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ORIGINAL ARTICLE

Analysis of the repeated absolute gravity measurements in the Czech Republic, Slovakia and Hungary from the period 1991–2010 considering instrumental and hydrological effects

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Abstract Since August 2001, the absolute gravimeter FG5#215 has been used for the modernization of the national gravity networks of the Czech Republic, Slovakia, and Hungary. Altogether 43 absolute stations were measured, some of them repeatedly. Absolute gravity at 29 stations had already been determined in 1990s by other absolute gravimeters (FG5 or JILAg). Differences of repeated measurements at most of the stations show an unexpected decrease of gravity (up to 22 µGal) over the whole region. An uncertainty assessment of absolute measurements with a special emphasis put on hydrological effects shows a statistical significance of the detected gravity variations at many stations. In this manuscript, three possible reasons of such findings are discussed: (1) a regional geodynamic activity, (2) systematic instrumental errors (offsets), (3) hydrological effects. The analysis and statistics of the gravity differences in context of international comparisons of absolute gravimeters show offsets up to 9 µGal related to data of the JILAg-6 and FG5#107 gravimeters. Data collected in this study demonstrate that considering instrumental and hydrological effects on gravity are crucial for a correct interpretation of repeated absolute gravity measurements.

Keywords Gravity acceleration · Absolute gravimeter · Offset · Uncertainty · Hydrological effects

1 Introduction

Contemporary absolute gravimeters (AGs) reach a typical precision of a few µGal in determination of the absolute value of the gravity acceleration. Thus, the AGs are capable of detecting geodynamic signals related to the postglacial rebound (Lambert et al. 2001; Williams et al. 2001; Timmen et al. 2011), vertical displacements due to crustal motions, as demonstrated for some stations in Zerbini et al. (2001) and Van Camp et al. (2011) or global variations of the gravity field due to the hydrological cycle (Hinderer et al. 2009).

The main limitations of infrequently repeated absolute gravity measurements, performed with different instruments, are due to offsets between the AGs and local hydrological effects. Neglecting these items may lead to misinterpretation of the repeated measurements by detecting unrealistic or

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apparent effects of regional geodynamics and, consequently, to depreciation of the capacity of this technique for geodynamic research.

The repeated absolute gravity measurements, the results of which are discussed in this text, were primarily performed with the goal of improving gravity reference frames of the national gravity networks of the Czech Republic, Slovakia and Hungary. All measurements collected for the period of about 20 years can be grouped into two parts: (1) measurements with FG5 and JILAg gravimeters till 2001, and (2) measurements with the FG5#215[1] in the period 2001–2010. Resulting gravity differences obtained at 29 stations, which reach values of up to 22 µGal, are analyzed. This contribution aims at investigation of hydrological and instrumental effects, which may occur in AG measurements performed with different instruments and at different epochs of the year to monitor gravity changes.

2 Accuracy in absolute gravimetry

At present, the most precise transportable absolute gravimeter is the FG5 (Niebauer et al. 1995) of Micro-g LaCoste, Inc. According to Niebauer et al. (1995) a large number of effects has to be taken into account to describe the accuracy of FG5s reliably. Some of them, e.g. diffraction effect (van Westrum and Niebauer 2003; Robertsson 2007), test mass rotation (Rothleitner and Francis 2010), electronic phase shift (Niebauer et al. 1995) or the self attraction effect (Robertson 1996), have a character of systematic errors. They can be different even for the same type of instrument, and cause biases of gravimeters. An offset of an AG is defined as a mean difference with respect to the gravity reference. Due to unknown true gravity values, gravity references and offsets must be periodically determined by means of the international comparisons of absolute gravimeters (ICAGs), see de Viron et al. (2011). The last ICAGs held in Sèvres (Vitushkin et al. 2002; Jiang et al. 2011) and Walferdange (Francis et al. 2004, 2010) show the following standard deviations of offsets for the FG5 gravimeters: 4.3 µGal (Sèvres 2001), 1.8 µGal (Walferdange 2003), 3.2 µGal (Sèvres 2005), 2 µGal (Walferdange 2007). The ICAG's results clearly demonstrate that offsets of AGs are very important error sources in current absolute gravity measurements and that ICAGs allow for their determination with the precision of 1 µGal. Based on the results of the last ICAGs and estimated uncertainties of AGs (Jiang et al. 2011), the standard uncertainty (JCGM 2008) of the FG5 gravimeters, which includes all errors associated with gravity determination, is represented by the value of 2.5 µGal.

Another possibility, how to check or determine AG offsets, is to carry out repeated measurements at a reference station equipped with a superconducting gravimeter (SG), see, e.g. Wziontek et al. (2008). Such a reference station can be very helpful for avoiding weak points of both techniques: offset changes of the AG and the instrumental drift of the SG. Of course, in order to determine the offsets, it is very important that a sufficient number of AG measurements are tied to the system of international comparisons. The offset of an AG should mainly be checked after a repair, replacement of important parts of the AG or after a significant adjustment of the gravimeter. The reference station plays a key role, e.g. in geodynamic studies in case that only one gravimeter is used (Van Camp et al. 2011). It helps to monitor possible offset changes, so to ensure the correctness of AG measurements performed at several stations throughout decades. From that point of view, the long-term reproducibility can be understood as a parameter which describes the degree of consistency of an AG after several years. The reproducibility is defined (JCGM 2008) as a closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. It includes random errors (e.g. setup error, errors of applied corrections for tides or atmosphere) but also errors which may cause systematic effects over a few months (e.g. in connection with the interferometer alignment, such as collimation or fringe size effect). The results published in Van Camp et al. (2005), Rosat et al. (2009), and Pálinkáš et al. (2010) indicate that the long-term reproducibility of the FG5 gravimeter is better than 1.6 µGal. However, long-term systematic errors (constant over long period, e.g. diffraction, rotation of the test mass) of AGs are not included in this parameter. Thus, the uncertainty of an AG has to be larger than its long-term reproducibility.

3 Reduction of hydrological effects on gravity

Global and local water storage variations have an important impact on gravity measurements. Therefore, for reliable estimates of vertical deformations from repeated AG measurements, corrections for hydrological mass variations should be applied. While global hydrological effects can be estimated from relevant models the more significant local hydrological effects are much more difficult to model. Consequently, the uncertainty due to unknown local hydrology has to be included in the analysis of the repeated AG measurements.

In case of global hydrological effects, as shown in Wahr et al. (1998) or Ramillien et al. (2008), especially continental water storage variations are very important. For estimation of gravity effects (sum of the Newtonian attraction and loading effects) of water masses the Water GAP Global Hydrology Model (WGHM, Döll et al. 2003) has been used, according

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[1] Gravimeter of the Center for Earth Dynamics Research, operated by the Research Institute of Geodesy, Topography and Cartography, Czech Republic.

to Pálinkáš et al. (2010). The results show, that it is possible to approximate the continental hydrological effect over the region under study by a harmonic function with the amplitude of 1.8 μGal and the maximum gravity at the beginning of March, since the differences between such a representation and the time series computed from the WGHM are less than 0.5 μGal.

