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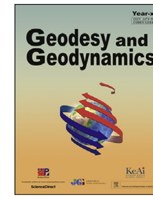

Scintrex CG5 used for superconducting gravimeter calibration

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ABSTRACT

The scale factor accuracy of superconducting gravimeters (SG) can be largely improved by a high repetition rate of calibration experiments. At stations where the availability of absolute gravimeters is limited, carefully calibrated spring gravimeters can be used for providing the reference signal assuming the irregular drift is properly adjusted. The temporal stability of the SG scale factor is assessable by comparing the temporal variations of M2 tidal parameters observed at neighboring SG sites or from synthetic tide models. Combining these methods reduces the SG scale factor error to a few 0.1‰. The paper addresses the particular procedure required for evaluating the calibration experiments based on spring gravimeters and presents results obtained at Conrad observatory (Austria). Comparing the M2 amplitude factor modulation helped to reveal a SG scale factor offset of about 0.2‰ due to re-installation.

1. Introduction

The accuracy of the gravimeter transfer function is a limiting factor for modern geodynamical studies based on gravity time series. Two aspects are concerned in particular:

- Validating different theoretical body tide or ocean loading models needs a scale factor accuracy of better than 1‰ [1].
- Temporal variations of the transfer function, if they exist, need to be ascertained at the same level of accuracy.

The standard method of superconducting gravimeter (SG) calibration relies on co-located gravity observation by using absolute gravimeters (AG) as reference [2]. The required accuracy is mainly limited by the given site noise conditions. In the time domain, the 1‰ accuracy level is achieved by side-by-side monitoring over at least 5–7 days [3,4]. Van Camp et al. [5] demonstrate that the 1‰ precision can be achieved within much shorter time under Gaussian white noise condition by starting the experiment close to spring tides and by increasing the AG sampling rate. Repeated calibration experiments over time periods of 5 years or more have rarely shown differences exceeding the calibration error [6]. The calibration results do not depend on the specific AG used [7]. Therefore, averaging the results of several experiments can help to improve the SG scale factor to an accuracy level far below 1‰ [5,8,9].

While spring type gravimeters can be calibrated by co-located SG observations [10], they also have potential to contribute to the SG calibration factor determination. Riccardi et al. [11] studied the performance of spring gravimeters used in the calibration experiment instead of an AG. As a result, they concluded that spring gravimeters are not suitable to provide the reference SG calibrations. However, Meurers [9] showed that using spring gravimeters is an option at those SG sites where AGs are not permanently or only rarely available, provided the instrumental drift of these instruments is properly considered. This problem is re-visited in this paper once more.

The concept of co-located gravity monitoring implicitly assumes, that observation errors follow a random distribution, and that both gravity sensors experience exactly the same gravity signal. Indeed, this assumption is never perfectly met, because the signals observed by both sensors differ inherently due to following reasons:

- different instrumental noise and ground noise response
- different Newtonian response to local sources due to the spatial separation of both sensors
- instrumental drift

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- sensor response on air pressure variations (e.g. non-compensated Archimedean forces in not perfectly sealed spring gravimeters)
- different transfer function introducing different time lags
- pre-processing filter response.

The last three items are less severe, as they can be considered with sufficient accuracy. While SGs exhibit extremely small instrumental drift that can be modeled by either a linear or exponential function of time [12], the drift of spring gravimeters is strong, irregular and unpredictable. The success of using spring type gravimeters for providing the reference signal therefore strongly depends on how carefully the drift is modeled, for example, by higher degree polynomial functions, and also on accurate spring gravimeter calibration. This paper addresses the related aspects of Scintrex CG-5 gravimeters.

The analysis of tidal parameter time series and comparing them with those of neighboring stations turn out as an appropriate tool for controlling the temporal stability of the SG transfer function and for identifying disturbed portions in gravity time series as well as potential offsets [13].

