Monitoring time variable gravity – bridging Geodesy and Geophysics

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Abstract

The gravity field of the Earth changes with time due to external forcing, but also due to direct gravitational effects of mass variations in the entire Earth system, which are mostly associated with deformation effects caused by loading. Temporal variations of the Earth rotation vector contribute to gravity changes as well. Time variable gravity therefore opens a research field, where Geodesy and Geophysics are closely linked. Today, superconducting gravimeters (SG) provide high accurate gravity time series that allow for monitoring and interpreting of physical signals reflecting a wide range of geodynamical phenomena like Earth tides, Earth rotation, normal modes and environmental gravity effects on all spatial and temporal scales. For more than 20 years, the SG GWRC025 has been operating in Austria, embedded in international projects. This paper presents a review of some important scientific achievements, to which the GWRC025 data contributed essentially.

Keywords: Time variable gravity, geodynamic processes, superconducting gravimeter

Kurzfassung

Das Schwerefeld der Erde ändert sich ständig durch die Gezeiten, aber auch durch direkte Gravitationseffekte von Massenverlagerungen im gesamten System Erde, die meist mit Deformation durch Auflast verbunden sind. Zeitliche Variationen des Erdrotationsvektors tragen ebenfalls zur Änderung der Schwerebeschleunigung bei. Die Untersuchung dieser zeitlichen Variationen eröffnet ein Forschungsfeld, das Geodäsie und Geophysik eng miteinander verbindet. Heute liefern supraleitende Gravimeter (SG) hochgenaue kontinuierliche Zeitreihen, mit denen physikalische Signale überwacht und interpretiert werden können, die eine Vielzahl von geodynamischen Phänomenen wie Erdgezeiten, Erdrotation, Eigenschwingungen und Massentransport auf allen räumlichen und zeitlichen Skalen widerspiegeln. Seit mehr als 20 Jahren ist das SG GWRC025 in Österreich im Einsatz und stellt wertvolle Messreihen für nationale und internationale Projekte zu Verfügung. Dieser Aufsatz gibt einen Überblick über einige wichtige wissenschaftliche Erkenntnisse, zu denen die Daten des GWRC025 wesentlich beigetragen haben.

Schlüsselworte: Schwerefeld, Supraleitende Gravimeter, zeitliche Schwereänderungen, geodynamische Prozesse

1. Introduction

Temporal variations of the gravity field are mainly caused by external forcing (tides). In addition, mass transports within the earth system on all spatial and temporal scales make the gravity potential time-dependent because they mostly change the density distribution of the earth. Finally, time variable earth rotation is involved as well. Therefore, changes in the mass distribution of the earth (mass transport) as well as changes of the earth rotation will directly influence the gravity of the earth and its figure. Mass transports also change the inertia tensor and hence contribute to the time variability of the earth rotation. On a non-rigid earth, they always cause a direct Newtonian effect as well as deformation due to time-dependent loading and inertial effects. Due to its direct link to the mass distribution, investigating the gravity field helps to understand both the structure and dynamical processes of the earth.

Superconducting gravimeters (SG) are currently the most accurate sensors for continuous observation of temporal gravity variations. In the time domain, they have a resolution less than 1 nm/s^2, and in the frequency domain 0.01 nm/s^2 resolution is achievable at tidal and normal mode frequencies under optimum site conditions (Warburton and Brinton, 1995; Richter and Warburton, 1998). The instrumental drift of SG sensors is well below 50 nm/s^2 per year and in most cases a linear function of time. Therefore, the drift can be well modeled based on co-located absolute gravimeter observations, which, in addition, provide the SG scale factor with an accuracy at the 1 per mille level. These characteristics qualify SGs as a unique tool for investigating short- and long-term geodynamic phenomena and make them capable to detect tiny gravity signals both in frequency and in time domain (e.g. Crossley et al. 1999, Hinderer et al. 2007). SG gravity time series contribute to give answers to many problems spanning from earth tides, earth rotation and normal modes to atmospheric or hydrological mass transports and global climate change.

