Effect of laser and clock stability and meteorological conditions on gravity surveyed with the A10 free-fall gravimeter – first results

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Abstract. The Institute of Geodesy and Cartography in Warsaw, Poland, operates the A10-020 free-fall 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. Time series of regular, monthly measurements conducted with the A10-020 at the Borowa Gora Geodetic-Geophysical Observatory for over two years at two laboratory test sites and one field station has 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 interferometer of the A10-020 were considered in the analysis. The effect of applying the frequency standard as well as laser interferometer 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. Also the possibility of the occurrence of gross errors in gravity determination with the A10 gravimeter was discussed.

Keywords: Key words: gravimetric survey, absolute gravimeter, metrological parameters, metrology

1 Introduction

A10 free-fall 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 manufacture (Micro-g LaCoste Inc., 2008). They also showed very good correlation with monitored groundwater level changes what proves high accuracy of the A10 gravimeter. 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 6-8 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 in Warsaw.

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 interferometer, they found no significant effect of the change of calibrated parameters on the determined gravity as long as laser modes drift symmetrically. They also investigated the dependence between the gravity value determined and the length of survey comparing the results of survey lasting from 30 minutes to 24 hours. 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 at the Institute of Geodesy and Cartography (Krynski and Roguski, 2009; Krynski and Sekowski, 2010a). Finally, comparisons of gravity determined using the A10-008 with those of FG5-216 showed offset of 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.*(2009) 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 at the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography (IGiK), Warsaw, in October 2008. Since then numerous absolute gravity measurements were performed under both laboratory and field conditions. Laboratory gravity measurements were conducted on two pillars (A-BG and BG-G2) while field determinations were performed the point No 156 of the Polish Gravity Control Network (POGK99) (Fig. 1). The time series analysed in the paper covers the period since November 2008 till August 2010. For that period, the calibration data of rubidium oscillator and the polarization-stabilized laser interferometer were available.

The A10-020 was used in 2009 and 2010 for re-measurement of the Finnish First Order Gravity Network. Results of those measurements confirmed the usefulness of the A10 free-fall gravimeter to the modernization of gravity control networks (Kryński *et al.*, 2010b). The performance of the A10-020 in terms of accuracy and sensitivity to variations of laser and frequency standard parameters as well as meteorological conditions are discussed in this paper.

2 Data used

Absolute gravity measurements at Borowa Gora Observatory with the A10-020 gravimeter are performed in regular monthly intervals. Some unexpected phenomena like earthquakes or rapid temperature changes, are much more likely to appear in longer surveys. Therefore, in order to avoid or minimize such effects as well as to unify the data set, all longer measurements were for the following analysis cut down to the first 8 sets, and all shorter measurements were excluded from the analysis. A small number of measurements (2 for A-BG, 5 for BG-G2 and 5 for 156) were excluded due to detected gross errors, some technical problems and other not fully recognized reasons. All those measurements differed substantially from long term observed average value at each point. Gross errors concerned mislevelment of the gravimeter (e.g. caused by changing temperature), accidental movement around the meter, meteorological conditions (strong wind, hot/cold weather).

Typical set scatter varied within the range of 30-60 μGal. Lowest observed set scatter is at the level of 15-20 μGal. The A10-020 gravimeter provides good quality data even when set scatter reaches values of 80-100 μGal.

Figure 1. *A10-020 at 156 field station*

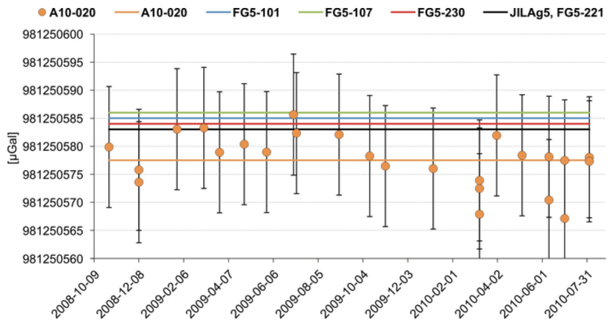

Figure 2. *Absolute gravity determinations at A-BG*

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 the rubidium oscillator and laser interferometer. Those settings were considered as constant values and were not modified. Results of gravity measurements at A-BG station with the use of factory settings for both laser and clock are shown in Figure 2 and their statistics 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 orange line indicates long term average value from the surveys with the A10-020.

