Absolute Gravimetry with the Hannover Meters JILAg-3 and FG5-220, and their Deployment in a Danish-German Cooperation

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Summary

Using absolute gravimetry, geodetic networks can be surveyed to realize a homogeneous gravity standard of regional to global extent and to monitor time dependent variations in the Earth's gravity field. With the receipt of the transportable free-fall gravimeter JILAg-3 at the Institut für Erdmessung (IfE, Leibniz Universität Hannover) in 1986, projects were initiated with a main objective to improve national and international gravimetric networks. Deficiencies in the definition of the absolute datum (gravimetric scale and level) could be overcome. As a second goal, absolute gravity determinations were performed to support the geodynamic research in regions where geophysical phenomena deform the Earth's surface.

Presently, the FG5 gravimeter is the state-of-the-art in the measurements of absolute gravity. With the high measuring accuracy, new applications have been risen, e.g. the monitoring of environmental changes. For IfE, the FG5-220 is the second absolute meter obtained in 2002, and is the follow-up of the JILAg-3. Comparisons of results with both absolute gravimeters among themselves and with other instruments show that the results from both instruments are well adjusted to the international gravity standard. But a bias of +0.09 µm/s^2 has to be considered for the JILAg-3 measurements when comparing with FG5-220 results. As a case study for an interdisciplinary long-term research, a Danish-German cooperation is described. Besides the establishment of a national gravimetric reference, a strong geophysical background characterizes the joint projects performed since 1986.

Zusammenfassung

Mit der Absolutgravimetrie können regionale und globale geodätische Netze eingerichtet und wiederholt vermessen werden, um einen homogenen Schwerestandard zu realisieren. Solch ein Bezugsystem ermöglicht auch die Überwachung von zeitlichen Veränderungen des Erdschwerefeldes. 1986 erhielt das Institut für Erdmessung (IfE, Leibniz Universität Hannover) das transportable Freifall-Gravimeter JILAg-3. Ein Hauptziel der damit initiierten Projekte war die Verbesserung nationaler und internationaler Schwerenetze mit einer möglichst genauen Definition des absoluten Schweredatums (Niveau und Maßstab). Die zweite Zielsetzung der absoluten Schwerebestimmungen bestand darin, die Forschung in geodynamisch aktiven Gebieten, in denen Deformationen der Erdoberfläche auftreten, zu unterstützen.

Das FG5-Absolutgravimeter ist gegenwärtig das am weitesten entwickelte Messinstrument bzgl. höchster Genauigkeit und effektivem Arbeitseinsatz. Aufgrund der Messgenauigkeit ergeben sich weitere Anwendungsmöglichkeiten, wie z. B. bei der Überwachung von Umweltveränderungen. In der Nachfolge des JILAg-3, das bis 2000 betrieben wurde, ist am IfE seit Ende 2002 das FG5-220 verfügbar. Vergleiche der Ergebnisse der beiden IfE-Instrumente untereinander und mit anderen Gravimetern zeigen, dass beide Absolutgravimeter gut in den internationalen Standard eingepasst waren bzw. sind. Allerdings muss für das JILAg-3 ein instrumentell bedingter Messversatz von +0.09 µm/s^2 gegenüber dem FG5-220 berücksichtigt werden. Als ein Fallbeispiel für eine langfristig angelegte interdisziplinäre Forschungsarbeit wird die seit 1986 laufende dänisch-deutsche Kooperation des IfE vorgestellt. Neben der Einrichtung des nationalen Schwerereferenzsystems charakterisieren besonders die geophysikalischen Hintergründe die Zielsetzungen der gemeinsamen Projekte.

1 Introduction

In January 1986, the Institut für Erdmessung (IfE), Leibniz Universität Hannover (LUH), received the absolute gravimeter JILAg-3 which was the first transportable system located in Germany (Torge et al. 1987). The free-fall system was developed at the Joint Institute of Laboratory Astrophysics (JILA, Faller et al. 1983) of the University of Colorado. The so-called JILAg-3 was the third gravimeter of a series of six JILA instruments and was successfully employed by IfE in more than 130 absolute gravity determinations worldwide (South America, China, Greenland, Iceland, Central and Northern Europe). In December 2002, IfE has received a new FG5 absolute gravity meter (FG5-220) from Micro-g Solutions, Inc. (Erie, Colorado), which is a »state-of-the-art« instrument (Niebauer et al. 1995) and replaces the older JILAg-3. Based on the JILA design, the FG5 generation has overcome several constructively predefined shortcomings and represents an essential improvement in operation and accuracy. The first fully operational FG5 instruments were already available in 1993, manufactured by AXIS Instruments Company in Boulder, Colorado (Carter et al. 1994). The FG5 series represents the currently most advanced instruments and has to be assumed as the best instrumental realization to measure the absolute gravity acceleration. Fig. 1 shows the two types of absolute gravimeters, the Hannover instruments JILAg-3 and FG5-220.

An absolute gravimeter allows the determination of the gravity acceleration g for specific positions as well as the detection of gravity changes with time at a given location. Some examples for gravimetric applications of IfE are given in Torge (1993), describing projects in tectonically active areas in Northern Iceland, the Venezuelan Andes, and in the Yunnan (China) earthquake study area. Gitlein et al. (2008) describes the gravimetric survey of the Fennoscandian postglacial rebound which is an isostatic uplift of the Earth's crust due to the melting of the ice sheet after the glacial maximum of the last ice-age.

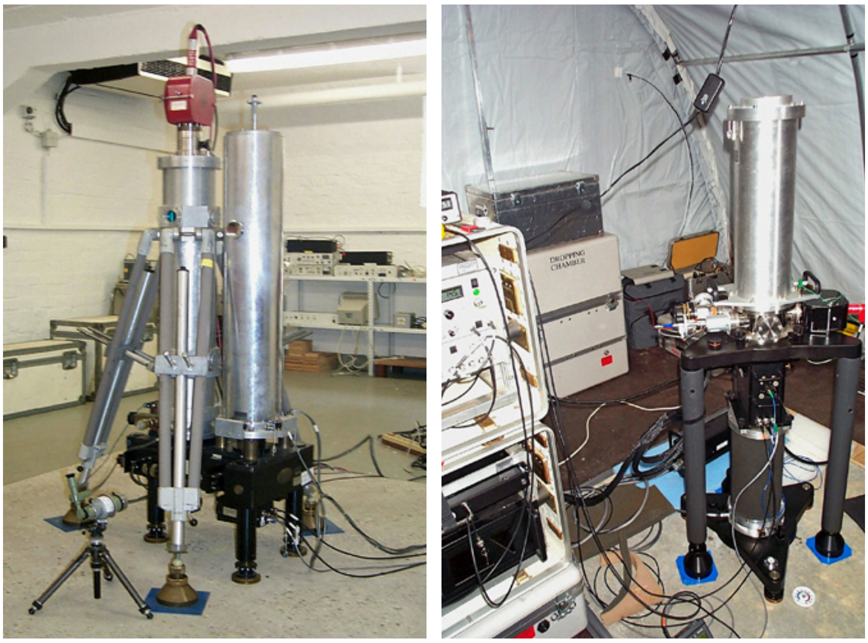

Fig. 1: The two absolute gravimeters of the Leibniz Universität Hannover: left side with JILAg-3 employed from 1986 to 2000 (here reference measurements in Hannover), right side with FG5-220 operated since 2003 (here in Smidstrup/Denmark, tent measurements)

All projects were established in close cooperation with government agencies and academic institutions of the cooperating countries.