In Austria, the Central Institute of Meteorology and Geodynamics (ZAMG) operates the SG GWR C025 since 1995 in close co-operation with the Department of Meteorology and Geophysics (University of Vienna) and the Federal Office of Surveying and Metrology (BEV). In the beginning, the SG was installed in an underground laboratory of the main ZAMG building in Vienna (VI, Austria) for more than 12 years. The station VI is located at the margin of the Vienna Basin at about 190 m altitude within late Tertiary sediments. In autumn 2007, the SG was moved to its final destination at Conrad observatory (CO), a geodynamical research facility situated at 1045 m a.s.l. within the Northern Calcareous Alps, 60 km SW of Vienna. CO is an underground installation as well.

The research objectives of GWRC025 are focused on earth tides and the impact of atmospheric and hydrological processes on temporal gravity variations. The knowledge of these environmental effects is indispensible for separating gravity signals of different origin. The CO site is co-located with a permanent GPS station operated by BEV. This opens the possibility to interpret long-term deformation at the Eastern margin of the Alps. Main task of this paper is presenting some of the scientific achievements where the VI and CO gravity time series provided important contributions.

2. Earth Tides

The elastic response of the Earth to tidal forcing depends on density and elastic properties in the Earth interior. Tidal parameters derived from observed tidal gravity variations at the Earth's surface relate the true tidal acceleration to that of a rigid, non-deformable planet. They can be described by Love-numbers, which depend on the degree of the spherical harmonic expansion of the tide generating potential. Our knowledge of the interior structure is mainly based on seismology which allows for modeling the physical properties of the Earth. Validating the theoretical Earth models can be done by comparing observed tidal parameters with model predictions (Baker and Bos 2003). The most recently developed body tide models (e.g. Dehant et al. 1999, Mathews 2001) differ by about 1 per mille only. Therefore, highly accurate sensor calibration is a mandatory requirement. In addition, the tidal amplitude factors and phases must be corrected for ocean loading effects which are provided by ocean tide models. The most recent validation has been presented by Ducarme et al. (2014) based on the average of load vectors from 8 different ocean tide models provided by the Free Ocean Tide Loading Provider (Scherneck and Bos, 2014). To keep the load calculation small, three European mid-continental stations at Pecny (PE, Czech Republic), Vienna (VI, Austria) and Conrad observatory (CO, Austria) have been selected, based on gravity time series over 5-12 years obtained from two well calibrated SGs. The agreement of the corrected gravimetric factors at these 3 stations is better than 0.04% in amplitude and 0.02° in phase. Their weighted means confirm previous results obtained from 16 stations in Europe (Ducarme et al. 2009) but with higher precision. They fit best to the theoretical body tide model DDW99/NH (Dehant et al. 1999) for M2 (Figure 1) and MATH01/NH (Mathews 2001) for O1.

The calibration accuracy and the quality of ocean load models and/or the load vector computation scheme are limiting factors for body tide model validation. SGs are commonly calibrated by co-located absolute gravity meters (Hinderer et al. 1991). This method provides calibration accuracy at the 1 per mille level. This accuracy can be increased by performing repeated calibration experiments (e.g. Van Camp et al. 2015, Crossley et al. 2018). Well calibrated spring gravimeters

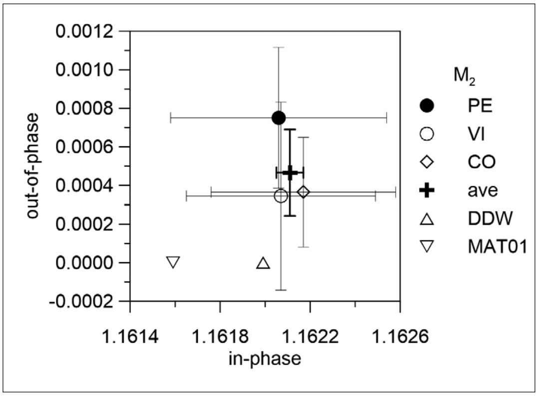

Fig. 1: In-phase and out-of-phase M2 tidal parameters after correcting for ocean tide loading derived from SG gravity time series at Pecny (PE), Vienna (VI) and Conrad observatory (CO) and comparison with theoretical body tide models DDW/NH and MAT01/NH. The average (bold cross) of the three stations deviates from the DDW prediction by less than 0.1 per mille.