The most reliably determined tidal parameters are achieved for the main semidiurnal constituent M2. Common patterns in the temporal variation of M2 tidal parameters have been detected in 10 European SG gravity time series by analyzing successive intervals and shifting the analysis window over each SG time series [13]. Comparing with synthetic tide models suggests them to be mostly due to insufficient frequency resolution of length-limited time series as 2nd and 3rd degree constituents within the M2 group respond differently to ocean loading. Long-term M2 modulation in analyses of consecutive 1-yr intervals is expected to appear as numerical artefact. The modulation amplitude is as small as 0.2‰ and was captured in the investigated SG time series [13]. If the scale factor instability was larger, it would be very unlikely to observe common patterns in the M2 tidal parameter variations. In addition, time-varying ocean load can contribute as well. The second part of the paper discusses how this kind of analysis can successfully support the SG scale factor determination.

2. Calibration experiments at Conrad Observatory

The SG GWR C025 acquired a 12 years gravity time series in Vienna (Austria) before it was moved to the new Conrad observatory (CO) 60 km SW of Vienna (VI) in autumn 2007. Since that time, the SG was calibrated by co-located AG experiments performed twice a year. In addition, several calibration experiments using a Scintrex CG-5 gravimeter helped to improve the SG scale factor. In October 2013 the SG sphere dropped down due to a temperature control problem, and the instrument had to be re-installed and re-initialized in spring 2015 (including cool-down, demagnetization and sphere levitation). The calibration experiments following there after did not reveal a scale factor change, at least no changes exceeding the 1‰ uncertainty, while the entire system's time lag increased by about 2.9 s.

2.1. Instrumental properties of the Scintrex CG-5

If commercial Scintrex CG-5 gravimeters are used for providing the reference signal, the specific properties of this gravimeter type must be considered. For example, the scale factor of spring gravimeters is varying with time. Hence, precise calibrations repeated on a regular time base are mandatory. The Scintrex Autograv CG-5 (SN 40236) used for SG calibration experiments at CO is regularly calibrated at the Hochkar calibration line (HCL) [14]. The latter consists of 4 stations established along a mountain road within the Austrian Alps. The calibration line covers a height difference of about 950 m and a gravity difference of 1980 $\mu m/s^2$ derived from absolute gravimeter observations. Short distances between the stations enable rapid access and therefore allow for accurate determination of the gravimeter drift. One cycle including all stations is completed within less than 2 h. Absolute gravity measurements repeated in 1995 as well as regular relative gravity measurements performed in the past decades proved high temporal stability which makes the HCL well suited for very accurate scale factor determination of relative gravimeters [15,16]. Gravity changes due to reconstruction work close to the stations are less than 200 nm/s^2 and are properly considered [17]. The formal calibration error is less than 0.05‰ if we assume that unknown environmental gravity variations do not exceed 100 nm/s^2. The sensor of Scintrex gravimeters is protected from ambient temperature and atmospheric pressure changes by sealing the sensor unit in a temperature stabilized vacuum chamber [17]. Therefore, buoyancy effects do not bias scale factors derived from vertical calibration lines.

Repeated observations at HCL evidence an almost linear decrease of the CG5 scale factor by 0.5‰ within the first 3.5 years. Since 2011 the scale factor remains on a constant level (Fig. 1). Short-term variability turns out to be within 0.05‰ and is mainly due to small gravity changes caused by hydrological sources. Fig. 1 shows the correction factor to be applied to the scale factor initially provided by the manufacturer. The scale factor was kept unchanged in the CG5 parameter set at all calibration experiments with except of considering a change in autumn 2009 as a result of repairing a sensor recovery problem by the manufacturer.

The Scintrex Autograv CG-5 is equipped with tilt sensors. The tilt signal is used for numerical correction of the sensor misalignment with respect to the plumb line. Therefore, tilt meter sensitivity and offsets have to be carefully controlled. They might change with time and if they remain undetected, they would bias the tilt correction systematically. For CG-5 (SN 40236), the tilt meter calibration has been frequently performed following the procedure recommended by the manufacturer [17], in most cases immediately before and after each SG calibration experiment. Results provided in Fig. 2 show that the tilt offsets are well determined in general. The tilt meter in *y*-direction obviously shows random offsets of about 10 arcsec perhaps as consequence of vibrations during transport. Given the tidal peak-to-peak amplitude of about 2500 nm/s^2 exploitable at mid-latitudes, an undetected 10-arcsec misalignment would reduce this signal by 10^{-6} per mille only, which is too small to affect the result of SG calibration experiments significantly. The sudden change of the tilt offset in *x*-direction between 2009 and 2010 is due to repair of the sensor recovery problem by the manufacturer.

