Aspects of gravimeter calibration by time domain comparison of gravity records

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Abstract

This paper addresses the accuracy problem of gravimeter calibration performed by time domain comparison of different gravity sensors. Un-modelled instrumental drift and the noise of the data are main sources of systematic error components. Several synthetic and real case studies are discussed to estimate accuracy limits. A simple drift elimination method is proposed that is well suited to be applied also for spring gravimeters with irregular drift. At least strong drift components have to be removed otherwise both calibration factor and time lag do not necessarily converge towards the figures within the required 0.1% accuracy limit.

Introduction

High calibration accuracy is still an important issue for getting reliable results in tidal research, gravity monitoring and microgravimetry. Gravimeter calibration can be done either in time or in frequency domain by comparing the instrumental response of two sensors on common signals (e.g. earth tides, artificial gravitational or inertial effects). The most important requirement is that signals of same physical origin are compared only and that the sensor transfer functions are considered. Time domain calibration methods like regression analysis can be applied successfully even on short data sets (< 200 h). Contrary, the frequency domain calibration method requires long observation periods (^{3} 720 h) in order to separate the main tidal constituents properly. Therefore it detects calibration factor variations in much lower temporal resolution than regression analysis, while drift determination, noise and different air pressure response of the sensors are less critical.

A severe problem is that the signal composition of both sensors differs due to following reasons:

- instrumental noise and response on micro-seismic noise
- instrumental drift
- transfer function introducing different time lags
- response on air pressure variations (e.g. non-compensated Archimedian forces in LCR gravimeters)

Absolute gravimeters (AG) are commonly used as reference sensors to calibrate superconducting gravimeters (SG). Experience has shown that long data series of up to 7 days' interval are necessary to get stable results with accuracy better than 0.1% (e.g. Francis 1997, Francis et al. 1998). SGs exhibit an extremely small and almost linear instrumental drift of less than a few µGal per year. Anti-alias filters and 1 Hz sampling permit additional numerical filtering of the SG output channel to obtain low noise data. Contrary, AG data is acquired with a much longer sampling interval (15 – 30 s) and generally shows a much larger scatter. Due to instrumental effects the existence of small drift components can be excluded neither in SG nor in AG records which could influence the calibration result systematically. Fig. 1 compares the data of a calibration experiment performed in Vienna on 19990925. It demonstrates the different noise level of the data sets used, but also clear systematic effects in the AG data. This paper tries to address the influence of systematic effects on the calibration result if they remain un-modelled prior to regression analysis. This is done in a more general aspect in order to get accuracy limits not only for AG-SG intercomparisons, but also for other gravity sensor combinations including spring type gravimeters (e.g. LCR, Scintrex). In this case the strong and irregular drift of spring gravimeters is expected to introduce systematic calibration errors. In addition, LCR gravimeters are known to give an abnormal response on air pressure variations (e.g. Arnoso et al. 2001).

