Harita Dergisi;Özel Sayı 18;401-406;06/2007

Precision Gravimetry in the New Zugspitze Gravity Meter Calibration System

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Abstract. The precise calibration of relative gravity meters is essential for the accuracy of gravimetric surveys. We show that in the new Zugspitze calibration system established in 2004 – 2005 excellent accuracies of the linear calibration factor of relative gravity meters in the range of $1–2 * 10^{-5}$ can be obtained. The calibration system is particularly useful for the precise calibration of Scintrex linear quartz gravity meters. The key advantages of the new calibration system are (a) the large gravity range of up to 528 mGal and (b) the short transport time of instruments by cable cars between the absolute gravity reference stations. This allows improving the accuracy of the Scintrex relative gravimetric observations by carrying out numerous ties over large gravity differences in a day or less. We study the accuracy and repeatability of Scintrex CG3 and CG5 calibration observations and the influence of seasonal effects due to environmental mass changes based on a time series of 57 calibration experiments over a period of 22 months. We show that variable attraction of snow can cause considerable effects up to 40 μGal, in particular on stations in the summit zone. This is confirmed by forward modelling using a hydrological snow model with a 1km grid. We conclude that gravity meter calibration should be preferably carried out between July and December when the snow effect is small and repeatability of calibration experiments is within ±10 μGal.

Keywords. Gravity meter calibration, Scintrex Autograv gravity meter, gravity change

1 Introduction: The Zugspitze Gravity Meter Calibration System

The precise determination of gravity differences with the widely used mechanical (e.g., LaCoste-Romberg) and electrostatic (e.g., Scintrex CG3 and CG5) spring gravity meters requires a best possible calibration. The excellent suitability of the Zugspitze summit (2962 m) for gravity meter calibration has already been recognized in 1937, when reference gravity stations have been established by pendulum observations (Weiken 1950). The stations have been used for gravity meter calibration, e.g., by Morelli (1951).

Today, with high precision free fall absolute gravity meters reference gravity values improved by 2 - 3 orders of magnitude in accuracy can be obtained. Therefore, in 2004 - 2005 a new calibration system has been established by repeated observations at 6 stations using the free fall absolute gravity meters FG5-220 (IFE) and A10-002 (BKG), cf. Figs. 1 and 2.

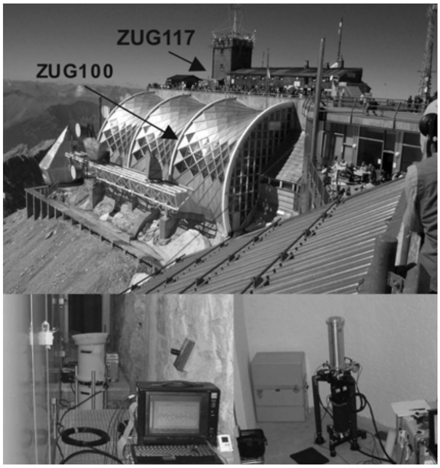

Fig. 1 Absolute gravity stations on Zugspitze summit; gravity meters A10 (BKG, lower left) and FG5 (IFE, lower right)

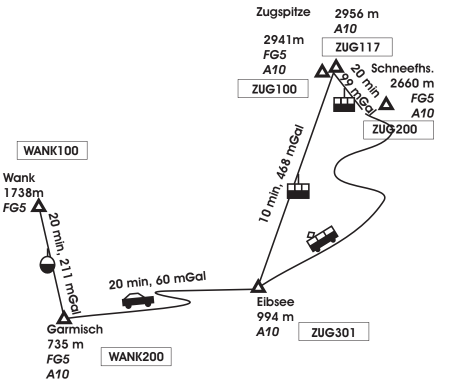

Fig. 2 Gravity stations, gravity differences and transportation in the Zugspitze calibration system

The calibration system is designed in particular for the best possible calibration of Scintrex Autograv CG3 and CG5 gravity meters for which only a linear calibration factor or at most a very small quadratic term have to be determined. The key advantages of the Zugspitze calibration system are large gravity differences of up to 528 mGal and – at the same time – transport times of only 10 – 20 minutes between the absolute stations. The short transport time allows carrying out a number of station ties within a day which considerably increases redundancy and accuracy of the relative gravimetric observation.

Table 1 Results of absolute gravimetry in the Zugspitze calibration system. For FG5 results cf. Timmen et al. (2006). A10 results are preliminary.

