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A FEASIBILITY OF ABSOLUTE GRAVITY MEASUREMENTS IN GEODYNAMICS

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ABSTRACT
The absolute gravity measurements are an important tool for reliable monitoring geodynamic phenomena. Based on the experience with the absolute gravimeter FG5#215 (gravimeter of the Center for Earth Dynamics Research), the accuracy of FG5 absolute gravimeters is presented in this study. The instrumental reproducibility of this meter is characterized by the value of 0.7 μGal. Discussed are important environmental effects on gravity measurements, such as atmospheric and hydrological effects, understanding of which is necessary for correct and reliable interpretation of the repeated absolute gravity measurements in geodynamics.

KEYWORDS: gravity acceleration, absolute gravimeter, FG5, metrology, repeatability, reproducibility, uncertainty, hydrological effects

1. INTRODUCTION

Advances in the terrestrial measurement of the gravity acceleration by absolute and superconducting gravimeters have led to relative accuracies of 10^{-9} (≈ 1 μGal = 10 nm s^{-2}). Thanks to this high accuracy the techniques of precise terrestrial gravimetry became an effective tool which can be employed in the Global Geodetic Observing System (GGOS) (Plag et al., 2009).

Absolute gravimeters (AGs) and superconducting gravimeters (SGs) can detect thin effects caused by mass changes in the Earth's interior, in the hydrosphere and atmosphere as well as the height changes caused by the geodynamic processes. The uncertainties inherent in the FG5 absolute gravimeters reach about ±1-2 μGal (Niebauer et al., 1995; Van Camp, 2005). The gravity change of 1 μGal can be interpreted as a height change of 2-5 mm relative to the Earth center of mass. It means, among others, that it is possible to monitor crustal deformations by means of absolute gravity measurements with an exceptional accuracy. Unlike GNSS techniques, the results are independent of observations at other sites as well as of the reference frame. Transportability makes from this instrumentation a very suitable tool for monitoring geodynamic processes.

The fact that the gravity signal is very complex, since it includes all information about the current state of dynamic processes on the Earth´s surface, in the Earth´s interior, in its atmosphere and hydrosphere, can cause difficulties in the geodynamic interpretation of repeated absolute measurements. Particularly, a good knowledge and a good understanding of hydrological effects on gravity seems to be critical for the utilization of AGs for monitoring crustal deformations (intraplate and interplate tectonic deformations), see Van Camp et al. (2002), Richter et al. (2004). The hydrological effects on the gravity are caused by the variations of water storage and by water redistribution in the Earth. They affect the measured gravity through the variable Newtonian attraction of water masses and through the loading effect as a result of the Earth deformation due to variable loading.

The goal of this text is to check and explain a feasibility of absolute gravity measurements using FG5 gravimeters for the investigation of geodynamic phenomena. The analysis of AG´s accuracy is presented based on the experience with the absolute gravimeter FG5#215. The important part of this text is the description of the hydrological effects on gravity and showing them as the most important environmental effects on gravity measurements.

2. FG5 ABSOLUTE GRAVIMETER

The FG5 absolute gravimeters are the most accurate AGs at present. The detailed description of the meter can be found in Niebauer et al. (1995). The free-fall acceleration is determined from the measurements of position (length) and time during the free-fall of the testing body. The relative accuracy of both measured components is better than 10^{-10}.

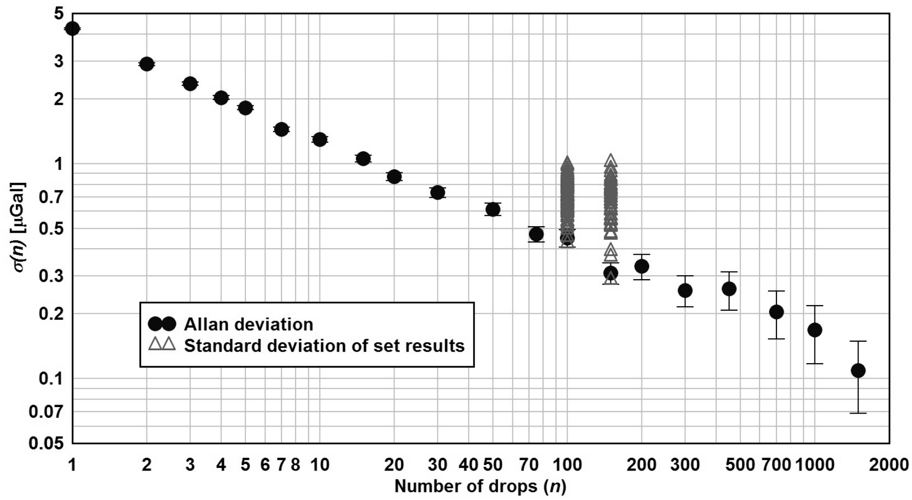

Fig. 1 The Allan deviation and the standard deviation of the set results computed from the FG5#215 measurements at the Pecný station.

