A new absolute gravity base in the German Alps

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Abstract: Within a cooperation between the *Institut für Astronomische und Physikalische Geodäsie* (IAPG), München, and the *Institut für Erdmessung* (IfE), Hannover, four new absolute gravity stations were established in the German Alps during the autumn season of 2004, a period with minimum snow coverage. Two stations are located close to the summit of the mountain Zugspitze, while the other two stations are situated at the foot and at the top of the mountain Wank. The four stations cover an elevation range of 2200 m and a gravity range of 0.00522 m/s^2 ($\equiv$ 0.522 Gal). The accuracy of each station determination is assumed to be within $\pm$20 to 40 nm/s^2. The main purpose of the new gravity base net is to serve as a high-precision long-range gravity calibration line for the determination of linear and quadratic calibration terms of modern relative gravimeters. The precision of the calibration line is in the order of $\pm 5\times10^{-5}$ which also considers uncertainties from unmodelled temporary gravity changes due to snow accumulation over a year.

Key words: absolute gravimetry, long-range gravimeter calibration line, German Alps

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1. Motivation: a long-range gravimeter calibration base

The determination of the gravity acceleration (*gravity*) requires different instrumental techniques and observation methods, depending on the application and the needed accuracy. Relative gravimetry contributes among others to the following geodetic tasks: support of absolute gravimetry (centring to safety points, gradient measurements), monitoring of changes in geodynamic research areas, densification of national gravity reference networks, and observation of dense gravity points for local geoid modelling. The required accuracies are in the order of ± 0.01 to a few ± 0.1 μm/s^2. For high-precision relative gravimetry, LaCoste-Romberg (LCR) gravimeters were employed nearly exclusively over some decades. The details of LCR systems are well described in the literature, cf. *Torge (1989).* Since more than 15 years, Scintrex offers a new series of relative gravimeters, the Autograv CG systems, e.g. see *Hugill (1988).* A main advantage of the CG instruments is that periodic errors of the measuring screw and transmission do not exist. The costly calibration measurements can be reduced to some relative observations between a few (e.g., four) reliable absolute gravity stations, allowing the determination of low order polynomial calibration terms. In the past, most calibration surveys in Germany were carried out in the gravimeter calibration system Hannover. This system was established between 1976 and 1982 for the determination of calibration functions of LCR gravimeters (polynomial and periodic calibration terms) with the intent of improving the manufacturer's calibration tables *(Kanngieser et al., 1983).* Since 2003, Scintrex gravimeter were also tested on the vertical calibration line Hannover (staircase of a 20-storied building, point intervals of 0.2, 2.0, and 10 μm/s^2, accuracy ± 0.02 μm/s^2 for the 200 μm/s^2 difference) as well as on a 932 μm/s^2 connection in the Harz mountains (accuracy about ± 0.10 μm/s^2 due to temporal groundwater variations and uncertainties in the reference values). All investigations of gravimeter calibration terms (time stability and gravity range dependency) in the Hannover system were restricted to a relative accuracy level of $1 \cdot 10^{-4}$, see *Timmen and Gitlein (2004).* Therefore, a new long-range gravity calibration line with short transportation times between the gravity points was established in the German Alps. The advantage of short distances between the calibration points is not only the time efficiency of the calibration procedure but also a reduction of the irregular transportation drift effects of the gravimeter spring system. The gravity base stations have been selected on stable floors in buildings with a quiet environment. This enables high precision measurements despite of the extreme alpine environmental conditions, such as very low temperatures or strong wind forces.

2. Absolute gravimetry with the FG5 ballistic gravimeter

2.1. Instrumental techniques and operational procedures

Modern absolute gravity measurements are based on time and distance measurements along the vertical to derive the gravity acceleration at a specific position on the Earth, c.f. *Torge (1989)*. Different types of transportable instruments are available. The most common type is presently the FG5 from Micro-g Solutions, Inc., see *Niebauer et al. (1995)*. The FG5 design is based on the instrumental developments at the Joint Institute for Laboratory Astrophysics (JILA), Boulder, Colorado *(Faller et al., 1983)*. During a free-fall experiment (drop), the trajectory of a mass (optical retro-reflector) is traced by laser interferometry over the falling distance of about 20 cm within an evacuated chamber. The time/distance data pairs (FG5: 700 equally spaced measuring positions) are adjusted to a fitting curve (almost-parabolic), giving the g-value for the reference height above floor level (FG5: $\sim$1.2 m). The equation of motion comprises a vertical gravity gradient to take the height dependence of g into account. The reference height of the derived free-fall acceleration g has to be defined with an accuracy of $\pm$1 to 2 mm within the dropping distance to preserve the accuracy of the measurement system.