Station (Height), Vertical Grav. Gradient	Epoch	Instrum.	Dur. (h)	Gravity (μGal) Scintr. ref. level 0.26 m	Gravity(μGal) A10 ref. level 0.705 m	Gravity(μGal) FG5 ref. level 1.20 m
ZUG117 (2956m)	2005 02 17	A10-002	1	980056179	980055946	980055688
-522.0μGal/m	2005 09 28	A10-002	0	980056146	980055914	980055656
ZUG100 (2941m)	2004 09 18	FG5-220	24	980062587	980062380	980062149
-465.3μGal/m	2005 02 17	A10-002	1	980062613	980062406	980062176
	2005 09 28	A10-002	0.3	980062586	980062379	980062149
ZUG200 (2660m)	2004 09 09	FG5-220	24	980155017	980154861	980154687
-350.5μGal/m	2005 02 17	A10-002	5	980155016	980154860	980154687
ZUG301 (994m)	2005 07 20	A10-002	0.5	980524498	980524373	980524233
-282.0μGal/m	2005 09 28	A10-002	0.3	980524504	980524379	980524239
WANK100 (1738m)	2004 12 01	FG5-220	24	980373710	980373537	980373346
-387.7μGal/m						
WANK200 (735m)	2004 12 03	FG5-220	24	980584700	980584573	980584432
-284.7μGal/m	2005 02 19	A10-002	1	980584694	980584568	980584427
	2005 07 20	A10-002	0.3	980584702	980584575	980584435
	2005 09 27	A10-002	0.3	980584701	980584574	980584433

Table 1 shows the absolute gravimetry results for all epochs and reference levels. The FG5 accuracy estimate is 3 µGal (Timmen et al. 2006). The preliminary A10 accuracy estimate obtained from comparisons at other stations is 5 - 10 µGal. The reduction to another reference level is done using the precisely observed vertical gravity gradients given in Table 1. This accounts for another error of about 3 µGal. Note the extremely large vertical gradient in station ZUG117 at the very top of Zugspitze. At ZUG100 – only 15 m below – the gradient is already considerably smaller.

At the summit stations ZUG100 and ZUG117 significant gravity changes have been observed. The gravity result in February is larger by 26 - 33 µGal than in September. We show in Sect. 5 that this variation can largely be attributed to the attraction of snow masses in the summit zone. At other stations, the largest change is 8 µGal which is within the observation accuracy.

As the calibration system is intended to serve as a long-term calibration reference, the height differences between the gravity stations have been precisely measured. This will allow checking the long-term stability by repeated observations. Each of the stations is connected by precision levelling to benchmarks. Some of the benchmarks have been tied by static GPS observations to GPS permanent stations provided by the Institute for Meteorology and Climate Research in Garmisch as well as by the German Sapos permanent network.

The absolute gravimetry stations are easily accessible. On station ZUG117, no FG5 observations have been feasible due to the restricted space. Station ZUG200 unfortunately is no more accessible due to construction activities.

2 Calibration of Scintrex CG3 and CG5 Gravity Meters

To obtain the maximum accuracy for the linear calibration factor, the instrument to be calibrated has to perform observations over a large gravity range with accuracy similar to that of the reference gravity differences from absolute gravimetry. Taking into account the accuracy of the reduction to the Scintrex reference level (0.26 m above ground), the reference gravity differences in the Zugspitze calibration system have an accuracy of 6 – 15 µGal. Thus, the best achievable calibration accuracy is about $1.2*10^{-5}$. *Instrumental errors* of the Scintrex gravity meters have to be thoroughly examined, and a suitable sequence of observations has to be found. If calibration is not carried out simultaneously with absolute gravimetry, gravity changes by *environmental mass changes* have to be considered in addition. They should be modelled as far as possible and required, or mitigated, e.g., by avoiding calibration at seasons when such effects are strong.

3 CG3 and CG5 Instrumental Errors

Previous investigation on the accuracy performance of the CG3 and CG5 gravity meters led to rather inhomogeneous results. In microgravimetric surveys, often excellent accuracies of a few µGal have been obtained. Timmen and Gitlein (2004) found a relative accuracy limit of $1*10^{-4}$. Hackney (2001) obtained rather poor accuracies in a gravimetric network in Australia. Budetta and Carbone (1997) observed a large change in the calibration factor by $1*10^{-3}$ over one year, together with a strongly varying drift parameter. For calibration experiments in the Zugspitze calibration system, the following error sources deserve special attention:

Transport After transport, many Scintrex gravity meters exhibit a significant time-dependent change in the reading, possibly due to the relaxation of tension in the sensor which has been accumulated during transport (Hackney 2001). For the CG3 310218 instrument of IAPG, this hysteresis is often strong (up to 60 µGal) during 30 minutes after transport. Figure 3 (top) shows strong but homogeneous hysteresis most of which is cancelled out in the station difference. Figure 3 (bottom) shows inhomogeneous hysteresis which can result in large errors. Hysteresis of the instruments CG3 310218 (IAPG) and CG3 303202 (BKG) has been found to decrease for most station occupations. In contrast to this, Hackney (2001) reported strongly increasing hysteresis of his instrument for all occupations. For the CG5 44 of BKG a considerably lower hysteresis magnitude has been found. Thus, hysteresis magnitude and direction seem to vary from instrument to instrument.