The free-fall acceleration is computed from about 600 recorded length-time couples (z_i , t_i) by solving the following equation

$$z_i = z_0 + v_0 \, (t_i + \frac{W_{zz}}{6} t_i^3) + \frac{1}{2} g_0 (t_i^2 + \frac{W_{zz}}{12} t_i^4) \, , \qquad (1)$$

where z_0, v_0, g_0 are the initial values of position, velocity and acceleration at an initial time of the data acquisition t=0 s. The W_{zz} is the vertical gravity gradient which is also used for the transfer of the free-fall acceleration to the specified height above the benchmark.

The gravity acceleration is obtained by correcting the free-fall acceleration for the Earth tides effect (zero tide system), polar motion effects (with respect to the IERS pole) and atmospheric effects (with respect to the normal atmosphere) in agreement with the International Terrestrial Reference System (ITRS) specifications as defined by the IUGG Resolution No. 2 adopted by the IUGG General Assembly in Vienna, 1991 (Geodesist's Handbook, 1992).

One free-fall of the test body is called a "drop" and it is repeated typically every 10-20 s. During one hour 100-200 drops are collected. This data file is called "set" and the corresponding average is the "set result". The measurement usually consists of minimum 12 sets during at least 12 hours. The weighted average of several "set results" is the "final result".

3. ACCURACY OF THE FG5 GRAVIMETERS

The initial step for the subsequent interpretation of gravimetric measurements should be the description and evaluation of the repeatability, reproducibility and uncertainty as fundamental parameters of the gravimeter accuracy. All these parameters have been determined for the FG5#215 (Kostelecký et al., 2002) on the basis of the long-term measurements at the Pecný station.

3.1. REPEATABILITY

The repeatability is defined (GUM, 1995) as closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurements. The repeatability of the FG5#215 is described by the Allan deviation. It describes the stability of the average gravity value as a function of the number of drops n, which helps to estimate an optimal number of drops necessary for effective achieving the reliable result. The Allan deviation has been computed from the series of 5600 drops carried out during 28 hours (200 drops in a set with 10 s period, one set per hour) by equation

$$\sigma(n) = \sqrt{\frac{1}{2(k-1)} \sum_{i=1}^{k-1} (y(n)_{i+1} - y(n)_i)^2} \, , \qquad (2)$$

where the Allan deviation $\sigma(n)$ is calculated for a set of k-1 subgroups of n drops, where $n=T/k$ (T is the total number of collected drops). y_i is the average gravity value of n drops in the subgroup i. The Allan deviation in Figure 1 decreasing proportionally to the number of drops due to the dominant effect of the instrumental white noise. Standard deviation of set results (100-150 drops) is 0.4 µGal. Practically it means, that from 24 sets the standard deviation of average gravity 0.08 µGal should be achieved. However, it will be shown, that such a value represents only the precision of the FG5#215 gravimeter, because it does not reflect many of errors