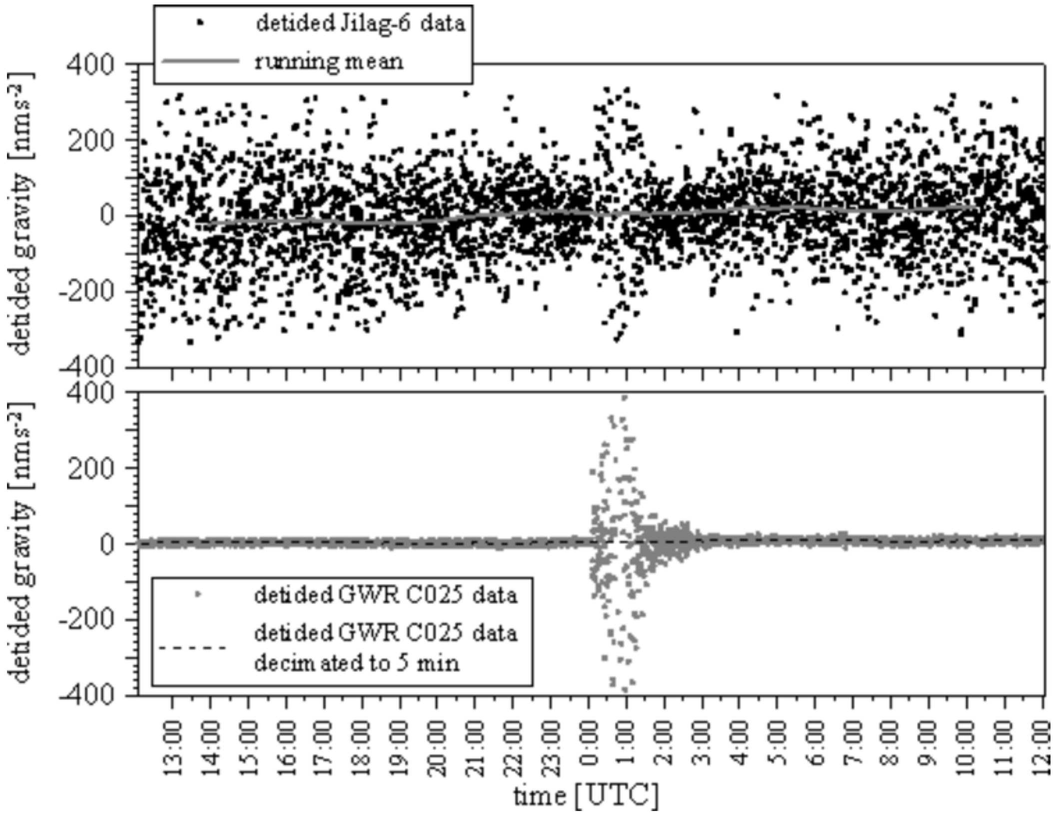

Fig. 1: Comparison of detided SG (bottom: GWR C025, 1s samples) and AG (top: Jilag-6, 25s samples) data (Vienna, 19990925)

Synthetic studies

Several test calculations have been performed to investigate the effect of

- random noise and time lag
- instrumental drift and different air pressure response

using a data set based on predicted model tides with 20s sampling. This sampling rate is typical for AG data. Both calibration factor and time lag were determined by LSQ-adjustment.

Random noise and time lag

The model tides were compared with two different data sets:

1. model tides with time lag of 20s
2. model tides with time lag of 20s and normally distributed noise with a standard deviation of 50 nms^{-2})

Several different noise models have been used. As long as the standard deviation is not larger than 50 nms$^{-2,}$ ^{in} each case the adjusted calibration factor fulfils the 0.1% accuracy requirement. However, convergence is very slow or even does not result exactly to the expected figure. This highly depends on the noise structure. The same is valid for the adjusted time lag. In addition, time lag adjustment does not essentially improve the result of the calibration factor adjustment. Obviously small un-modelled time lags do not influence the result strongly in spite of the fact, that neglecting different sensor time lags is equivalent to an additional signal consisting of diurnal, semidiurnal and long-periodic components. If there is no noise present in the data, the adjusted calibration factor is identical almost exactly with the expected one even when the time lag is not adjusted. Adjusted time lags correspond exactly to the expected ones. Fig. 2 is shown as an example.