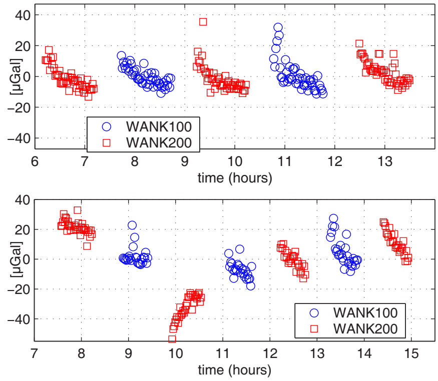

Fig. 3 CG3 hysteresis after transport. Each signature corresponds to a 60 sec observation set. Station occupation duration is 30 - 60 min (25 - 60 sets), and cable car transport between stations is about 25 min. Top: strong but homogeneous hysteresis, bottom: inhomogeneous hysteresis

Temperature effects The temperature of the gravity sensor is stabilized by heaters within 10^{-3} K. Residual temperature variations are observed with an accuracy of 10^{-5} K and corrected for. During observations in the Zugspitze calibration system, relatively strong residual variations have been observed for ties between station pairs with very different ambient temperature. Thus, an error of the temperature correction coefficient could cause significant errors. We did not find a correlation between the sensor temperature and gravity reading. However, this should be further studied.

Stability of the instrument electronics On the $1*10^{-5}$ accuracy level, instabilities of the instrument electronics could play a role. E.g., the AD converter of the electrostatic gravity sensor is not specified to be stable to this accuracy.

Accelerations due to microseismics, wind and human noise The large number of observations (cf. Sect. 4) allow comparisons between instruments, stations and days with respect to the amplitude of these effects.

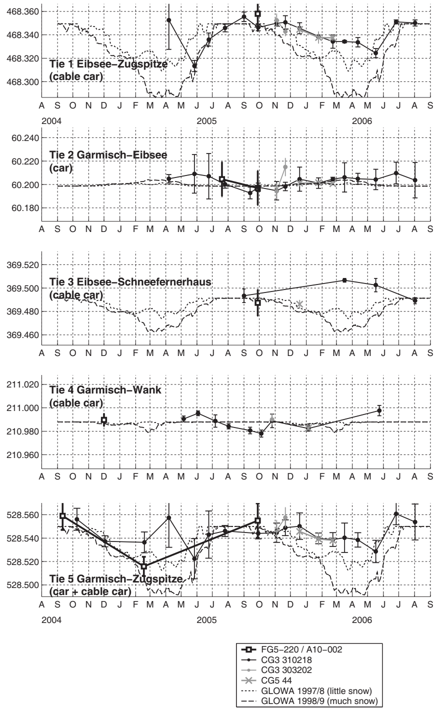

Fig. 4 Time series of gravity differences (in mGal) for 5 station ties from absolute gravimetry and calibrated Scintrex relative gravimetry, together with seasonal gravity variation obtained from the GLOWA Danube snow model

4 A Time Series of Calibration Experiments

To investigate the instrument accuracy and long-term stability as well as gravity changes due to environmental mass changes, a time series of 57 calibration experiments have been carried out during a total time span of 22 months. At each epoch, gravity differences (ties) between one or several pairs of stations have been observed with CG3 310218. For some epochs, simultaneous observations of CG3 303202 and CG5 44 of BKG have been carried out. The results are shown in Fig. 4 together with the reference gravity differences from absolute gravimetry. Each Scintrex gravity difference is derived from 3 - 9 single ties observed during one day. From least squares adjustment very good accuracies of 1 - 6 μGal have been obtained for most station ties (Fig. 4). For station tie no. 2 only 3 - 4 single ties have been observed at some epochs due to time limitations, resulting in poorer accuracies of up to 20 μGal. Results for tie no. 5 are obtained from the sum of ties no. 1 and 2, except for the first epochs which have been observed directly.

The consistency between epochs is rather poor for the first few epochs of ties no. 1 and 5, when stations were occupied during 5 min only and undetected hysteresis effects may have caused large errors. Later, the station occupation duration was gradually increased to 30 min, leading to an improved repeatability below ±10 μGal for ties no. 2 – 4 which is similar to the accuracy of the reference gravity differences from absolute gravimetry. Ties no. 1 and 5 involving Zugspitze summit are constant within ±10 μGal from July to December only, while showing a seasonal trend from January to June with results smaller by up to 40 μGal. The time variation in both absolute and relative gravimetry results is approximately consistent with differences in snow attraction obtained by forward modelling using data of the GLOWA-Danube snow module, cf. Sect. 5.