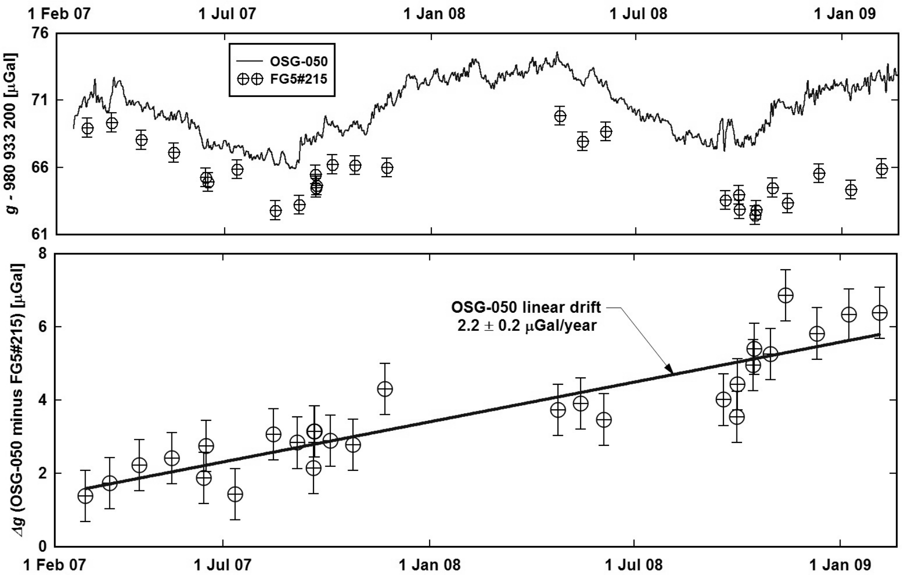

Fig. 2 Top: Time series of the OSG-050 and the FG5#215 at the Pecný station. Bottom: Differences between SG and AG allow to determine a long-term reproducibility of the FG5#215 (represented by error bars 0.7 μGal) and the instrumental drift of the OSG-50 (linear term 2.2 μGal/year).

acting during the measurement. A good repeatability has an importance e.g. for calibration of super-conducting gravimeters, but for the repeated absolute measurements in geodynamic networks it does not play so important role.

3.2. REPRODUCIBILITY

The reproducibility is defined (GUM, 1995) as closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurements. Of course, the open question is the degree of changeability of relevant conditions. For geodynamic purposes, the most important parameter should describe the "long-term" accuracy of individual gravimeter under different environmental conditions and with different set-ups of the gravimeter. According to D'Agostino and Germak (2009) there is reasonable to define:

- "short-term" reproducibility as a variability of the results within an observation session (typically 24 sets during 24 hours). We can evaluate this value from the standard deviation of set results (100 or 150 drops per set) related to 118 observation sessions with the FG5#215 at Pecný, see Figure 1. The average set standard deviation reaches value of 0.7 μGal which means the standard deviation of the average gravity result (24 sets) of 0.14 μGal. Thus, the short-term reproducibility is higher than the repeatability mainly due to variable environmental effects on the gravity during the measurement.
- "medium-term" reproducibility as a variability of the results between different observation sessions, where mainly the instrument set-ups play an important role. The set-up error of the FG5#215 was determined during the determination of the fringe signal effect on the observation results (Pálinkáš and Kostelecký, 2007). The instrument set-up was changed in very fast step of 6 hours during which 1000 drops were collected. The standard deviation of such 6 hours observation sub-set is 0.45 μGal (repeatability is less than 0.2 μGal) and practically describe the medium-term reproducibility of the meter.
- "long-term" reproducibility as a variability of the results after several months or years that, includes mainly the variation of systematic instrumental errors after maintenance, repair or tuning of the meter. This parameter has an essential importance for geodynamic applications of the absolute gravimetry and the estimation of such a parameter is described in the special paragraph.

3.3. LONG-TERM REPRODUCIBILITY OF THE FG5#215

The results of long-term observations with the absolute gravimeter (AG) FG5#215 and the superconducting gravimeter (SG) OSG-050 at the Geodetic Observatory Pecný are used for the evaluation of the "long-term" reproducibility of the FG5#215. This important parameter describes the accuracy of a single absolute session (at least 12 hours) under long-term variable instrumental and environmental conditions at a single site. It is necessary to emphasize that the FG5#215 is not a "laboratory" instrument which is only used for measurements at the reference station Pecný. It is often used for typical „field" measurements, mainly in the Czech Republic, Slovakia and Hungary. The time series at the Pecný station thus include errors coming from the frequent transport of the gravimeter and from periodical or occasional repairs, maintenance or tuning of the meter.

A comparison of AG and SG gravity series is helpful for an experimental determination of the long-term reproducibility thanks to the possibility to compare the variation of absolute measurements with the more precise observations of SG (precision of one-hour ordinate is of about 0.05 μGal). On the other hand, it is important to take into account the SG´s slight instrumental drift that causes a consecutive divergence of the AG and SG observations. Note, that the AG measurements are free of any instrumental drift.

The differences between the SG and AG results obtained at the Pecný station are shown in Figure 2. Altogether 28 absolute measurements have been accomplished since February 2007 when the OSG-050 was installed at the station.

The linear instrumental drift of 2.2 ± 0.2 μGal/year has been determined for the OSG-050 from the differences between the SG and the FG5#215 measurements. The standard deviation of a single difference is 0.7 μGal. This value practically describes the long-term reproducibility of the FG5#215. Surprisingly, it is only slightly higher than the medium-term reproducibility (set-up error) which is 0.45 μGal. Such a value is probably too optimistic and would rather be determined from a longer time period, e.g. two years, as described in Van Camp (2005). Here, the standard deviation of 1.6 μGal was determined from 96 measurements of the FG5#202 during 8 years of AG and SG parallel measurements at the Membach station.