Within the operational procedure of the FG5-220, as employed at the *Institut für Erdmessung* (IfE), *University of Hannover*, the time interval between two drops is 10 s which includes the reset of the falling corner cube and the online adjustment. For the reduction of local noise and other disturbances, 1500 to 3000 drops are performed automatically per station determination. The measurements are subdivided into sets of 50 drops each, starting every 30 minutes, and distributed over 1 to 2 days. The result of a station determination is the average of all drops, reduced for gravity changes due to polar motion, atmospheric mass flow and Earth tides.

Relative gravimetric measurements are still highly important to transfer the absolute gravimetry results to network points at floor level or to another height level along the vertical that has been agreed on, e.g., for comparisons of different absolute gravity determinations. However, to preserve the accuracy of the absolute measurements for present and future investigations and applications, the gravity result should not be affected by uncertainties in the vertical gradient due to measurement errors, or deteriorated by unknown non-linearities in the gradient *(Timmen, 2003)*. These demands are fulfilled by defining the reference height close to a position where the influence of an uncertainty in the vertical gravity gradient becomes nearly zero. The corresponding position is approximately 1/3 of the falling distance below the top of the free-fall trajectory. Therefore, all gravity determinations with the Hannover instrument are referred to the reference height of 1.200 m above floor level or above ground mark.

2.2. Gravity reductions

For the reduction of the gravity value from the reference height to the groundfloor marker, the observed gravity difference (hereafter called vertical gravity gradient) was used. Following the IfE standard procedure, the gradient was measured with a Scintrex Autograv CG3M using a tripod of about 1 m height. By observing the difference 10 times, the gravity transfer to the ground was obtained with a standard deviation of $\pm 0.01\ \mu\mathrm{m/s}^2$.

Furthermore, the absolute gravity observations of the Alps 2004 campaign were reduced for the following temporal gravity variations:

- Polar motion effects: The daily pole coordinates are provided by the *International Earth Rotation Service*. Residual errors are below 1 $\mathrm{nm/s}^2$.
- Gravimetric Earth tides: The series development from *Tamura (1987)* delivers the tidal effects for the solid Earth, and synthetic tidal parameters interpolated from a worldwide $1^\circ \times 1^\circ$ grid *(Timmen and Wenzel, 1995)* take the Earth's elastic behaviour into account. This grid was computed from
  - body tide amplitude factors using the Wahr-Dehant model of an ocean-free, uniformly rotating, and ellipsoidal Earth with inelastic mantle, liquid outer core, and elastic inner core, and

  – from ocean tide gravitation and load derived from a $1^\circ \times 1^\circ$ ocean tide model.

  For the time-constant M0S0 tides, the amplitude factor 1.000 and phase lead 0.000° was used according to the IAG standards. Because the measurements are distributed over 1 to 2 days, the average result can be affected only by a residual error of a few nm/s^2.

- Gravity variations due to atmospheric mass flow (direct effect of air mass attraction and indirect effect by deformation of the Earth's surface): In accordance with the IAG Resolution No. 9, 1983, this reduction refers to the U.S. Standard Atmosphere, 1976, and was applied by calculating the attraction and deformation effects for a local (spherical distance $\leq 1^\circ$), regional ($\leq 10^\circ$), and global ($\leq 180^\circ$) zone with corresponding resolutions of 0.01°, 0.2°, and 1.125°. The global 2D data are available from the *European Centre for Medium-Range Weather Forecasts* (ECMWF), and were provided by the *University of Cologne* in cooperation with the *German Computing Centre for Climate and Earth System Research*. The calculation procedure is explained in Gitlein and *Timmen (2006)*.

