The use of the A10-020 absolute gravimeter for the establishment and modernization of national gravity controls in Europe

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Abstract

The Institute of Geodesy and Cartography operates the A10-020 absolute gravimeter since October 2008, and since that time it had been used for the establishment and modernization of gravity control in several European countries, i.e. Finland, Sweden, Norway, Denmark and Poland. Majority of gravimetric surveys were performed on outdoor stations. While surveys in Norway and Denmark covered in total no more than 45 stations, work done in Finland, Sweden and Poland included more than 300 field stations in total, and for each of the countries lasted for a few years. Thus it was vital for the A10-020 gravimeter to remain reliable during the whole period of gravity control establishment.
In order to assure long term reliability of the instrument specific procedures were implemented including laser, clock and barometer calibration as well as participation in local and international AG comparison campaigns. The offset of the A10-020 from AG campaigns as well as long term stability of metrological components will be presented. Their impact on the realization of gravity reference in the mentioned countries will be discussed. Consistently throughout the whole period of the A10-020 operation gravity surveys were performed on monthly basis at the Borowa Gora Observatory at three separate stations. They provide valuable material for the evaluation of long term gravity variations for assessment the A10-020 performance throughout its operation.
Starting from May 2016, the Borowa Gora Geodetic-Geophysical Observatory is equipped with the iGrav-027 superconducting gravimeter. The current reference function will thus be realized by a combination of the A10-020 and iGrav-027 records, and at the same time will serve as a continuous verification of the A10-020 gravimeter performance for all sorts of gravimetric surveys. Results of first 18 months of simultaneous gravity residual signal of the A10-020 and iGrav-027 will be presented. The impact of annual hydrological variation in the realization of the reference level will be discussed as the sensitivity of the A10-020 gravimeter throughout the years proved to be good enough to reflect the observed and modelled hydrological effect in Poland reaching annual peak to peak variations up to 200 nm/s^2.

1. Introduction

From 2008 to 2015 the A10-020 absolute gravimeter had been used for multiple projects related to modernization and establishment of gravity control. In particular, about 350 stations were surveyed in Finland (~50 stations, 2009-2011), Sweden (~100 stations, 2011-2015), Poland (168 stations, 2012-2015), Denmark (15 stations, 2011), Norway (28 stations, 2011). All are presented in the central figure of the poster (Fig. 1). Single survey campaigns covered from 15 to 35 stations within a 2-3 week time span. About 30 stations from those presented in Figure 1 were surveyed more than once. Measured gravity values were reduced to benchmark level with the use of vertical gravity gradients determined at all stations. Activities related to the modernization of gravity control in Poland included the determination of vertical gravity gradients on all stations (Dykowski and Krynski, 2015). In order to assure the A10-020 reliability within the 7 years of extensive usage multiple activities had to be implemented along with A10-020 surveys in Europe. These major activities are elaborated in the following sections and are listed below:

- Metrological calibrations of the A10-020 gravimeter;
- Participation of the A10-020 in absolute gravimeter comparison campaigns;
- Regular gravity surveys with the A10-020 gravimeter at Borowa Gora Observatory.

Since May 2016, the iGrav-027 superconducting gravimeter was installed at the Borowa Gora Geodetic-Geophysical Observatory that can serve as a gravity variation reference, and together with the A10-020 gravimeter it realizes a continuous gravity reference function. Results up to the end of 2017 are presented in the last section.

2. Metrological calibrations of the A10-020 gravimeter

In order to assure full reliability of the A10-020 gravimeter several periodic control activities have been implemented. The most basic ones concerned calibration of the A10-020 internal components: He-Ne laser (Fig. 2), rubidium oscillator (Fig. 3), and the barometer (Fig. 4). In the period from 2008 to 2015 all three A10-020 components were calibrated at least once per year. Calibrations were performed in multiple National Metrological Institutes as well as associated institutions with relevant infrastructure.