The fact, that the presented long-term reproducibility has been computed from the differences between the AG and SG measurements and, therefore, it is free of errors caused by additional corrections (Earth tides, atmosphere, polar motion), cannot be neglected. For a complete calculation of the long-term reproducibility, the „instrumental" reproducibility of 0.7 μGal has to be enlarged. While the earth-tide and polar motion corrections can be applied with an accuracy of about 0.1 μGal, the atmospheric effects on gravity are routinely reduced with an accuracy of about 1.0 μGal using a barometric admitance based on the local pressure information. A comparison between computing atmospheric effects in such a way and that using 3D atmospheric pressure data shows differences from 0.3 μGal to -2.2 μGal (Neumeyer et al., 2004). The overall long-term reproducibility of the FG5#215 at single site is about 1.2 μGal. It consists of the instrumental contribution of 0.7 μGal and the atmospheric contribution of 1.0 μGal.

The long-term reproducibility is an important parameter in many applications of AG measurements in geodynamics, when the measurements are repeatedly carried out with the same meter at the same site during several years. The estimated long-term reproducibility of 0.7 μGal (instrumental part) and/or of 1.2 μGal (total value) can be interpreted as the best accuracy achievable for a single absolute measurement with the FG5#215 at a quiet station like Pecný.

3.4. UNCERTAINTY OF THE FG5 GRAVIMETERS

In the evaluation of the AG uncertainty, errors coming from employing more than one AG must be taken into account. The "group" or "type" uncertainty of the FG5 gravimeters can be evaluated from the results of the repeated international intercomparisons of absolute gravimeters. They show an agreement between participating gravimeters, expressed as a standard deviation of an individual gravimeter with respect to the reference value. From the last three intercomparisons these characteristics are as follows: 1.9 μGal in Walferdange-2003 (Francis et al., 2004), 3.2 μGal in Sèvres-2005 (Vitushkin et al., 2007) and 2.1 μGal in Walferdange-2007 (Francis et al., 2009). Generally, we can say that the uncertainty of the FG5 gravimeters is of about 2.5 μGal mainly due to systematic offsets between individual instruments.

4. HYDROLOGICAL EFFECTS ON GRAVITY

Beside atmospheric effects, hydrological effects on gravity are known to cause significant disturbances in time-dependent gravity observations. Knowledge of hydrological effects and their elimination from the gravity data is an important step in many geodynamic studies. Hydrological effects are caused by hydrological mass changes (quantity and distribution) which affect the gravity due to 1) Newtonian attraction of variable masses, 2) response of the Earth to this surface mass loading. It is useful to distinguish three different hydrological effects (Llubes t al., 2004) depending on distance from the gravity station: 1) local effects (caused by water masses located at a distance up to 1 km), 2) regional effects (1-1000 km), 3) global effects (>1000 km). The measured gravity data contain the integral effect of all mentioned partial effects. The global and regional hydrological effects are interesting due to their relation to the dynamics of the Earth (seasonal and secular variations of different origins which can also be partly related to global climate changes). In contrast with it, in geodesy the local effects are considered in geodesy as disturbing effects which superimpose on the important signal of regional or global origin.

