Estimating the thermal effect in gPhoneX observations

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Abstract: Stationary relative gravimeters are used in variety of applications, mainly due to their high sampling rate which is more suitable for study of certain geodynamic effects than absolute gravimeters. Study of weak signals is almost exclusively in the domain of superconducting gravimeters, as they possess the highest accuracy and stability of all types of relative gravimeters. Possible alternative to superconducting gravimeters are portable earth tide metal spring gravimeters. Zero-length spring gravimeters (e.g. LCR instruments) are usually considered to be the most accurate mechanical spring gravimeters. However, compared to superconducting instruments they remain too unstable for long-term gravity monitoring. Main reason supporting this statement is related to instrument's sensitivity to temperature changes and temperature induced tilts. Gravity observations from the gPhoneX #108 gravimeter stationed at Hurbanovo gravimetric observatory were tested in order to confirm the correlation between the observed gravity changes and ambient temperature changes and provide a solution for correcting the gPhone data for influence of the ambient temperature changes. Paper also aims to serve as a guide for other operators to estimate a parameters required for the calculation of ambient temperature correction.

Key words: relative gravity observations, ambient temperature changes, spring gravimeters

1. Introduction

Spring relative gravimeters find their use in wide range of applications. They are mainly used in terrain measurements, as they are much more compact, easier to manufacture and transfer between observed points than absolute gravimeters (*Fores et al., 2019*). Metal spring gravimeters can also be used as observatory monitoring gravimeters for stationary gravity measurements although this utilization is predominantly dedicated to superconducting gravimeters (SG). The SG is a relative gravimeter in which the mechanical spring is replaced with a very stable electro-magnetic field

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doi: 10.31577/congeo.2022.52.4.1

and a spherical superconducting test mass. The magnetic field is produced by two superconducting coils and since there is almost zero resistivity in superconductors, both the persistent currents flowing in the magnet coils and the induced currents in the sphere are ultra-stable and noise free as mentioned by the manufacturer (*GWR Instruments, Inc., 2022*, `https://www.gwrinstruments.com`). As a result, the SG is the most stable and low noise relative gravimeter providing unprecedented accuracy and a very stable instrumental drift usually smaller than 5 μGal/year as shown by *Van Camp and Francis (2007)*. More than 30 observatories throughout the world have been equipped with the SG, creating the core of a Global Geodynamics Project (GGP) which continues as the International Geodynamics and Earth Tide Service (IGETS) since the 2016 (`http://isdc.gfz-potsdam.de/igets-data-base/`). Maintaining a superconducting state requires an efficient cooling unit, able to keep the temperature below the transition temperature of the niobium (4°K), which the sensor is made of. Although an improved refrigeration system requiring stable 1.5 kW power supply has been invented and used by the manufacturer, SG gravimeters still remain extremely demanding in terms of the operation and maintenance (*Fores et al., 2019*).

A possible alternative for stationary gravity measurements, a zero-length spring gravimeter gPhoneX has been introduced by the Micro-g LaCoste in 2013 (`http://microglacoste.com`). The instrument uses an automatic Aliod Beam Nulling feedback system allowing measurements of gravity changes at the level of 0.1 μGal (*Fores et al., 2019*). Due to non-linear instrumental drift, thermal sensitivity and presence of low period noise, one should consider spring type relative gravimeters too unstable for long-term stationary observations (*Hábel et al., 2020*). However, there is still a wide range of geodynamic phenomena that can be monitored using the gPhoneX gravimeter, when the correct procedure of data preprocessing is followed. Although the latest spring type gravimeters use a thermostat oven to protect the sensor from temperature variations (*Micro-g LaCoste, Inc., 2022*), small changes of the sensor temperature occur at the level of 10^{-6} °C. These changes are indistinguishable from the drift induced gravity changes, thus removing the instrumental drift from the data is usually sufficient enough. Several studies have proven, that stable ambient conditions play a key role in obtaining the best possible accuracy when using the zero–length spring type gravimeters (*Fores et al., 2019; Niebauer et al., 2016; Andò and Carbone, 2001*). However, in certain situations (for example power outages), it is not possible to maintain a stable room temperature, therefore the environmental conditions change induces a signal that is not related to gravity changes. Presence of such signal in the gravity recordings is undesired and needs to be removed before a further research on the data. The linear admittance factor for ambient temperature changes has been implemented in the gMonitor software (for more information, see the gMonitor manual) by the MicroG-Lacoste. Although the correction proposed by the manufacturer is sufficient for a small temperature signal in the gravity data we show, that during rapid occasional temperature changes using a single value admittance factor leads to underestimation of the real temperature signal in the gravity data.