2.3. Accuracy

Repeatability and accuracy of the FG5-220 system is routinely controlled (especially before and after field projects) at the reference stations Hannover (gravimetric laboratory of IfE, see Fig. 1) and Bad Homburg (absolute gravity datum reference station with continuous GPS, superconducting gravimeter, absolute air pressure, and groundwater monitoring, operated by BKG (*Bundesamt für Kartographie und Geodäsie*, Frankfurt)). In addition, the Hannover instrument is routinely compared with other FG5 systems, contributing to the Fennoscandian land uplift project. In this project, annual surveys are conducted since 2003 by three or four absolute gravimeters to provide ground truth data for the GRACE satellite mission *(Timmen et al., 2006)*. Table 1 gives the instrument comparison results obtained before and after the Alps campaigns. The comparisons were made by simultaneous parallel registrations at stations Metsähovi/Finland and Onsala/Sweden, or by double occupations at Ås/Norway (*University of Life Science*, UMB) and Vaasa/Finland. A nearly simultaneous comparison of the FG5-220 and

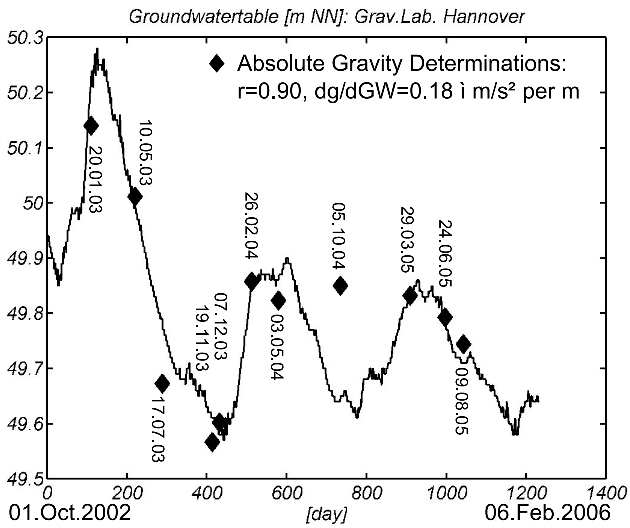

Fig. 1. Groundwater table at the gravimetry laboratory in Hannover and absolute gravity determinations with FG5-220 since 2003. The two time series are correlated by 90 percent. The derived FG5-220 precision is almost $\pm 0.01\mu$ m/s^2.

FG5-221 (*Finnish Geodetic Institute,* FGI) in Vaasa in May 2004 yielded a difference of 14 nm/s^2. Comparisons at Onsala in October with three absolute gravimeters agreed within 20 nm/s^2, see Table 1.

The long-term accuracy (hardware, software, gravimeter experts) is controlled through international absolute gravimeter comparisons in Walferdange (Luxembourg), organized by the *European Center of Geodynamics and Seismology* (ECGS, see *Francis et al., 2005*). The first comparison was held in November 2003 with 15 simultaneously observing instruments, assigned for research in geophysics (e.g. geodynamics) or for metrological purposes (definition of standards). The agreement between the gravimeters was excellent, the standard deviation of the differences was only ± 19 nm/s^2. The next comparison is planned for 2007. Thus, an overall accuracy of better than ± 30 nm/s^2 is indicated for a station determination with a single absolute gravimeter. For the period of the gravimetric campaigns in the German Alps in September and December 2004, the FG5-220 system was obviously well controlled.

Table 1. Comparisons of the IfE absolute gravimeter FG5-220 with FG5-221 (FGI), FG5-226 (UMB), and FG5-301 (BKG), and with the Bad Homburg reference value (mean from both epochs). The differences are calulated as g(FG5-220) minus g(i)

Date	Station	FG5-220 compared with	Diff. [nm/s^2]	Remark
Nov 03	Bad Homburg (BH)	mean	-6	
April 05	"	"	6	
Mar+Apr04	Ås	FG5-226	22	
May 04	Vaasa AB	FG5-221	14	
May 04	Metsäh. AB	FG5-221	-3	Simult.
May 04	Metsäh. AC	FG5-221	44	Simult.
Oct 04	Onsala AS	FG5-226	-23	Simult.
Oct 04	Onsala AS	FG5-221	3	Simult.
Oct 04	Onsala AN	FG5-226	-14	Simult.
Oct 04	Onsala AN	FG5-221	15	Simult.
		Mean (excl. BH)	7	
		rms	±21	