The Scintrex CG-5 is a quartz spring gravimeter exhibiting a strong and irregular drift. The instrumental drift is dominated by a

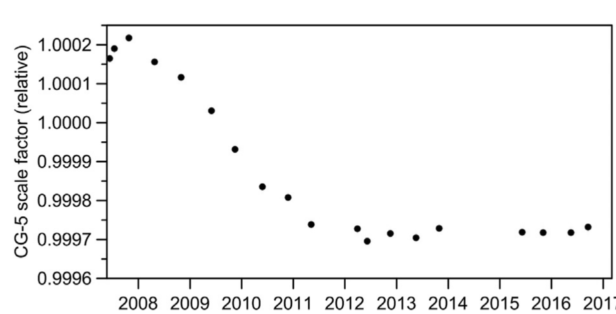

Fig. 1. Temporal variation of the Scintrex Autograv CG5 (SN 40236) scale factor resulting from repeated calibrations at the Hochkar calibration line (Austria) shown by the correction factor to be applied to the manufacturer's initial scale factor, which was kept unchanged in the CG5 parameter set.

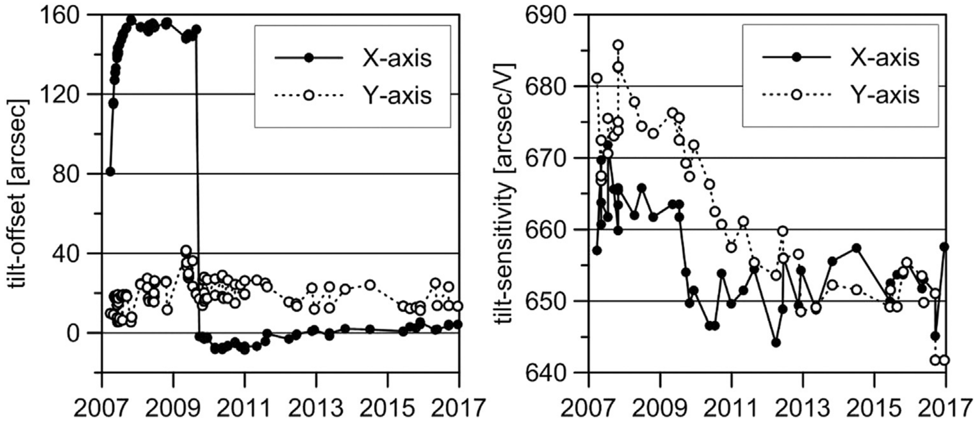

Fig. 2. Tilt meter offsets and sensitivity of Scintrex Autograv CG5 (SN 40236).

linear term, which varies with time. For the instrument used here, it is about 5 μm/s^2 per day and shows a nearly annual cycle (about 377 days) of unknown origin (Fig. 3). Determining an appropriate drift model is challenging and crucial for achieving reliable results. Even if the linear part dominates, the non-linear components play an important role as well.

2.2. SG/CG5 calibration experiment — Setup

The Scintrex CG-5 basically samples gravity at a fixed rate of 6 Hz. For suppressing seismic noise, gravity readings are then averaged over a user-selected period of time. Outliers are rejected automatically based on a standard deviation criterion. Tilt corrections are applied according to the tilts observed at the end of the averaging period. For the SG calibration experiments performed at CO, averaging periods of 120 or 60 s have been used providing about 700 or 1400 samples respectively per day. Side-by-side monitoring was scheduled along periods between 1 and 4 months in order to obtain a large number of data pairs for the statistical analyses, considering the trade-off between the length of the monitoring period and the complexity of the drift model to be applied. Temporal CG5 scale factor variation has been taken into account by linear interpolation of the results shown in Fig. 1.

