Fig. 3. It can clearly be seen that the centre frequency is slowly decreasing as the behaviour of red and blue side-locks is almost symmetrical. The observed change in central frequency amounts to 3.1 MHz during the analysed period. The change of 1 MHz in laser frequency, as expected, corresponds to 2.07 μGal change in measured gravity (Niebauer et al. 1995). Decrease in observed laser frequency results in the increase in gravity. Along the presented period, correction to measured gravity due to laser frequency was increasing up to 6.1 μGal.

Calibrated parameters of laser frequency were applied using linear interpolation between calibration epochs for each side-lock. The interpolated values along with clock frequency were used to reprocess all measurements with the g8 software (Micro-g LaCoste Inc. 2008).

4.3 Influence of Calibration Results on Determined Gravity

The calculated difference in gravity between the results obtained with the use of calibrated gravity values and factory settings corresponds with the laser central frequency change of 2.07 μGal/MHz and 1 μGal/0.005 Hz change in clock frequency. At the end of the presented time series the difference reaches the level of about 6.5 μGal which exceeds the determined standard deviation of gravity measurements. That proves that periodical calibrations are necessary for proper gravity value determination. Statistics of the results before and after applying calibration data are given in Table 2.

Applied calibration data clearly improves estimated standard deviations at both laboratory stations. For A-BG station the difference between average FG5 results

Table 2 Statistics of gravity determinations before and after applying calibration data (μGal) ($g_{ref} = 981{,}250{,}000$ μGal)

	A-BG factory settings	A-BG applied calibration	BG-G2 factory settings	BG-G2 applied calibration	156 factory settings	156 applied calibration
$g_{meas} - g_{ref}$	577.5	580.6	438.2	440.5	157.0	160.6
Standard deviation	4.7	4.1	3.5	3.0	4.6	5.4
Maximum–minimum	18.5	14.8	13.5	13.5	18.0	18.3

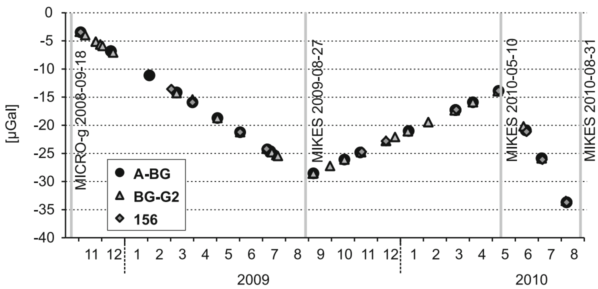

Fig. 4 Red/blue modes separation differences before and after applying calibration data

($g_{meas} - g_{ref} = 583.7 \pm 2.2$ μGal) and calibrated A10 results ($g_{meas} - g_{ref} = 580.6 \pm 4.1$ μGal) is 3.1 μGal. Slight increase in standard deviation at 156 station is caused by uneven distribution of measurements during the presented time series (due to meteorological conditions). For time series at 156 analysed in separated periods standard deviations also improve.

Change in gravity for both side-locks also significantly influences the estimated red/blue modes separation, which is expected to be near zero value. Since larger gravity value (blue lock) is decreasing and the smaller gravity value (red lock) is increasing the modes separation decreases. Difference between modes separation before and after including calibration data is shown in Fig. 4.

Decrease in modes separation is clearly visible. It indicates that calibration is needed to bring the red/blue modes separation down near zero. Still, after calibration, a big separation in some observations is observed. It seems to be due to the change of the temperature in the laboratory. However, it could also be caused by variations of the laser parameters between two calibrations, which could not have been observed.

5 Weather Conditions Impact on Gravity Determinations

The impact of weather conditions on determined gravity is clearly visible at 156 field station, where the A10-020 is exposed to all weather influences (in spite of using a tent to protect the meter). Hot/cold weather conditions occasionally make it impossible to perform measurements (as the working temperature range of the A10 is limited), hence the limited number of measurements on the outside point and irregular distribution in time. Barometric pressure has the most significant influence on calculated gravity but will not be discussed as measurements are already corrected for that effect. Strong wind may significantly increase measurement set scatter and can also be visible even under laboratory conditions.