Already in 1986, an international collaboration was initiated between IfE and the scientific department of the former Geodetic Institute of Denmark. In the early 1990th, the Danish National Survey and Cadastre (Kort&Matrikelstyrelsen – KMS) was established, integrating the scientists of the dissolved Geodetic Institute in its research units. Since 2005, the responsible Danish researchers, cooperating with IfE, are affiliated with the Geodynamics Department of the Danish National Space Center (DNSC-DTU). The cooperation with IfE is still ongoing, and meanwhile some absolute gravity stations exist with observations covering a time span of almost 20 years. The next measurements are scheduled for summer 2008.

2 Characteristics of absolute gravimetry

To realize the advantages of absolute gravimetric measurements, some particular features of the gravity acceleration g, or just termed gravity g, for a defined geometrical point should be explained first. The gravity acceleration at a surface point depends on:

1. the position relative to the Earth's masses and their density distribution (integral effect caused by the gravitational force of the Earth's masses), and
2. the position relative to the Earth's rotation axis (effect caused by the centrifugal force due to the Earth rotation).

The g-value of a point at the Earth's surface (e.g. bench mark attached to a pier) changes with:

- varying distance to the centre of masses of the Earth (geocentre) caused by vertical movements of the measuring point, e.g. due to crustal deformations, and by secular variations of the position of the geocentre (subtle effect, requires long-time series),
- mass shifts and redistributions within the system Earth (incl. atmosphere and hydrosphere), and especially with near-surface variations within the crust (e.g. groundwater changes, sediment compaction),
- changing distance to the Earth's rotation pole due to lateral movements (subtle effect, e.g. plate tectonics).

Absolute gravity measurements are most sensitive to height changes and provide an obvious way to define and control the vertical height datum. No additional reference points (connection points) at the Earth surface, and no observations to celestial bodies (quasars, stars, planets, moon) or satellites are needed. Shortcomings of relative gravimetry, like calibration problems and deficiencies in the datum level definition, could be overcome. The accuracy of an absolute gravity net is independent of geographical extension which allows applications on local, regional and global scale with consistent measurement quality. An independent verification of displacements measured geometrically with GPS (Global Positioning System), VLBI (Very Long Baseline Interferometry), and SLR (Satellite Laser Ranging) is possible. A combination of gravimetric and geometric measurements may enable to discriminate among subsurface mass movements associated with or without a surface deformation.

3 General objectives of geo-scientific and state-geodetic surveys

The benefit of absolute gravimetry has already been exploited in different scientific projects. The International Absolute Gravity Basestation Network (IAGBN) serves, among other purposes, for the determination of large scale tectonic plate movements (Boedecker and Fritzer 1986, Boedecker and Flury 1995). The recommendations of the Interunion Commission of the Lithosphere on Mean Sea Level and Tides propose the regular implementation of absolute gravity measurements at coastal points, 1 to 10 km away from tide gauges (Carter et al. 1989). The height differences between gravity points and tide gauges have to be controlled by levelling or GPS. In Great Britain, the main tide gauges are controlled by repeated absolute gravity determinations in combination with episodic or continuous GPS measurements (Williams et al. 2001). Torge (1998a) and Torge (1998b) describe the changing role of gravity reference networks due to the modern approach at realizing the network standards by absolute observations.

Overall, absolute gravimetry can be an important research tool to study geodynamic processes, especially land uplift effects due to postglacial rebound (PGR). Lambert et al. (1996) gives an overview about the capability of absolute gravity measurements in determining the temporal variations in the Earth's gravity field. In Lambert et al. (2001), the gravimetric results for the research of the Laurentide postglacial rebound in Canada are described. Mäkinen et al. (2007) compares observed gravity changes in Antarctica with modelled predictions of the glacial isostatic adjustment as well as of the glacier mass balance.

Since 1986, several gravimetric projects were performed by IfE with the absolute gravimeters JILAg-3 (e.g. Torge 1990, Torge 1993, Timmen 1996) and FG5-220 (Gitlein et al. 2008, Timmen et al. 2006a). These activities served for the following main objectives:

- establishing and improving international and national gravity reference networks to realize a homogeneous gravity standard (datum definition in level and scale) of regional to global extent; calibration systems for relative gravimetry are needed;
- installing and strengthening regional and local networks in tectonically active areas with absolute gravimetric measurements and following re-observations; such monitoring systems serve for geophysical research on the rheology of Earth's mantle and crust;
- monitoring the vertical stability of tide gauge stations to separate sea level change from land surface shifts; this serves to constrain parameters related to global climatic change.

With the initiation of the GRACE satellite experiment (Gravity Recovery and Climate Experiment, e.g. Wahr and Velicogna 2003, Tapley et al. 2004), a new request has been risen for absolute gravimetry:

- providing most accurate »ground truth« for GRACE.

The results from both data sets describe changes of the gravity field at the Earth's surface or at the geoid. The terrestrial data can not only be used to validate the GRACE products (Müller et al. 2006) but may also serve as a completion of the satellite results.

In the future, two additional tasks may become important applications:

- monitoring of human-caused changes in aquifers and deep water reservoirs by water extraction;
- contributing to the definition of ground-based geodetic reference networks within the activities the IAG's Global Geodetic Observing Systems (GGOS).

GGOS will provide the observational basis to integrate the different geodetic techniques. The purpose of the globally collected geodetic data is to collate and analyse information about global processes and changes which are important for the world societies. An overview and further details about GGOS can be obtained from Pearlman et al. (2006). In Ilk et al. (2005), detailed information about mass transport processes in the Earth system are given.

4 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,

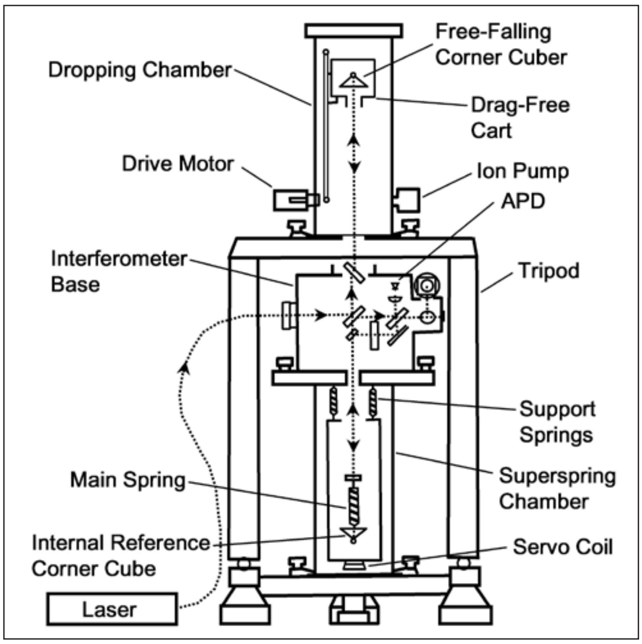

Fig. 2: Schematic diagram of the FG5 absolute gravimeter, after Micro-g Solutions Inc. (1999)

cf. Torge (1989). The expression »absolute« is based on the fact, that the time and length standards (rubidium clock, helium-neon laser) are incorporated as components of the gravimeter system. No external reference like a connecting point is required. The FG5 series is presently the most common gravimeter model, which may be considered as the successor system of the JILA generation (Carter et al. 1994, Niebauer et al. 1995). The influence of floor vibration and tilt on the optical path could largely be removed by the improved interferometer design. The iodine-stabilized laser, serving as the primary length standard, is separated from the instrumental vibrations, caused by the dropping procedure, by routing the laser light through a fibre optic cable to the interferometer base, see Fig. 2.

