Timmen, L., Gitlein, O., Klemann, V., Wolf, D. (2012): Observing gravity change in the Fennoscandian uplift area with the Hanover absolute gravimeter. - Pure and Applied Geophysics, 169, 8, 1331-1342

DOI: 10.1007/s00024-011-0397-9

Observing Gravity Change in the Fennoscandian Uplift Area with the Hannover Absolute Gravimeter

Ludger Timmen[1], Olga Gitlein[1], Volker Klemann[2], Detlef Wolf[2]

[1] Institut für Erdmessung (IfE), Leibniz Universität Hannover, Germany. E-mail: timmen@ife.uni-hannover.de, Fax: +49 511 7624006.

[2] Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ), Potsdam, Germany

Abbreviated title: Absolute Gravimetry in the Fennoscandian Uplift Area

The Nordic countries Norway, Sweden, Finland and Denmark are a key study region for the research of glacial isostasy. In addition, it offers a unique opportunity for absolute gravimetry to show its capability as a geodetic tool for geophysical research. Within a multi-national cooperation, annual absolute gravity measurements have been performed in Fennoscandia by IfE since 2003. For the Hannover gravimeter FG5-220, an overall accuracy of ±30 nm/s² is indicated for a single station determination. First results of linear gravity changes are derived for 10 stations in the central and southern part of the uplift area. Comparing with the predicted rates of a glacial rebound modelling, the gravity trends of the absolute measurements differ by 3.8 nm/s² per year (r.m.s. discrepancy) from the uplift model. The mean difference between observed and predicted rates is 0.8 nm/s² per year only. A proportionality factor of −1.63 nm/s² per mm (±0.20) has been obtained which describes the mean ratio between the observational gravity and height rates.

Keywords: Absolute gravimetry, Fennoscandian land uplift, glacial isostatic adjustment (GIA), postglacial rebound (PGR).

1. The Fennoscandian Land Uplift

In the Fennoscandian land uplift area, the Earth's crust has been rising continuously since the last glacial maximum in response to the deloading of the ice. This process is an isostatic adjustment of the Earth's elastic lithosphere and underlying viscous mantle. For a general overview Wolf (1993) gives a historical review about the changing role of the lithosphere in models of glacial isostasy.

The Fennoscandian rebound area is dominated by the Precambrian basement rocks of the Baltic Shield, which is part of the ancient East European Craton and comprises South Norway, Sweden, Finland, the Kola Peninsula and Russian Karelia. The region is surrounded by a flexural bulge, covering northern Germany and northern Poland, the Netherlands and some other surrounding regions. The bulge 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 area is about 2000 km in northeast-southwest direction; see Figure 1 for the approximate shape (after Ågren and Svensson, 2007). Presently, the central area around the northern part of the Gulf of Bothnia is undergoing an uplift at a rate of about 1 cm/year.

(Figure 1)

Geophysical approaches to study the postglacial rebound are associated with the evidence for ancient shore lines and lake level data, the knowledge or assumptions about the geometry of the ice sheets (thickness, position), and some Earth model parameters (lithosphere thickness, mantle viscosity). After Lambeck et al. (1998b), the inverse solution for the sea level data includes both ice and Earth model parameters as unknowns. Despite the recent progress in understanding the underlying models, definite models for the isostatic rebound do not yet exist. Lateral rheological variations have to be taken into account to obtain a more realistic glacially induced uplift model (Kaufmann et al., 2000).

To monitor and investigate the recent land uplift in Fennoscandia, various measurements were collected since 1892: mareograph records, geodetic levellings, and relative gravity measurements since 1966. With these observations, the capability of terrestrial point measurement techniques to determine the land uplift was proven along east-west profiles. They follow approximately the latitudes 65°N (observed 1975−2000), 63°N (1966−2003), 61°N (1976−1983), and 56°N (1977−2003); see Ekman and Mäkinen (1996) or Mäkinen et al. (2005). According to Ekman (1996), the maximum orthometric height change of 1 cm/year in the uplift centre is associated with a maximum gravity change of about −20 nm/s² (−2.0 μGal) per year. Based on these numbers, a geoid change of 0.6 mm/year has been derived for the central area.