The comparisons of GRACE data, hydrological models and terrestrial observations (AG and SG) in Boy and Hinderer (2006) or Weise et al. (2009) show a strong correlations with significant discrepancies in amplitudes due to terrestrial observations affected by the local hydrology. Numerous studies, such as Virtanen (2001), Van Camp et al. (2006), Meurers et al. (2007), Naujoks et al. (2009), Longuevergne et al. (2009), Creutzfeldt et al. (2010), or Lampitelli and Francis (2010) show that it is very difficult to model the local hydrological effects, ranging between 0 and 16 μGal peak to peak for European SG stations. The corrections due to local hydrology cannot usually be applied at the stations with AG measurements, because here neither hydrological measurements nor hydrogeological studies are available. The above-mentioned studies state that the local effects also contain an important seasonal term. From the time series of SGs in Europe (Weise et al. 2009; Van Camp et al. 2010), clear seasonal gravity variations can be seen for ground stations (Wettzell, Medicina, Bad Homburg, or Pecný in this study), while for underground stations (Membach, Moxa, Strasbourg, Vienna), the seasonal signal is attenuated. It can be caused by compensation of the gravity effect of variable water masses distributed below and above the instrument, or, it may also be due to opposite phases of the large-scale and local hydrological effects at these stations. In case of a ground station, where hydrological variations run below the instrument, an amplification of seasonal variations can be expected due to in-phase effect of local and large-scale hydrological variations in Europe.

4 Absolute gravity measurements and the analysed data

The subject matter of this study are the absolute gravity measurements that were carried out with two types of free-fall gravimeters, JILAg and FG5. The free-fall acceleration is determined by measurements of positions (distances) and corresponding times during the free-fall of a corner cube and by consequent solving the equation of motion. According to Niebauer et al. (1995), the equation has the following form

$$z(t) = z_0 + v_0\left(t + \frac{\gamma}{6}t^3\right) + \frac{1}{2}g_0\left(t^2 + \frac{\gamma}{12}t^4\right), \qquad (1)$$

where z_0, v_0 and g_0 are the initial position, velocity and a free-fall acceleration at time $t = 0$, γ is the vertical gravity gradient determined by relative gravimeters. The gravity acceleration is obtained by correcting the free-fall acceleration for Earth tides (considering the zero-tide system) and polar motion (with respect to the IERS pole) in compliance with the International Earth Rotation and Reference Systems Service (IERS) conventions given by McCarthy et al. (2004). The effect of atmospheric mass variations are usually corrected using the barometric admittance factor of −0.3 μGal/hPa and the difference between the measured and normal atmospheric pressure at the station (Merriam 1992). Finally, the gravity acceleration should be transferred to the reference height (Timmen 2003) of an AG (cca 1.2 m above a benchmark for FG5), in order not to loose accuracy due to uncertainty of the vertical gravity gradient.

4.1 Absolute gravity measurements before 2001

Until 2001, 41 absolute measurements at 29 selected stations (11 in the Czech Republic, 9 in Slovakia and 9 in Hungary, which were later remeasured with the FG5#215), had been carried out using 5 different gravimeters:

- **JILAg-5**, Finnish Geodetic Institute (FGI), Finland,
- **JILAg-6**, Bundesamt für Eich- und Vermessungswesen (BEV), Austria,
- **FG5#101**, Bundesamt für Kartographie und Geodäsie (BKG), Germany,
- **FG5#107**, Defense Mapping Agency (DMA), USA,
- **FG5#206**, Institut de Physique du Globe de Strasbourg (IPGS), France.

At the ICAG-1994 comparison measurements held in Sèvres (Marson et al. 1995), biases up to 14 μGal were detected for FG5 and for some of JILAg AGs. The error dependent on the amplitude of the interference signal was detected and evaluated in Niebauer et al. (1995). With regards to these findings all older measurements were reprocessed by their authors considering the above mentioned results. In case of the FG5#101 and #206, the bulk interferometers were replaced by the fiber model in 2000 and 2002, respectively. The measurements discussed in this text are related to the FG5s equipped with the bulk type of interferometer, except for two measurements with the FG5#101 in 2000. In the evaluation of gravity differences Δg, the final results of measurements accomplished till 2001 are labeled $g_{(\mathrm{old})}$. The data do not include two measurements performed before 1994 in Budapest (with the JILAg-6 and the FG5#107). These measurements are affected by local effects associated with mining works (mainly the water pumping from the karst aquifer) near to the underground absolute station.

4.2 Absolute gravity measurements with the FG5#215 from 2001 to 2010

The FG5#215 gravimeter, manufactured in 2001, was used for absolute measurements at 43 stations in the Czech, Slovak, and Hungarian gravity networks from 2001 to 2010. At least one measurement was performed at each of the 29 stations mentioned in Sect. 4.1.

Except for the corrections mentioned in Sect. 4 the effect of interference fringes according to Pálinkáš (2007), where the relation between results of the FG5#215 and fringe sizes was described by the linear term of 1.5 μGal/100 mV, has been applied to the results. The fringe correction is computed from the difference between the reference fringe value of 300 mV and the average fringe size during the measurements. All the measurements with the FG5#215 were carried out with fringe sizes in the range from 170 to 390 mV, depending mainly on the laser power and the rotation of the Faraday isolator. An effect of both is tested in Pálinkáš (2007), where a necessity of additional fringe corrections is shown.

The nominal accuracy of the observed quantities (distance and time) at the uncertainty level better than 10^{-10} was ensured by regular calibrations of the laser (5 times in 10 years) and rubidium clock (4 times per year). During each measurement, the FG5#215 barometer is compared with a more accurate and regularly calibrated barometer.

In the evaluation of gravity differences Δg, the final results accomplished with the FG5#215 are labeled $g_{(\mathrm{FG5\#215})}$. Note, that all gravity data were transferred to the level of 1.2 m above the benchmark using the same vertical gravity gradients at particular stations for both epochs of absolute measurements ($g_{(\mathrm{FG5\#215})}$ and $g_{(\mathrm{old})}$).

4.3 Differences between repeated measurements

This section focuses on the gravity differences between two epochs of absolute measurements $\Delta g = g_{(\mathrm{FG5\#215})} - g_{(\mathrm{old})}$ at 29 stations. The differences are listed in Table 1. Regarding the fact, that only 6 stations were measured more than once before 2001, it contains altogether 39 differences. Of this number, 19 differences are related to the JILAg-6, 13 to the FG5#107, 4 to the FG5#201, 2 to the FG5#206 and 1 to the JILAg-5. The geographical distribution of the differences is displayed in Fig. 2. The stations Pecný, Polom, Žilina, Gánovce, Modra and Liesek were repeatedly observed by the FG5#215. In those cases, the gravity differences in Table 1 are related to the average values. Gravity residuals are shown in Fig. 3.

The above-discussed harmonic function with the amplitude of 1.8 μGal was used to correct gravity differences Δg for the continental hydrological effects at the stations. The differences $\delta g_{\mathrm{hydro}}$ between continental effects related to two epochs (before and after 2001) of absolute measurements at particular stations are in Table 1. Then, the corrected differences are $\Delta g_h = \Delta g - \delta g_{\mathrm{hydro}}$.

Generally, the differences in Table 1 and Fig. 2 show an unexpected gravity decrease (up to 22 μGal) at most of the stations over the whole region. By contrast with these findings, no gravity decrease can be seen at any station repeatedly measured by the FG5#215, see Fig. 3.