3. Absolute gravimetric survey in the Alps 2004 and results

The two stations at the Zugspitze were occupied in September 2004 and for logistical reasons the Wank stations were observed in early December 2004. The closest German city is Garmisch-Partenkirchen, see Fig. 2. Both observation campaigns took place during a season in 2004 with minimum snow coverage (Fig. 3) which was chosen as the preferred constellation for comparisons with future re-measurements. This should ensure optimal environmental conditions with respect to the investigation of the uplift of the Alpine orogenesis and the deglaciation due to climate changes. The gravity and height values are shown in Fig. 4. The geometrical point definitions were supplemented by differential GPS observations in close proximity of the gravity points. Up to three full days of simultaneous GPS registrations were performed between two adjacent stations. The local connections between the GPS and the gravimetry points were obtained by geometrical leveling. Two permanent GPS stations, one at the Zugspitze summit and one at the Wank, ensured the integration within the national reference frame. The overall accuracy of the height differences is assumed to be better than ±5 mm.

The four absolute gravity points were marked by fixing a screw in the

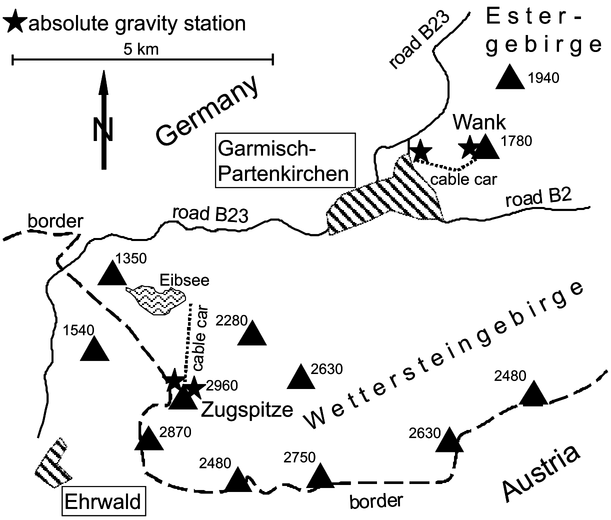

Fig. 2. Absolute gravity stations established in 2004.

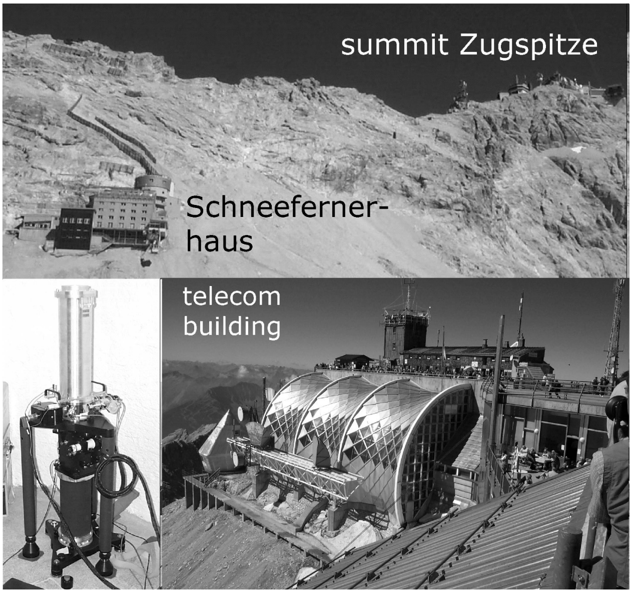

Fig. 3. The two absolute gravity stations at the Zugspitze observed by FG5-220 during a period with minimum snow and ice coverage in 2004.