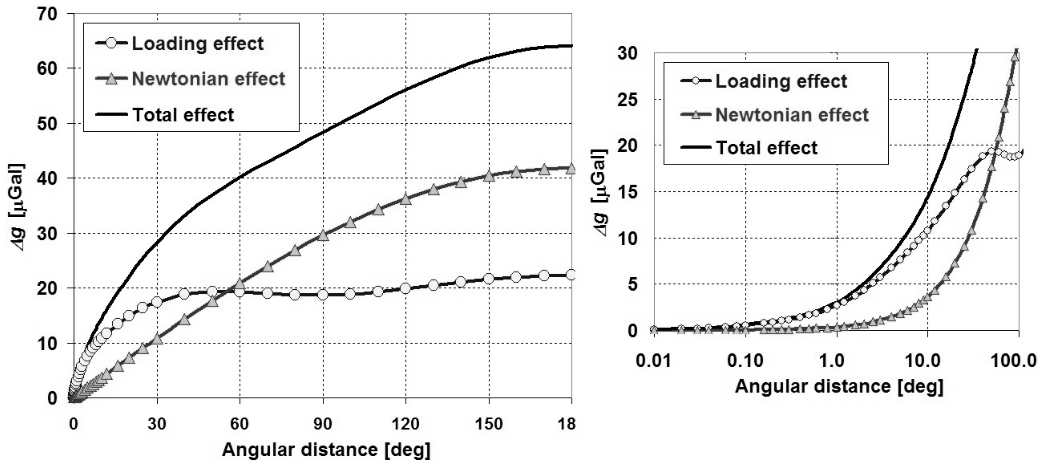

Fig. 3 Effect on gravity (loading part, Newtonian part and the total effect) caused by a centered homogeneous shell of water (of angular distance) and thickness of 1 m. The right figure is depicted by logarithmic scale in the horizontal axis for better interpretations of the effect for lower angular distances.

4.1. GLOBAL AND REGIONAL HYDROLOGICAL EFFECTS

The contribution of hydrological mass changes can be computed using Green's function (Farrell, 1972). Green's function for gravity effect of unit weight is

$$g(\psi) = \frac{g}{m_e} \sum_{n=0}^{\infty} \left[n + 2h_n - (n+1)k_n \right] P_n(\cos\psi) , \quad (3)$$

where ψ is the angular distance between the unit weight and the gravity station, m_e the mass of the Earth, g mean gravity at the surface and P_n the Legendre polynomials of degree n, h_n and k_n are the load Love numbers of degree n.

To estimate the Newtonian and loading effects of variable water masses, the load defined by a centered homogeneous shell of water (of angular distance ψ) and thickness of 1 m was considered for computation (Llubes et al., 2004). The gravity effect of such a model can bee seen in Figure 3. They show the loading effects for the distances from 1 deg to 40 deg (≈ 100-4000 km) and the monotonic increase of the Newtonian effect. It is evident, that the variable masses at a distance >100 km will have an impact on the precise terrestrial observations.

One of the most important hydrological effect of global origin is caused by variations of continental water storage (van Dam et al., 2001). Two global hydrological models Land Dynamics (LaD - Milly and Shmakin, 2002) and WGHM (Döll et al., 2003) have been used for evaluation of gravity effect caused by continental water storage variations. The models LaD and WGHM contain monthly water storage data (in kg m^{-2}) on continents in 1^o x 1^o and 0.5^o x 0.5^o grid, respectively. Based on these data for the period 2004-2007, the gravity effect has been computed for Europe in the 2^ox2^o grid using equation (3). The obtained time series were individually fitted by annual harmonic functions. The parameters of these functions (amplitude and phase) are shown in Figures 4a/4b. The differences between the fitted harmonic function and the corresponding time series were less than 0.3 μGal at all computed points. The Figures 4a/4b show the gravity variations up to 6 μGal with the maximum gravity in February-March for European stations. A comparison of both models shows an agreement better than 1 μGal in amplitude and 13 days in phase. From global models the WGHM is usually preferred for its high data resolution and a comprehensive content of different water storage components in the data (groundwater, snow, surface water, canopy, soil).

It is necessary to say that the presented results do not include hydrological effects from the zones < 1 km around the station. It means, that the local hydrological effects are not modelled because they must be solved separately considering: 1) the hydro-geological study of the area and 2) the real topography of the station vicinity.

4.2. LOCAL HYDROLOGICAL EFFECTS

For the estimation of the gravity effect of near zones the three dimensional model has to be used. It is sufficient to deal with the Newtonian effect since the loading effect is negligible (see Fig. 3). To take into account the existence of underground water stored immediately below the gravimeter, a simple model based on a concentric cylinder with a radius r, thickness t and density ρ can be used. The Newtonian attraction of this cylinder at the point located on the top plane in its axis is