SG data were sampled at 1 Hz and low-pass filtered by applying the GGP decimation filter g1s1m (http://www.eas.slu.edu/GGP/ggpfilters.html). G1s1m is a Chebyshev filter with a length of 1009 samples and attenuation of 1.8×10^{-7} at Nyquist frequency. The filter output was then averaged over the respective CG5 averaging periods (120 or 60 s). Disturbed data (e.g. earthquakes) were rejected both from the resulting CG-5 and SG time series.

2.3. Drift determination

The strong and irregular drift of the spring gravimeter violates the assumption that both sensor outputs reflect a same signal. Therefore a model for the differential drift between CG5 and SG has to be adjusted together with the SG scale factor commonly based on a polynomial approach. The choice of the polynomial degree is a crucial point. The adjusted SG scale factor is strongly biased if the model does not sufficiently remove all drift components [9]. Fig. 4 shows exemplarily the result of a SG calibration experiment during June—August 2015. Typically, the SG scale factor converges very slowly with increasing number of data pairs used in the adjustment (Fig. 4a) and strongly depends on the chosen degree of the drift polynomial (Fig. 4b).

In order to select the degree of the CG-5 drift polynomial on an objective basis, the following criteria have to been introduced:

- The SG scale factor has to approach a stable convergence level (Fig. 4a)
- The RMS error of the adjusted SG scale factor is not reduced further by increasing the polynomial degree (Fig. 4b)
- The frequency distribution of CG-5 residuals after subtracting the tides and the drift should be close to a Gaussian distribution

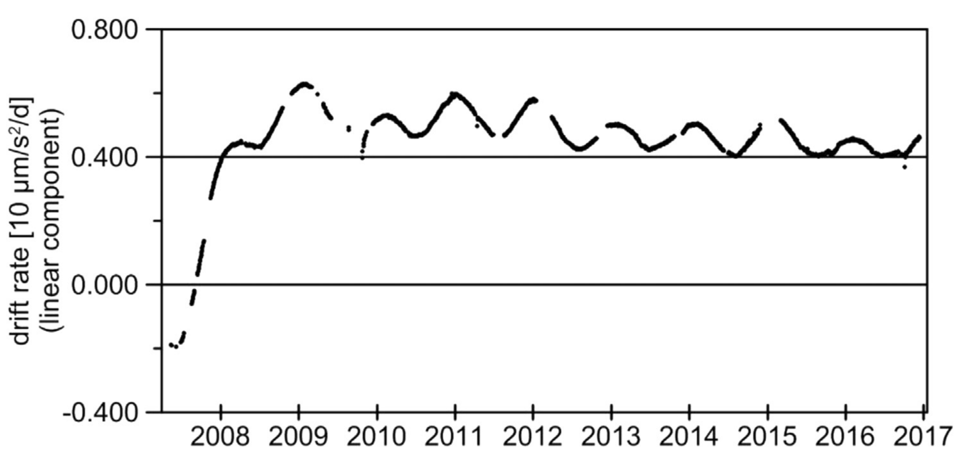

Fig. 3. Temporal variation of the linear drift rate (Scintrex Autograv CG-5 SN 40236) obtained by LSQ adjustment of consecutive 2 days' periods.