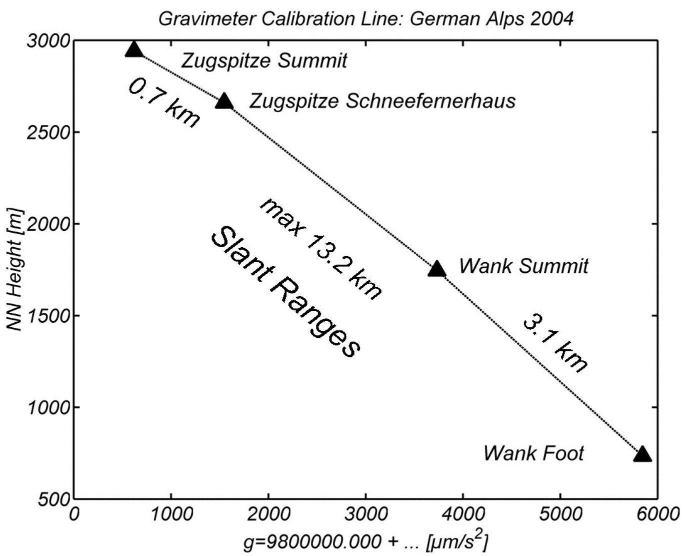

Fig. 4. Distribution of the FG5-220 absolute gravity sta-tions with respect to height and gravity range.

concrete floor using a dowel. The screw top is leveled with the floor. Close to each of the four points, a plate with the inscription "SCHWEREFEST-PUNKT" was attached to the walls to indicate that the points are part of the official national geodetic network. Eccenter points were installed in the vicinity of the absolute points by employing two Scintrex Autograv CG3M relative gravimeters. These eccenters are easily accessible to perform calibration measurements with relative gravity meters. Because the Scintrex sensing element is surrounded by a sealed chamber with low vacuum to exclude instrumental air pressure effects, the large air pressure difference between the stations should not disturb the meter calibration measurements. Since 2004, a long series of calibration tests has been carried out using Scintrex CG instruments (*Flury et al., 2006*, see also chapter 4). The transportation of the relative gravimeter between the absolute stations requires only 15 – 30 minutes by cable cars. This allows for a large number of repetitions in short time and very good drift control. The largest gravity difference (summit Zugspitze to foot Wank) can be measured up to 10 times per day. For a further improvement of drift control, an additional absolute station has been established at Eibsee (Fig. 3) in 2005. It has been observed by the small A10-002 absolute gravity meter of *Bundesamt für Kartographie and Geodäsie* (BKG) in Frankfurt/Main. In addition, several of the base stations and one of the eccenter points at Zugspitze have been re-occupied in 2005 with the A10-002 instrument (*Flury et al., 2006*).

The coordinates and the results of the absolute gravity observations are given in Table 2 and Table 3. The accuracy of the gravity values is assumed to be about $\pm 0.03 \mu\text{m/s}^2$ (empirical estimate). A quantitative estimation of the site stability and the instrument's stability is given by the drop and set sequences and the corresponding drop-to-drop and set-to-set scatters, see Fig. 5. However, such contemplations do not immediately reveal problems related to floor instabilities and the instrument's set up, resulting in floor recoil effects. These effects also include a systematic part, triggered by the dropping procedure, and the resulting vibrations disturb the gravity acceleration observations. The effect has thoroughly been investigated by *Klopping et al. (1991)* and *Timmen et al. (1993)*, and it may cause errors of up to a few 0.01 $\mu\text{m/s}^2$ for FG5 gravimeters. For this project, the investigation of the raw data (time/distance data pairs) showed that no systematic impact of the dropping mechanism was evident.

4. Conclusions

In 2004, a gravimetry calibration base was established in the German Alps, consisting of four absolute gravity stations. The calibration system allows the accurate determination of linear and/or quadratic calibration terms of relative gravimeters. This new line is especially designed for Scintrex CG relative gravimeters which have no higher order calibration parameters.

In *Flury et al. (2006)*, the effects of environmental mass changes are discussed considering snow (main contributor), glacier melting and groundwater. Numerical investigations were based on a snow model of the GLOWA-Danube hydrological project. In addition, a time series (total time span: 22 month) of 57 calibration experiments with two Scintrex CG3 and one CG5 relative gravimeter were examined to assess the environmental uncertainties of the calibration line as well as the stability and accuracy of the instruments. The Scintrex gravimeters which were employed simultaneously

Table 2. Coordinates of the absolute gravity locations occupied by FG5-220 in the German Alps 2004

Station	Reg. No.	φ [deg]	λ [deg]	H [m NN]	Description
Zupspitze	ZUG100	47.4211	10.9851	2940.96	telecommunication building at summit
Schneefernerhaus	ZUG200	47.4164	10.9798	2659.81	station for environmental research
Wank Berg	WANK100	47.5072	11.1443	1738.03	station of the Wank cable car (summit)
Wank Tal	WANK200	47.5041	11.1062	735.29	station of the Wank cable car (foot)