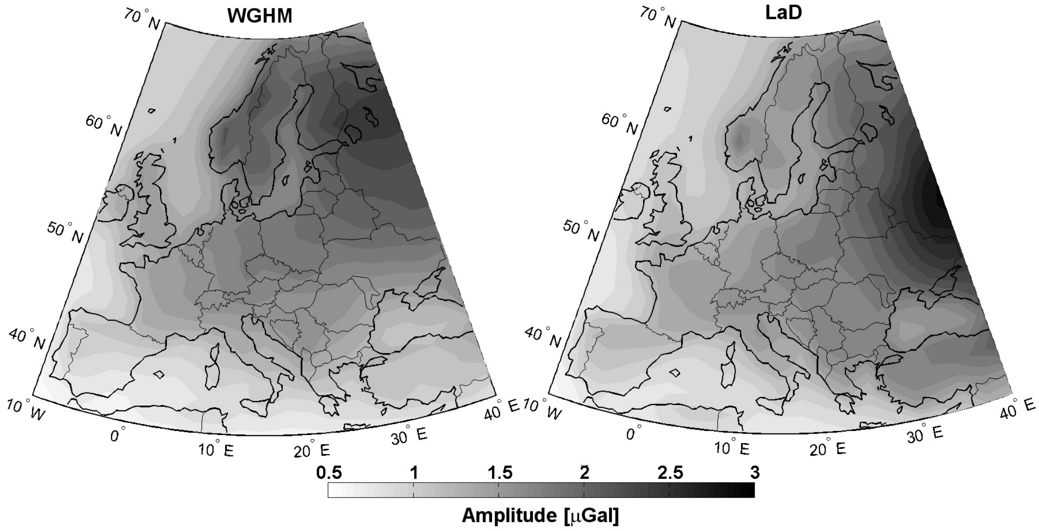

Fig. 4a Amplitude of the annual harmonic function which represents the gravity effect caused by continental water storage variations based on the WGHM and LaD models.

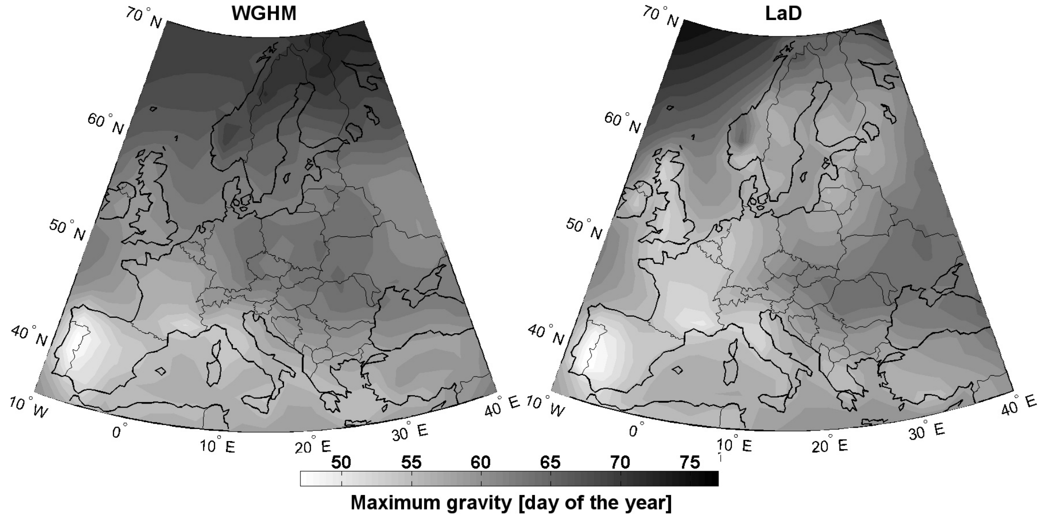

Fig. 4b Phase of the annual harmonic function which represents the gravity effect caused by continental water storage variations based on the WGHM and LaD models.

$$\Delta g_{Cyl} = 2\pi G\rho\left[t + r - \sqrt{t^2 + r^2}\right], \tag{4}$$

where G ($6{,}673 \cdot 10^{-11}$ $\mathrm{m^3kg^{-1}s^{-2}}$) is the gravitational constant. In the limit case for $r \rightarrow \infty$ we get the classical Bouguer correction

$$\Delta g_{Boug} = 2\pi G\rho t\,. \tag{5}$$

A contribution of individual zones can be seen from Figure 5, where 10% volumetric soil moisture variations (ρ = 100 kg $\mathrm{m^{-3}}$) for a cylinder with the thickness of $t = 10$ m was considered (1 m of water column). The gravity variations caused by this model were computed using the equation (4) depending on the cylinder radius.

The situation modelled in Figure 5 shows that more than 90% of gravity variations come from the zones up to 100 m from the gravimeter and practically no signal exists outside of 300 m or, better, it exist, but is almost constant. Of course, the real situation is usually not so simple like in the case of the homogeneous cylinder model and therefore the local models should be based on a very good knowledge of the real topography and of water mass distribution in the station vicinity (Peter et al., 1995; Bower and Courtier, 1998; Kroner, 2001; etc.).