During a free-fall experiment (drop), the trajectory of a test mass (optical retro-reflector) is traced by laser interferometry over the falling distance of about 20 cm within an evacuated chamber. The »co-falling« drag-free cart provides a molecular shield for the dropped object. The multiple time/distance data pairs collected during the drop (FG5: 700 pairs at equally spaced measuring positions, JILAg: 200) are adjusted to a fitting curve (almost parabolic), giving the gravity acceleration g for the reference height above floor level (FG5: ~1.2 m, JILAg: ~0.8 m). The equation of motion

$$z(t) = z_0\left(1+\frac{1}{2}\gamma t^2\right) + v_0\left(t+\frac{1}{6}\gamma t^3\right) + \frac{1}{2}g\left(t^2+\frac{1}{12}\gamma t^4\right), \quad (1)$$

$$\text{with } t = t' + \frac{z}{c}, \quad (2)$$

comprises a vertical gravity gradient γ to take the height dependence of g into account. The initial displacement z_0 and velocity v_0 are unknowns valid at the time $t = 0$. Because of the finite velocity of light c, the term z/c is added to the observed time values t' before the adjustment procedure is carried out. The acceleration g is defined for the position $z = 0$ which is, in common practice with FG5 and JILA meters, the resting position of the test mass at the start of the free-fall experiment (»top-of-the-drop«). This reference height of the derived free-fall acceleration g depends on the setup of the instrument and should be defined by the operators with an accuracy of ±1 mm to preserve the accuracy of the measurement system. For further theoretical considerations about the equation of motion in absolute gravimetry, it's recommended to study, e.g., Cook (1965) and Nagornyi (1995).

Within the operational procedures with FG5-220, as employed at IfE, the time interval between two drops is 10 s (JILAg-3: 12 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 computer controlled drops are performed per station determination. Generally, the measurements are subdivided into sets of 50 drops each (JILAg-3: 300 drops), and distributed over 1 to 2 days. For JILAg-3, the instrumental adjustment was manually controlled before and after each set of 300 drops. The result of a station determination is the average of all drops, reduced for gravity changes due to Earth tides, polar motion, and atmospheric mass movements.

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 absolute gravity result should not be affected by uncertainties in the vertical gradient due to measurement errors from relative gravimetry 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 almost zero (»dead-gradient-point«). The corresponding position is approximately 1/3 of the falling distance below the first measured position of the free-fall trajectory as used in the adjustment computation (FG5-220: ~1.21 m above floor level). Therefore, all gravity determinations with the current Hannover FG5 instrument are referred not only to the ground floor mark but also to the reference height of 1.200 m above floor level or above ground mark.

For the reduction of the absolute gravity value to the ground floor mark, the observed gravity difference (hereafter called gradient) is needed. Following the IfE standard procedure, the vertical gravity gradient is determined with two LaCoste & Romberg gravimeters with integrated SRW feedback systems (Röder et al. 1988) or with a Scintrex Autograv CG3M (since 2002) using a tripod of about 1 m height. By observing the difference 10 times with each relative meter, the gravity difference is normally obtained with a standard deviation of about ±0.01 µm/s². Referring the gravity difference to a height difference of 1.000 m, the vertical gravity

Fig. 3: Measurement of the non-linear vertical gravity gradient with a Scintrex relative gravimeter. Tripods are used for variable setup heights.

gradient γ is obtained. Here, a linear gravity change with height is assumed. For geodynamic research, often a more accurate knowledge about the non-linearities in the vertical gradient is required. In those cases, gravity differences Δg are measured between variable height levels h above the ground mark (cf. Fig. 3). A least-squares adjustment of observation equations provides an overconstrained solution for the coefficients γ_1 and γ_2 describing the linear and quadratic part of the vertical gravity gradient:

$$\Delta g\left(h_i,h_j\right)=\gamma_1\left(h_j-h_i\right)+\gamma_2\left(h_j^2-h_i^2\right) . \qquad (3)$$

With Eq. (3), an observed absolute gravity value with its defined reference height can be referred to any position within the perpendicular above the ground mark up to about 1.5 m (highest relative gravity measurement position).

Furthermore, the absolute gravity observations are reduced for the following temporal gravity variations (Timmen 1994):

- Gravimetric Earth and ocean tides: the series development from Tamura (1987) delivers the tidal effects for the solid Earth, with synthetic tidal parameters interpolated from a worldwide 1°×1° grid (Timmen and Wenzel 1995) to take the Earth's elastic behaviour into account. This grid was computed from
  - body tide amplitude factors using the Wahr-Dehant model (Wahr 1981, Dehant 1987) of an ocean-free, uniformly rotating, and ellipsoidal Earth with inelastic mantle, liquid outer core, and elastic inner core, and
  - ocean tide gravitation and load (Agnew 1997) derived from an 1°×1° ocean tide model (Schwiderski 1980).

For the time-constant M0S0 tides, the amplitude factor 1.000 and phase shift 0.000° are used according to the IAG standards (»zero-tidal gravity«). Because the measurements are distributed over 1 to 2 days, the average result can only be affected by residual errors of some nm/s². Near the coasts, larger uncertainties are possible.

- Polar motion effects: the daily pole coordinates are provided by the International Earth Rotation and Reference System Service. Residual errors are below 1 nm/s² (Timmen 1994).
- Gravity variations due to atmospheric mass variations (direct effect of air mass attraction and indirect (loading) effect by deformation of the Earth's crust and the sea surface): variations in the local gravity acceleration and atmospheric pressure are known to be correlated with an admittance of about –3 nms⁻² per hPa as an average factor, which is in accordance with the IAG resolution No. 9, 1983 (IGC 1988). This reduction refers to the U.S. Standard Atmosphere, 1976. At IfE, a more accurate reduction is applied for all FG5 measurements with geodynamic objectives. The attraction and deformation effects for a local (spherical distance ≤0.5°), regional (0.5° to 10°), and global (10° to 180°) zone with corresponding resolutions of 0.005°, 0.1°, and 1.125°, are calculated. The global data are available from the European Centre for Medium-Range Weather Forecasts (ECMWF), and are provided to IfE 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).

Fig. 4: The absolute gravimetry station Vestvolden in Copenhagen, established with FG5-220 in 2003

For the site selection, preferences are given to buildings with a stable environment inside the observation room (stable temperature, no direct sun, relative humidity below 70 %) and a solid foundation like a concrete pier, a reinforced concrete base plate, or a concrete platform attached to bedrock. As an example for an absolute gravity station, Fig. 4 shows the reference station in Copenhagen (Vestvolden) which was used as a military shelter in former times.

5 Measuring offset between the gravimeters JILAg-3 and FG5-220

During the period from 1986 to 2000, the JILAg-3 gravimeter was used by IfE for absolute gravity determinations on more than 80 different sites worldwide. The measurements with the presently employed FG5-220 started in 2003, and more than 40 different sites in central and northern Europe have already been occupied. For both instruments, the accuracy and stability have continuously been controlled by comparisons with other absolute gravity meters, and with repeated measurements in several stations after time intervals of some months to few years.

For JILAg-3, Torge (1991) estimated the short- and long-term accuracy of a station determination between

Tab. 1: Mean gravity values for station Clausthal (Germany) derived with JILAg-3 (n = 29 occupations, 1986–2000) and FG5-220 (n = 4 in 2003). The given s_i are standard deviations for a single gravity determination.