Applying a hydrological correction using the harmonic function with amplitude of 1.8 μGal, thus without the contribution from local hydrology, brings only a very small improvement of the final result. Nevertheless, a large difference from the continental hydrology shows that the repeated measurements are related to the hydrological extremes (maxima in Spring and minima in Fall), when the in-phase effect from local and continental hydrology contribution can be expected, for the ground stations in Europe, see Sect. 3. Thus, the complete hydrological effect may significantly influence the gravity differences; it will be analysed in Sect. 6.3. It is the case of the stations Gánovce, Modra, Žilina and Kőszeg (related to JILAg-6 measurements in 1993), where the $\delta g_{\mathrm{hydro}}$ correction is higher than 3 μGal, see Table 1. The statement concerning the in-phase effect is supported by the fact, that after applying the $\delta g_{\mathrm{hydro}}$ correction all gravity differences at mentioned stations are smaller in absolute values. From all the discussed stations only Polom and Budapest are typically underground stations.

The analysis and explanation of a clear systematic tendency in gravity differences will be done in Sect. 6 after an uncertainty assessment of the gravity differences has been performed.

5 Estimation of uncertainties

For the evaluation of statistical significance, an uncertainty assessment of the discussed gravity differences is essential. Therefore, the following contributions to the uncertainty should be taken into account: (1) instrumental errors including errors of additional corrections for the tides, atmosphere and polar motion, (2) transfer errors due to different reference instrumental heights of AGs, (3) environmental error sources, where a contribution from an unknown local hydrology plays the most important role.

Recalling the statements of Sect. 2, the standard uncertainty of the FG5 gravimeters is characterized by the value of $u_{\mathrm{FG5_I}} = 2.5\,\mu\mathrm{Gal}$. However, a lower accuracy has to be considered for FG5 measurements before 1995 since an important modification of the photodetector circuit board was made after 1995 (Niebauer et al. 1995). Taking into account uncertainties presented in Marson et al. (1995), Robertsson et al. (2001), and Timmen et al. (2008), the uncertainty $u_{\mathrm{FG5_{II}}} = u_{\mathrm{JILAg}} = 5\,\mu\mathrm{Gal}$ was used for the older measurements with the FG5 instruments ($\mathrm{FG5_{II}}$—equipped with the old type of comparator on the photodetector circuit board) and also for all measurements with the JILAg gravimeters. The same uncertainties were adopted for both instruments in spite of the fact, that the JILAg gravimeters are much more sensitive to tilts (Niebauer et al. 1995) and biases due to the tilt coupling may arise.

Table 1 List of repeated absolute gravity measurements before and after 2001 ($g_{\text{(old)}}$ and $g_{\text{(FG5\#215)}}$) at the date shown in third and fifth columns of the table with corresponding gravity differences $\Delta g = g_{\text{(FG5\#215)}} - g_{\text{(old)}}$

Station	State	Date	Instrument	Date FG5#215	Δg (µGal)	δg_{hydro} (µGal)	Δg_h(µGal)
Benešov n. Č.	CZ	19.10.1995	JILAg-6	30.7.2002	−6.4	−0.3	−6.1
Jeseník	CZ	23.11.1999	JILAg-6	22.6.2004	−7.2	−0.3	−6.9
Jihlava	CZ	25.11.1999	JILAg-6	17.6.2004	**−21.0**	−0.3	**−20.7**
Kraslice	CZ	17.11.1995	FG5#101	15.6.2004	−8.3	0.0	−8.3
Kvilda	CZ	18.10.2001	JILAg-6	14.7.2005	1.4	0.1	1.3
Litoměřice	CZ	17.10.1995	JILAg-6	16.7.2002	−8.0	0.0	−8.0
Pecný	CZ	11.2.1992	JILAg-6	28.10.2005*	2.5	−1.8	4.3
Pecný	CZ	21.2.1995	FG5#101	28.10.2005*	−3.0	−1.9	−1.1
Pecný	CZ	12.9.1993	FG5#107	28.10.2005*	−1.4	1.6	−3.0
Pecný	CZ	20.11.2000	FG5#206	28.10.2005*	1.3	0.2	1.1
Pecný	CZ	6.12.1998	JILAg-5	28.10.2005*	−0.6	−0.3	−0.3
Plzeň	CZ	16.10.2001	JILAg-6	12.7.2005	**−20.0**	0.1	**−20.1**
Polom	CZ	8.9.1993	FG5#107	21.9.2008*	−3.1	1.6	−4.7
Svitavy	CZ	8.11.1998	JILAg-6	24.6.2004	**−15.9**	0.0	**−15.9**
Valtice	CZ	22.10.1995	JILAg-6	8.4.2003	−3.4	2.6	−6.0
Banská Bystrica	SK	27.6.1996	FG5#107	28.9.2005	−7.4	−0.8	−6.6
Bardejov	SK	22.9.1994	FG5#107	9.10.2003	**−13.0**	0.2	**−13.2**
Bardejov	SK	29.6.1996	FG5#107	9.10.2003	−12.0	−0.6	−11.4
Bratislava	SK	3.9.1993	FG5#107	27.9.2005	**−18.4**	0.1	**−18.5**
Gánovce	SK	8.3.1993	JILAg-6	20.8.2007*	**−14.0**	**−3.2**	−10.9
Hurbanovo	SK	29.9.1994	FG5#107	18.9.2004	**−13.7**	−0.2	**−13.5**
Liesek	SK	23.6.1996	FG5#107	18.5.2008*	−5.6	−0.6	−5.0
Modra	SK	10.3.1993	JILAg-6	22.12.2007*	−6.9	**−3.2**	−3.7
Modra	SK	7.6.2000	JILAg-6	22.12.2007*	**−12.9**	−1.2	**−11.7**
Modra	SK	15.8.2000	FG5#101	22.12.2007*	4.0	0.3	3.7
Plešivec	SK	19.6.1996	FG5#107	30.9.2005	−10.6	−1.0	−9.6
Žilina	SK	4.3.1993	JILAg-6	7.10.2005*	**−21.4**	**−3.2**	**−18.2**
Budapest	HU	28.5.1996	FG5#107	24.5.2007	1.2	0.1	1.1
Budapest	HU	11.8.2000	FG5#101	24.5.2007	3.7	1.9	1.8
Debrecen	HU	23.11.2001	JILAg-6	10.10.2008	−9.4	−1.1	−8.3
Iharosberény	HU	6.10.1994	FG5#107	3.6.2010	−4.6	1.5	−6.1
Kőszeg	HU	4.5.1993	JILAg-6	7.10.2008	**−18.2**	**−3.2**	**−15.0**
Penc	HU	26.11.2000	FG5#206	26.5.2007	**−9.6**	0.4	**−10.0**
Siklós	HU	12.12.1991	JILAg-6	22.5.2007	−7.9	0.1	−8.0
Siklós	HU	6.4.1995	JILAg-6	22.5.2007	−6.6	−1.1	−5.5
Sóskút	HU	20.11.2001	JILAg-6	4.6.2010	−6.7	0.3	−7.0
Szecsény	HU	23.7.1993	FG5#107	25.5.2007	−4.9	1.7	−6.6
Szecsény	HU	3.6.1996	FG5#107	25.5.2007	1.1	0.3	0.8
Zalalövő	HU	10.12.1997	JILAg-6	8.10.2008	0.8	−1.7	2.5

δg_{hydro} represents differences between continental hydrological effects related to two epochs of measurements—corrected gravity differences are $\Delta g_h = \Delta g - \delta g_{\text{hydro}}$. Gravity differences exceeding the margin of error at 95 % confidence (see Sect. 5) are highlighted in bold and so are δg_{hydro} higher than 3 µGal (it indicates that the gravity difference is computed from measurements carried out in epochs of hydrological maxima-minima). "$*$" means that an average gravity value computed from repeated measurements of the FG5#215 (see Fig. 3) has been used—followed by the average date of measurements