From all epochs where simultaneous absolute and relative gravimetry is available, linear calibration factors for the employed Scintrex instruments have been determined by least squares adjustment. Table 2 shows the calibration accuracies obtained.

instrument	# of ties	calibr. factor accuracy
CG3 310218	9	1.2e-5
CG3 303202	5	2.0e-5
CG5 44	7	1.4e-5

Table 2 Accuracies of calibration from repeated calibration experiments

5 Effects of Environmental Mass Changes

Snow Around Zugspitze summit, in winter maximum snow heights of up to 5 m are observed (1 - 2 m water column equivalent). In the higher regions, significant snow masses persist until June. We used a snow model from the GLOWA-Danube hydrological project (Mauser and Ludwig 2002) to compute the attraction of snow mass up to a distance of 40 km on each gravity station. The model contains snow water column equivalent in a 1 km grid and daily resolution for the years 1995 to 1999. For the computation of attraction, the snow data have been represented by point masses on a digital terrain model grid. In the near zones around the gravity stations, the coarse GLOWA Danube snow grid has been interpolated to a 50 m high resolution digital terrain model. Thus, the proper terrain height of the snow data is used. However, the model cannot represent local (sub-grid) snow variability. Nevertheless, a point-wise comparison with observed snow height at a station of German Weather Service (DWD) near Zugspitze summit showed a fairly good agreement.

As no model data have been available for the time period of the calibration experiments, the results for a winter with little snow (1997/98) and for another with very much snow (1998/1999) have been selected for a qualitative comparison. Figure 4 includes the differences in snow attraction for all station ties. For ties no. 2 and 4, the effect of the snow model is below 9 μGal throughout the year. For ties no. 1 and 5, large variations up to 60 μGal are obtained which are largely due to the snow effect at the Zugspitze summit station ZUG117.

For these ties, both the observed gravity differences and the modelled differences in snow attraction decrease rather slowly in the period from December to May together with increasing snow mass accumulation in the summit region. The values increase again sharply in June and July together with snow melt in the summit region. The amplitudes of the modelled snow effect are, however, larger than the observed gravity variations. For calibration purposes it is important to note that in the period from July to December the snow effects are small also for the ties involving Zugspitze summit. For tie no. 3 the agreement is poor. Probably the Scintrex accuracy estimates obtained for this tie are too optimistic.

Glacier melting The melting of the small Schneeferner glacier below Zugspitze summit was estimated to cause a gravity change of about 2 μGal/year. This effect is slightly too small to be detected in the gravity time series available so far.

Groundwater and other water storages The valleys around Garmisch contain important groundwater storages with significant temporal variations. Unfortunately, there are no hydrological observations available close to the gravity stations. The time series of gravity differences may contain effects from water storage changes, but they seem to be smaller than ±10 μGal.

Atmosphere The gravity observations have been reduced for the deviation from normal air pressure using the empirical regression coefficient 0.3 μGal/mbar. However, in the complex topography of the Zugspitze calibration system the effect of actual air mass distribution may deviate significantly from this simple relation.

6 Conclusions

The large number of observations carried out during the calibration experiment time series allow valuable insight into the characteristics and accuracy of the Scintrex CG3 and CG5 gravity meters. The repeatability of the gravity differences in the Zugspitze calibration system observed by these instruments is within ±10 μGal for most station pairs which is similar to the accuracy of the reference gravity differences from absolute gravimetry. For ties involving Zugspitze summit, a seasonal variation of up to 40 μGal is observed. This is approximately consistent with the variation in snow attraction derived from the snow module of the GLOWA Danube hydrological model. The effects of snow are large in the months January to June, which should be avoided for precise calibration. The effects of other environmental mass changes seem to be moderate. Hysteresis after transport has been identified as a critical error source for several CG3 instruments. A preliminary recommendation is to extend station occupations to a duration of at least 30 minutes.

Taking properly into account the instrument characteristics and the seasonal effects, in the Zugspitze calibration system gravity differences of about 500 mGal can be observed with an accuracy of 5 - 10 μGal by the Scintrex CG3 and CG5 instruments, allowing a calibration with an excellent relative accuracy of $1 - 2 \cdot 10^{-5}$.

Acknowledgement

The support of the observation campaigns by the Environmental Research Station Schneefernerhaus is gratefully acknowledged. The GLOWA Danube snow data have been made available by the Commission for Glaciology of Bavarian Academy of Sciences.

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