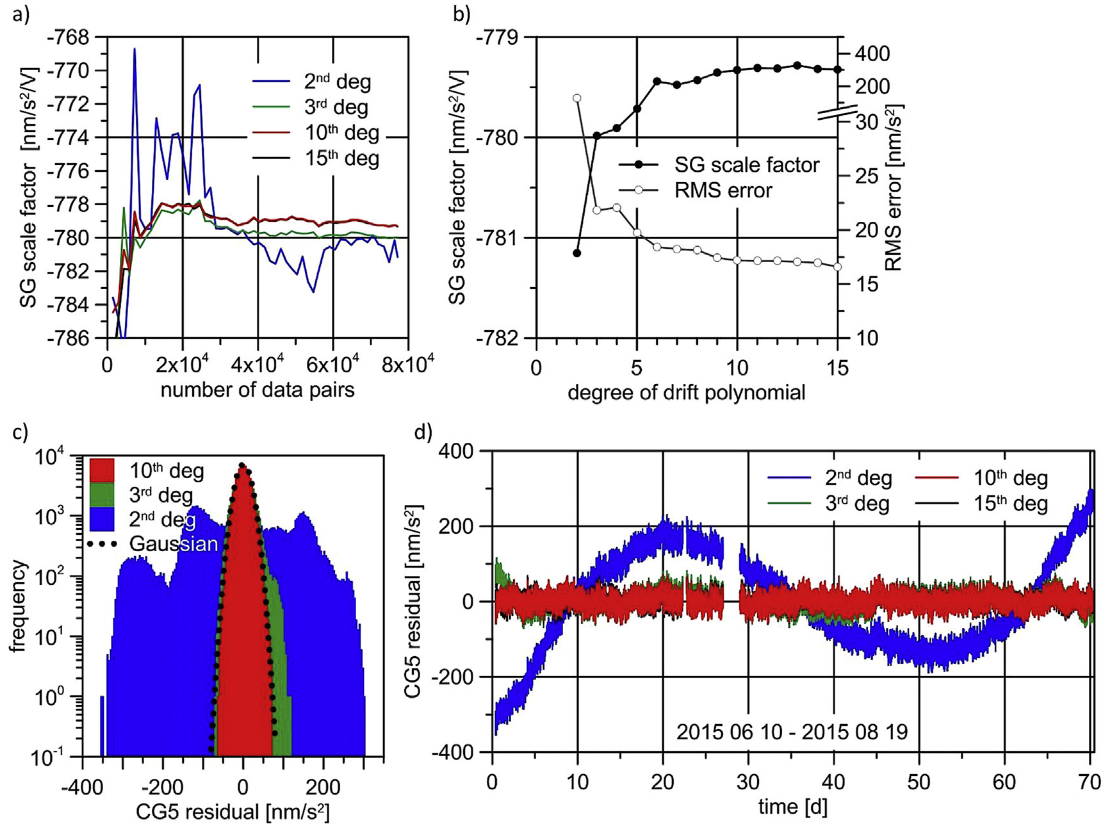

Fig. 4. SG/CG-5 calibration experiment June–August 2015. a) Dependency of the SG scale factor from the CG-5 drift model and from the number of data pairs, b) Dependency of SG scale factor and RMS error from the CG-5 drift model, c) Frequency distributions of CG-5 gravity residuals after subtracting tides and different CG-5 drift models, d) CG-5 gravity residuals after subtracting tides and different CG-5 drift models. In this example, finally a 10th degree polynomial has been adjusted for modeling the drift.

(Fig. 4c), i.e. the residuals are closely imaging random noise (Fig. 4d)

2.4. SG/AG calibration experiment – Setup

Several calibration experiments using Jila-g or FG-5 absolute gravimeters have been performed as the standard method applied at CO. 1 Hz SG data is low-pass filtered as described above. Samples corresponding to the respective AG drop samples are extracted from the filtered time series. Outliers are removed according to a standard deviation criterion. Occasionally, the AG time series exhibits a weak apparent drift due to Helium gas contamination of the AG time reference [18]. In those cases, the drift was adjusted by a low degree polynomial.

3. Calibration results

So far, 17 SG/CG-5 and 17 SG/AG calibration experiments have been performed. Fig. 5 shows the resulting SG scale factors and their error bars. The magnitude of the scale factor derived from SG/AG calibration experiments differs slightly from that of the SG/CG-5 experiments by less than 0.4 $nm/s^2/V$ or 0.5‰. In most cases, the