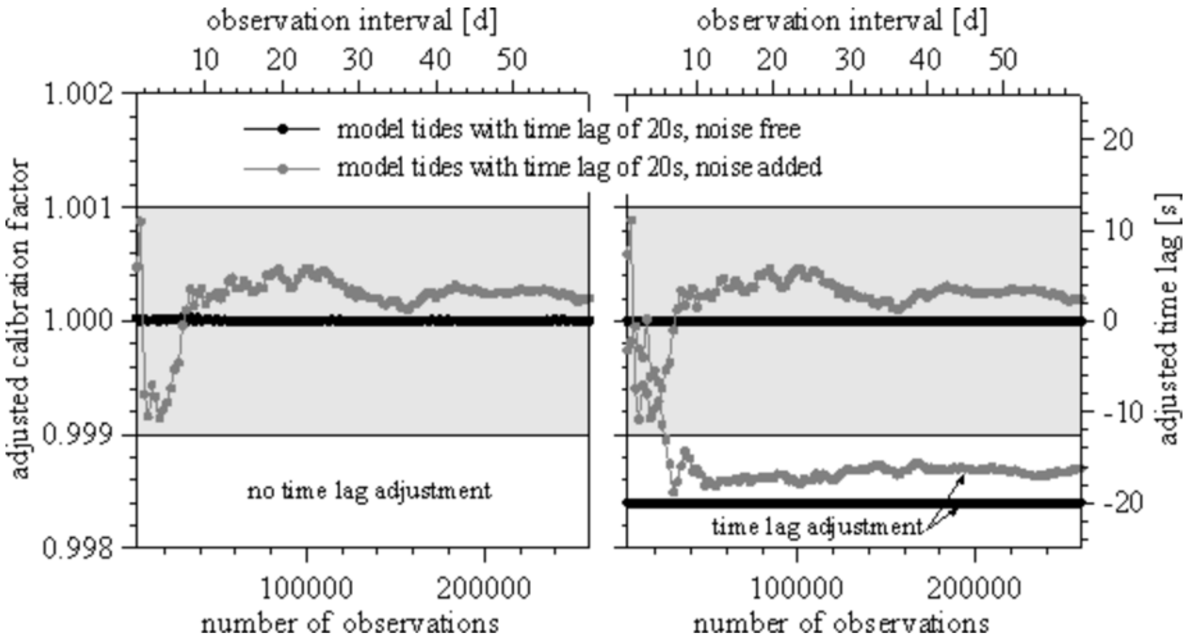

Fig. 2: Influence of phase shift and noise on the adjusted calibration factor. Adjustment results are shown in dependence upon the number of samples used. Both sensors' data consist of model tides (20s samples); those of the 2^{nd} sensor have a time shift of 20s. Grey dots indicate the results obtained when random noise is superimposed to the data of the second sensor.

Instrumental drift and different air pressure response

A major problem is the presence of instrumental drift in the compared data sets, because drift separation in the time domain is a difficult task. Francis and Hendrickx (2001) applied a simultaneous adjustment of the calibration factor and a third degree drift polynomial when calibrating a LCR gravimeter by collocated SG observations. They achieved temporarily stable accuracy of about 0.1% by analysing 15 days' intervals. However, the drift behaviour of some spring gravimeters does not permit low degree polynomial adjustment. For those cases another method is proposed here. It is based on the approach by Lassovsky (1956) who used the zeros of model tides as supporting points of the drift function. In this study a similar procedure has been applied. After subtracting the air pressure effect by using a single admittance model, gravity readings at moments when the model tides are zero yield the drift supporting points. Finally a continuous drift function is constructed by cubic spline interpolation.

In order to investigate both the efficiency of this method and the effect of un-modelled drift components, several test calculations have been performed by comparing model tides (20s samples) to those with different drift models superimposed. The drift models consist of both a linear and a random component:

1. systematic component: 5 nms^{-2}/14 days,
   random component: 10 supporting points/14 days, standard deviation 5 nms^{-2}
2. systematic component: 5 nms^{-2}/14 days,
   random component: 30 supporting points/14 days, standard deviation 5 nms^{-2}

3. systematic component: 30 nms^{-2}/14 days,

   random component: 10 supporting points/14 days, standard deviation 5 nms^{-2}

where the number of supporting points controls the frequency content of the drift model. The selected drift parameter enables to study the effect of even very irregular instrumental drift like that of LCR gravimeters.

The examples shown in Fig. 3 prove the drift elimination method to work properly even when high frequency drift components are present. If the drift is eliminated before adjusting the calibration factor, the latter converges very quickly towards the expected figure. High frequency drift components make convergence worse. In this case a time interval of about 6-8 days is required to get accurate results. If the drift is not subtracted, the error of the adjusted calibration factor remains below the 0.1% accuracy level after one week observation period except when high systematic drift components are present.