can be used alternatively provided the irregular instrumental drift of the reference sensor is properly adjusted (Meurers 2012). The temporal stability of the SG scale factor can be assessed by comparing the modulation of the M2 gravimetric factor derived from successive 1-year tidal analyses at nearby SG stations (Meurers 2017). This modulation is mainly due to the inherently limited frequency resolution of tidal analyses, because limited time series never allow for separating all tidal constituents of the tidal spectrum (Meurers et al. 2016). It must appear similarly in tidal analysis results from neighboring stations or synthetic tidal time series including ocean loading.

Because SGs exhibit low and regular instrumental drift, they are most suitable for investigating the gravimetric factors of constituents within the long-period tidal frequency band. Ducarme et al. (2004) analyzed an average gravimetric factor of 1.163 ± 0.001 derived from 9 SG stations after correcting for ocean loading. This number deviates from body tide models by 0.6 %. Also the phase differs significantly from zero. The transfer function of the SG sensors is known with much higher accuracy. This indicates that the oceanic loading correction is still not accurate enough. Comparing the tidal parameters corrected for ocean loading therefore provides a valuable tool for assessing the accuracy of ocean load models derived from satellite altimetry and calculation procedures.

3. Earth Rotation

Four eigenmodes are expected for a rotating elliptical planet with liquid outer and solid inner core: the Chandler wobble, free core nutation (FCN) or Nearly Diurnal Free Wobble (NDFW) in an Earth fixed reference frame, free inner-core notation and inner-core wobble (e.g. Rosat et al. 2017). While the two first rotational modes are clearly visible in high accurate gravity time series, the inner-core related modes are hard to detect. The gravimetric factors in the diurnal band obtained from tidal analyses are strongly influenced by resonance effects of the NDFW close to the NDFW frequency at about 1.005 cpd. Ducarme et al. (2007) retrieved the FCN eigenperiod from records of 21 globally distributed SG stations as 429.7 sidereal days with a 95% confidence interval of (427.3, 432.1) sidereal days. This number is close to the estimate of 431.18 ± 0.10 sidereal days obtained from VLBI data spanning over 27 years (Krásná et al. 2013).

Ducarme et al. (2006) analyzed tidal records of nine SG stations and determined the gravimetric amplitude factor of the polar motion (Chandler and annual wobble) by applying a regression analysis on the gravity residuals after removing the tides and air pressure effects. They obtained an average factor for the Chandler wobble of 1.179, which differs considerably from predictions by Earth response models at the Chandler wobble frequency due to the indirect effects of ocean tides. The correction based on equilibrium ocean pole tides reduced the arithmetic mean to 1.1605, which is much closer to the model predictions.