Table 3. Absolute gravity values (at reference height and floor level) of the FG5-220 Alps stations

Station	Date in 2004	Drops	Ref.height [m]	$g_{Ref.h}$ [μm/s^2]	s_{Drop} [nm/s^2]	δg/δh [μm/s^2 / m]	g_{Floor} [μm/s^2]
Zupspitze	18./19. Sep.	1983	1.200	9800621.48	103	-4.653	9800627.06
Schneefernerhaus	09./10. Sep.	1494	1.200	9801546.87	150	-3.505	9801551.08
Wank Berg	01./02. Dec.	1997	1.200	9803733.46	107	-3.877	9803738.11
Wank Tal	03.-05.Dec.	3198	1.200	9805844.32	141	-2.847	9805847.74

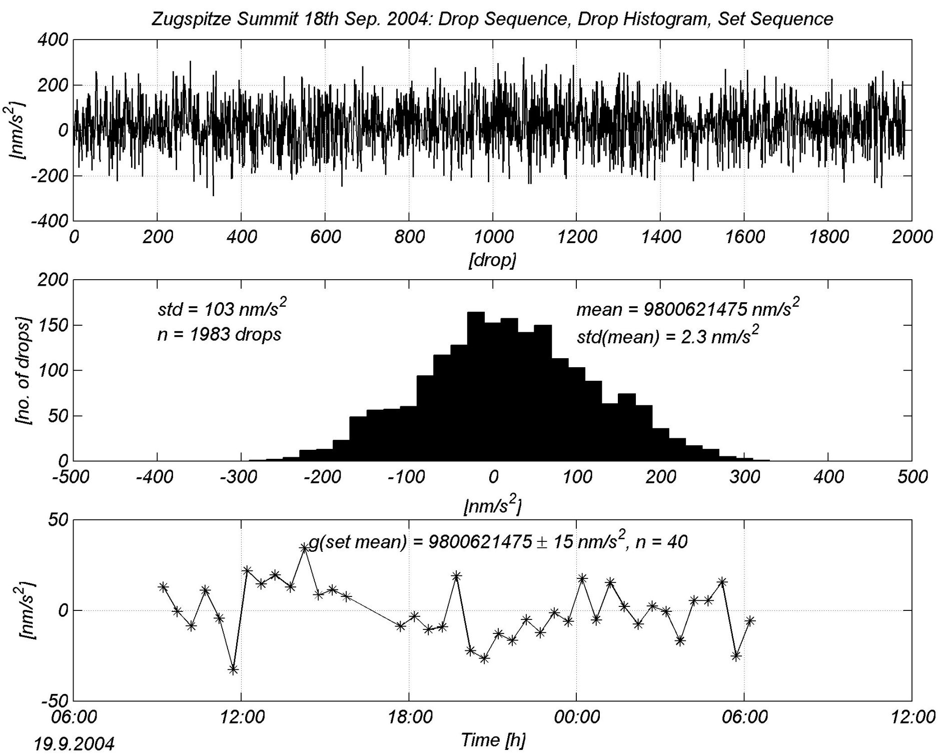

Fig. 5. Statistical compilation of the station determination ZUG100 (Zugspitze).

with the FG5 and the later A10 absolute gravity measurements showed a calibration accuracy of ± 1 to 2×10^{-5}. Larger hydrological effects due to snow accumulation of up to 0.4 μm/s^2 were found. Therefore, the preferable season for calibration measurements should be the period from July to December. Generally Scintrex gravimeters might be sensitive to the large atmospheric pressure variations of more than 200 hPa along the calibration line. Following the investigations of *Hugill (1988)*, air pressure induced disturbances in the order of 0.1 μm/s^2 can not be excluded. For the CG3 gravimeter of IfE, investigations in an evacuated chamber over a 150 hPa range showed no effect.

The new calibration base is a stand-alone calibration system, but may also serve as an extension to existing systems. Because of the large gravity range of 0.005 m/s^2 (0.5 Gal) and the short transportation ways between the points (with cable car and motor car), this new base is an ideal supplement to the Hannover calibration system. A calibration accuracy of $\pm 5\times 10^{-5}$ is achievable within one measuring day, presupposing that a relative gravimeter with a corresponding accuracy potential is employed.