The dependence of the calibration result on the pre-processing method is tested finally by using real gravity data from GWR C025. Model tides derived by tidal analysis of a 6.5 years' recording of this SG in Vienna served as reference signal. As second sensor, SG data sets covering a 14 days' interval each were applied after different kind of pre-processing:

1. no corrections
2. air pressure correction (single admittance model), but no drift elimination
3. no air pressure correction prior to drift elimination
4. air pressure correction prior to drift elimination

All data sets were decimated to 20s samples. Fig. 4 (top) shows the residuals after subtracting the drift for the case studies 4 (black) and 3 (grey) respectively. It proves that considering the air pressure effect is a necessary step to get more reliable drift functions. If this effect is not corrected, it remains as high frequency drift signal in the data and therefore sometimes cannot be fully eliminated by the proposed method. This aspect is important, if the two sensors are expected to respond on air pressure differently (e.g. LCR gravimeters). The results of the calibration factor adjustment are displayed in Fig. 4 (bottom). If no correction is performed at all, both the calibration factor and time lag converge after an about 7 days' observation interval, but to wrong figures. Fast and stable convergence occurs only after removing the air pressure effect and instrumental drift. Reliable time lags are obtained only if the air pressure effect is subtracted and if drift remains untouched. Drift elimination corrupts the time lag information of the data. As mentioned before, time shifted data can be composed of the original one and of a systematic drift consisting of semidiurnal, diurnal and long period components that are removed at least partially by drift elimination.

The time domain calibration method is well suited to determine calibration factor variations in high temporal resolution. This is demonstrated by the last case study. During a more than 1-year period started in June 2000, the LCR D-9 gravimeter equipped with a SRW-D type feedback system (Schnüll et al. 1984) was monitoring parallel to the GWR C025 in Vienna. Tidal analyses of successive, non-overlapping periods prove that the calibration factor of GWR C025 is very constant (Meurers 2001). The amplitude factors for the main tidal waves vary by less than 0.1% even when intervals as short as 1 month are analysed (Fig. 6, open squares). Therefore the SG can be used as stable reference to calibrate the feedback.