JILAg-3/FG5-220 Comparison	Remarks	Gravimeter	Period	Mean g-Result [µm/s²]
Clausthal (Harz Mountains)	IfE reference station for JILAg-3, ref. height 0.000 m	JILAg-3	1986 to 2000	9811157.345 $s_i = \pm 0.049$, n = 29
		FG5-220	Jan. to Oct. 2003	9811157.251 $s_i = \pm 0.023$, n = 4
				$\Delta g = +0.094$

±0.05 to ±0.1 µm/s² (including residual errors from environmental effects). In the mean, an accuracy estimate of ±0.07 µm/s² was obtained. The instrumental precision by itself is assumed to be ±0.04 to 0.05 µm/s² which does not consider errors introduced by real gravity changes, e.g. due to subsurface water variation. For FG5-220, a realistic mean accuracy estimate seems to be about ±0.03 µm/s² (Timmen et al. 2006b, Francis and van Dam 2006). Because most of the IfE measurements serve for local and regional gravimetric control, especially for geodynamic investigations in tectonically active areas, the long-term measuring stability of the two gravimeters is a major concern. To compare the results of JILAg-3 with recent observations of FG5-220, no systematic difference due to the gravimeters themselves should exist, or the instrumental offset should be well-known. One possibility for detecting such an offset is to compare observation series of both instruments performed at a reference station where a long-term stable gravity acceleration can be assumed (no significant secular change). The JILAg-3 reference station Clausthal in the Harz Mountains (stable bedrock) was occupied by FG5-220 at 4 different epochs in 2003 (January, May, June, and October). In Tab. 1, the mean result is compared with the mean from 29 gravity determinations with JILAg-3 performed in the period from 1986 to 2000. The standard deviation of the mean values is in both cases about ±0.01 µm/s². An obtained discrepancy of +0.094 µm/s² indicates a significant offset between the measuring levels of these two absolute gravimeters.

A very similar discrepancy is reported by Torge et al. (1999a). During the surveying of the German zero-order base net Deutsche Schweregrundnetz 1994 (DSGN94) by the Institut für Angewandte Geodäsie (IfAG), now Bundesamt für Kartographie und Geodäsie (BKG), the measurements were carried out with the absolute gravimeter FG5-101 at all 30 absolute points. IfE contributed with JILAg-3 measurements at five stations. Comparing the results of JILAg-3 and FG5-101 for these 5 sites, a mean difference of +0.082 µm/s² was obtained. In ad-

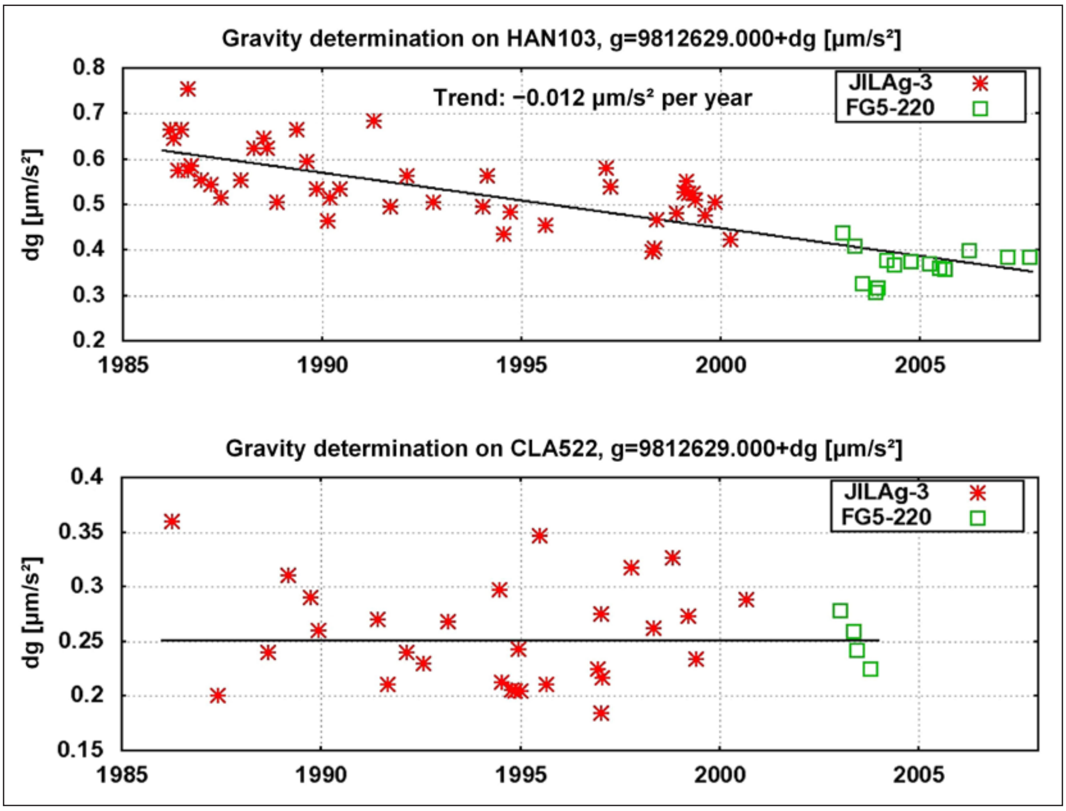

Fig. 5: Absolute gravity determinations with JILAg-3 and FG5-220 at stations Hannover (HAN103, trend −0.012 ±0.001 µm/s² per year) and Clausthal (CLA522, trend −0.001 ±0.002 µm/s² per year). An instrumental offset of −0.09 µm/s² (±0.01 µm/s²) was applied to the JILAg-3 results.

dition, three comparisons between JILAg-3 and FG5-101 were performed in Clausthal in 1994 (mean discrepancy: +0.094 µm/s^2), and one comparison during the International Comparison of Absolute Gravimeters in 1994 (ICAG94, Marson et al. 1995) in Sèvres/France (+0.090 µm/s^2), and one during ICAG97 (Robertsson et al. 2001) in Sèvres (+0.081 µm/s^2).

A clear indication for a gravimeter dependent bias between JILAg-3 and the two German FG5 instruments No. 101 and No. 220 is given. Thus, IfE applies an offset correction of –0.09 µm/s^2 to the JILAg-3 results when comparing with FG5-220 data. From the above given comparisons, the deduced offset can be assumed to be valid with an uncertainty of about ±0.01 µm/s^2.

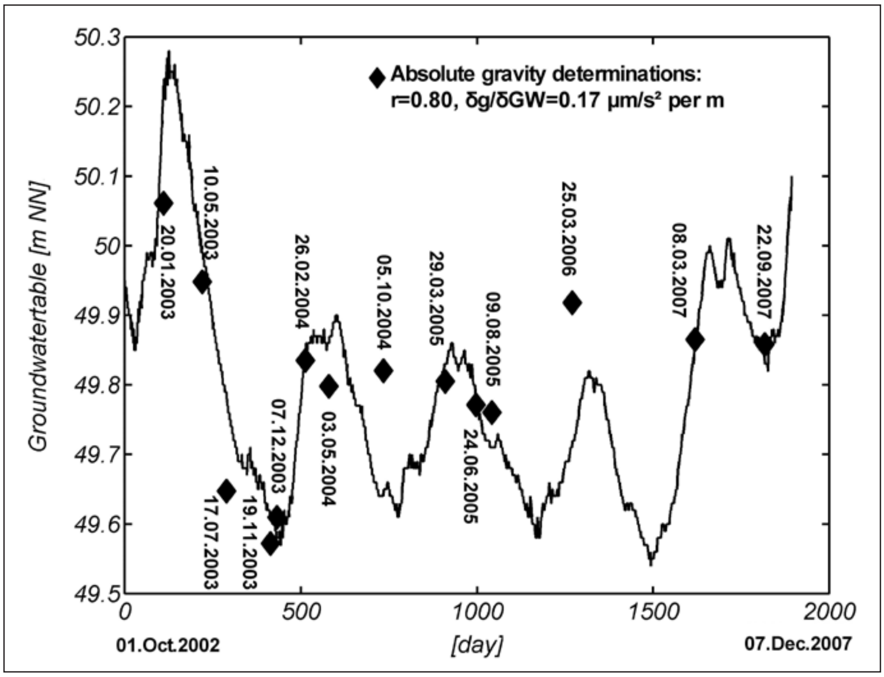

Fig. 6: Groundwater table at the gravimetry laboratory in Hannover and absolute gravity determinations with FG5-220 since 2003. The transfer function from gravity to groundwater change, with the linear coefficient 0.17 µm/s² per m, has been applied to the absolute gravity determinations to convert the g-values to groundwater readings.