Results of the laser calibrations are shown in Figure 2. The red/blue mode drift appears symmetrically with respect to the central frequency which has a linear trend, and after 7 years becomes smaller than the initial calibration value by ~8 MHz, which corresponds to ~160 nm/s^2 difference in the calculated gravity value. Hence a necessity to monitor laser frequency on regular basis. The sudden shift in red/blue mode frequency after 2014 is a result of the change in internal temperature setting for laser and IB components.

Results of clock calibrations range within 0.015 Hz which corresponds to ~30 nm/s^2 in gravity variation (Fig. 3). Up to 2016 the A10-020 clock shows a regular downward trend. Increase in clock frequency value in 2017 might be caused by small helium exposure of the A10-020 rubidium clock due to the maintenance of the iGrav-027.

The last component to be calibrated for the A10-020 was the internal barometer used for the determination of the barometric correction. Calibrations were done within a maximum expected range of ambient pressure values from 900 to 1100 hPa. As shown in Figure 4, the pressure value offset of the barometer of the A10-020 depends on the actual air pressure value ranging from -1.9 hPa to -3.1 hPa. Within a typical range in which the A10-020 is operated the average offset is around 2.7 hPa which results in a systematic error of ~10 nm/s^2 for the standard barometric correction.

Typically, in the data reprocessing, the calibrated laser wavelength and clock frequencies are interpolated for the epoch of given survey in between two consecutive calibrations and implemented into g software.

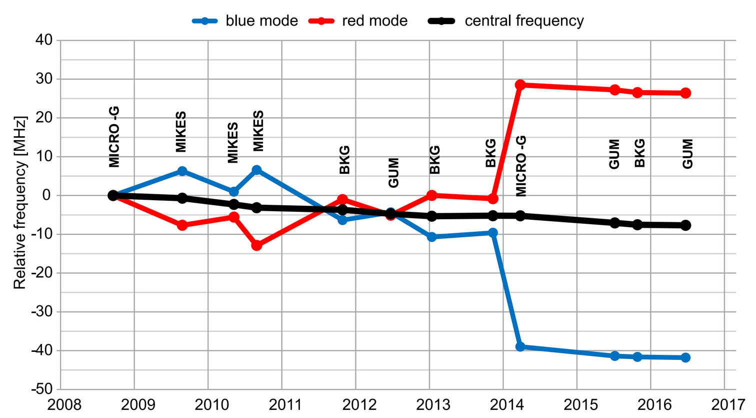

Fig. 2. Results of A10-020 laser calibrations (relative to 1st calibration)

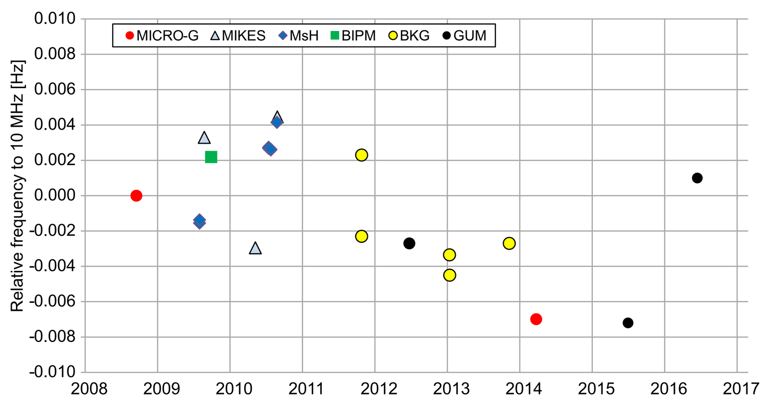

Fig. 3. Results of A10-020 clock calibrations (relative to 10 MHz)