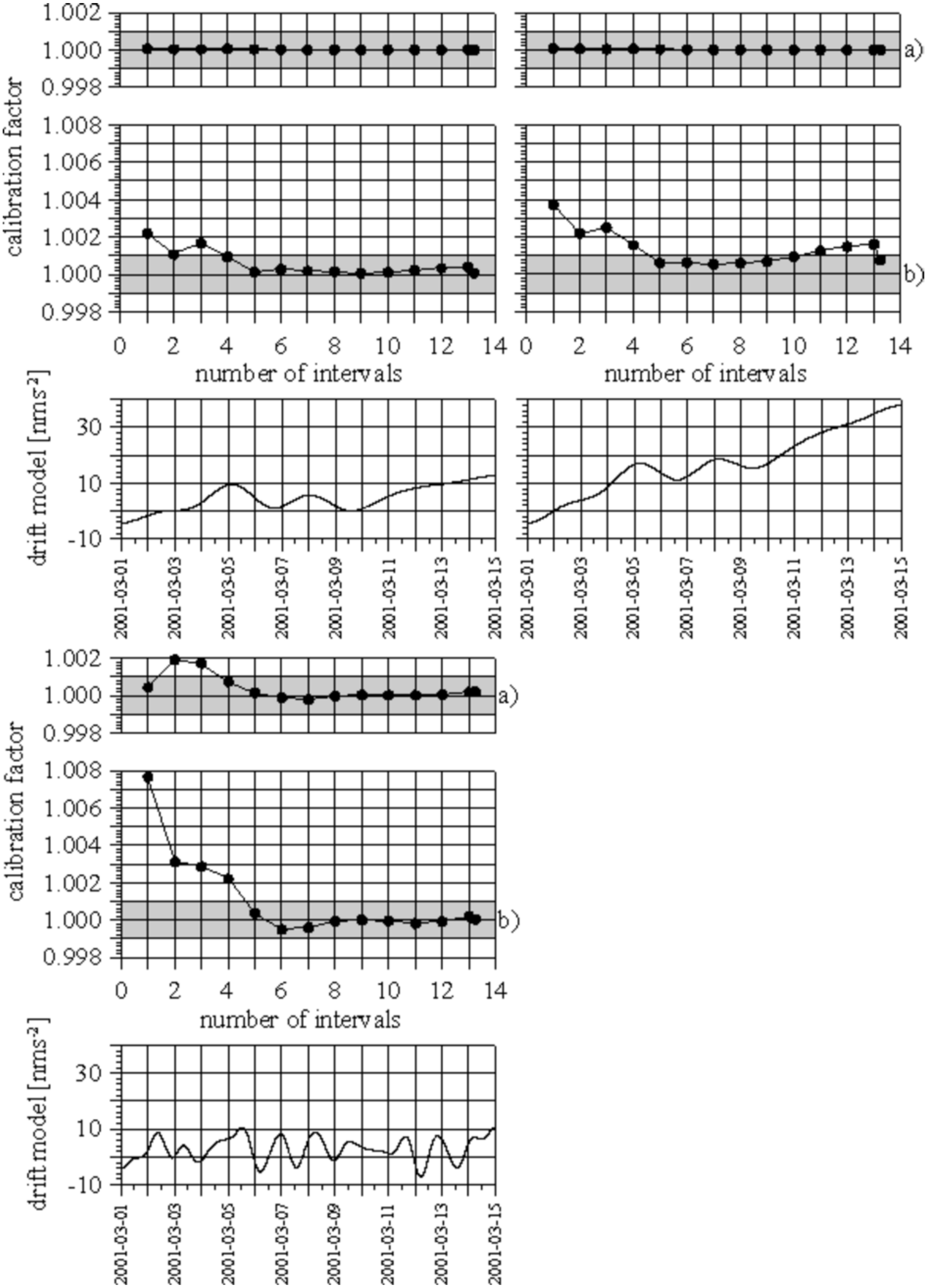

Fig. 3: Influence of un-modelled drift on the adjusted calibration factor. Adjustment results are shown in dependence upon the number of observation intervals used and the pre-processing method. Both sensors' data consist of model tides (20s samples); those of the 2nd sensor are superimposed by instrumental drift. Different drift models have been applied (see text).

pre-processing method:

a) drift correction

b) no drift correction

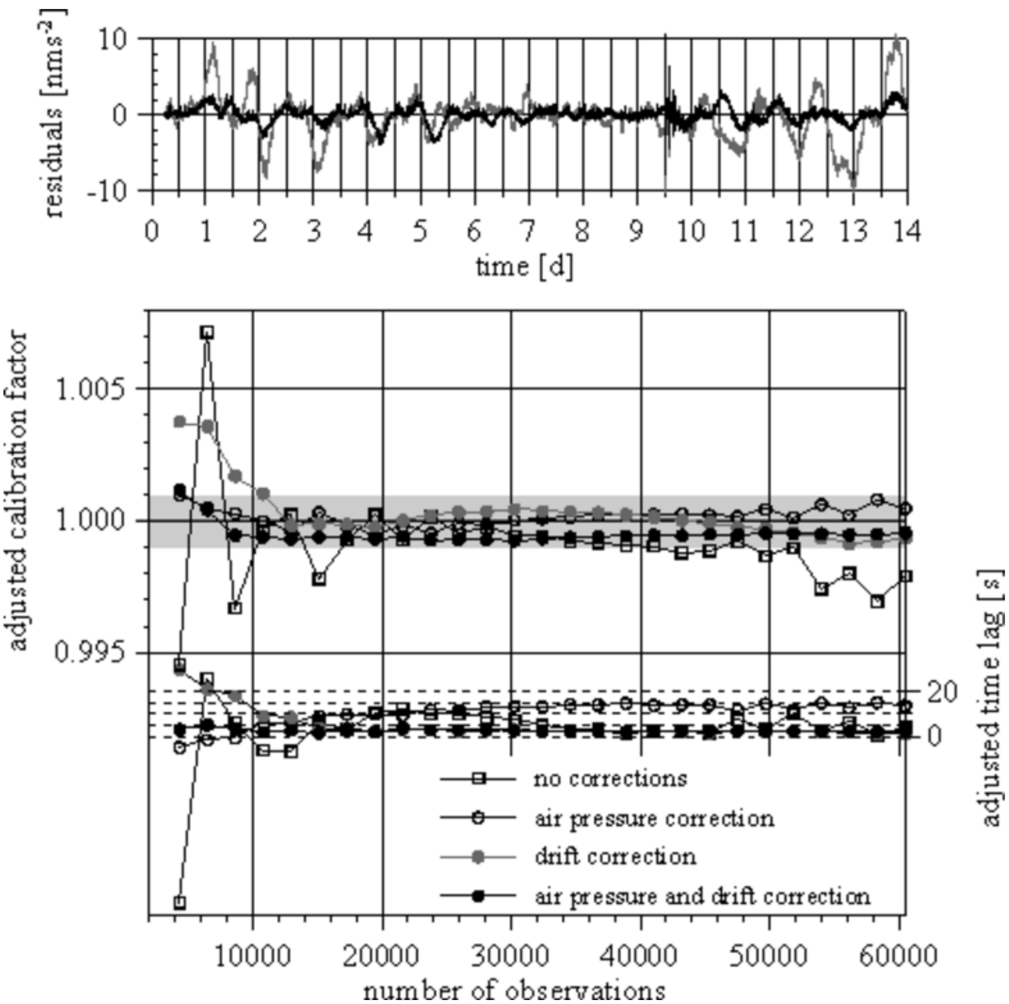

Fig. 4: Influence of different pre-processing steps on the calibration factor adjustment.

Bottom: Adjustment results are shown in dependence upon the number of observations used and the pre-processing method. 1st sensor: model tides derived by tidal analysis of a 6.5 years' recording of GWR C025. 2nd sensor: GWR C025 data (19970302 – 19970316), decimated to 20s samples.

Top: gravity residuals calculated by subtracting the drift. Air pressure has been (black) or has not been considered prior to drift elimination (single admittance model).

The feedback calibration factor turned out to be extremely unstable in time probably due to a still unknown malfunction of its electronics. The LCR D-9 as a spring-type gravimeter exhibits strong and irregular instrumental drift. In addition, its response on air pressure variations differs significantly from that of the SG. The admittance factor results to –5 nms^{-2}/hPa instead of –3.5 nms^{-2}/hPa. Therefore the drift of both sensors has been eliminated after air pressure correction applying the respective admittance factors. Prior to this step both data sets were decimated to 5 min samples. Successive overlapping intervals covering 2000 samples each (approximately 7 days) have been analysed. Fig. 5 shows the temporal variations of the feedback calibration factor resulting from the single adjustments.

The long-term behaviour of this variation can be recognized also in Fig. 6 (grey dots), where the amplitude factors of M_2 and O_1 are plotted versus time. The latter were calculated by performing tidal analyses of successive 1-month intervals evaluated by using a constant feedback calibration factor. Common features indicate sensitivity variations to be the reason. When taking the temporal sensitivity variation according to

Fig. 5 into account, the amplitude factors get much more stable, especially in case of M_2, and common features disappear (Fig. 6, black dots).

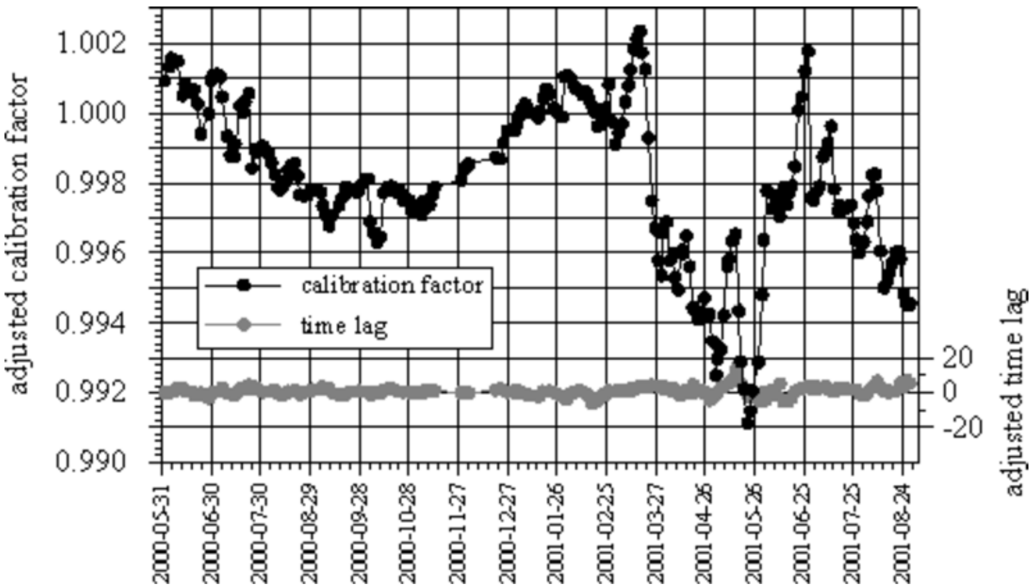

Fig. 5: Calibration factor of LCR D-9/SRW-D resulting from adjustments of successive intervals of 7 days (2000 samples, 5 min sampling) using GWR C025 data as reference.