Fig. 5 shows the time series of absolute gravity determinations in Hannover (point 103), as well as at station Clausthal (point 522) observed with the two Hannover instruments (offset correction applied). The former station is located on Holocene and Pleistocene sediments (sand, clay, and marl of low consolidation), and is affected by natural (wind forces on the adjacent buildings) and man-made (machines, traffic) microseisms. The Clausthal station (Institute of Geophysics) is less exposed to microseisms due to its location in the Harz mountains (bedrock, far away from heavy traffic). The history of the Hannover measurements reveals a linear gravity decrease of about 0.25 µm/s^2 over a period of 21 years, whereas in Clausthal no significant secular gravity variation can be found. An explanation for the phenomenon in Hannover is not yet available, and requires discussions with other experts, e.g. from hydrosphere research. Fig. 6 explains the scatter in the time histories which is not only caused by measurement uncertainties but also by real gravity variations. E.g., from February to December 2003 the groundwater table at the gravimetry laboratory in Hannover fell about 70 cm which corresponds to a gravity decrease of about 0.13 µm/s^2. Also the decline in the four observed *g*-values at the Clausthal station in 2003 may be connected to the very dry season in northern Germany. Checking the groundwater readings for the period 1986 to present, a declining trend over the years is not visible. But these readings from the groundwater gauge consider only the upper aquifer of the subsurface hydrology around the gravimetry laboratory, and not the deeper aquifers. Thus, it can not be excluded that the long-term trend in the gravity series might be caused by a change in the subsurface water content.

With taking the offset correction of –0.09 µm/s^2 into account for all JILAg-3 observations, a stable measurement level for a time span of more than 20 years is assumed to be available with the two Hannover instruments. This also fulfils the present knowledge that the FG5 gravimeter is the state-of-the-art in the measurements of absolute gravity. Nevertheless, to meet the accuracy requirements for long-term research over many decades and for comparability with other instruments, the observation level of the JILAg-3/FG5-220 couple has to be verified by comparisons with other absolute gravimeters. Since the 1980th, International Comparisons of Absolute Gravimeters (ICAG) are performed at the Bureau International des Poids et Mésures (BIPM) in Sèvres, and since 2003 also at the European Centre of Geodynamics and Seismology (ECGS) in Walferdange, Luxembourg. Such extensive comparison campaigns with a large number of absolute gravimeters may reveal biases not only between single instruments but also between different instrumental developments and technological realizations. Tab. 2 summarizes the results from the comparisons ICAG89 (Boulanger et al. 1991), ICAG94 (Marson et al. 1995), and ICAG97 (Robertsson et al. 2001). In 1989, five JILA-type instruments and five individual developments participated. The JILAg-3 result differed from the mean of the JILA group by +0.018 µm/s^2, from the mean of the group with individual developments by +0.033 µm/s^2, and in the average by +0.024 µm/s^2 from the mean of all 19 stations determinations performed by the 10 instruments.

Tab. 2: JILAg-3 absolute gravity meter controlled by external (international) and internal (repetition) comparisons to ensure consistent long-term measurement accuracy (n = number of observations)

JILAg-3 External Comparisons	Remarks	Gravimeter Group	Mean g-Result [µm/s²]	Std. Dev. of a Single Observ. [µm/s²]	Δg [µm/s²] (JILAg-3 minus Mean)
ICAG89, BIPM (Boulanger et al. 1991, Tab. 7)	referred to site A, ref. height 0.050 m, 19 station determinations with 10 absolute gravimeters	5 JILA	9809259.754	±0.062, n = 11	+0.018
		GABL, BIPM, IMGC, NIM, NAO	9.739	±0.092, n = 8	+0.033
		all 10 meters	9.748	±0.074, n = 19	**+0.024**
		only JILAg-3	9.772	n = 2	
ICAG94, BIPM (Marson et al. 1995, Tab. 4)	referred to site A0, ref. height 0.900 m, 12 observations with 11 absolute gravimeters	4 JILA	9809257.103	±0.049, n = 4	+0.027
		6 FG5	7.104	±0.028, n = 7	+0.026
		1 IMGC	7.090	n = 1	+0.040
		all 11 meters	7.102	±0.033, n = 12	**+0.028**
		only JILAg-3	7.130	n = 1	
ICAG97, BIPM (Robertsson et al. 2001, Tab. 5)	occupied site A with 12 instruments, ref. height 0.900 m	4 JILA	9809257.081	±0.055, n = 4	+0.056
		7 FG5	7.070	±0.037, n = 7	+0.066
		1 GABL-E	7.144	n = 1	−0.008
		all 12 meters	7.081	±0.045, n = 12	**+0.055**
		only JILAg-3	7.136	n = 1	
ICAG97, BIPM (Robertsson et al. 2001, Tab. 5)	occupied site A2 with 13 instruments, ref. height 0.900 m	4 JILA	9809257.166	±0.035, n = 4	+0.035
		6 FG5	7.137	±0.029, n = 6	+0.064
		IMGC, NIM-2a, ZZB	7.139	±0.101, n = 3	+0.062
		all 13 meters	7.146	±0.050, n = 13	**+0.055**
		only JILAg-3	7.201	n = 1	
JILAg-3 Internal Comparisons	**Remarks**	**Observation Periode**	**Mean g-Result [µm/s²]**	**Std. Dev. of a Single Observ.**	**Δg [µm/s²]**
Clausthal/Harz	IfE ref. station for JILAg-3, 29 obs. over 15 years, floor level	period 1986 to 2000	9811157.345	±0.047, n = 29	
		only 1986 to 1996	7.341	±0.048, n = 20	**−0.004**
		only 1997 to 2000	7.354	±0.046, n = 9	**+0.009**
Yunnan Earthquake Area, China (Torge et al. 1999b, Tab. 3)	JILAg-3 observ. at 4 (1990/1992) and 5 (1992/1995) identical stations	epoch 1992 minus 1990	**−0.038**	±0.073, n = 4	
		epoch 1995 minus 1992	**−0.008**	±0.050, n = 5	

In 1994, for the first time FG5 instruments contributed to the comparison, and the discrepancy of JILAg-3 to the mean result of all 11 meters was +0.028 µm/s². These two comparisons may indicate a small offset of about +0.02 to 0.03 µm/s² for JILAg-3. In 1997, the situations changed somewhat. The sites A and A2 were observed, and for both points the JILAg-3 result was +0.055 µm/s² above the average of all instruments. In addition to these external comparisons with other gravimeters, the lower part of Tab. 2 shows some internal comparisons for JILAg-3. Looking at the Clausthal series with respect to the whole time span (1986–2000), and the two periods 1986–1996 and 1997–2000, a systematic change in the measuring level can not be detected. The Clausthal series neither confirms nor contradicts the ICAG97 experience. Both results are consistent considering the precision estimate of ±0.04 to 0.05 µm/s² for a single station determination with JILAg-3.