2. Site description

The impact of ambient temperature changes on stationary gravity measurements was studied on the data from gPhoneX #108 located at the Hurbanovo Gravimetric Observatory, which is part of the Hurbanovo Integrated Station (HUVO). The HUVO is located at 47.87238° N and 18.19316° E with the approximate elevation of 112 m above the Baltic mean sea level, near the famous Geomagnetic Observatory Hurbanovo. The area around the HUVO is flat as it is located in the upper part of the Danubian lowland. Digital elevation model of nearby area is depicted in Fig. 1. The instrument is placed on a pillar isolated from the building foundations with intention of reducing high frequency environmental noise and the observation site induced tilts. The room is equipped with an air conditioning unit, reducing the daily ambient temperature variations to $\pm 1\,^{\circ}$C. Additional thermal insulation has been placed around the instrument (Fig. 2) further lowering the short-term ambient temperature variations to less than $0.1\,^{\circ}$C. From the perspective of a noise, the site can be characterized as moderately noisy with high frequency noise caused by nearby transportation and public buildings. A decrease of the noise can be observed during the weekends and holidays, when these buildings are not used. From the geological perspective the area is stable with sandy clay loam soil texture dominating within one hundredth meters radius from the site. In the vicinity of the gravimeter a well for ground-

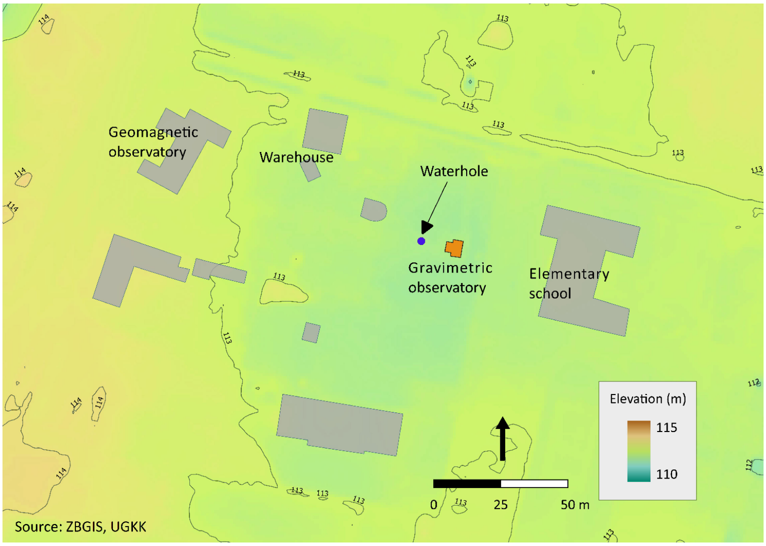

Fig. 1. Digital elevation model of the area surrounding the Hurbanovo Gravimetric Observatory.

Fig. 2. Hurbanovo Gravimetric Observatory (left), detail on the gPhoneX #108 and its thermal insulation (right).

water table measurements is located as well as soil moisture sensors. Data from these sensors can be used for the calculation of the local hydrology effect. Since 2020 the HUVO is part of IGETS, providing gravity recordings complemented with the measured atmospheric pressure (*Janak et al., 2021*).