4. Normal Modes

SGs perform better than modern seismological instrumentation at frequencies lower than about 0.8 mHz (Widmer-Schnidrig 2003) and hence are widely used for normal mode studies. The gravity records of GWRC025 with 1Hz sampling both from VI and CO have been intensively incorporated in numerous free oscillation investigations because of the high quality of the acquired data. The research focus in this field is widely spread. Based on data of the 2004 Mw = 9.3 Sumatra-Andaman earthquake acquired by 18 world-wide distributed SGs, Xu et al. (2008) determined the eigenfrequency, initial amplitude, and Q of the radial mode ${}_0S_0$ with high accuracy as $0.8146565 \pm 1.2 \cdot 10^{-6}$ mHz, 1.582 ± 0.054 nm/s^2, and 5400 ± 22 respectively. They confirm the numbers obtained by Rosat et al. (2007), who provided observational evidence of geographical variations of ${}_0S_0$ amplitude due the ellipticity and rotation of the Earth for the first time. While for a spherically symmetric Earth the ${}_0S_0$ amplitude is independent of the location at Earth's surface, theoretical predictions indicate a 2 % amplitude increase from the equator to the poles (Rosat et al. 2007). The observation of the frequency splitting of low frequency (< 1 mHz) normal modes helps to constrain 1D-density models of the Earth. Rosat et al. (2003) report on the first clear observation of the ${}_2S_1$ mode based on a stack of 5 SG stations after the Peru Mw = 8.4 earthquake in 2001. Again from the Sumatra event, ${}_2S_1$ splitting frequencies have been determined from 11 SG records (Rosat et al. 2005).

A still open problem in global geodynamics is the detection of the frequency triplet of the Slichter mode ${}_1S_1$. Knowledge of the Slichter mode frequencies would constrain the core's density structure and the density jump at the inner core boundary of the Earth. However, it is challenging to retrieve the Slichter triplet from SG records, because their amplitudes are close to the SG noise level in the corresponding frequency band. The detection has been claimed by some authors in the past but later on not confirmed by many others using multi-station stacking techniques in order to improve the detection capability based on SG data (e.g. Guo et al. 2006).

5. Environmental Effects in Gravity Time Series

Environmental effects in gravity time series are mainly caused by mass transport phenomena within atmosphere and hydrosphere and superimpose each other. In case of the atmosphere the resulting temporal gravity change is closely related to the air pressure variation observed at a station. Therefore it is possible to remove air pressure effects to a high extent (> 90 %) in order to retrieve the sensor response to geodynamical processes that would be masked otherwise.

5.1 Atmospheric Signals

The direct Newtonian effect dominates at lower frequencies and is partly compensated due to the displacement caused by surface loading of the air pressure. Atmospheric gravity signals are not always associated with air pressure variations because pure Newtonian effects can be caused also by vertical air mass redistribution whereby the surface air pressure does not change (Meurers 2000).

At higher frequencies the inertial effect gets important as well and leads to a sign reversal of the air pressure admittance function (Zürn and Wielandt 2007), which was proven to appear in gravity time series (Zürn and Meurers 2009). For removing the gravity effect of the atmosphere, operational 3D weather models (Klügel and Wziontek 2009) are combined with admittance approaches using the air pressure admittance to gravity in the tidal frequency band. The Federal Agency for Cartography and Geodesy (BKG) in Germany offers an atmospheric attraction computation service (ATMACS) which provides correcting time series based on regional and global models.

At higher frequencies, a frequency dependent admittance function derived from cross spectrum analysis must be used. This function is site-dependent. Figure 2 compares the admittance function beyond 0.1 mHz at VI and CO. Zürn and Wielandt (2007) developed simplistic models for explaining the admittance function: the inverted Bouguer plate (IBPM) and the atmospheric gravity wave (AGW) approach for an elastic crust. At CO, the AGW model matches the observation qualitatively while the IBPM model fits better at VI, at least at frequencies below 2 mHz.

For providing de-aliasing products used for satellite gravity missions like GRACE (Gravity Recovery and Climate Experiment) different approaches for modeling the atmospheric gravity effect are successfully applied by using spherical harmonic coefficients. Karbon et al. (2014) proved them to perform similar to the ATMACS products.