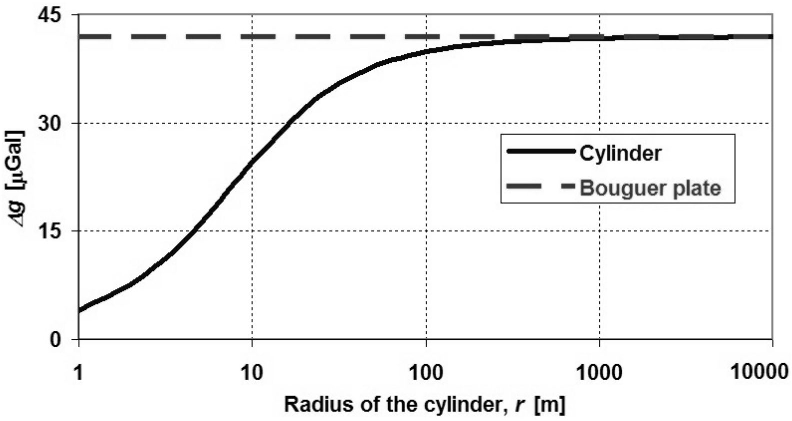

Fig. 5 Gravity variation caused by the Newtonian attraction of water masses homogeneously distributed within the 10 m thick cylinder with 10% porosity and variable radius.

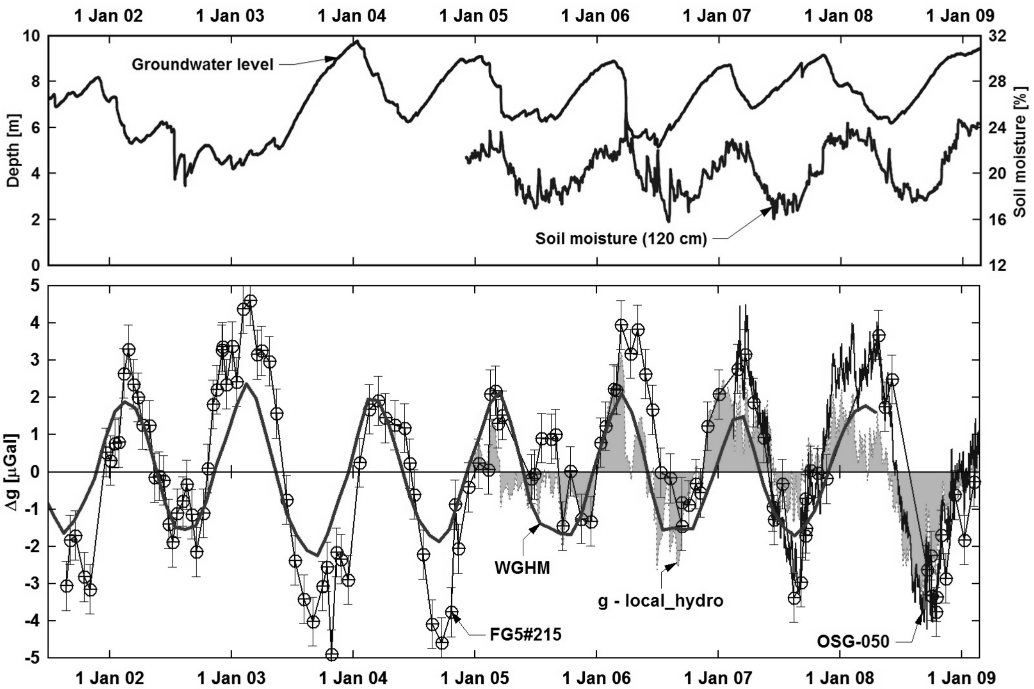

Fig. 6 Top: Variations of the groundwater level and the soil moisture in the depth of 120 cm. Bottom: Gravity variations at the Pecný station based on the measurement with the FG5#215 and OSG-050. The curve "g-local_hydro" represents the corrected gravity series for local hydrological effects. The curve WGHM is the effect of the continental water storage variation based on the WGHM data.

The local hydrological effects at Pecný have been computed with respect to the local topography represented by the digital elevation model of the area 1500 m x 1500 m (DEM) around the Pecný station. The variable water masses have been considered down to the depth of 10 m (maximal depth of groundwater level variations). The specified 10 m thick soil layer in the area of 1500 m x 1500 m has been divided into the 0.5 m x 0.5 m x 0.5 m cubic cells. The gravity effect of the subsurface water masses was as a sum of the Newtonian attractions of all cells (except cells within the cellar of the observatory) in the specified area. For such a computation the position (with respect to the gravimeter) and the water masses in individual cells should be known. The position can be easily determined from the DEM but the accurate assessment of a relevant spatial water distribution is not an easy task.