3. Data and methods

The impact of temperature on gravity values was studied using the data ranging from the October 2020 until the October 2021 between two level calibrations. Gravity readings from the gPhoneX #108 were first filtered using the ETERNA 3.4 (*Wenzel, 1996*) N01S1M01 low pass filter with a maximal output frequency of 0.003 Hz, removing the earthquake signal and the high frequency noise. Gravity residuals were obtained by applying the following corrections to the filtered gravity record:

$$g_{residuals} = g_m + c_T + c_{OL} + c_{PM} + c_A + c_{tilt} + c_{ghe} + c_{ntol} - drift\,. \qquad (1)$$

Earth tides c_T and ocean loading c_{OL}, polar motion c_{PM}, and atmospheric pressure changes c_A as well as other correction related to parameters specific for the gPhoneX such as tilt correction c_{tilt} were taken from the gMonitor software which controls the measuring process and provides standard corrections as described by *Timmen (2010).*

In addition to these corrections, data were also corrected for the influence of global hydrological effect c_{ghe} and non-tidal ocean loading effect c_{ntol} using the mGlobe software (*Mikolaj et al., 2016*), further improving signal to noise ratio (SNR) for the study of the temperature influence on the gravity measurements. Global hydrological effect calculations were based on the NOAH025v2.1 3-hour model (*Rodell et al., 2004*) and linearly interpolated to fit the temporal resolution of gravity recordings from the gPhoneX #108. Non-ocean tidal loading effect calculations were driven by data from the ocean model for circulation and tides (*Thomas, 2002*).

For consistency, the data were not corrected for the influence of the local hydrology due to unreliable soil moisture data during first months of the studied period. Observations were then corrected for the instrumental drift, approximated by a linear function, and for the off-level correction to further improve Signal to Noise Ratio. Linear approximation of the drift was chosen due to insufficient amount of absolute gravity measurements at the gPhoneX site. Decimation from 1 s to 1 min. interval was performed to reduce the amount of data and three periods of uninterrupted data were chosen for further analysis (Fig. 3). The first period (A) starting from the October 2020 can be characterized by a steady temperature decrease starting at the beginning of the month and a sudden rebound back to the originating temperature in November 2020. This temperature changes originate from air-conditioning unit failure, which was unable to maintain temperature in the room above 20 degrees of Celsius. During the slow temperature decrease, the internal temperature (sensor temperature) has also dropped resulting in a short-term drift change that can be seen even after temperature in the room stabilizes in December 2020. The second period (B), starting from the January 2021 with small temperature variations and relatively stable room temperature. Finally the last 3 month period (C) from the July 2021 can be characterized by a moderate to large temperature variations with periodic pattern. These rapid changes prevent the drift from stabilizing before the temperature drop occurs in September 2021 back to prior values.

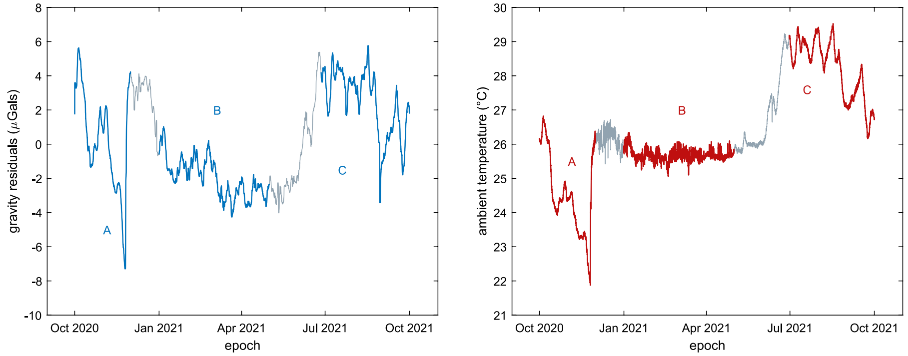

Fig. 3. Gravity residuals (left) and room temperature changes (right) with highlighted periods of data (A, B, C) used in analysis.