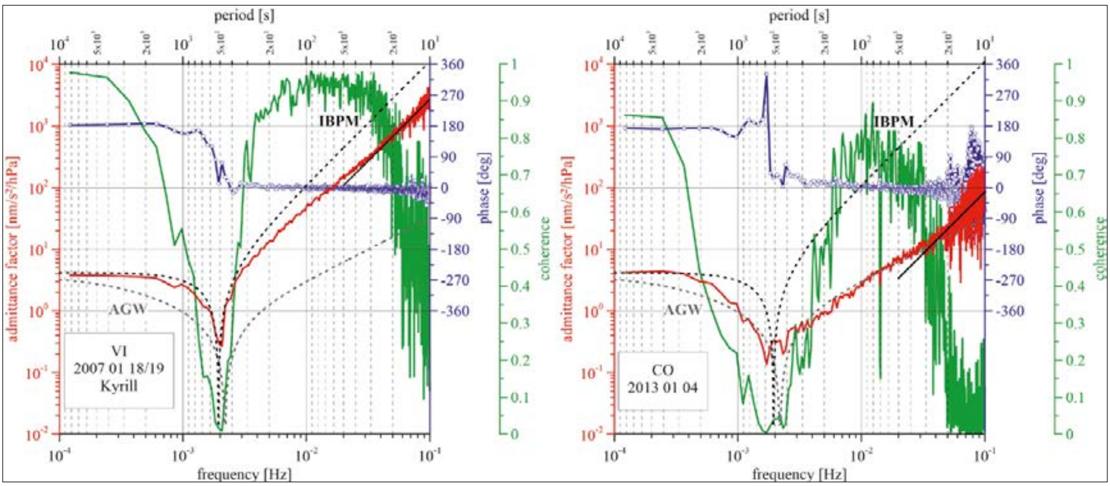

Fig. 2: Frequency dependent admittance function at Vienna (left panel) and Conrad observatory (right panel). The admittance factor is displayed in red; phase in blue and coherency in green. The sign-reversal at about 2 mHz is clearly visible. In both cases, high-frequency air pressure variations were caused by heavy storm events.

5.2 Hydrological Signals

In order to retrieve gravity signals caused by hydrological mass transport (precipitation, soil moisture, ground water table etc.) the gravity time series has to be corrected for tides (body tide and ocean loading), the atmospheric effect and the pole motion effect. The tidal analysis provides a tidal model including the ocean loading as well as the air pressure admittance within the tidal frequency band taken into account. The pole motion effect is based on earth rotation data provided by the international earth rotation service (IERS). Figure 3 compares the gravity residuals obtained by this procedure for the stations VI and CO. For clarity, a same time period of about 4 years has been selected. Figure 3 shows clearly, that hydrological processes at CO are much more complex than at VI. This is mainly due to water mass transport from topography downwards to below the SG sensor happening in case of heavy rain or rapid snow melt events. Gravity immediately reacts on precipitation events by a sudden gravity decrease, because both VI and CO are underground installations and therefore the precipitation within the dominating close surrounding is located above the sensors. The precipitation effect can be almost perfectly modeled by an equivalent water sheet spread over the topography of a terrain model with high spatial resolution (Meurers et al. 2007).

Figure 4 presents an example of a heavy rain event at CO. Even very little rain fall is retrieved by the SG in the time domain and shows up in gravity changes of 1 nm/s^2 and less. The sudden residual drop due to heavy rain can be well explained by the simplistic water sheet model. This example proves the high quality of the correction procedures applied for removing environmental effects from gravity time series based on modern meteorological instrumentation. A small-amplitude residual disturbance is visible between 10 and 11 UTC (Figure 4). Distrometer data provide the SYNOP code and allow for classifying the precipitation type. At the beginning, precipitation consists of a mixture of hail and rain. The SG experiences the Newtonian effect immediately. However, solid hail particles need some time for melting before they are monitored by the rain gauge, i.e. their contribution is apparently delayed during the hail phase. Later, the rain gauge indicates ongoing rain fall although rain has stopped as shown by the distrometer. The rain gauge obviously reflects the ice melting process at this moment. Vertical air mass redistribution could contribute to the residual disturbance as well.