Table 1 presents the statistics of gravity measurement with the A10-020 at all three stations in Borowa Gora. Standard deviations show that

Table 1. *Statistics of gravity determinations at Borowa Gora Observatory [μGal]*

Station	No. of obs.	Max - Min	Std Dev.
A-BG	26	18.53	4.68
BG-G2	48	13.54	3.49
156	15	18.00	4.60

repeatability of results is better than specified by the manufacturer 10 *μGal*.

4 Calibration of the laser and the rubidium oscillator

Several calibrations of both, the rubidium oscillator and polarization-stabilized laser interferometer of the A10-020 gravimeter were performed over the period of the analysed time series of gravity determinations. Most of calibrations were performed in Finland related to the project of the re-measurement of the Finnish First Order Gravity Network.

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 to IGiK. Subsequently it has been calibrated three times at the Finnish National Meteorology Institute of Finland called MIKES (MIKES 2009, 2010a, 2010b) and one time at BIPM (Sévres, France) during the ICAG 2009 campaign. In addition, four calibrations were performed at the Metsahovi Radio Observatory of the Helsinki University of Technology using the frequency of the hydrogen maser. All results are shown in Figure 3 with relative offset to nominal frequency of 10 MHz.

Since the results of the rubidium oscillator calibration do not exhibit any visible pattern, the linear trend was applied to fit the results. All measurements were then re-processed using values interpolated from linear trend model. Changes in clock frequency resulted in linear change of gravity during the analysed period from -0.15 to 0.51 *μGal*. Change of 0.005 Hz in clock frequency corresponds to 1 *μGal* in measured gravity (increase in rubidium oscillator frequency causes the increase in observed gravity).

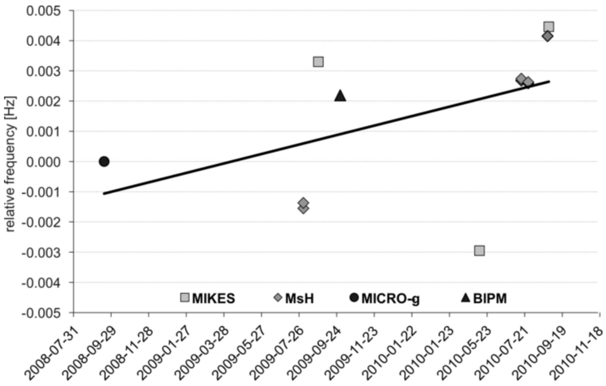

Figure 3. *Rubidium oscillator calibration results*

4.2 Laser calibration

The polarization stabilized laser (ML-1 model) of the A10-020 had initially been calibrated at Micro-g LaCoste, Inc., before the delivery to IGiK. After that it was calibrated three times at MIKES (MIKES 2009, 2010c, 2010d). The laser can be 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. This is done because the mean of the side locks is much more stable than any of the side-locks themselves. Consequently, observed absolute gravity change is the result of a change in centre frequency. Calibration results in terms of relative changes are presented in Figure 4 with relative offset to initial calibration at Micro-g LaCoste, Inc. It can clearly be seen that the centre frequency is slowly decreasing as the behaviour of red and blue side-locks is almost symmetrical. It is also visible that the red lock drift is stronger that results in decrease in central frequency. 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 from 0.02 to 6.06 μGal.

Calibrated parameters of laser frequency were applied linearly between calibration epochs for each side lock. Each frequency value was transformed into laser wavelength value. This value along with clock frequency was used to reprocess all measurements using the g8 software

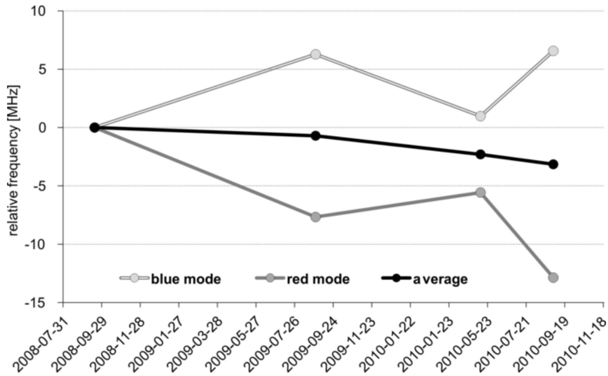

Figure 4. *Laser interferometer calibration results*

provided by Micro-g LaCoste, Inc. for absolute data acquisition and reprocessing.