On the Figure 3, we can see the same pattern in both temperature and gravity residual time series. A cross-correlation function has been used to evaluate dependency of gravity residuals on temperature changes. Cross-correlation is a signal that compares the displacement of two time series gravity g and temperature T relative to one another defined by (*Papoulis* *and Pillai, 2002*) as:

$$C_{gT}(n, n+m) = E\left[\, g(n)\, T(n+m)\right], \tag{2}$$

where $E[g(n)]$ is the expected value of a random variable defined in terms of the probability density function. For a stationary random processes, the C_{gT} formula can be simplified as (3), taking into account only statistical properties depending on time difference m and neglecting the contribution of absolute time n in the process:

$$C_{gT}(m) = E[\, g(0)\, T(m)]\,. \tag{3}$$

Figure 4 provides a graphical evidence of the correlation between the residual gravity and temperature changes with the most significant correlation present at a lag of 0 minutes. The relationship between the temperature and measured gravity can therefore be studied without consideration of a time delay. The cross-correlation functions computed from three different time periods confirm that the greater the temperature changes are the stronger the correlation in zero lag is.

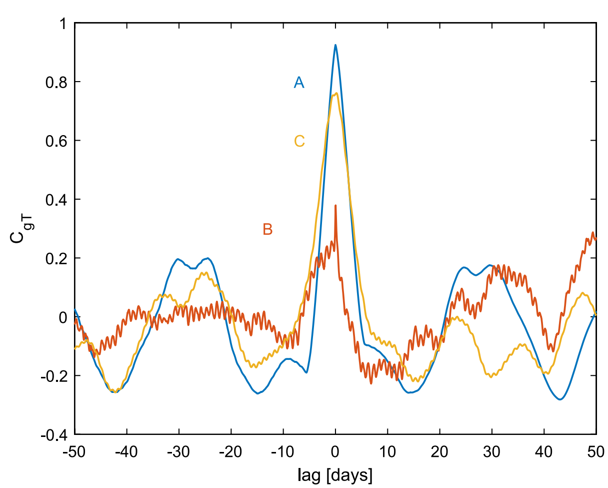

Fig. 4. Cross-correlation function of temperature and residual gravity series.

4. The ambient temperature correction

The changes in ambient temperature are present in the gravity record, due to thermal expansion of the instrument causing a vertical motion of the sensor and additional drift changes. To correct gravity data for temperature influence, the manufacturer (`http://microglacoste.com`) provides the following equation:

$$T_{e_i} = a(T_i - b), \tag{4}$$

where a is the ambient temperature admittance factor, b is the temperature set-point and T_e is the effect of ambient temperature changes. When using a single admittance factor, we assume a constant behaviour of instrument's body during the temperature changes regardless of the time temperature gradient or absolute value of the temperature. To test, how the mentioned parameter changes over time with the temperature changes, data were divided into a 7-day blocks with 6-days of overlap. Applying the Least Square Method (LSM) on Eq. (4), the varying ambient temperature admittance factor a and set-point b were estimated. Overlaps in the data were used as a smoothing filter to avoid the steps in admittance factors and consequently in the ambient temperature correction computed later. The temperature admittance factor a was also estimated using the whole datasets, resulting in a single value, which can be used in gMonitor software to automatically correct the gravity recordings.

We depict the ambient temperature admittance factor only, because the set-point estimates vary only slightly, and mostly depend on the approximate value one chooses before the estimation process. Average temperature values from the whole periods were used as first approximate set-point values. Estimated ambient temperature admittance factor together with the temperature set-point was used to compute the ambient temperature correction and to correct gravity residuals in individual datasets. Averages over studied time periods are given in the Table 1.

Table 1. Estimated parameters a and b.