As an additional check for an offset occurrence or change of JILAg-3, the measurements in China have been analysed. The gravimetry group of IfE performed three campaigns in an earthquake study area in Yunnan/China in the years 1990, 1992 and 1995 (Torge et al. 1999b). The distances between the stations were up to a few hundreds of kilometres. Within that time period, no major earthquake happened in the area, and no gravity change could

Tab. 3: FG5-220 absolute gravimeter controlled by external (international) and internal (repetition) comparisons to ensure consistent long-term measurement accuracy

FG5-220 External Comparison	Remarks	Epoch	Δg [µm/s²] (FG5-220 – Mean g)
ICAG2003, ECGS (Francis et al. 2006, Tab. 16)	13 abs. meters, 14 points, 52 determinations	Nov. 2003	**−0.019** std. dev. (Mean of 13 meters) ±0.018
FG5-220 Internal Comparison	**Remarks**	**Epoch**	**Δg (FG5-220) [µm/s²] (Single – Mean g)**
Bad Homburg (gravimetry lab. of BKG, Wilmes and Falk 2006)	IfE reference station for FG5-220 since 2003	Feb. 2003	+0.017
		Nov. 2003	−0.014
		Apr. 2005	−0.002
		Apr. 2006	+0.003
		Nov. 2007	−0.004

be detected. Assuming a change in the measuring level of the meter of, e.g., +0.05 µm/s² between the campaigns, all occupied stations of at least one epoch should be affected by it. But the results of the three epochs do not indicate such a systematic shift. Of course, there is still the small chance that tectonically induced gravity variation in the whole region might have compensated an occurred instrumental offset.

From Tab. 2, it may be concluded that JILAg-3 was well embedded in the international absolute gravity definition. A larger discrepancy to other instrument groups did not really become obvious during the international comparisons. But a bias to the international standard, here defined as the average of all participating gravimeters at BIPM, of up to +0.05 µm/s² can not be excluded. From the ICAG94 and ICAG97 comparisons, a measurement offset of +0.09 µm/s² becomes visible when just comparing JILAg-3 with FG5-101 as already mentioned before. Thus, from the Hannover point of view, the offset correction for JILAg-3 has mainly to be considered as a bias with respect to the FG5-220 and the FG5-101 gravimeters, and not to the international standard. Interpreting the results of the international comparisons in Sèvres with respect to the instrument groups, a systematic error, inherent in the instrumental design of the JILAg or FG5 gravimeters, does not exist or is within the 0.02 µm/s² level. Nevertheless, biases for single instruments are possible, e.g. due to not-detected changes within the instrumental adjustments.

To investigate the stability of the presently employed gravimeter FG5-220 of IfE, Tab. 3 gives the result from the international comparison in Walferdange/Luxembourg 2003 (external comparison, Francis and van Dam 2006), and FG5-220 reference measurements in Bad Homburg (station of BKG, Wilmes and Falk 2006) from 2003 to 2007. Within ±0.02 µm/s², the Hannover FG5 instrument agrees with the internationally realized measuring level. With respect to the FG5-220 observations in Bad Homburg, it has to be mentioned that the differences between the single epochs also contain real gravity changes due to time-varying environmental effects like seasonal hydrological variations. As shown in Tab. 3, the five station determinations agree very well, better than expected from empirical estimates, with a mean scatter of ±0.01 µm/s² only. An instrumental instability can not be identified. A similar experience is also gained from the yearly repetition surveys, and from the comparisons with the other FG5 absolute gravimeters involved in the Nordic absolute gravity project, to determine the Fennoscandian land uplift, cf. Timmen et al. (2006b) and Bilker-Koivula et al. (2008).

6 The cooperation of IfE with the Danish partners 1986–2007

As a case study for a long-term cooperation in gravimetry, the joint projects of IfE and the Danish institutions (see section 1), with scientists from geodesy and geophysics, will be described in the following. Besides the general information and the results of the measurement campaigns, this overview considers more intensely the geophysical background of the isostatic deformation of the Earth's crust in northern Europe. The monitoring of this geodynamical process is still the main focus of the ongoing cooperation.

Fig. 7 depicts the geographical positions of the observed stations. The coordinates and the objectives of the station determinations are compiled in Tab. 4. The stations contributing to the Fennoscandian land uplift network are also serving as »ground truth« measurements for the GRACE mission. All stations are part of the national gravimetric reference network to ensure a most accurate network standard. Absolute gravity observations were performed in Denmark, Greenland, and the Faeroe Islands. The absolute measurements were all embedded

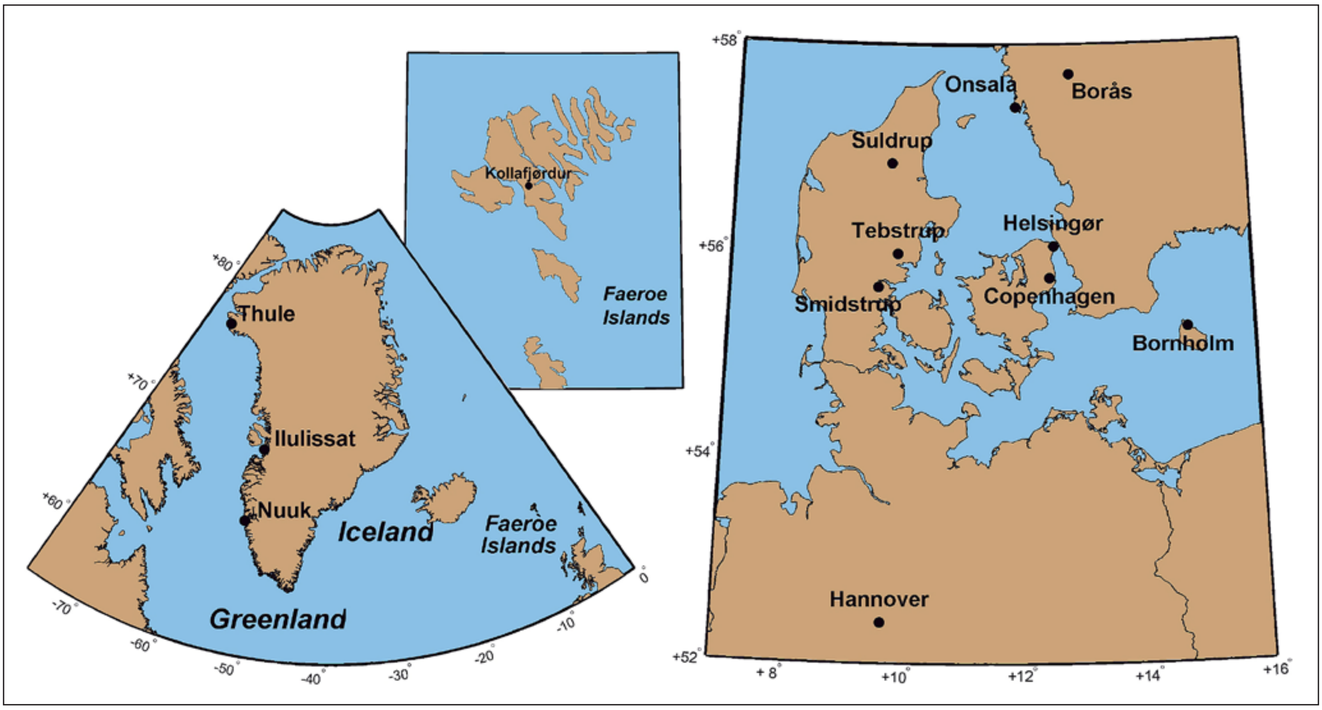

Fig. 7: The absolute gravity sites occupied by JILAg-3 and FG5-220 within the Danish-German cooperation since 1986

Tab. 4: Coordinates and purposes of the absolute gravity sites occupied by JILAg-3 and FG5-220 within the Danish-German cooperation since 1986