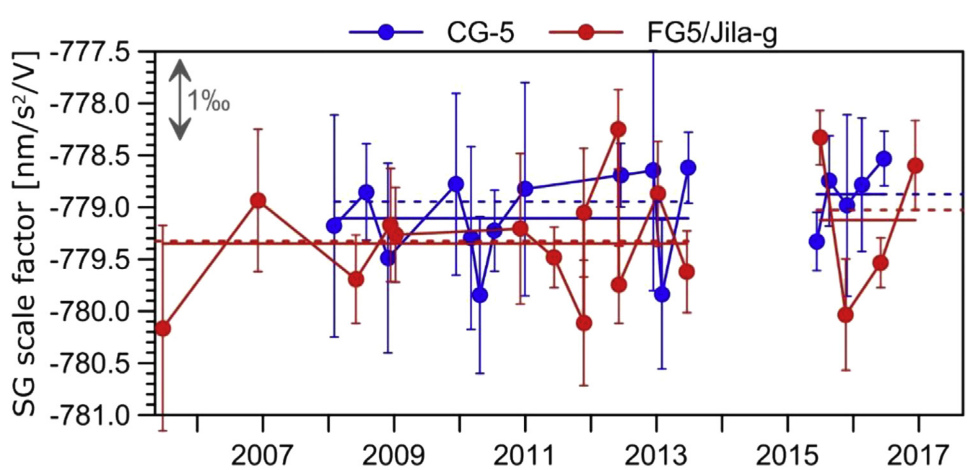

Fig. 5. SG scale factors derived from SG/CG-5 (blue) and SG/AG (red) experiments at CO. Weighted (dashed lines) and unweighted (solid lines) averages are presented for the periods before and after the SG re-initialization.

single results deviate by less than 1‰ from the weighted average (dashed lines in Fig. 5), using the squared inverse of the standard deviation of each calibration as weight. The error of the weighted mean is of the order 0.1 nm/s^2/V each while the RMS deviation from the weighted mean is twice as large. Therefore, the difference between both calibration types is probably significant. The reason is unknown at present. It could hint to different reaction of the gravimeter spring if operated in a stationary mode vs. the non-stationary mode of a field campaign. However, currently this is not proven at all. The frequency distributions of the SG scale factors derived from the SG/CG-5 and SG/AG calibration experiments have comparable quality (Fig. 6). SG/CG-5 experiments seem to perform even better. Certainly, the additional SG/CG-5 calibration experiments provide a suitable tool for detecting SG scale factor variations. As mentioned, the SG needed re-installation after the failure end of 2013. Averaging the results obtained from experiments before and after the re-initialization indicates a small SG factor change of 0.1‰ (SG/CG-5) and 0.4‰ (SG/AG). Detailed numbers are provided in Table 1.

Currently, the number of experiments performed after re-initialization is small. In addition, the averages strongly depend on the weights used for calculating the means. However, the significance of the SG scale factor changes can be assessed by comparing the temporal variations of the M2 tidal parameters observed at neighboring SG sites [13]. Here, we make use of three additional 1-h gravity time series processed by the station operators who have best knowledge of their instruments' calibration history. M2 tidal parameters have been derived from successive 1-year data windows shifted over the respective time series.

Both amplitude factors and phases show common patterns, which are mainly due to the inherently limited frequency resolution of tidal analyses. Length-limited time series never allow for separating all tidal constituents of the discrete tidal spectrum. Therefore, constituents are collected into groups assuming tidal parameters being equal within a specific group. This concept fails if, for example, 2nd and 3rd degree constituents with different response to ocean loading mix up in a group. Next to M2, 3rd degree constituents exist with considerable amplitude and cause the lunar perigee modulation with a period of 8.85 yr. The problem has been recently studied in detail by Meurers et al. [13].

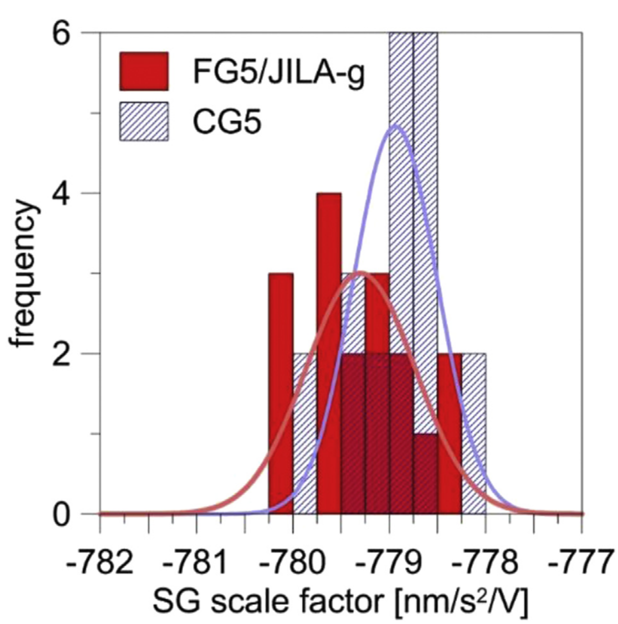

Fig. 6. Frequency distribution of the SG calibration experiments at CO.