Nakiboglu and Lambeck (1991) deduced an eustatic sea level rise of 1.15 ±0.38 mm/year from the tide gauge observations which has been taken into account for the uplift determination by Ekman (1996). More recent papers show different results for the eustatic sea level trend, e.g. Wöppelmann et al. (2007) obtained 1.83 ±0.24 mm/year (GIA corrected) or 1.31 ±0.30 (GPS corrected) for the global trend, and Milne et al (2001) deduced 2.1 ±0.3 mm/year (GPS corrected) from tide gauges in the Fennoscandian region. Lidberg et al. (2007) corrected the tide gauge records from Ekman (1996) by GPS velocities and confirmed the value 1.05 ±0.25 mm/year (GIA corrected) derived by Lambeck et al. (1998a).

Since 1993, permanent GPS stations were established in Fennoscandia to implement a further geodetic method with several advantages compared to the classical techniques (continuous data acquisition, homogeneous point distribution, large extension of the measurement area, low cost, three-dimensional survey). In this respect, the project BIFROST (Baseline Inferences for Rebound Observations, Sea Level, and Tectonics) has been based on the GPS technique and geophysical modelling, and has delivered a maximum height change rate (with respect to a geocentric reference ellipsoid) of about 11 mm/year, cf. Milne et al. (2001); Johansson et al. (2002); Scherneck et al. (2003); Lidberg et al. (2007).

In March 2002 the gravity satellite GRACE (Gravity Recovery And Climate Experiment) was launched to measure the detailed stationary Earth's gravity field and its regional and large scale variations with time. During the mission duration of GRACE (nearly eight years already), a temporal geoid change of approximately 5 mm can be expected in the centre of the Fennoscandian land uplift area, corresponding to a gravity change of about 160 nm/s² (≡ 16 µGal). This is a clear secular gravity change on regional scale, and it is a challenging task to detect this signal from GRACE gravity data most accurately (Wahr and Velicogna, 2003). Early results from Tapley et al. (2004) confirm that this satellite mission is able to resolve geoid variations for a range of spatial scales down to 400 km for particular regions with large signals. They found that the error level in the 2003 solutions was in the order of 2 to 3 mm for spatial features of about 600 km. Considering the large extension of the land uplift area, Fennoscandia is a suitable application region for GRACE. Vice versa, the temporal gravity field change can also be used for the validation of the GRACE results. Because the observation of the rebound signal is interfered by mass variations due to oceanographic, land hydrology and atmospheric processes, these effects have to be accounted for in the GRACE data analysis with appropriate mathematical approaches (e.g. Wiehl et al., 2005). Hence, the combination with other geological and geodetic measurements is inevitable.

2. Absolute Gravimetry

Besides the geometrical approaches, terrestrial absolute gravimetry is a further geodetic technique to study land uplift or subsidence. In general, it is applied as a complementary tool to the geometrical methods. The absolute 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's surface are needed. Shortcomings of relative gravimetry, like calibration problems and deficiencies in the datum level definition, can be overcome. Both absolute and relative gravimetry can measure gravity changes between two points. But only the absolute technique by itself solves the ambiguity problem whether both points are undergoing a decrease or increase with different magnitudes, or one point experiences an increase and the other a decrease. In addition, the accuracy of an absolute gravity net is independent of geographical extension and the covered gravity range. Thus, applications on local, regional and global scales with a consistent measurement quality are feasible. 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 discrimination among subsurface mass movements associated with or without a surface deformation.

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, 1−10 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). Overall, absolute gravimetry can be an important research tool for studying geodynamic processes, especially land uplift effects due to postglacial rebound (PGR). Lambert et al. (1996) gives an overview of 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.