Station	φ [deg]	λ [deg]	H [m NN]	Remarks/Purpose
Tebstrup	55.9683	9.8725	84	geodynamics: Fennoscandian land uplift line (east-west, 56° N) • national grav. reference • destroyed since 2005
Helsingør	56.0463	12.5797	32	geodynamics: Fennoscandian land uplift line (east-west, 56° N) • national grav. reference
Copenhagen, Gamlehave	55.7619	12.5653	19	national grav. reference • former Danish Geodetic Institute • destroyed
Copenhagen, Buddinge	55.7389	12.5019	43	national grav. reference • not any more accessible
Copenhagen, University	55.6976	12.5626	12	national gravity reference
Copenhagen, Vestvolden	55.6869	12.4350	24	geodynamics: Fennoscandian land uplift net • national grav. reference
Smidstrup GPS	55.6406	9.5593	123	national grav. reference • outside station (tent)
Suldrup GPS	56.8418	9.7421	121	national grav. reference • outside station (tent)
Bornholm, Tejn	55.2438	14.8473	13	geodynamics: Fennoscandian land uplift net • national grav. reference • city hall
Nuuk, Godthåb (Greenland)	64.178	308.260	23	geodynamics: crustal deformation • absol. control: deglaciation due to climate change • national grav. reference • IAGBN
Ilulissat, Jakobshavn (Greenland)	69.220	308.899	27	geodynamics: crustal deformation • absol. control: deglaciation • national grav. reference
Thule/air base (Greenland)	76.538	291.198	27	geodynamics: crustal deformation • absol. control: deglaciation • national grav. reference
Kollafjørdur (the Faeroe Islands)	62.1055	353.0337	20	geodynamics: crustal deformation • absol. control: tide gauge stability • national grav. reference • agriculture station: old point destroyed, new point in same building

in local relative gravity networks which ensured the integration into the national network. The old absolute point in Kollafjørdur (Faroes) from 1987 and the point in Tebstrup are destroyed caused by building alterations. A new point was established in 2004 in Kollafjørdur in an adjacent room. The tie between a position very close to the old point (~20 cm) and the new point was determined by relative gravimetry. The stations Tebstrup and Helsingør provide the absolute tie within the east-west land uplift profile along the 56°N latitude crossing Denmark and Sweden.

Because of the dynamics within the Earth's system (tectonics, climate change, sea-level rise), the national and international base networks are not stable with time. With the high accuracies of modern geodetic techniques, combined with the high quality of the base net stations (stable environment, customized facilities), the networks serve more and more as control systems for environmental changes and surface deformations. Denmark is part of the Fennoscandian land uplift area. The Earth's crust is rising continuously since the last glacial maximum due to the deloading of the ice. This process is an isostatic adjustment of the Earth's crust in connection with magma flow in the upper Earth's mantle. The Fennoscandian rebound area is dominated by the Precambrian basement rocks of the Baltic Shield, which is part of the old East-European Craton, and comprises South Norway, Sweden, Finland, the Kola Peninsula, and Russian Karelia. The region is flanked by a flexural bulge, covering northern Germany and northern Poland, Netherlands, and some other surrounding regions. This area was once rising due the Fennoscandian ice load and, after the melting, sinking with a much smaller absolute value than the uplift rate in the centre of Fennoscandia. Denmark is part of the transition zone from the uplift to the subsidence area. The maximum spatial extension of the uplift phenomenon is about 2000 km in northeast-southwest direction; see Fig. 8 for the approximate shape and location (after Ekman and Mäkinen 1996). Presently, the central area around the northern part of the Bothnian Gulf is undergoing an uplift rate of about 1 cm/year.

The Trans-European Suture Zone (TESZ) is a main geological boundary in Europe, separating the East-European Craton from the Phanerozoic terranes in the west and south-west (Palaeozoic western Europe and Meso-Europe). The Sorgenfrei-Tornquist Zone is part of the TESZ and crosses Denmark north of Copenhagen in the immediate vicinity of the absolute gravity station Helsingør. Among other stations, the absolute gravity stations Copenhagen/Vestvolden, Helsingør and Onsala (Sweden) belong to the Nordic Geodetic Observation System (NGOS) and may be considered as the central part of a north-south profile crossing perpendicularly the graben system of the sature zone between the Baltic Shield and the younger Palaeo-Europe.

Four east-west profiles across the Fennoscandian postglacial rebound area have been utilized by relative

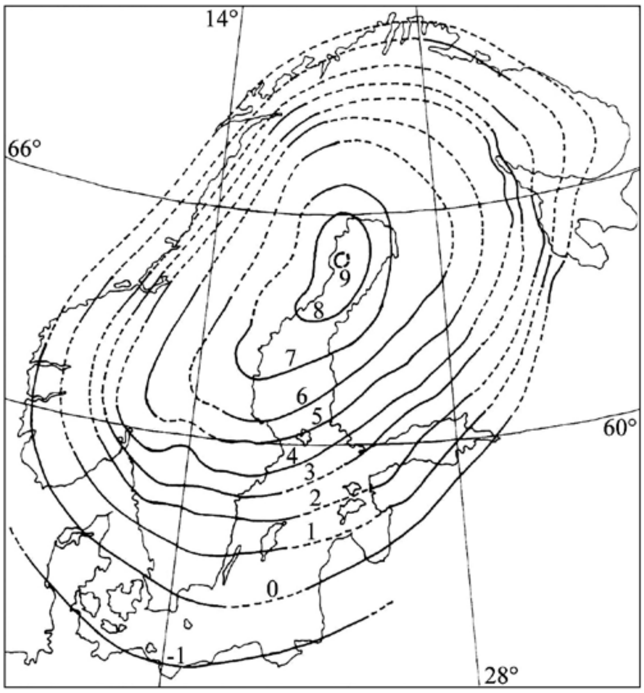

Fig. 8: Map of the postglacial uplift of Fennoscandia (in mm/yr and with respect to the sea level) in accordance with Ekman and Mäkinen (1996). Because of the sea-level rise of about 1 mm/yr, the value of 1 mm/yr has to be added to the markings of the contour lines to obtain absolute height changes with respect to the geocentre.

gravimetry and levelling. They follow approximately the latitudes 65°N (observed 1975–2000), 63°N (1966–2003), 61°N (1976–1983), and 56°N (1977–2003), see Mäkinen et al. (2004) or Ekman and Mäkinen (1996). The east-west directions were chosen to ensure only small gravity differences between the relative gravimetry points (less than 10 µm/s²). This requirement avoids errors from uncertainties of the gravimeter calibrations. With the availability of transportable absolute gravimetry in Central Europe, the 56° profile (Denmark-Sweden) has been supported with JILAg-3 (in 1986) and FG5-220 (2003, 2005) measurements. The establishment of the Danish precision gravity reference network is described in detail (measurement data, station descriptions, results) in a publication of the National Survey and Cadastre (Kort & Matrikelstyrelsen, see Andersen and Forsberg 1996).

The absolute gravimetric results from JILAg-3 and FG5-220 station determinations in Denmark, Greenland, and the Faeroe Islands are summarized in Tab. 5. Some of the measurements were not performed along the perpendicular above the ground marks but as good as possible next to it. The national network points were established for the requirements of relative gravimetry, and suitable setup positions for the absolute meters had to be found in close range to the net points. In such cases, relative measurements were performed between the absolute measurement positions (sensor height about 0.8 m

Tab. 5: Absolute gravity values (at reference height and floor/mark level) of the JILAg-3 and FG5-220 stations in Denmark, Greenland and the Faeroes. The JILAg-3 offset correction of −0.09 µm/s² has been applied. The given accuracies are empirical estimates; further explanations are given in the text.