Fig. 7 compares the M2 tidal parameters and their temporal variation at the SG sites Membach (MB, Belgium, blue line), Walferdange (WA, Luxembourg, light blue line), Pecný (PE, Czech Republic, green line) and Conrad Observatory (CO, Austria, red line). The analysis results of the observed time series compare well to those of a synthetic model consisting of body tides [19] and ocean load tides calculated by applying the SPOTL package [20] and the TPXO7.2 ocean tide model. SPOTL does not include any 3rd degree tidal constituent, i.e. there is no loading for those waves in the synthetic time series. Results from synthetic time series are shown for CO only (orange line) with an arbitrary offset for clarity. At CO, the SG scale factor change indicated by the statistical analysis (Fig. 5, Table 1) has been considered as real effect of the re-initialization process; i.e. the SG scale factor has been corrected accordingly for all CO data since 2015 applying the average scale factor change derived from the SG/AG and SG/CG-5 experiments respectively (Table 1). Fig. 7 presents the tidal parameter time series which convincingly show the same M2 modulation at all SG sites and closely follow the synthetic time series as expected. This holds particularly true since 2015, which indicates that the estimated scale factor change (Fig. 5) reflects a true effect. The amplitude factors at the stations Pecný and Conrad Observatory being only 240 km apart are close together. In particular, they coincide almost perfectly before 2015. The small deviation from the Pecný amplitude factors after 2015 indicates the SG scale factor change, as derived from Table 1, to be slightly overestimated. If we use a constant SG scale factor for the complete CO time series, then the SG scale factor offset since 2015 is clearly discovered (Fig. 7, light red line). Based on the M2 modulation comparison, a SG scale factor offset as small as 0.2‰ could be revealed as an effect of SG re-initialization.

4. Conclusion

The performance of SG/AG and SG/CG5 calibration experiments is of comparable quality. Single experiments scatter around the averages by roughly ±1‰ in both cases. The weighted means differ by less than 0.5‰. As the errors of the weighted means are about 0.1 nm/s^2/V or 0.2‰, this difference might be significant. For the SG/CG-5 experiments, observation periods of more than 2 months are required. Temporal CG-5 scale factor changes have to be monitored by repeated calibrations along a calibration line and properly considered. High degree (8–12) polynomials are suitable functions for approximating the irregular instrumental drift of CG-5 gravimeters. Statistical investigation of the adjustment error and the CG-5 gravity residuals helps to select the appropriate polynomial degree based on objective criteria. The SG/CG5 calibration

Table 1
SG scale factors obtained for GWR C025 at Conrad Observatory.

	All experiments			Experiments until 2013			Experiments since 2015		
	n	Unweighted mean	Weighted mean	*n*	Unweighted mean	Weighted mean	*n*	Unweighted mean	Weighted mean
SG/AG	17	−779.30 ± 0.14	−779.21 ± 0.10	13	−779.35 ± 0.15	−779.33 ± 0.13	4	−779.12 ± 0.40	−779.03 ± 0.16
SG/CG-5	17	−778.86 ± 0.11	−778.91 ± 0.11	12	−779.11 ± 0.13	−778.95 ± 0.16	5	−778.87 ± 0.13	−778.88 ± 0.17