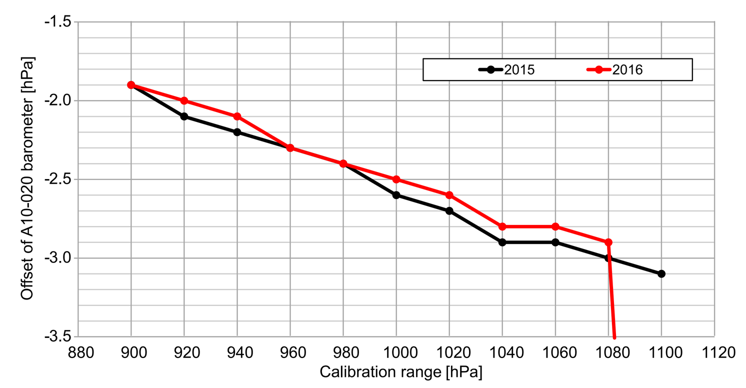

Fig. 4. Results of A10-020 barometer calibrations

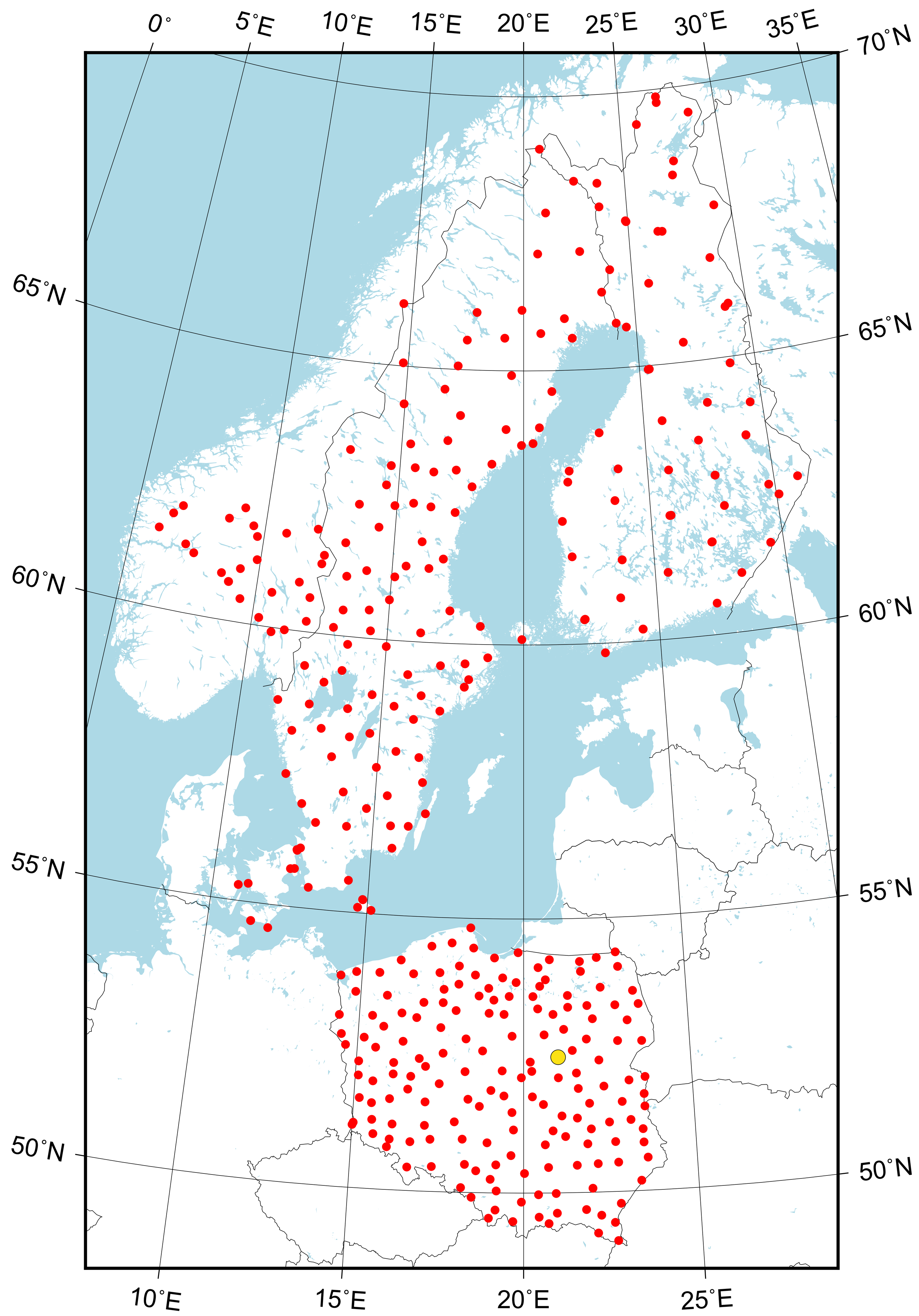

Fig. 1. Gravity stations surveyed with the A10-020 gravimeter within 2008 to 2015