In 2002, the Institut für Erdmessung (IfE) of the Leibniz Universität Hannover has received a new FG5 absolute gravity meter from Micro-g Solutions, Inc. (Erie, Colorado), which is a “state-of-the-art” instrument. The absolute measurements are based on time and distance measurements along the vertical to derive the gravity acceleration at a specific position on the Earth. 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. 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-stabilised laser, serving as the primary length standard, is separated from the instrumental vibrations caused by the free-fall experiments, by routing the laser light through a fibre optic cable to the interferometer base; see Figure 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) are adjusted to a fitting function, giving the gravity acceleration g for the reference height above floor level (FG5: ~1.2 m). For the reduction of local noise and other disturbances, 1500−3000 computer controlled drops are performed per station determination. Generally, the measurements are subdivided into sets of 50 or 100 drops each, and distributed over 1−3 days. The result of a station determination is the average of all drops, reduced for gravity changes due to Earth’s body and ocean tides, polar motion, and atmospheric mass movements. For more details, readers may be referred to Timmen et al. (2008). A good overview about the principles of absolute gravimetry is given, e.g., in Torge (1989) and Torge (1993). Van Camp et al. (2005) concentrate especially on long time series of absolute gravity measurements and the inherent uncertainties.

(Figure 2)

3. Project Realisation

To determine recent crustal deformations by absolute gravimetry, secular gravity changes should be measured with a precision of about ±5 nm/s² per year. This can be achieved by annual measurements over 5 to 10 years. To exploit absolute gravimetry in combination with GPS for a "pointwise" validation of the GRACE results or to support the GRACE data evaluation by terrestrial gravimetry, the temporal variations of gravity disturbances (or gravity anomalies) are needed in accordance with the resolution of the GRACE data. Because of the long-wavelength nature of the GRACE results, the terrestrial point results derived from absolute gravimetry have to be reduced for all local effects changing gravity with time. In this connection, a severe problem is the subsurface water mass movement (change of groundwater table, temporary water storage in clefts and crevasses). Such impacts are partly considered by the station selection. Moreover, by measuring every year the absolute gravity value at a station over a 5-year period, the impact of ground water variations is averaged out to a large extent within the computation of the linear gravity rate. In addition, observations of the ground water table in boreholes and in nearby wells during the absolute gravity surveys are taken and used to assess the disturbing impact. Furthermore, a second favourable averaging effect arises from deriving a spatial mean over a larger area with a few hundred of kilometres extension. For that reason, and to allow the determination of an uplift model (mathematical surface model, like in Fig. 1) with possible regional structures, a rather large number of stations have to be observed every year over the whole Fennoscandian area.

A joint project for the annual gravimetric survey of the land uplift in Fennoscandia has been established in 2003. The Working Group on Geodynamics of the Nordic Geodetic Commission (NKG) serves as a platform to organise the project. Besides the IfE from Hannover (with the absolute meter FG5-220), the following institutions are participating in the project: Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences (UMB, Ås, FG5-226); Federal Agency for Cartography and Geodesy (BKG, Frankfurt/Germany, FG5-301); Finnish Geodetic Institute (FGI, Masala, FG5-221); Norwegian Mapping Authority (Statens Kartverk/SK, Hønefoss); Onsala Space Observatory (Chalmers University of Technology, Onsala/Sweden); Swedish Mapping, Cadastre and Land Registration Authority (Lantmäteriet/LM, Gävle, FG5-233); Technical University of Denmark, National Space Institute (DTU Space, Copenhagen). FGI procured the new FG5-221 at the beginning of 2003, UMB the FG5-226 in spring 2004, and LM the FG5-233 in autumn 2006. Nearly all absolute gravity sites are co-located with permanent GPS stations, and also tide gauges are in the vicinity of coastal stations. The gravity points, GPS stations and tide gauges are connected locally, using terrestrial surveying techniques, like levelling, to control the local vertical variations. The employment of more than one absolute gravimeter allows simultaneous (parallel) observations in stations with two sites close to each other and control measurements on identical sites. This strategy increases the network reliability and accuracy because it helps to identify possible offsets of the instruments. To exclude uncertainties introduced by relative gravimetry (e.g. via the measured vertical gravity gradient) into the absolute gravimetric results, the final absolute values are all related to a common height at 1.200 m above the reference mark at floor level, cf. Timmen (2003). The figures 3 and 4 show typical conditions for the absolute gravimetric field work in Fennoscandia.