4.3 Influence of calibration results on observed gravity

Each measurement had been reprocessed using calibrated clock and laser values. Changes occurred in measured gravity as well as in red/blue side lock separation.

Figure 5 shows difference in gravity between the results obtained with the use of calibrated gravity values and factory settings. The observed difference clearly 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 about the level of 6.5 μGal which exceeds the observed standard deviation of 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.

Observed gravity is a result of the average between red and blue side lock gravity determinations. Calibration parameters are evaluated for each of the side locks. Increase in gravity observed by the red side lock is bigger than decrease in gravity observed by the blue side lock, hence the increase in observed average gravity.

Change in gravity for both side locks also significantly influences the observed red/blue modes separation, which is expected to be small value. According to the manufacturer, during the time of usage, side locks can switch their places (usually one of the locks, in our situation

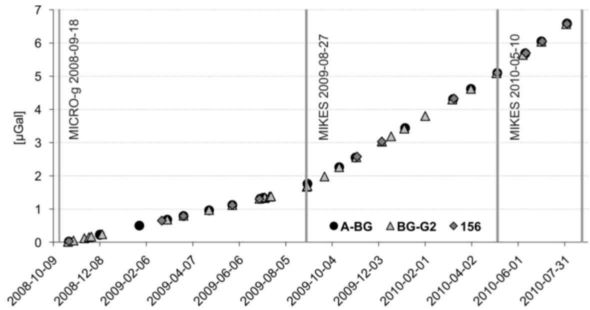

Figure 5. *Gravity differences after application of calibration data*

Table 2. *Measurement statistics before and after applying calibration data [μGalGal] (g_{ref} = 981250000 μGal)*

	A-BG Factory settings	A-BG Applied calibration	BG-G2 Factory settings	BG-G2 Applied calibration	156 Factory settings	156 Applied calibration
$g_{meas} - g_{ref}$	577.51	580.57	438.20	440.48	156.95	160.65
Std Dev.	4.68	4.13	3.49	3.05	4.60	5.43
$Max - Min$	18.53	14.77	13.54	13.47	18.00	18.27

blue side lock gives higher gravity value than the red side lock). Since larger gravity value (blue lock) is decreasing and the smaller gravity value (red lock) is increasing the modes separation decreases. The smaller the modes separation is, the bigger the chances that the modes could switch places. Difference between modes separation before and after including calibration data is shown in Figure 6.

Decrease in modes separation is clearly visible, and indicates that including calibration is needed to bring the red/blue modes separation down near zero. Each time the modes separation after calibration become negative, it means that red and blue locks switched their places. Still, after calibration, a big separation in some observations is observed. It seems to be caused by 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.

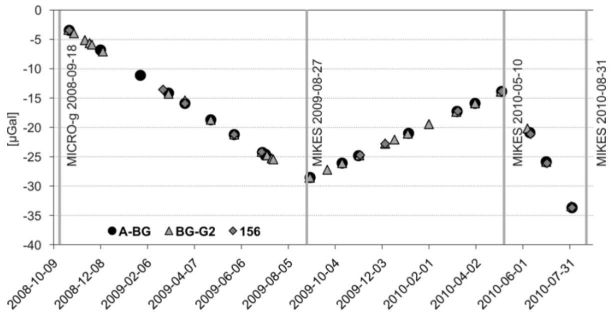

Figure 6. *Red/blue modes separation differences before and after applying calibration data*

5 Weather conditions impact on gravity determinations

The impact of weather conditions on observed gravity is clearly visible at 156 field station, where A10-020 gravimeter is exposed to all weather influences (even though being covered with a tent). 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. Barometric pressure has the most significant influence on observed 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.