The uncertainty of the vertical gravity gradient has to be considered in order to transfer properly measured gravity from the reference height of the instrument to an arbitrary reference level (reference level of a gravity network, comparison, etc.). If the repeated measurements are performed using the same type of instrument and if the gradient is stable in

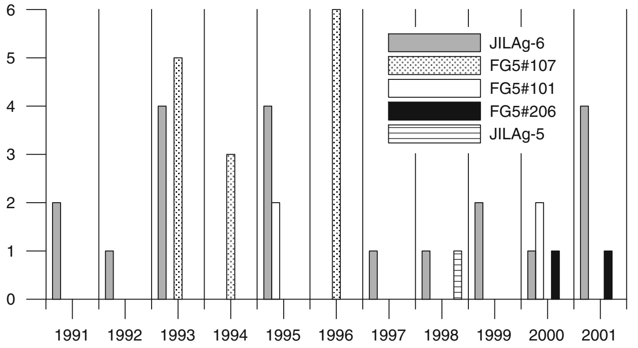


Fig. 1 Number of absolute gravity measurements $g_{(\mathrm{old})}$ carried out by different gravimeters before 2001

time, the gradient error cancels out and the gravity differences between individual epochs are not affected. But this requirement is not fulfilled if we compare the results of the JILAg and FG5 gravimeters. In this case, the gradient uncertainty of ±5 µGal/m was considered at 0.4 m, which corresponds to the difference between the effective heights (Niebauer 1989) of both instruments. Consequently, the uncertainty of gravity difference between FG5 and JILAg meters has to be enlarged for $u_\gamma = 2\,\mu$Gal.

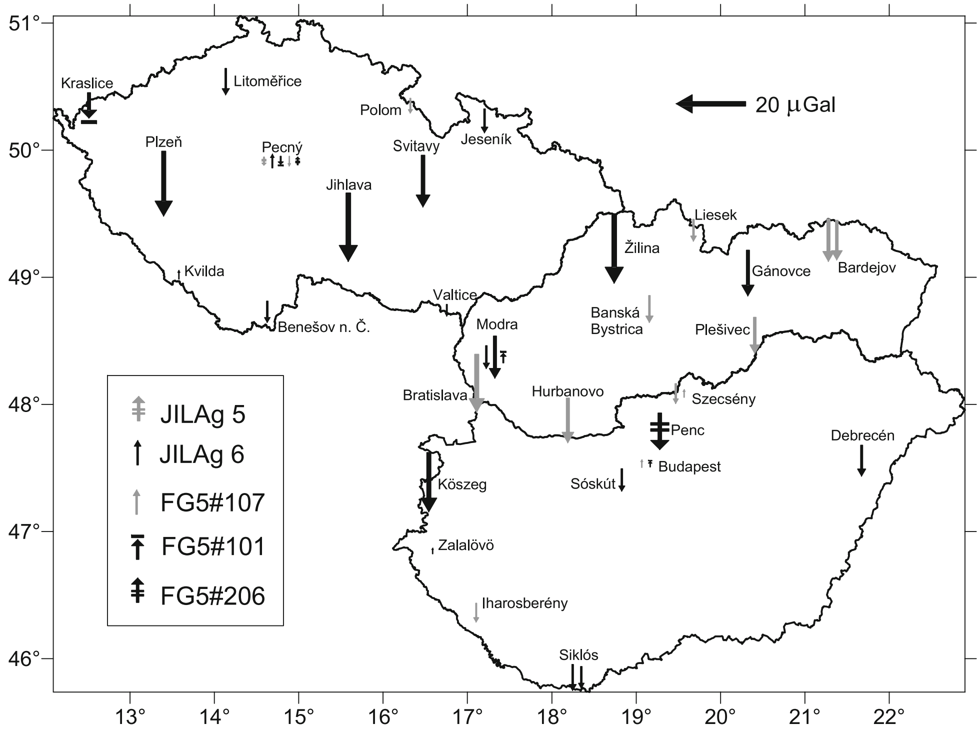
With regard to Sect. 3, where hydrological variations up to 16 µGal (peak to peak) for European SG stations were discussed, the additional uncertainty of $u_{\mathrm{hydrology}} = 3\,\mu$Gal was used for evaluation of errors coming from the local hydrology. If we assume the normal distribution of the hydrological parameters at 99 % confidence level, then, statistically, we can expect gravity variations within the range of 15 µGal. However, we have to say that this approach is critical. The local hydrological effects at the discussed stations are, of course, very different and generally they are not related to the SG stations which were used for the uncertainty estimate. Moreover, the assumption of normal distribution for the local effects is also questionable. Therefore, the treatment of the local hydrology in this study should be understood as an attempt to take it into account even though no relevant information is available.

Finally, we can estimate the uncertainties of the analysed gravity differences depending on the compared instruments. The following three cases were considered supposing the normal distribution of errors:

- FG5#215 versus other FG5 (equipped with the new type of comparator)
  $u_{\mathrm{I}} = (u^2_{\mathrm{FG5_I}} + u^2_{\mathrm{FG5_I}} + u^2_{\mathrm{hydrology}})^{1/2} = 4.6\,\mu\mathrm{Gal}$,
- FG5#215 versus other FG5 (equipped with the old type of comparator)
  $u_{\mathrm{II}} = (u^2_{\mathrm{FG5_I}} + u^2_{\mathrm{FG5_{II}}} + u^2_{\mathrm{hydrology}})^{1/2} = 6.3\,\mu\mathrm{Gal}$,
- FG5#215 versus JILAg
  $u_{\mathrm{III}} = (u^2_{\mathrm{FG5_I}} + u^2_{\mathrm{JILAg}} + u^2_\gamma + u^2_{\mathrm{hydrology}})^{1/2} = 6.7\,\mu\mathrm{Gal}$.

The margin of error at 95 % confidence $U = 2u$ are used for detection of outliers among the gravity differences in Table 1.

Fig. 2 Gravity differences Δg between absolute measurements with the FG5#215 and measurements carried out before 2001 with different types of gravimeters