6. Summary

In 2008-2015 the A10-020 absolute gravimeter proved to be a successful tool for the modernization and establishment of gravity controls in Europe, yet it was possible only while implementing specific control procedures listed below:

- Metrological calibration of the absolute gravimeter subcomponents: laser, clock and barometer on the regular basis to monitor drifts of calibrated parameters.
- Link to international gravity reference level via participation in the international absolute gravimeter comparison campaigns (i.e. ICAG/ECAG, regional, local).
- Regular absolute gravity determinations in a known and monitored environment to control the gravimeter behaviour.
- Since 2016, a more comprehensive control of the gravity reference level for the realization of GAGRS can be performed with the use of the A10-020 absolute gravimeter and the iGrav-027 superconducting gravimeter.

References (selected)

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3. International campaigns of absolute gravimeters

Within the years 2008-2015, the A10-020 participated in 4 local AG comparisons in Poland with the FG5-230 of the Warsaw University of Technology. Also 4 times the A10-020 participated in International Comparison of Absolute Gravimeters campaigns (ICAG2009, ECAG2011, ICAG2013, ECAG2015). Results of the comparisons (offset values for the A10-020) for Key Comparison and Pilot Study are shown in Figure 5. The official offset value determined for the A10-020 at ECAG2011 was „modified" as it was considered not fully reliable by the A10-020 operators.
Figure 6 (yellow dots) presents the raw time series of gravity determination with the A10-020 gravimeter on BG-G2 station at the Borowa Gora Geodetic-Geophysical Observatory. Raw results mean corrected for Earth tides (Tamura), ocean loading (FES04), standard barometric correction, polar motion as well as metrological calibrations shown in section 2. The red dots in Figure 6 represent the raw A10-020 results corrected for the offset from the Pilot Study solution of AG comparison campaigns. Offsets of the A10-020 determined during AG comparisons were considered using interpolation when re-computing all observations with the A10-020 between 2008 and 2013. Because of the service of the A10-020, in 2014, the offsets from ECAG2015 were directly used since 2015 on.

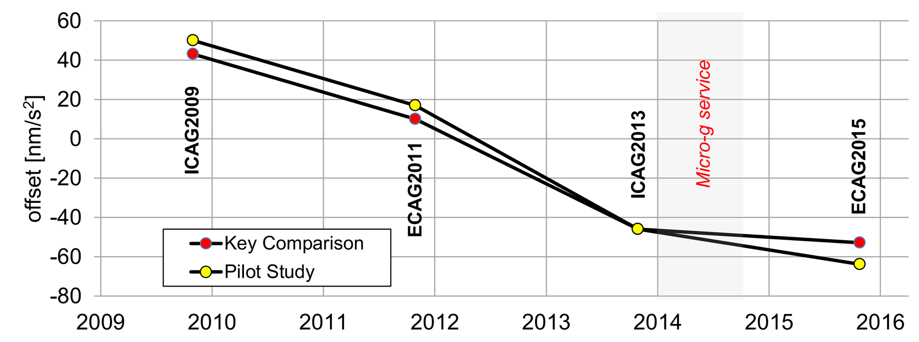

Fig. 5. Results of the participation of the A10-020 gravimeter in ICAG and ECAG campaigns within 2008-2015.