Even though the lower unit of the meter is sealed and temperature stabilized, the laser still suffers the influence of ambient temperature variations (time required to reach thermal equilibrium was no less than 4 h). Figure 5a shows red/blue separation together with outside temperature (data from meteorological station in the BG Observatory) at 156 field station. Linear Pearson correlation coefficient between those two parameters of about −0.77 is big enough to indicate strong anticorrelation of ambient temperature and calculated separation. Large linear correlation coefficient allows to reliably determine a factor of change in separation per degree, which is about -2.59 ± 0.58 μGal/°C (Fig. 5b). Separation value itself could be a help factor in the evaluation of measurement reliability. Large separation value indicates that both side-locks drift from one another. Average value will not suffer from the fact that red and blue side-lock drift symmetrically.

6 Calibrated Time Series

Application of calibration data clearly influences determined gravity values. Absolute gravity determinations with the A10-020 show steady increase improving the downward trend observed in factory settings time series for points A-BG, BG-G2. The field station 156 still has not enough measurements to draw such conclusions. Applied calibration data to all measurements, increased long term average gravity by 3.1, 2.3, 3.7 μGal at A-BG, BG-G2, 156, respectively. Calibration resulting values also improved few measurements, which before calibration could have been considered as outliers. Gravity values for A-BG before and after applying calibration data are presented in Fig. 6. Black and grey lines indicate linear trend fitted to each result.

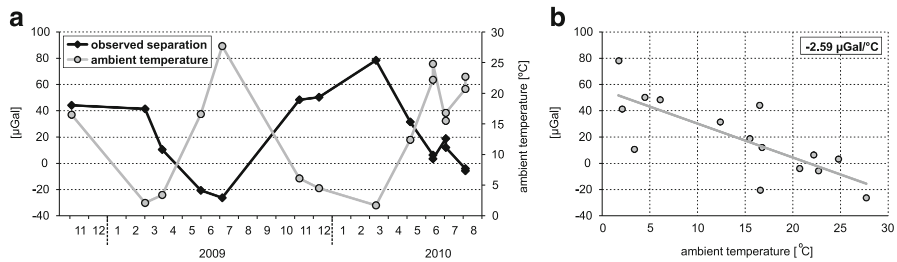

Fig. 5 Red/blue separation and ambient temperature at 156 field station (**a**); correlation of ambient temperature changes and estimated separation (**b**)

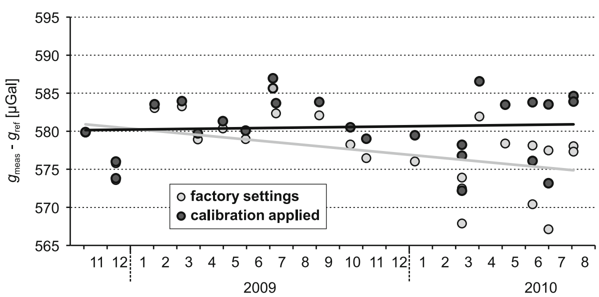

Fig. 6 Results of gravity measurements at A-BG station before and after applying calibration data ($g_{\mathrm{ref}} = 981{,}250{,}000$ µGal)

7 Conclusions

Nearly 200 gravity determinations were performed so far with the A10-020 absolute gravimeter at the BG Observatory (about 90 of them had been analysed in this paper). Precision and repeatability of the A10 depend on numerous factors such as metrological parameters, ability and experience of the operator in setting up the meter, weather conditions, etc.

Repeatability of gravity determinations with the A10-020 in laboratory and field conditions at Borowa Gora, expressed in terms of standard deviation, is better than suggested by the manufacturer 10 µGal. Such good results can be achieved by the team experienced in the use of the A10 that applies an effective measurement schedule and introduces metrological data.

It has been shown that application of calibration data substantially affects gravity determinations with the A10-020. It results in significant increase in determined gravity as well as decrease in calculated red/blue separation. The improvement of gravity determination with the A10-020 due to calibration is fully compatible with the one obtained by Falk et al. (2012). The results obtained indicate that calibration should be performed possibly more often than once a year. Falk et al. (2012) recommend performing calibration every 6 months.

Interpretation of current gravity survey results requires substantial carefulness at least until obtaining and applying calibration data. The results obtained showed that correction due to the change of metrological parameters can exceed the standard deviation of the gravity determined. No extrapolation of calibration data is recommended as the behaviour of variations of metrological parameters is difficult or even impossible to predict.

The experience gained indicates that increasing separation of red and blue locks is a sign of the quality of the measurement (increase in separation suggest that metrological parameters have changed and gravimeter possibly requires calibration). The more stable are environmental conditions the better and more reliable is the performed measurement as red/blue separation is expected to be close to zero.

Consequently calibrations should be periodically performed on semi-annual basis to assure good reliability of gravity data obtained with the A10 absolute gravimeter.

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