From technical issues, the laser performance is temperature dependent, even though sealed and temperature stabilized in the lower unit of the meter, still suffers the influence of ambient temperature variations. Figure 7 shows red/blue separation together with outside temperature (data from meteorological station) at 156 field station. Linear Pearson correlation coefficient between those two parameters of about -0.77 is quite large. It indicates strong anticorrelation of ambient temperature and observed separation. Strong linear correlation allows to determine a factor of change in separation per degree, which is about -2.59 μGalGal/oC and is clearly visible in Figure 8. Separation value itself could be a help factor in the determination of measurement reliability. Large separation value indicates that both side lock drift from one another. Average value will not suffer from the fact that red and blue side lock drift with the same value. As the author's experience show, red side lock has visibly bigger long term drift than the blue side lock. If that situation happens with

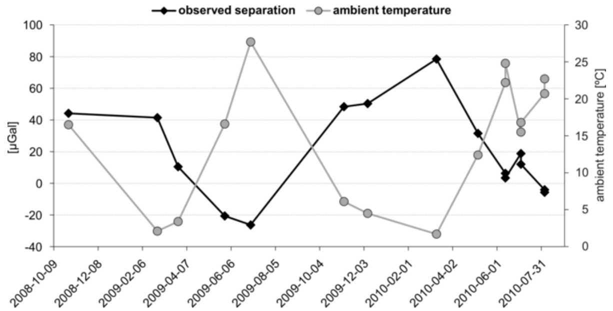

Figure 7. *Red/blue separation and ambient temperature at 156 field station*

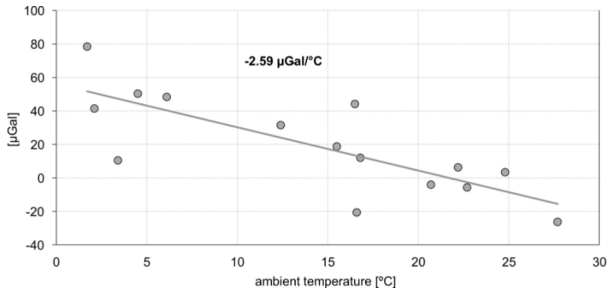

Figure 8. *Correlation of ambient temperature changes and observed separation*

significant temperature changes gravity value would be smaller than it should be.

Unfortunately temperature inside laboratories is recorded regularly only starting from July 2010, therefore no respective comparisons could be made. Temperature inside laboratories is insensitive to large outside temperature variations, therefore outside temperatures cannot be compared with observed separation.

6 Calibrated time series

Application of calibration data clearly influences observed 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. At all stations investigated gravity value increased with the same pattern as shown in Figure 5. Applied calibration

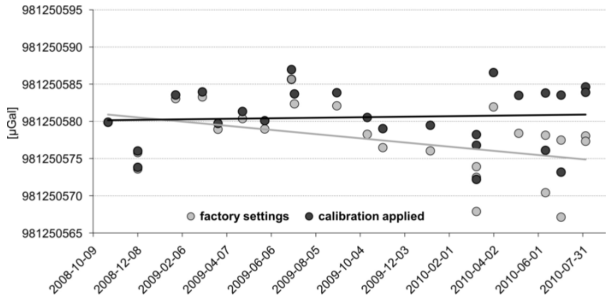

Figure 9. *Results of gravity measurements at A-BG station before and after applying calibration data*

data to all measurements, increases long term average gravity by 3.06, 2.28, 3.70 μGalGal 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 Figure 9. Black and gray lines indicate linear drift fitted to each result.

7 Conclusions

The A10-020 free-fall gravimeter was used to perform nearly 200 gravity determinations at the Borowa Gora Observatory. Precision and repeatability of the A10 gravimeter depends on numerous factors such as metrological parameters, ability and experience of the operator in setting up the meter, weather conditions, etc.

It has been shown that calibration data substantially affects gravity determinations with the A10-020. Applied calibration data to the A10-020 showed significant increase in observed gravity as well as decrease in observed 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. (2009). Several calibrations performed during the investigated time series improved gravity determinations stability. Calibration should be performed in the future possibly more often than once per year. Falk et al. (2009) recommends performing calibrations every 6 months.

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

Experience gained indicates that increasing separation is a sign of the quality of the measurement. The more stable are environmental conditions the better and more reliable is the performed measurement as red/blue separation is expected to be as close to zero as it is possible. Small separation value will indicate good stability of obtained results.

As long as in laboratory conditions separation is near zero (not important which side lock gives higher value) it could be considered that calibration parameters are stable. When separation increases it is a sign that current measurements could require calibration parameters to be included. Nevertheless periodically performed calibrations on semi-annual basis should be performed to assure good reliability of gravity data obtained with the A10 free-fall gravimeter.

8 Acknowledgements

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