(Figure 3, Figure 4)

In Gitlein et al. (2008), a summary of the performed measurements from 2003 to 2008 is given. Altogether, 46 different stations were occupied by the group of 5 participating absolute gravimeters. E.g. in 2008, 33 gravity stations were surveyed at least once, and 11 stations were observed by two or more absolute meters partly simultaneously. Figure 5 shows the stations occupied by the IfE gravimeter FG5-220 in the period from 2003 to 2008. The IfE experts visited 34 different stations in the uplift area with their instrument and performed 84 gravimetric station determinations (2003: 16 stations, 2004: 16, 2005: 15, 2006: 12, 2007: 15, and 2008: 10).

(Figure 5)

4. Measurement Accuracy and its Control

The manufacturer of the FG5-system performed an error budget analysis to determine the single instrumental uncertainty contributions through calculations and measurements of known physical effects. In Niebauer et al. (1995) a total uncertainty of 11 nm/s² is obtained from the FG5 instrumental error budget. To assess the accuracy of the Hannover absolute gravimeter from the user point of view, the measurement experiences with FG5-220 are used to derive an empirical accuracy estimate. The accuracy and stability have been continuously controlled by comparisons with other absolute gravity meters, and with repeated measurements in several stations after time intervals of some months to a few years. A rigorous control of the absolute accuracy with respect to a “true” gravity value at the moment of an absolute gravity measurement is not possible. The real g-value with a superior accuracy is not known, and a “standard” absolute gravimeter which is superior to the state-of-the-art FG5 meters does not exist. Therefore, the empirical accuracy estimate has to be understood as describing the agreement of the instrument’s measuring level and its time stability with regard to the international absolute gravity datum definition. Here, the international datum is defined by the physical standards (time and length) and, in addition, as the average result obtained from all operational absolute gravimeters participating in the international comparison campaigns.

Since the 1980s, International Comparisons of Absolute Gravimeters (ICAG) are performed at the Bureau International des Poids et Mésures (BIPM) in Sèvres, and since 2003, with a 4-years' time interval, also at the European Centre of Geodynamics and Seismology (ECGS) in Walferdange, Luxembourg. For the gravimeter FG5-220 of IfE, Table 1 gives the result from the international comparisons in Walferdange 2003 and 2007 (external comparisons, Francis and van Dam, 2006; Francis et al., 2010), and FG5-220 reference measurements in Bad Homburg (station of BKG, Wilmes and Falk, 2006) from 2003 to 2008. Within 20 nm/s², the Hannover FG5 instrument agrees with the internationally realised 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 Table 1, the six stations determinations agree very well, better than expected from empirical estimates, with a mean scatter of 11 nm/s² only (root-mean-square difference, r.m.s.). An instrumental instability cannot be identified. Similar experiences are 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. (2006) and Bilker-Koivula et al. (2008).

(Table 1)

The results from parallel measurements in the Fennoscandian land uplift area are summarized in Table 2. It compares observations of FG5-220 with other meters participating in the Nordic absolute gravity project since 2003 (Gitlein, 2009). Such measurements are normally performed by simultaneous registrations with two gravimeters at adjacent piers during one day (see Figure 6), and swapping the places on the next day to start the parallel measurements again.

(Table 2)

(Figure 6)

The overall discrepancy (r.m.s.) of the comparisons is 23 nm/s² which proves the high accuracy of the absolute gravimetric survey of Fennoscandia. The mean values show that no significant offset of the IfE instrument exists in comparison with the other four absolute gravimeters. Considering that the discrepancies in Table 2 are caused each time by both of the participating gravimeters, an instrumental precision of better than 20 nm/s² can be assumed for a single gravimeter. The Hannover group estimates a mean absolute accuracy for their FG5-220 to be about 30 nm/s². This empirical estimate incorporates:

- instrumental errors, e.g. due to instrumental vibrations or laser instabilities;
- gravitational "noise" due to incomplete modelling and reduction of gravity variations with time (Earth's body and ocean tides, polar motion, atmospheric mass movements).