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References

Faller J. E., Guo Y. G., Geschwind J., Niebauer T. M., Rinker R. L., Xue J., 1983: The JILA portable absolute gravity apparatus. Bull. Inf. Bur. Grav. Int., **53**, 87–97.

Flury J., Peters T., Schmeer M., Timmen L., Wilmes H., Falk R., 2006: Precision Gravimetry in the New Zugspitze Gravity Meter Calibration System. Presented at the 1st International Symposium of the International Gravity Field Service (IGFS), 28 Aug. to 1 Sep. 2006, Instanbul (submitted for symposium proceedings).

Francis O., van Dam T., Amalvict M., Andrade de Sousa M., Bilker M., Billson R., D'Agostino G., Desogus S., Falk R., Germak A., Gitlein O., Jonhson D., Klopping F., Kostelecký J., Luck B., Mäkinen J., McLaughlin D., Nunez E., Origlia C., Palinkas V., Richard P., Rodriguez E., Ruess D., Schmerge D., Thies S., Timmen L., Van Camp M., van Westrum D., Wilmes H., 2005: Results of the International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003. In: C. Jekeli, L. Bastos, J. Fernandes (Eds.): Gravity, Geoid and Space Missions, GGSM 2004, IAG Symp. 129, 272–275, Springer.

Gitlein O., Timmen L., 2006: Atmospheric Mass Flow Reduction for Terrestrial Absolute Gravimetry in the Fennoscandian Land Uplift Network. In: P. Tregoning, C. Rizos (Eds.): Dynamic Planet, IAG Symp. 130, 451–466, Springer.

Hugill A. L., 1988: The new Scintrex CG-3 Autograv gravity meter: description and test results. Paper Presented at the ASEG/SEG Conference, February 1988, Adelaide, Australia.

Kanngieser E., Kummer K., Torge W., Wenzel H.-G., 1983: Das Gravimeter Eichsystem Hannover. Wiss. Arb. d. Fachrichtung Verm. wesen der Univ. Hannover, Nr. 120, 95 p.

Klopping F. J., Peter G., Robertson D. S., Bertis K. A., Moose R. E., Carter W. E., 1991: Improvements in absolute gravity observations. Journal of Geophysical Research, 96, B5, 8295–8303.

Niebauer T. M., Sasagava G. S., Faller J. E., Hilt R., Klopping F., 1995: A new generation of absolute gravimeters. Metrologia, 32, 159–180.

Tamura Y., 1987: A harmonic development of the tide generating potential. Bulletin d'Inf. Marées Terrestres, 99, 6813–6855.

Timmen L., 2003: Precise definition of the effective measurement height of free-fall absolute gravimeters. Metrologia, 40, 62–65.

Timmen L., Gitlein O., 2004: The capacity of the Scintrex Autograv CG-3M no. 4492 gravimeter for "absolute-scale" surveys. In: P. M. L. de Menezes (Ed.): Revista Brasileira de Cartografia (Brazilian Journal of Cartography), 56/02, 89–95.

Timmen L., Gitlein O., Müller J., Denker H., Mäkinen J., Bilker M., Pettersen B. R., Lysaker D. I., Omang O. C. D., Svendsen J. G. G., Wilmes H., Falk R., Reinhold A., Hoppe W., Scherneck H.-G., Engen B., Harsson B. G., Engfeldt A., Lilje M., Strykowski G., Forsberg R., 2006: Observing Fennoscandian Gravity Change by Absolute Gravimetry. In: F. Sansò, A. J. Gil (Eds.): Geodetic Deformation Monitoring: From Geophysical to Enggineering Roles, IAG Symp. 131, 193–199, Springer.

Timmen L., Röder R. H., Schnüll M., 1993: Absolute gravity determination with JILAG-3 - improved data evaluation and instrumental technics. Bulletin Géodésique, 67, 71–80.

Timmen L., Wenzel H.-G., 1995: Worldwide synthetic gravity tide parameters. In: H. Sünkel and I. Marson (Eds.), Gravity and Geoid, Proceed. IAG Symp. 113, 92–101.

Torge W., 1989: Gravimetry. de-Gruyter, Berlin-New York.