Time period	**Average admittance factor (μGal/°C)**	**average set-point (°C)**
A	3.20	24.52
B	1.71	25.68
C	2.68	28.06

5. Results

When comparing estimated admittance factors with averages (Fig. 5 left), we can see the greatest variations during the period B, which is in contrast to the small temperature changes that occurred during the time. Despite the higher differences of weekly admittance factor estimates with respect to the average value, only small daily temperature changes of 0.1 °C occur which caused that in the end the correction values for the period B are very similar (Fig. 5 right).

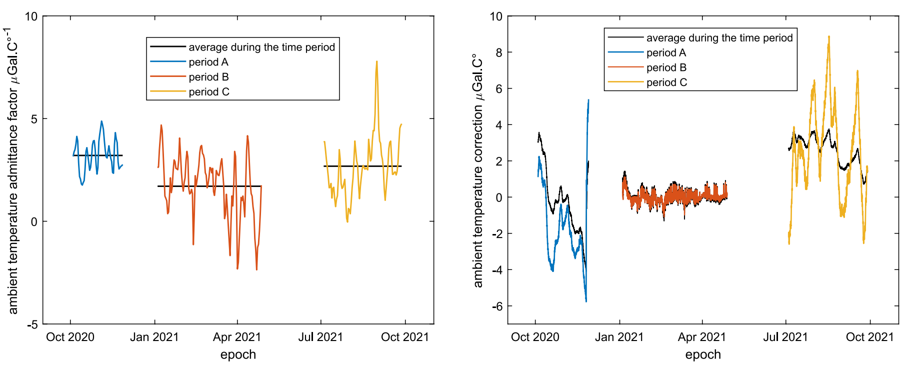

Fig. 5. Ambient temperature admittance factors (left) and ambient temperature corrections (right).

Both varying and single value admittance factor corrections were used to correct the gravity residuals. Cross-correlation function was used to test whether the correlation between the two time series decreased or increased after applying the temperature correction in order to prove the effectiveness of used procedure (see Figs. 6, 7, and 8 left). Evaluation of gravity residuals corrected for temperature influence was also tested in frequency domain ranging from 16 mHz (1 min.) to ∼5.6 μHz (50 hours), where gPhoneX gravimeters are the most effective (see Figs. 6, 7 and 8 right). Spectral analysis remains a powerful and widely used tool for analysis of higher frequencies in gravity recordings (*Valˇko and Pálinkáš, 2015; Francis, 2021*) to describe instruments sensitivity at certain frequency range. It also provides useful information about the significant periods occurring in the observed gravity signal. The power-spectrum obtained from the averaged Welch's periodograms (*Welch, 1967*) was used in order to emphasize the changes

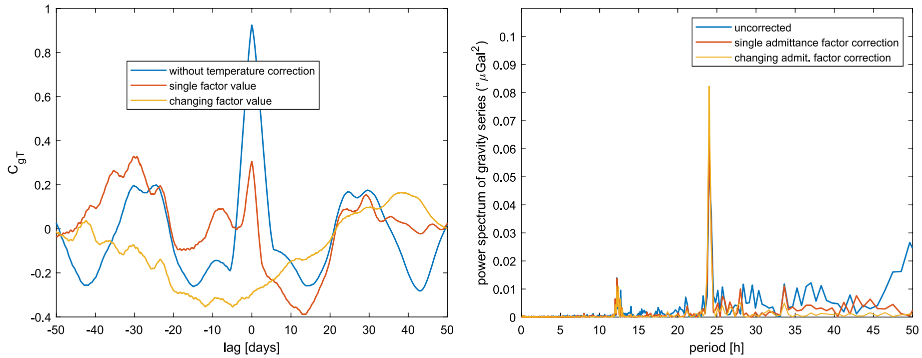

Fig. 6. Cross-correlation between temperature and gravity residuals (left) and power spectrum of gravity of gravity residuals (right) for period A.