Mikolaj et al. (2015) calculated the short- and long-term hydrological gravity effects at the Vienna station in spite of the fact that in situ soil moisture measurements were not available. The approach they applied combines gravity residuals, a priori soil moisture information from global hydrological models and in situ meteorological data like temperature, precipitation and snow height, i.e. missing soil moisture data is replaced by the response of a properly calibrated model based on the meteorological time series. The method is applicable for all stations where in situ soil moisture data are lacking provided they are located in relatively flat terrain. Figure 5 shows the mean global hydrological effect of several different global land surface models of the GLDAS (Rodell et al. 2004)

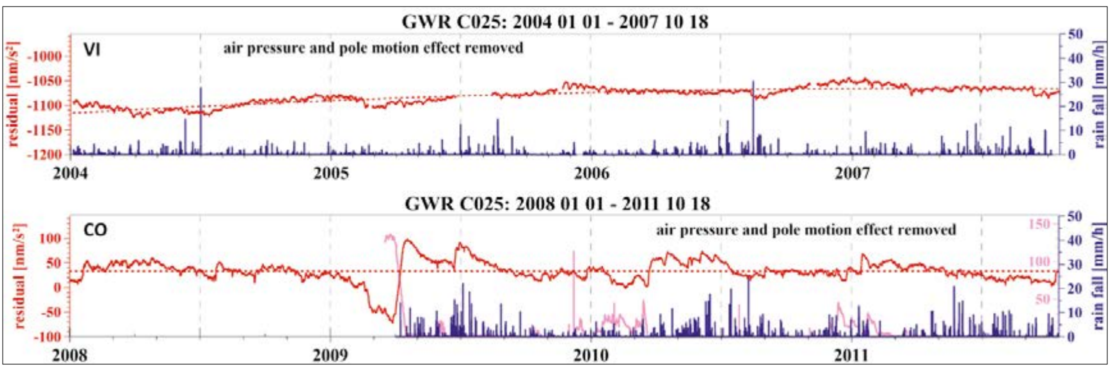

Fig. 3: Gravity residuals (red) at the stations VI (upper panel) and CO (lower panel) after subtracting the tides, atmospheric effects and the pole tide from the observation. Rain fall is displayed in blue, height of snow cover in pink. Dashed lines represent a low polynomial drift. Sections of same time interval have been selected for both stations for easier comparison.

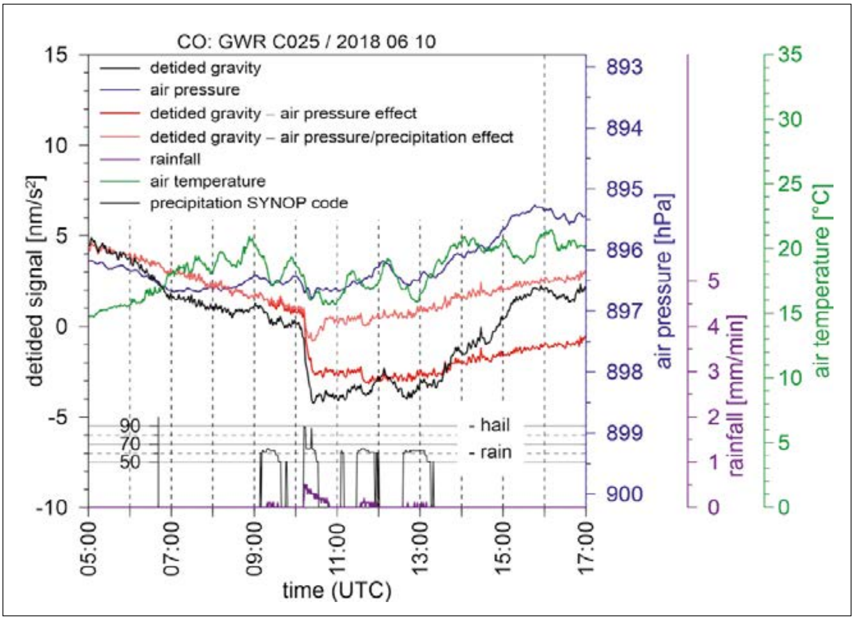

Fig. 4: *Gravity residuals corrected for the precipitation effect during a heavy rain event at CO in June 2018. The light red solid line shows the gravity residuals after subtracting the precipitation effect.*