Station	Instr.	Date	Drops	Reference Height [m]	gref. height [µm/s²]	Accuracy [µm/s²]	δg/δh [µms⁻²/ m]	$g_{floor/mark}$ [µm/s²]
Tebstrup	JILAg-3	22.08.1986	1470	0.803	9815803.00	±0.07	−2.595	9815805.08
	FG5-220	10.–11.06.2003	1788	1.200	9815801.839	±0.03	−2.573	9815804.93
Helsingør	JILAg-3	23.08.1986	1500	0.803	9815801.87	±0.07	−2.642	9815803.99
	FG5-220	07.–08.06.2003	2088	1.200	9815800.732	±0.03	−2.647	9815803.91
	FG5-220	18.–20.06.2005	2600	1.200	9815800.772	±0.03	−2.620	9815803.92
Copenhagen, Gamlehave	JILAg-3	20.08.1986	1470			±0.07	(eccentric)	9815496.04
Copenhagen, Buddinge	FG5-220	03.–04.06.2003	1387	1.200	9815428.769	±0.03	−2.580	9815431.86
Copenhagen, University	FG5-220	17.–18.10.2005	1850		9815463.007	±0.03	−2.450	9815465.95
Copenhagen, Vestvolden	FG5-220	05.–06.06.2003	1296	1.200	9815472.791	±0.03	−2.830	9815476.19
	FG5-220	17.–19.10.2004	2096	1.200	9815472.778	±0.03	−2.830	9815476.17
	FG5-220	15.–16.10.2005	2698	1.200	9815472.778	±0.03	−2.830	9815476.17
	FG5-220	03.–05.05.2007	2395	1.200	9815472.798	±0.03	−2.830	9815476.19
	FG5-220	09.–11.10.2007	2197	1.200	9815472.798	±0.03	−2.830	9815476.19
Smidstrup GPS	FG5-220	10.–11.06.2005	2650	1.200	9815568.785	±0.04	−3.220	9815572.65
Suldrup GPS	FG5-220	15.–17.06.2005	3200	1.200	9816383.100	±0.04	−3.194	9816386.93
Bornholm, Tejn	FG5-220	20.–22.10.2004	2099	1.200	9815497.182	±0.03	−2.660	9815500.37
Nuuk, Godthåb	JILAg-3	14.–15.05.1988	1500		(see text)	±0.07	(eccentric)	9821906.46
Ilulissat, Jakobshavn	JILAg-3	17.–18.05.1988	1500		(see text)	±0.07	(eccentric)	9824833.79
Thule, air base	JILAg-3	20.–22.05.1988	3000		(see text)	±0.07	(eccentric)	9829215.59
Kollafjørdur old	JILAg-3	29.–30.06.1987	2255	0.806	9820864.69	±0.07	−2.637	9820866.82
new	FG5-220	01.–04.11.2004	3245	1.200	9820863.409	±0.03	−2.630	9820866.56

Tab. 6: Gravity measurements performed by JILAg-3 compared with FG5-220 determinations within the Danish-German cooperation since 1986. The JILAg-3 offset correction of −0.09 µm/s² has been applied.

Station	Gravimeter/ year	Comparison height [m]	δg/δh (mean) [µms⁻²/ m]	g [µm/s²]	Δg [µm/s²]
Helsingør	JILAg-3/1986	1.000	2.64	9815801.35	−0.09
	FG5-220/2003			9815801.26	−0.05
	FG5-220/2005			9815801.30	
Tebstrup	JILAg-3/1986	1.000	2.58	9815802.49	−0.13
	FG5-220/2003			9815802.36	
Copenhagen, Buddinge 102	JILAg-3/1986	0.000	(abs. points Gamlehave, Buddinge centred to base net point 102)	9815430.16	−0.02
	FG5-220/2003			9815430.14	
Kollafjørdur, Faeroes	JILAg-3/1987	0.000	(new centred to old +0.30 µm/s²)	9820866.82	+0.04
	FG5-220/2004			9820866.86	

above floor level, use of a tripod) and the mark. The accuracy of the slant range observations is similar to the vertical gradient determinations. The given accuracies for the absolute observations are empirical estimates, and are in agreement with the explanations in section 5. For JILAg-3, an uncertainty of ±0.07 µm/s² was estimated, for the FG5-220 measurements in buildings ±0.03 µm/s², and for the tent measurements (outdoor) with FG5-220 ±0.04 µm/s². These estimates include the effects from uncertain reduction models. For the given *g*-values at floor level or at the floor mark, the accuracy is only a little bit less. Assuming an error of ±0.02 µm/s² for the determined gravity difference between reference height and the floor point, the uncertainties of $g_{\text{floor/mark}}$ is very similar to $g_{\text{ref.height}}$.

It is remarkable that the observations with FG5-220 in Vestvolden/Copenhagen show almost no differences between the single epochs. The numbers are partly the same. For this four years period, it seems that the gravity value is almost stable, just varying up to ±0.01 µm/s² around a mean value. These gravity results confirm this site as a location within the transition zone separating the uplift from the subsidence area. The observation series will be continued.

Because some of the stations in Tab. 5 were observed with JILAg-3 and re-observed recently with FG5-220, a compilation of the epoch comparisons from Helsingør, Tebstrup, Copenhagen/Buddinge, and Kollafjørdur is presented in Tab. 6. As described in section 5, the offset correction of –0.09 µm/s² has been applied to the JILAg-3 results. For the three stations in Denmark, an average gravity decrease of 0.07 µm/s² is obtained for a time span of about 17 years. Interpreting this as a secular land uplift signal, the gravity rate of –0.004 µm/s² per year implies an uplift rate of 2 mm per year. Statistically, this result is not significant, but at least, it indicates the possibility of a small rise of the Danish land. The good agreement between the two determinations on the Faeroe Islands reveals a stable situation for that location for the period 1987 to 2004. Nevertheless, a small real gravity change during that time span, e. g. 0.1 µm/s², can not be excluded due to the measurement uncertainties.

7 Conclusions

With absolute gravity meters, it becomes feasible to control networks with extensions of up to thousands of kilometres (from local to global range) over large time spans (at least some decades). Gravimetry is a geodetic tool to monitor crustal deformations (height changes) due to isostatic adjustments or other tectonic phenomena. It can also help to constrain parameters related to other subsurface mass movements like hydrological variations. Within the activities to set up GGOS, absolute gravimetry can become a fundamental technique to strengthen geodetic reference frames: supplementary to geometrical methods like SLR, VLBI, and GPS, it is an independent technique to reveal site instabilities and vertical shifts with respect to the Earth's centre of mass.

Within national and international projects, the cooperation of IfE with surveying agencies and research institutions has been proven as a successful procedure to accomplish geo-scientific and state-geodetic objectives. The still ongoing collaboration with Danish scientists is an example for originating applications in high precision absolute gravimetry.

The accuracy of long-term time series of absolute gravimetric measurements depends, among others, on possible instrumental offsets between present and future developments. That should be controlled carefully by performing gravity determinations at common national and international reference stations with the available state-of-the-art gravimeters. This creates time histories for the stations and might reveal biases caused by different instrumental designs and technological developments. From the German point of view, especially the station Bad Homburg is an appropriate site. It is equipped with continuous GPS and superconducting gravimetry. The impact of environmental effects is rather small, and up to now, no secular gravity change could be detected within its history of about 15 years.

With its measurement series since 1986, the station Clausthal has also proven its importance for absolute gravimetry. The offset correction for JILAg-3 could mainly be identified and fixed with –0.09 µm/s² by the measurements of JILAg-3, FG5-101, and FG5-220 at the Clausthal site. Like Bad Homburg, no significant secular trend in gravity could be detected up to now.

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