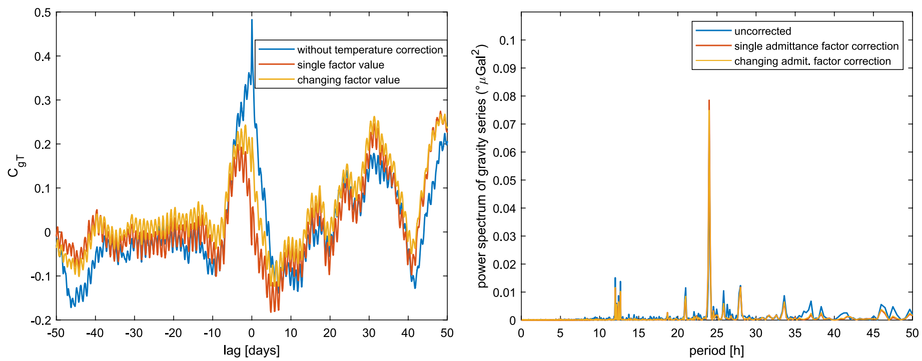

Fig. 7. Cross-correlation between temperature and gravity residuals (left) and power spectrum of gravity of gravity residuals (right) for period B.

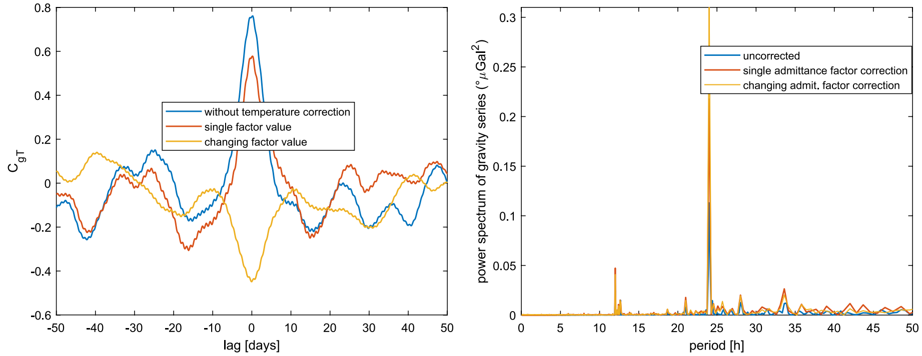

Fig. 8. Cross-correlation between temperature and gravity residuals (left) and power spectrum of gravity of gravity residuals (right) for period C.

instead of the actual amplitude size of periodic signal. It helps us to see if the temperature affects the gravity at certain frequencies/periods. Expected significant period is e.g. 24 hours.

For the time period A, characterized by rapid temperature changes, a correction based on changing admittance factor over time produces the best results in terms of the temperature correlation. In this case, the standard procedure wasn't able to account for gravity changes caused by temperature variations and led to underestimation of the temperature effect. The time period B with a stable ambient temperature proves that, even when the temperature effect is small, use of the correction still decreased the influence of temperature variations on gravity measurements. Best results for the time period C with moderate temperature changes were obtained when using changing admittance factor approach.

For periods A and C the standard approach (averages) tends to underestimate the real temperature effect. On the other hand using changing admittance factor approach resulted in a negative correlation of gravity residuals to temperature series, which indicates that this approach tends to overestimate the temperature effect and to overcorrect the gravity data. Despite the overcorrection of the data, the overall (absolute) value of correlation coefficient is slightly better after the use of non-standard approach. Table 2 provides the correlation coefficient of temperature and residual gravity series at lag of 0 minutes for results provided in Figs. 6 to 8.

Table 2. Correlation coefficients of temperature and residual time series for a lag of 0 minutes.