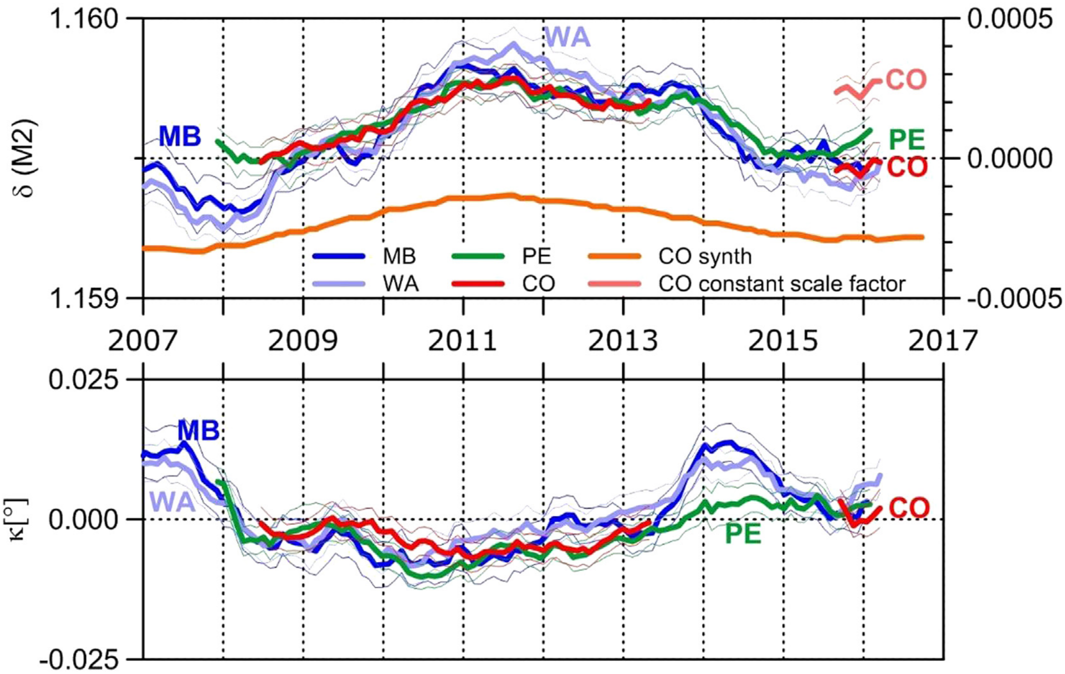

Fig. 7. M2 tidal parameter modulation at the SG stations Membach (MB, blue line), Walferdange (WA, light blue line), Pecný (Czech Republic, green line) and Conrad observatory. At CO, the SG scale factor offset due to the re-initialization in 2015 as indicated by the statistical analysis (Table 1, Fig. 5) has been considered (CO, red line). M2 amplitude factors obtained using a constant scale factor for the entire CO time series (light red line) show a significant offset since 2015. The light red line is hidden behind the red line before 2015 as until then the same SG scale factor has been applied. The orange line reflects the M2 amplitude factor modulation of synthetic tides at CO.

experiments increase the total number of experiments remarkably in case of limited availability of absolute gravimeters.

Comparing the temporal variations of M2 tidal parameters at neighboring stations or of synthetic tides allows for assessing the time-stability of the SG scale factor. Combing all these methods helps to determine the SG scale factor with accuracy far below 1‰. In particular, SG scale factor changes can be detected even if they are less than the SG scale factor uncertainty. At CO, a SG scale factor offset as small as 0.2‰ has been revealed. The offset occurred during re-initialization of the SG in spring 2015.

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1994	Assistant Professor, University of Vienna
Since 1997	Associate Professor, University of Vienna
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Since 2000	Associate Editor of Studia geophysica et geodaetica
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2004–2014	Vice-Director of Study Programmes SPL28, University of Vienna
2007	Invited Lecturer of the EAGE Distinguished Lecturer Programme 2007
Since 2014	Director of Study Programmes SPL28, University of Vienna
2010/2011	Head of the Department of Meteorology and Geophysics, University of Vienna
Since 2015	Member of the Directing Board of the International Geodynamics and Earth Tide Service (http://igets.u-strasbg.fr/) hosted by the International Association of Geodesy
Research Interests	
Gravimetry, earth tides, low frequency geodynamics, gravity variations, Potential theory	