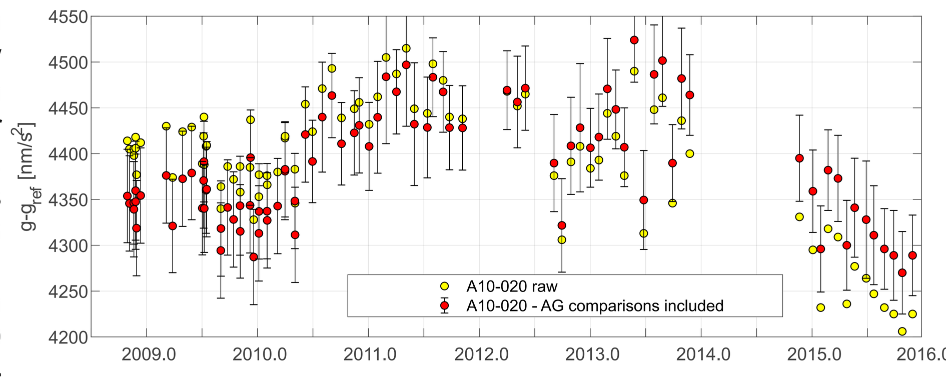

Fig. 6. A10-020 at BG-G2 station raw and including ICAG/ECAG Pilot Study offsets.

4. AG determinations at Borowa Gora Observatory

Regular gravity measurements with the A10-020 on a test network in Borowa Gora Observatory (Fig. 1 - yellow dot), performed in different weather conditions, provides valuable information on the performance of the gravimeter in between its comparisons with other AGs.
The test network consists of three stations, two lab stations and one field station. Regular monthly measurements are conducted following the standard survey scheme used on all gravity control stations across Europe during the surveys with the A10-020. The gravity is measured in at least two independent setups of 8 sets each. Within each set, 120 drops are performed every second. If gravity values from two setups differ by more than 100 nm/s^2 another setup is performed. Figure 7 presents A10-020 results on a lab station BG-G2 along with gravity variation resulting from hydrology - MERRA model (Boy and Hinderer, 2006).
Annual statistics of gravity determinations with the A10-020 at the Borowa Gora Observatory: raw, corrected for ICAG/ECAG offsets, and corrected for hydrology, are presented in Table 1. The application of consecutive corrections improves the results allowing to reevaluate the total uncertainty budget for the A10-020 and proving that it is better than 100-110 nm/s^2 (Dykowski et al. 2014).

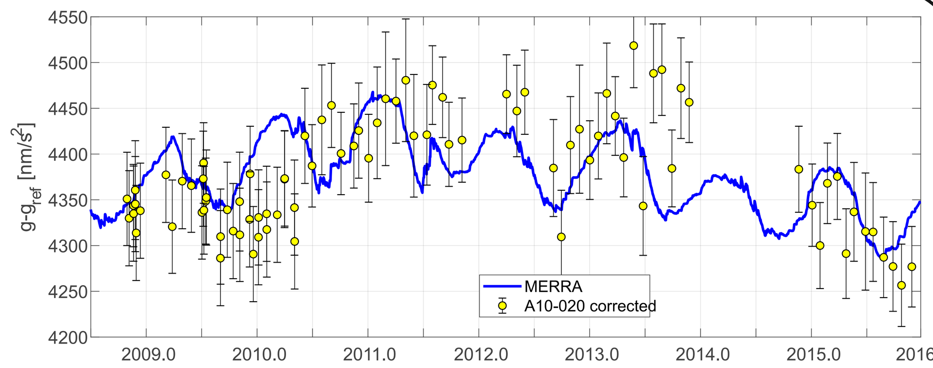

Fig 7. A10-020 at BG-G2 station with MERRA hydrology (2008-2015)

Table 1. Annual statistics of A10-020 at BG-G2 station [nm/s^2]

Year	Raw			+ ICAG/ECAG offsets			+ hydrology (MERRA)		
	Avg	Std	Max-Min	Avg	Std	Max-Min	Avg	Std	Max-Min
2008	4404	13	41	4346	13	41	4366	17	51
2009	4393	32	112	4346	31	109	4349	34	129
2010	4413	45	146	4379	49	152	4334	61	185
2011	4468	30	84	4451	29	89	4401	39	133
2012	4409	58	161	4421	54	150	4417	32	106
2013	4409	50	177	4446	52	175	4434	71	221
2014	-	-	-	-	-	-	-	-	-
2015	4255	37	112	4319	37	112	4353	33	96
all	**4391**	**71**	**309**	**4382**	**61**	**254**	**4373**	**57**	**277**