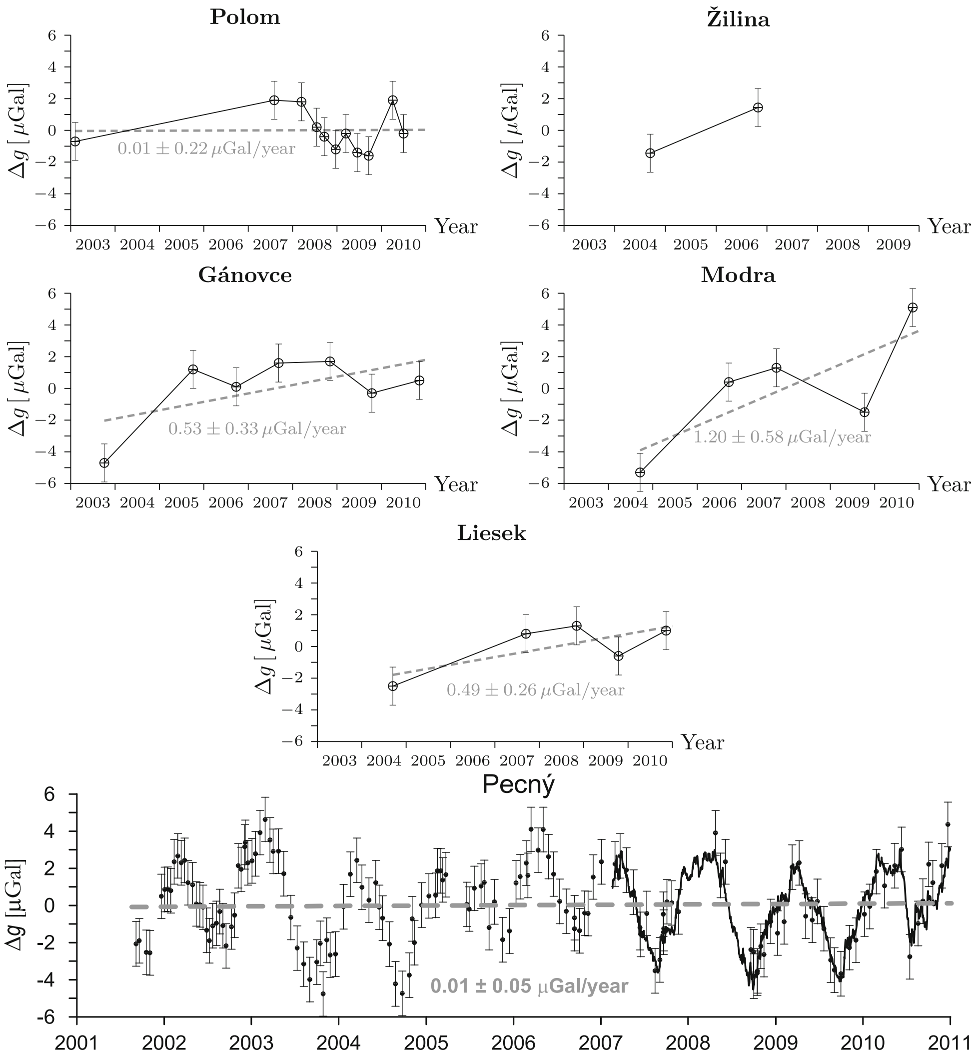


Fig. 3 Gravity variations at the stations repeatedly measured with the FG5#215 after 2001, *error bars* of 1.2 μGal represent the long-term reproducibility of the FG5#215 determined at the Pecný station by comparison with the superconducting gravimeter OSG-050. The *solid line* at Pecný station represents the drift-free OSG-050 time series. The *dashed lines* show linear fits of gravity variations with numerical rate estimates

6 Analysis of the gravity differences

The gravity differences at the various stations are given in Table 1 and their geographical distribution is shown in Fig. 2. Systematic features clearly appear:

- differences are mostly negative (31) and only positive at 8 stations,
- 11 differences (28 %) can be declared as statistically significant at the confidence level of 95 %,
- using the weights $1/u^2$, the weighted average of all differences Δg and Δg_h (after applying corrections for continental hydrology) is -6.6 ± 1.2 μGal and -6.4 ± 1.1 μGal, respectively. The averages show statistically highly significant non-zero values.

To find the reason for these systematic effects, three possible important sources will be discussed: (1) regional geodynamics manifesting itself as vertical crustal movements of the region (Van Camp et al. 2011), (2) instrumental effects, such as offsets of AGs not taken into account in the error budget, (3) unmodeled hydrological effects.

6.1 Review of geodynamic activities in the region

The studied area includes three geological units—Bohemian Massif, Western Carpathians, and Pannonian Basin. The rates of the vertical surface movements in Central Europe were determined in Vyskočil (1994) based on the analysis of repeated levellings from 1945 to 1975. The results of this study can be summarized as follows: (1) The most important vertical deformations can be expected in the Pannonian Basin, specifically in the West–East direction, where the Eastern part show rates up to −2 mm/year and the Western part up to +2 mm/year, (2) In the Bohemian Massif and Western Carpathians the expected rates are within 1 mm/year. The accuracy of these characteristics is estimated to be of about 1 mm/year over the distance of 300−500 km (Vyskočil 1994). Of course, due to the well-known accumulation of pseudo-random errors in levelling networks, it will be difficult to detect small vertical movements over larger distances.

To discuss the results of the repeated gravity measurements in the context of vertical deformations, a factor of $-0.2\,\mu$Gal/mm is used according to Williams et al. (2001). Note that in this case, the accepted value of the gradient (ranging from $-0.1\,\mu$Gal/mm to $-0.26\,\mu$Gal/mm, see Van Camp et al. 2011) does not play an essential role for further interpretations. The average gravity change of $-6.4 \pm 1.1\,\mu$Gal during 9.4 years (average time-span of the repeated observations), should correspond to the gravity decrease with the rate of $-0.7\,\mu$Gal/year. Consequently, a regional uplift of 3–4 mm/year could be expected. Such a hypothesis has no support in existing studies dealing with the vertical crustal deformations of the territory under study.

An independent information on the vertical rates can be obtained from the time series of GNSS observations provided by the permanent stations of the EUREF Permanent Network (EPN), (Bruyninx 2004). The estimates of the trend are uncertain at the level of 2 mm/year due to uncertainties in the centre of mass of the Earth and ITRF instabilities (Altamimi et al. 2007). Two different rates determined in two methodologically diverse ways are represented in Fig. 4: (1) vertical rates in ITRF05 for EPN stations in the discussed region, (2) vertical rates derived from repeated absolute gravity measurements. The results show (Fig. 4) a ratio of about ten between these two solutions. Considering uncertainties coming from the EPN solution and results of repeated levellings we can infer that the gravity measurements provide unrealistic rates. A hypothesis about a significant gravity decrease in the region has to be rejected also with regard to the results of repeated absolute measurements using FG5#215 at six stations, see Fig. 3. These time series show no gravity decrease at any station. However, these time series are too short (except Pecný) to provide reliable trend estimates.

All these results justify the assumption that the decreasing gravity values detected by the repeated AG measurements may be induced either by the AG offsets or by hydrological effects or by a combination of both.

6.2 Offsets of AGs

The absolute gravimeter FG5#215 took part in four international comparisons which provided the following offsets:

- Walferdange 2003 (Francis et al. 2004) $-0.9\pm1.0\,\mu$Gal, (decrease to $-0.3 \pm 1.0\,\mu$Gal when the fringe size correction is applied, according to Pálinkáš (2007))
- ICAG-2005 (Jiang et al. 2011) $0.0 \pm 1.1\,\mu$Gal,
- Walferdange 2007 (Francis et al. 2010) $-0.8\pm0.9\,\mu$Gal,
- ICAG-2009 $0.8 \pm 1.4\,\mu$Gal.

The offsets of the FG5#215, that have been obtained up to now, do not show significant non-zero values so that additional corrections for offsets were not applied. The offset variation of the gravimeter has been monitored at the Pecný reference station since 2001 (see Fig. 3), since 2007 with the support of the superconducting gravimeter. The results of the intercomparisons and of the repeated measurements at the reference station allow us to assume that the FG5#215 offset has been below $2\,\mu$Gal since 2001. Therefore, the gravimeter FG5#215 has been used as a reference gravimeter for the following analysis. Now, let us assume that no real gravity variations due to hydrology and geodynamics exist. Then, the gravity differences ($\Delta g = g_{(\mathrm{FG5\#215})} - g_{(\mathrm{old})}$) would reflect the offsets of other gravimeters. Consequently, the differences should be comparable with the offsets determined in the international comparisons. Such a comparison for individual gravimeters is illustrated in Figs. 5, 6, and 7. The evaluated differences with respect to the determined uncertainties along with the average gravity differences for individual gravimeters are given in Table 2. The results clearly indicate systematic effects in differences if the results of the FG5#215 are compared with the results of the JILAg-6 and FG5#107 gravimeters. From both comparisons, a significant dominance of negative differences and significant average gravity differences with respect to the standard deviations are evident. In an ideal case, an informative value of the comparisons of gravity differences and offsets could be raised by performing more frequent observations around the dates of ICAG campaigns to mitigate the influence of possible gravimeter offset variations which can happen after more important interventions, like the maintenance or repair of the instrument.