Period	**Correlation coefficient for lag of 0 minutes**		
	Uncorrected	Corrected using the standard approach	Corrected using the varying admittance factor
A	0.925	0.310	−0.290
B	0.482	0.084	0.179
C	0.758	0.575	−0.448

Power spectrum of both gravity residuals, before and after temperature correction, shows that the amplitude of the main 24-hours period wasn't affected, which an imperfect tidal correction, observing site tilt or some other effects. On the other hand, part of the spectrum containing frequencies with periods different than 24 hours has been slightly reduced after applying the correction in time periods A and B. This can be related to the quasi-periodic process of the air conditioning unit.

Optimal procedure of correcting gravity for the influence of temperature lies in choosing between the standard method applicable for stable to moderate temperature changes and the changing admittance factor for the rapid temperature changes. At last, in Figure 9 we provide comparison of gravity residuals uncorrected for temperature effect and residuals obtained by applying the varying admittance factor with forward calculated gravity effect of local hydrological masses based on MERRA2 data (*GMAO, 2015*).

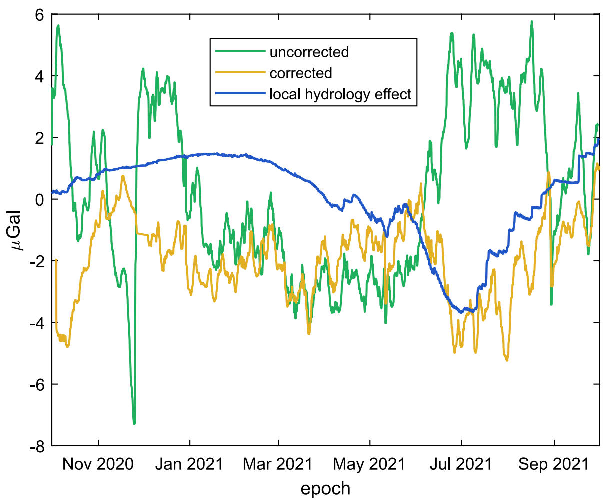

Fig. 9. Comparison of residual gravity time series uncorrected for temperature effect, corrected with varying admittance factor and local hydrological gravity effect based on MERRA2 model.

By comparing the gravity residuals with expected hydrological signal we can see that the series corrected for temperature effect, especially in the second half of the observed time period, are in better agreement than temperature uncorrected data. The non-linear drift common for spring gravimeters, makes the gravity observations less suitable for long-term monitoring of weak gravity signals. Large unexplained noise with amplitude of around 1.5 μGals of unknown origin remains present in the corrected series, which decreases the overall accuracy of stationary gravity measurements.

6. Conclusions

Although modern relative spring gravimeters usually use some sort of shielding to protect the measuring system from environmental condition changes, small impact of temperature still remains present in the gravity readings. New generation of portable Earth tide gravimeters (PET) using metal spring with zero length (gPhoneX) are the most sensitive to environmental changes as they were designed for indoor stationary measurements. A method for reducing the data for influence of temperature has been proposed by the manufacturer based on temperature admittance factor. Effectiveness of the proposed approach was tested on three datasets differing from each other based on the ambient temperature variations. Results show, that the approach proposed by manufacturer can be easily used to efficiently reduce the dependency of gravity residuals on the room temperature. Such approach however has its setbacks, for example when a significant rise or decrease of the average temperature in the room occurs, the temperature effect is either underestimated or overestimated depending on character of temperature changes. This effect is caused by additional drift, that is introduced when the long-term temperature average in the room changes. During such occasions a changing admittance factor averaged over weeks can be used. This approach also accounts for the irregular drift changes induced by the long-term temperature changes. However, it's important to note that for usual short-term temperature changes smaller than 0.1 °C and stable room temperature a use of constant temperature admittance factor is sufficient. During all studied time periods use of the ambient temperature correction reduced the correlation of gravity residuals to temperature, and therefore we recommend gPhoneX users to use the temperature correction even when the conditions are stable.