5. Contribution of Borowa Gora Observatory to the new definition of GAGRS

Since May 2016 the iGrav-027 superconducting gravimeter (Fig. 9) provides high precision gravity records at the BG Observatory (Sekowski et al., 2016). Figure 8 presents the gravimetric laboratory with the location of the iGrav-027 gravimeter as well as pillars for absolute gravity determinations. Three well established monuments allow to perform small scale absolute gravimeter comparisons. Figure 10 presents the A10-020 gravity determinations at BG-G2 station from 2015 until the end of 2017, together with total (local + non local - red in figure) hydrological effect based on the MERRA model (by EOST loading service) along with the iGrav-027 residual signal (blue in figure). Error bars for the A10-020 gravity values are estimated experimental total uncertainties ranging within 50-70 nm/s^2. In general, the agreement of the A10-020 with the iGrav-027 observations is very satisfactory. The standard deviation of gravity determined with the A10-020 with respect to that determined with the iGrav-027 equals to 38 nm/s^2 while resulting from standalone A10-020 result it equals to 65 nm/s^2. The iGrav-027 gravity records have been corrected for Earth tides (from tidal analysis), polar motion, standard atmospheric correction improved by non-local part of the MERRA atmospheric loading (EOST loading service). The drift of the iGrav-027 gravimeter is evaluated with gravity determinations with the A10-020 absolute gravimeter. The evaluated linear term for the iGrav-027 drift does not exceed 50 nm/s^2/year what confirms the expected specification for the instrument.
A combination of co-located the A10-020 absolute gravimeter together with the iGrav-027 superconducting gravimeter allows to monitor and realize the current gravity reference value meeting the basic requirement for the definition of the Global Absolute Gravity Reference System (GAGRS).

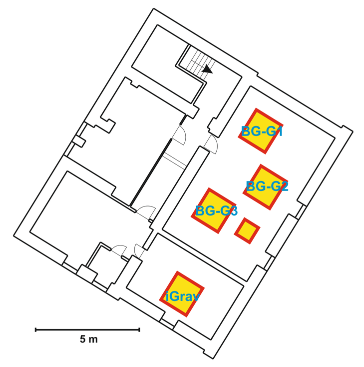
Fig. 8. Gravimetric laboratory at the Borowa Gora Observatory


Fig. 9. The iGrav-027 operational configuration

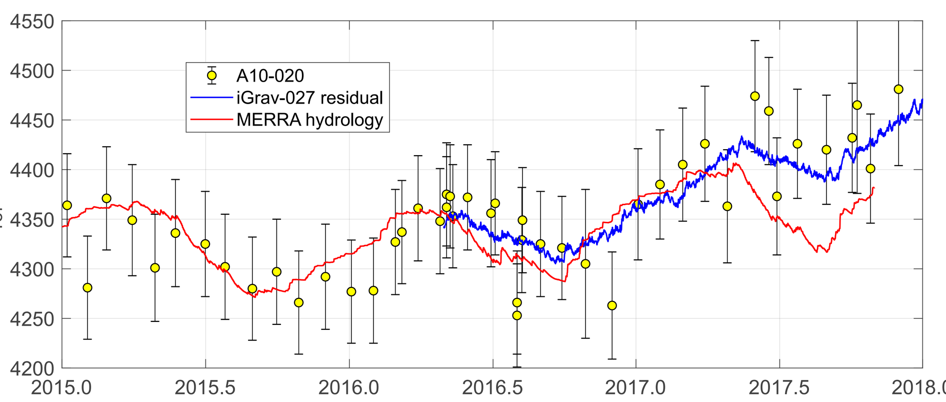

Fig. 10. A10-020 at BG-G2 station with MERRA hydrology (red) and iGrav-027 residual (blue) - period 2015-2017

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