The gravity differences for the JILAg-6 gravimeter in Fig. 5 show surprisingly consistent results even for 11 years of measurements with significant and reliable negative differences in the years 1993, 1995, 2000, and 2001 when at least three measurements are available. Both the overall average difference of $-8.7 \pm 1.7\,\mu$Gal and especially the average gravity value of $-11.2 \pm 3.5\,\mu$Gal computed from six measurements from the period 2000–2002 correspond very well with the significant offset of the JILAg-6 gravimeter ($-10.1 \pm 2.5\,\mu$Gal) detected in the ICAG-2001. A disagreement with the results of the ICAG-1997 and ICAG-1994 can be seen from Fig. 5. It can be caused by (1) year by year offset variations which cannot be reliably compared with the gravity differences due to insufficient number of observations in corresponding years, (2) JILAg-biased CRVs due to their more significant contribution to the ICAGs 1994–1997, (3) the fact the JILAg instruments can be biased due to the tilt coupling (Niebauer et al. 1995). The tilt coupling errors are highly site-dependent and in case of a poor site stability (e.g. the site A in the BIPM where the ICAGs were carried out until 1997) they might play a major role. It is interesting that the same offset of $-9\,\mu$Gal was also determined

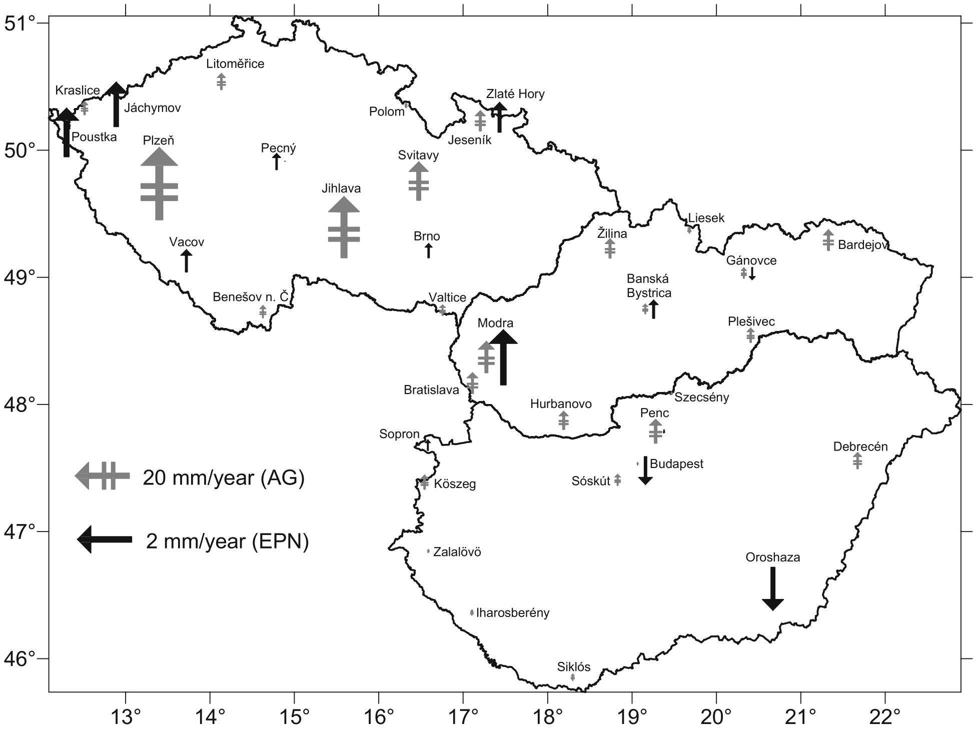


Fig. 4 Vertical rates computed from (1) repeated AG measurements using a factor of −0.2 µGal/mm to convert gravity changes into vertical deformation rates, (2) time series of the EPN stations in ITRF05

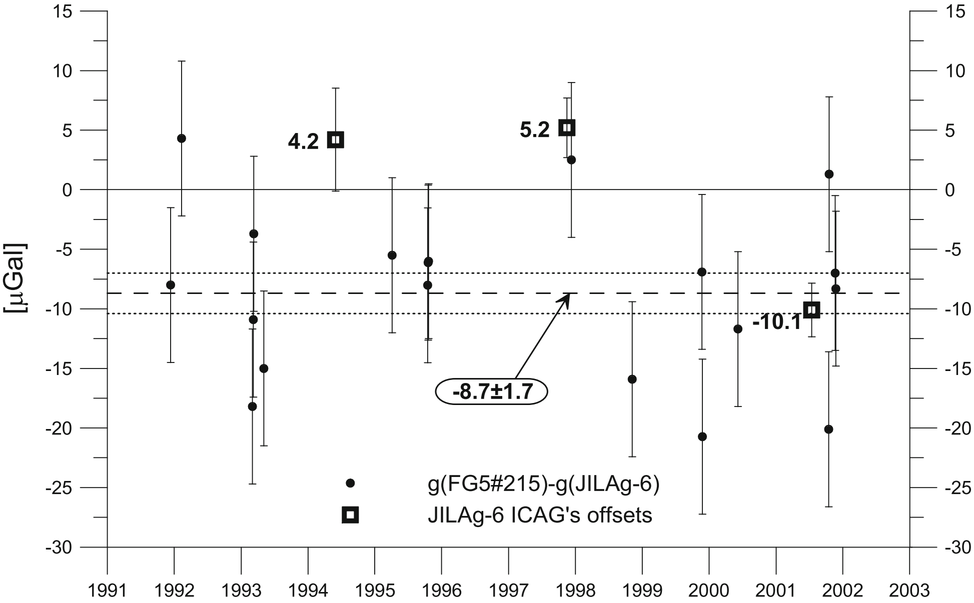


Fig. 5 Gravity differences Δg_h of the JILAg-6 gravimeter with respect to the FG5#215 gravimeter and the JILAg-6 offsets determined in ICAG's. The *dashed line* represents the average gravity difference and the *dotted lines* shows the 1-σ error bound

from 15 years of measurements with the other gravimeter of this type—JILAg-3—as reported by Timmen et al. (2008). Another example of the negative offset of the JILAg gravimeters is given by Liard et al. (2003), where again the JILAg-2 gravimeter is "higher" by 4 µGal than the FG5#106. These results might indicate on the positively biased JILAg meters, e.g. due to the tilt coupling errors.

The agreement between the gravity differences and ICAG's offsets at the confidence level of 95 % for the FG5#107 can be seen in Fig. 6. The gravity differences are significantly negative for the whole period of measurements 1993–1996. A final offset of −4.8 ± 1.1 µGal was evaluated as a weighted average of three results (ICAG-1994, ICAG-1997 and the average gravity difference with respect to the FG5#215 of −7.4 ± 1.6 µGal).