Acknowledgements. Research presented in this paper was prepared with the support of the grant VEGA 1/0809/21 "Joint evaluation of water–mass and ice mass variations based on GRACE, SWARM and GRACE-FO satellite missions data".

References

Andò B., Carbone D., 2001: A methodology for reducing the effect of meteorological parameters on a continuously recording gravity meter. IEEE Trans. Instrum. Meas., **50**, 5, 1248–1254, doi: 10.1109/19.963193.

Fores B., Klein G., Le Moigne N., Francis O., 2019: Long-Term Stability of Tilt-Controlled gPhoneX Gravimeters. J. Geophys. Res. Solid Earth, **124**, 11, 12264–12276, doi: 10.1029/2019JB018276.

Francis O., 2021: Performance assessment of the relative gravimeter Scintrex CG-6. J. Geod., **95**, 10, 116, doi: 10.1007/s00190-021-01572-y.

Global Modeling and Assimilation Office (GMAO), 2015: MERRA-2 tavg1_2d_slv_Nx: 2d, 1-Hourly, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: May 5th 2022, doi: 10.5067/VJAFPLI1CSIV.

GWR Instruments, Inc., 2022: The Superconducting Gravimeter. Available online (accessed on May 5th 2022): https://www.gwrinstruments.com/about.html.

Hábel B., Janák J., Papčo J., Vaľko M., 2020: Impact of environmental phenomena on continuous relative gravity measurements performed in urban area. Studia Geophys. et Geod., **64**, 3, 330–348, doi: 10.1007/s11200-021-0536-4.

Janak J., Papco J., Novak A., 2021: GphoneX Gravity Data from Hurbanovo - Level 1. doi: 10.5880/igets.hu.l1.001.

Micro-g LaCoste, Inc., 2022: Product manuals. Available online (accessed on June 1st 2022): http://microglacoste.com/support/product-manuals/.

Mikolaj M., Meurers B., Güntner A., 2016: Modelling of global mass effects in hydrology, atmosphere and oceans on surface gravity. Comput. Geosci., **93**, 12–20, doi: 10.1016/j.cageo.2016.04.014.

Niebauer T. M., Blitz T., Constantino A., 2016: Off-level corrections for gravity meters. Metrologia, **53**, 2, 835–839, doi: 10.1088/0026-1394/53/2/835.

Papoulis A., Pillai S. U., 2002: Probability, random variables, and stochastic processes, 4th ed. McGraw-Hill, Boston.

Rodell M., Houser P. R., Jambor U., Gottschalck J., Mitchell K., Meng, C.-J., Arsenault K., Cosgrove B., Radakovich J., Bosilovich M., Entin J. K., Walker J. P., Lohmann D., Toll D., 2004: The Global Land Data Assimilation System. Bull. Am. Meteorol. Soc., **85**, 3, 381–394, doi: 10.1175/BAMS-85-3-381.

Timmen L., 2010: Sciences of geodesy. I: Advances and future directions. Springer, Heidelberg, New York. ISBN: 9783642117404

Thomas M., 2002: Ocean induced variations of Earth's rotation – Results from a simultaneous model of global circulation and tides. PhD dissertation, University of Hamburg, Germany, 129 p.

Vaľko M., Pálinkáš V., 2015: SGNoise - a tool for the ambient noise level analysis at superconducting gravimeter stations. Studia Geophys. et Geod., **59**, 2, 188–199, doi: 10.1007/s11200-014-0928-9.

Van Camp M., Francis O., 2007: Is the instrumental drift of superconducting gravimeters a linear or exponential function of time? J. Geod., **81**, 5, 337–344, doi: 10.1007/s00190-006-0110-4.

Welch P., 1967: The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust., **15**, 2, 70–73, doi: 10.1109/TAU.1967.1161901.

Wenzel H. G., 1996: The nanoGal software: Earth tide data processing package: Eterna 3.3. Bull. d'Inf. Marées Terrestres, **124**, 9425–9439.