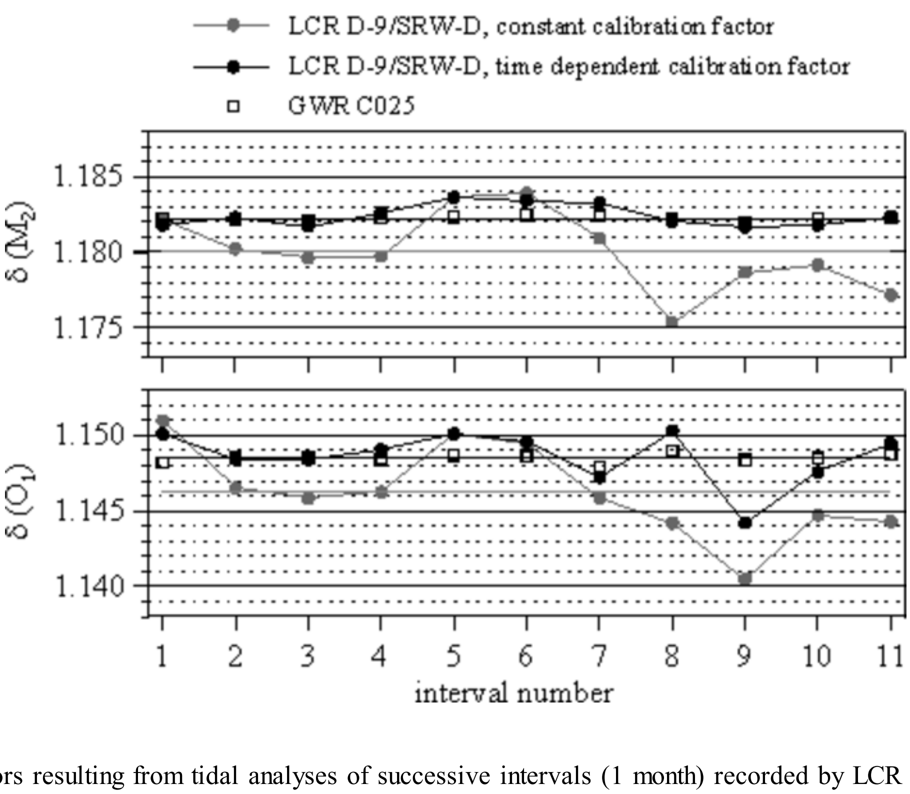

Fig. 6: Amplitude factors resulting from tidal analyses of successive intervals (1 month) recorded by LCR D-9/SRW-D and GWR C025.

Conclusions

The time domain calibration method has limited accuracy. The main sources of systematic error components are the noise of the data and un-modelled instrumental drift. For noisy data the calibration factor converges very slowly with increasing number of observations involved, but does not necessarily result exactly to the correct figure, depending on the noise structure. However, the adjusted calibration factor fulfils the 0.1% accuracy requirement. The same is valid for the time lag adjustment that does not essentially improve the result of the calibration factor.

If strong drift components are not removed both calibration factor and time lag do not converge towards the correct figures even after observation periods longer than 7 days. On the other hand, drift elimination does no longer permit a time lag adjustment because it corrupts the phase information of the data.

If the compared sensors exhibit low and regular drift like SGs, accuracy better than 0.1% can be obtained from data covering an interval of 6-8 days. Although AG data sometimes show a small apparent drift caused by time dependent systematic effects, drift elimination is not recommended when calibrating a SG by comparing with AG data, as it removes physical signal components (e.g. air pressure effect) at least partially and perhaps differently for both instruments.

The situation is quite different when calibrating a spring-type gravimeter by comparison with SG data. Spring gravimeters often show strong and irregular instrumental drift and different response to air pressure variations. In this case the drift has to be eliminated before the regression analysis, and the air pressure effect has to be subtracted for both sensors before drift determination.

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