The gravity differences for the gravimeters FG5#101 and FG5#206 represented in Fig. 7 show again the agreement with the ICAG's results at the confidence level of 95 %. While the ICAG's results for the FG5#101 do not show statistically significant offsets, the FG5#206 seems to be affected

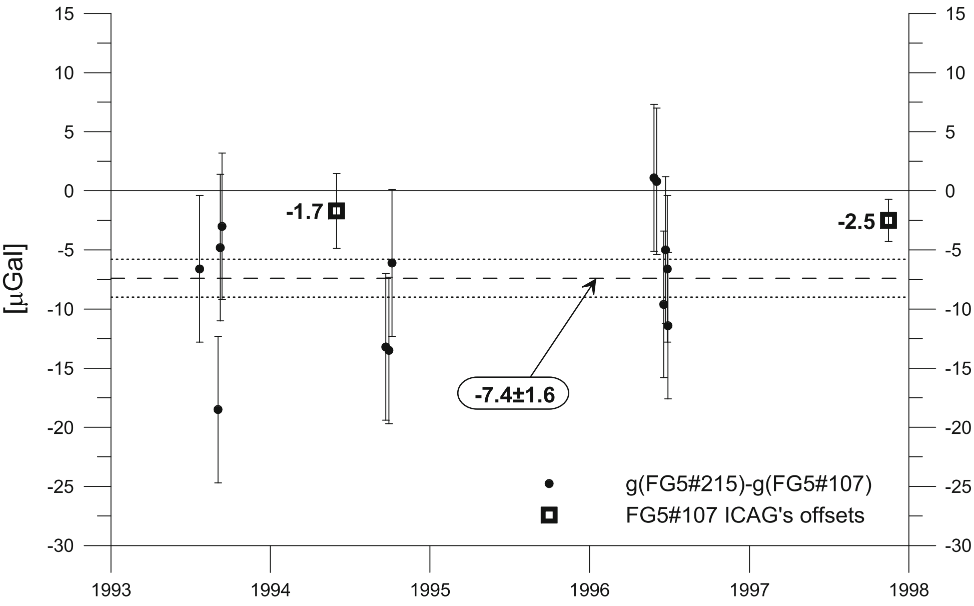


Fig. 6 Gravity differences Δg_h of the FG5#107 gravimeter with respect to the FG5#215 gravimeter and the FG5#107 offsets determined in ICAG's. The *dashed line* represents the average gravity difference and the *dotted lines* shows the 1-σ error bound

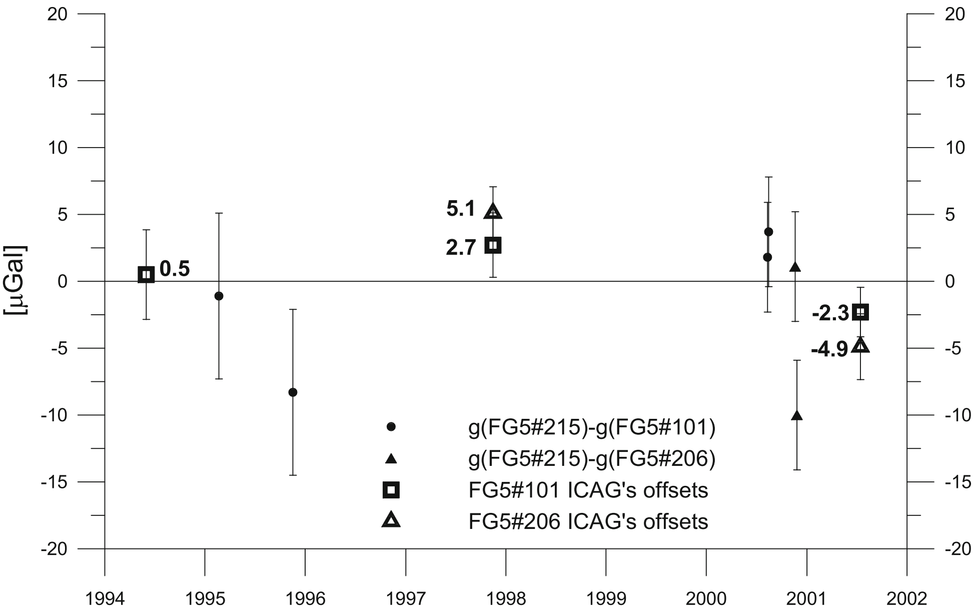


Fig. 7 Gravity differences Δg_h of the FG5#101 and FG5#206 gravimeters with respect to the FG5#215 gravimeter and the offsets determined in ICAG's. The bulk interferometer was replaced by the fiber model for the FG5#101 in 2000

by significantly different offsets in both ICAGs. Unfortunately, there are not enough measurements for a reliable confirmation.

6.3 Offsets versus hydrological effects

The analysis of gravity differences implies, that the offsets of JILAg-6 and FG5#107 are the sources of systematic tendencies in this study. To answer the question whether the indicated gravity changes are of purely instrumental origin or not, it is necessary to assess to what extent the results may be influenced by the local hydrological effects. Unfortunately, we have not necessary information to quantify these effects at each station. Nevertheless, recalling the results of the above-mentioned studies dealing with hydrological effects on gravity, we must admit a possible impact of these local effects especially when the compared data are related to the hydrologically extreme periods (March and September). An indicator for such a situation can be the difference between continental hydrological effects related to the date of observations—$\delta g_{\mathrm{hydro}}$, see Sect. 4.3.

The average $\delta g_{\mathrm{hydro}}$ amounts to the value of -0.3 ± 0.2 μGal, i.e., it is statistically insignificant because the repeated measurements are not generally performed in opposite periods. However, for the JILAg-6 the average "$\delta g_{\mathrm{hydro}}$" is 0.8 μGal (difference between $\varnothing\Delta g$ and $\varnothing\Delta g_h$ in Table 2) so that an amplification due to in-phase effect of the local and large-scale hydrological effects on the ground stations cannot

Table 2 Statistics for Δg differences and in brackets for Δg_h (with corrections for continental hydrology based on the WGHM model)

Gravimeter	Number of					$\o\Delta g$	$\sigma_{\o\Delta g}$	$\o\Delta g_h$	$\sigma_{\o\Delta g_h}$
	Measurements	$\Delta g > u$	$\Delta g > 2u$	$-\Delta g$	$+\Delta g$	[μGal]			
JILAg-5	1	0 (0)	0 (0)	1 (1)	0 (0)	–	–	–	–
JILAg-6	19	13 (12)	7 (7)	15 (15)	3 (3)	−9.5	1.7	−8.7	1.7
FG5#101	4	1 (1)	0 (0)	2 (2)	2 (2)	−1.2	2.8	−1.3	2.5
FG5#107	13	7 (7)	3 (3)	10 (10)	2 (2)	−7.1	1.7	−7.4	1.6
FG5#206	2	1 (1)	1 (1)	1 (1)	1 (1)	−4.1	5.4	−4.4	5.5

The columns show numbers of differences exceeding the limits u and $2u$ (uncertainties at the level 1-σ and 2-σ), positive and negative values and averages $\o\Delta g$ ($\o\Delta g_h$) with standard deviations