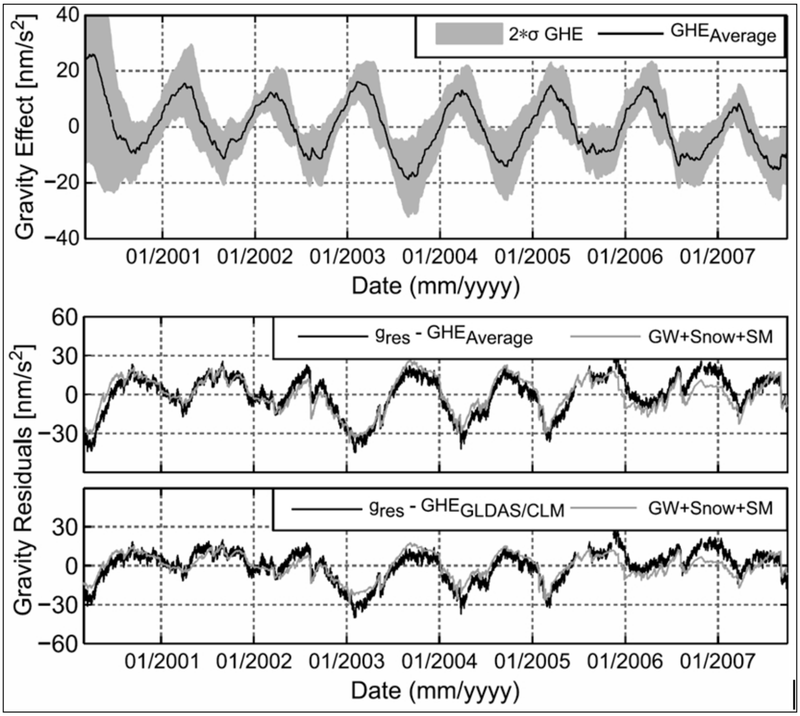

Fig. 5: *Global and local hydrological effect and gravity residuals at VI. The uppermost panel shows the average ($GHE_{average}$) of five different global hydrological models und its uncertainty. The local gravity effect combines local models of soil moisture (SM), groundwater (GW) and snow water equivalent. The middle and lower panels display the gravity residuals after subtracting the global part ($GHE_{average}$) and the GLDAS/CLM global model respectively (black solid line) compared to the contribution of the local hydrology model (grey solid line).*

and compares the gravity residuals corrected for the global contribution with the response of the local model which partly compensate each other. This is typical for underground installations like VI (Longuevergne et al. 2009). The gravity residuals are reduced by about 30% after applying the global and local hydrological correction.

Hydrological signals separated from SG gravity time series can be used successfully in hydrological research as they provide an integrated view in particular on local hydrological processes. Using these signals as a ground truth for global signals retrieved from satellite missions like GRACE (e.g. Crossley et al. 2012) turns out to be very problematic, in particular if surface and underground installations are mixed, given the complexity of local hydrology varying from station to station and the different sensitivity of space borne and ground based gravity sensors with respect to the spatial scale of the hydrological phenomena (Van Camp et al. 2014a, 2014b).

6. Conclusion

Superconducting gravimetry is an important pillar supplementing the investigation of the Earth's gravity field, its temporal changes and low-frequency geodynamics based on geodetic techniques like space gravity field missions, satellite altimetry or Very Long Baseline Interferometry (VLBI). The few examples of successful cooperation of the geophysical and geodetic scientific community, not only in Austria but world-wide, prove the necessity of modern research facilities providing the most modern instrumentation. They also show the importance of collaboration across the scientific disciplines. Conrad observatory is an excellent example of a research facility supporting the research interests of geophysics and geodesy and connecting involved scientists in Austria.

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