A one-dimensional distribution of local water masses (depending on the depth) below the ground was taken into account at Pecný using the hydrogeologic study of the area (mainly determination of the soil porosity as a function of the depth) and on the measured groundwater level and soil moisture in different depths (see, Figure 6). The combined gravity series (FG5#215 and OSG-050), before and after correction for the local hydrological effects, can be seen along with the effect of the continental hydrology in Figure 6.

4.3. ACCURACY OF ESTIMATION OF HYDROLOGICAL EFFECTS

The hydrological effects (both local and global) reach values which overlap the 1 μGal accuracy of the present FG5 gravimeters. Therefore, it is necessary to deal with them and to take them into account to get a maximal benefit from FG5 gravimeters in geodynamic studies.

The variations of the continental water storage show gravity effects of 6 μGal in Europe. The accuracy of the global hydrology data and, thus, the accuracy of modelled gravity variations is unclear. Moreover, seasonal effects of oceanic and atmospheric origins can be expected in the measured gravity. However, it can be assumed that these global phenomena will affect gravity with the dominant annual cycle and will not be affected by too sharp changes like in the case of local effects. The repeated AG measurements in the same period of the year can therefore minimize the errors of global hydrological effects on the level below the FG5 accuracy.

The problem of local effects is much more complicated. A precise estimation of the local effect must be based on local measurements (soil moisture, groundwater, precipitation…) and on a detailed hydrogeological study of the station vicinity. All these issues are expensive and laborious. Of course, the seasonal effect is dominant also in local effects, which can be again removed by repeated measurements in the same period of the year. Unfortunately, a part of the gravity signal generated by the close vicinity of the gravity station (distance of 100 m is critical) is much more rough, then the contribution of the rest of the globe and, therefore, sharp gravity changes after some extreme events have to be expected. It seems, that for delicate geodynamic studies like crustal deformations, the best way is to organize measurements always in the same time of the year to mitigate the errors coming from hydrological effects. In that case we should calculate with an additional uncertainty of gravity measurements of 2 μGal. Of course, it can be recommended to measure at least 4 times per year to get both, an information about hydrological effects and a robust gravity value.

5. CONCLUSIONS

The repeated absolute gravity measurements are a reliable tool for monitoring geodynamic phenomena. To get a full benefit from these measurements, it is necessary to have, among others, a good knowledge of the instrumental accuracy and of environmental effects on gravity as the main disturbing effect.

The data of 8 years of AG measurements and 2 years of SG measurements at the Pecný station allowed us to determine the accuracy parameters of the FG5#215 such as repeatability, reproducibility and uncertainty. The important parameter from the geodynamic point of view is mainly the "long-term" reproducibility and uncertainty. The "long-term" reproducibility represents the accuracy of gravity measurements with the same meter at the same site as a typical situation at a geodynamic station. The estimate of this parameter for the FG5#215 is 0.7 μGal (instrumental part). The uncertainty of the FG5 gravimeters of about 2.5 μGal should be considered mainly due to systematic errors between individual gravimeters. For delicate geodynamic studies, such as crustal deformations, it is useful to use only gravimeters for which the variations of systematic errors are well determined from regular participations in international comparison measurements of absolute gravimeters and from regular parallel measurements with a SG at a reference station. It is recommended to perform repeated measurements always with the same absolute gravimeter at the given site.

Important environmental effects on gravity caused by the mass variations in the atmosphere and hydrosphere have to be taken into account in interpretation of repeated absolute gravity measurements. The atmospheric effects on gravity are routinely reduced with an accuracy of about 1.0 μGal, using a barometric admittance based on the local pressure information. Besides atmospheric effects, the hydrological effects cause significant disturbances in time-dependent gravity observations. The global part of the hydrological effect can be effectively removed by repeated AG measurements in the same period of the year. The local hydrological effects are therefore the main limitations for a reliable utilization of absolute gravity measurements in geodynamics. The local effects may overshadow the gravity effects associated with large scale geodynamic processes. Unfortunately they cannot be easily modelled and thus eliminated from the gravity data. The most practical way is to organize measurements always in the same time of the year to mitigate the errors coming from seasonal local hydrological effects. In that case we should calculate with an additional uncertainty of gravity measurements of 2 μGal.

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