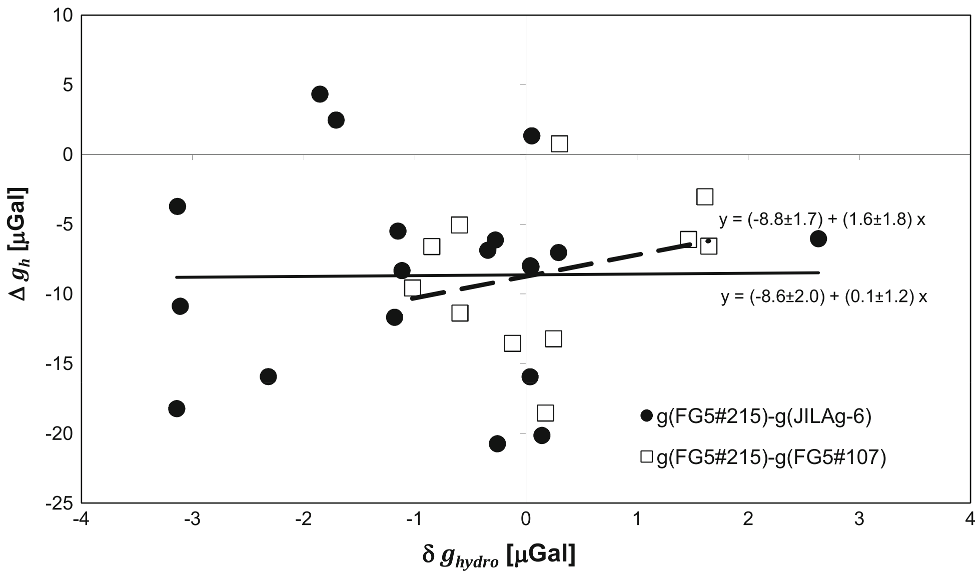


Fig. 8 Relation between gravity differences and differences between corrections for continental hydrology as a test of the amplification due to the in-phase effect of continental and local hydrology on the ground stations. The differences are related to the JILAg-6 and the FG5#107. In case of the FG5#107, two differences for the underground stations (Budapest, Polom) are not included

be excluded. In such a case, the gravity differences at ground stations, corrected for the continental hydrology, should still contain a component which is proportional to the applied corrections and represents the amplification effect due to local hydrology. This relation is shown in Fig. 8 for the JILAg-6 and FG5#107 gravimeters along with the corresponding linear polynomial fit. The results do not confirm the assumption of the amplification effect. The dominance of negative differences is evident irrespective of the compared periods of measurements. Therefore, the offsets, represented by the constant terms of the approximation polynomials, should be the main reason for systematic tendencies in the data sets.

Another source of systematic effects due to hydrology can be expected, if the data were taken from the significantly extreme season (e.g. dry summer). Such a situation is demonstrated in Fig. 3 by the time series of the FG5#215. The results for the stations Gánovce, Modra, and Liesek, where the measurements were carried out every time in the same period of the year, show lower values in 2003 and 2004. It agrees with the time series at the Pecný station and is probably caused by dry summers in these years. Note, that in 2003, low-gravity values were also observed at other sites in Europe: Steffen et al. (2009), Timmen et al. (2011), and Van Camp et al. (2011), as a consequence of the unusually dry season from spring to autumn. In context of the analysed dataset, the measurements related to the FG5#107 can be affected similarly, because the measurements were performed during three short time spans. Especially for six measurements carried in June 1996 after a dry spring in Central Europe, lower gravity values could have been expected. Nevertheless, such a hypothesis would just lead to the increase in the offset of the FG5#107.

7 Summary and outlook

The gravity differences between the repeated absolute measurements with the FG5#215 (2001–2010) and the previous measurements carried out with other gravimeters (1991–2001) in the Czech Republic, Slovakia, and Hungary, show sizeable unexpected gravity decrease up to 22 μGal at many stations with an average gravity rate of change of about −0.7 μGal/year.

The gravity differences were evaluated with regard to their uncertainties and statistical significance. The uncertainty assessment includes instrumental errors and environmental effects on the gravity with respect to the hydrological effects. The gravity effects coming from the continental water storage variations were computed with the help of the WGHM model and used for the correction of the original gravity differences. This allowed to pinpoint problematic differences related to the AG measurements in opposite seasons that could be suspected of being significantly affected also by the local hydrological effects. The relation between the gravity differences and the WGHM based corrections was used for detecting a possible systematic effect of the local hydrology assuming that an in-phase effect of the continental and the local hydrology might exist at ground stations. This assumption was not confirmed as the main reason for systematic errors discussed in this study.

Two other possible reasons of larger gravity differences were discussed: (1) regional geodynamic activity, (2) systematic errors of gravimeters. The results show a clear systematic behavior when the data are treated as instrumentally dependent. The statistics of the gravity differences shows important systematic effects related to the data of the JILAg-6 and FG5#107 gravimeters. A verification and evaluation of the gravimeter offset was done for all gravimeters employed in the repeated measurements using the results of the international comparisons of AGs periodically held in Sèvres and Walferdange in the period 1994–2007. The results of the ICAG´s campaigns along with regular calibrations of the laser, clock and barometer justify us to take the absolute measurements with the FG5#215 gravimeter as a reference in this study. A comparison of the gravity differences detected by the repeated measurements and the offsets resulting from ICAGs was done for all gravimeters. The offset (negative bias) estimates for the JILAg-6 and FG5#107 gravimeters obtained from the repeated measurements w.r.t. FG5#215 and ICAGs are $-9\,\mu$Gal and $-5\,\mu$Gal, respectively.

A check of gravity differences for possible systematic effects of instrumental origin is an important step for a reliable utilization of AGs in geodynamics, especially when infrequent AG time series are used. The situation is even worse when different AGs are used. The data in this study clearly demonstrate that a consideration of offsets between the instruments is crucial for a correct interpretation of the repeated absolute gravity measurements. As it was shown in Van Camp et al. (2011), Lambert et al. (2006), or Timmen et al. (2011), the absolute gravimetry has a capacity for detecting subtle geodynamic signals, but the offset issue must be satisfactorily solved. The system of international and regional comparisons of AGs represents a very important tool for the determination of AG offsets on the microgal level and thus, for the definition of an absolute gravity reference at such an uncertainty level. Nevertheless, the offsets stability has to be checked more frequently, in case the precision of 1–2 μGal would like to be declared. The reference gravity stations equipped with superconducting gravimeters and connected to the system of comparisons play a key role in this respect. The current level of AG comparisons and the number of reference stations in Europe allows the offsets to be determined with an accuracy of 1 μGal. Therefore, the local hydrological effects seem to set the main limitations for a reliable utilization of the absolute gravimetry in geodynamics. Nevertheless, as shown in Van Camp et al. (2011), the hydrological effects should not prevent us from monitoring slow gravity changes caused by crustal deformations. The repeated absolute measurements carried out twice a year (fall and spring), as described in Van Camp et al. (2011), show that it is possible to clearly detect and separate the hydrological and geodynamic signals. Such an approach allows us to evaluate the hydrological sensitivity of individual gravimetric stations, which contributes significantly to the evaluation of uncertainties and, thus, to a correct interpretation of the results.

In the future, offset-free AGs, which regularly pass the system of AG comparisons would be very helpful for long-term monitoring of gravity changes. However, comparisons are made on 2–4 years basis and offset changes in between has to be captured too. Reference stations equipped with a superconducting gravimeter should play an important role here. Pecný station serves for this purpose for the FG5#215. Monthly repeated absolute measurements at the station together with results at comparisons are able to provide clear information about offset changes and by that way to support a quality of all measurements provided with the FG5#215 outside the Pecný station.

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