5. Gravity Changes in Fennoscandia

Repeated observations with the FG5-220 from IfE were performed at 10 stations in Fennoscandia nearly every year from 2003 to 2008. From these results, linear gravity changes were calculated for each station (Gitlein, 2009). Table 3 summarizes the observational gravity trends and the comparison with the predicted rates of the glacial rebound model provided by Klemann (2004). The trends for three stations are presented exemplarily in Figure 7. All station determinations of the summer/autumn campaign 2003 have not been taken into account because the gravity values seem to be systematically too low by 50 to 90 nm/s² compared to the following years. This effect can only partly be explained by a possible instrumental offset, cf. section 4. A real gravity decline is assumed and should be connected to the very dry season in northern Europe. E.g. in northern Germany, both IfE reference stations, Hannover (IfE laboratory, based on glacial sediments) as well as Clausthal (Institut für Geophysik, TU Clausthal, Harz Mountains, bedrock), show a strong decline of the observed gravity values from February to November 2003. In Clausthal the observed gravity acceleration decreased by about 50 nm/s² and in Hannover by 100 nm/s² (Timmen et al., 2008). The monitoring of the groundwater table in Hannover confirmed the large seasonal gravity variation (correlation 90%). A similar effect in Fennoscandia cannot be excluded.

(Table 3)

(Figure 7)

From Table 3, a decrease in gravity due to land uplift is evident at almost all stations. The largest gravity changes were found around the uplift centre as depicted in Figure 1. In Copenhagen, close to the zero uplift line, the obtained gravity rate is nearly zero. Overall, the regional rebound signal is clearly visible, but still seems to be disturbed by environmental mass variations, e.g. at station Vaasa AB. From the experiences over the last 5 years, the hydrological changes are considered as a main contributor, which is also indicated by the water level observations of the reservoirs and wells close to some of the absolute stations. The largest discrepancy to the predicted results has been found for station Onsala. The measurements do not indicate land uplift. Up to now, this is not understood. Looking into literature, Haas et al. (1997) found larger discrepancies for the coastal station Onsala when determining atmospheric loading parameters from geodetic VLBI data. They suspect not-modelled effects due to wind driven ocean loading as a possible reason. The absolute gravimetric time series has to be extended.

Overall, the observational trends from FG-220 are in a good agreement with the predicted results. The obtained standard deviations seem to be realistic estimates for the accuracy of the deduced secular gravity changes. The disturbances caused by unaccounted hydrological effects are cancelled out in the trends to some extent due to the annual gravity measurements. Thus, absolute gravimetry has shown its capability to observe the Fennoscandian land uplift within the rather short time span of 4−5 years.

6. Ratio between Observational Gravity and Height Rates

Jachens (1978) gives an introduction and an overview about the relationship of observed temporal gravity variations and elevation changes for a fixed point on the Earth's surface. In tectonically active areas like Fennoscandia with a still ongoing postglacial rebound (PGR), the ratio between gravity rate and height rate $\dot{g}/\dot{h}$ depends on two contributing factors: (1) vertical displacement of the observation point along the free-air gravity gradient, and (2) temporal variation of the density distribution of materials in the subsurface. The combination of geometrical and gravimetrical observations may help to separate the effects of both contributors and can serve as an observational constraint for geophysical research on the mechanism of crust formation and on the rheology of Earth's mantle and crust. From a simple theoretical contemplation, a ratio of −1.7 nm/s² per mm is obtained when assuming a free-air gradient (1) of −3.1 nm/s² per mm for the vertical surface displacement and an ongoing mass increase with density 3300 kg/m^3 in the upper mantle (Bouguer plate approximation) which yields an effect (2) of 1.4 nm/s² per mm for the variation in the density field.

As an approximation, Wahr et al. (1995) provide a ratio (or proportionality factor) of −1.5 nm/s² per mm for a postglacial rebound signal. The authors assumed a free-air gradient (1) of −3 nm/s² per mm for the surface shift and derived from theoretical considerations a relation (2) of 0.65 mm per nm/s² (≡ 1.5 nm/s² per mm) for a viscoelastic response of the solid Earth to a surface load (Maxwell solid). In Mäkinen et al. (2005), the results from relative gravimetry surveys of the Nordic land uplift lines (east-west profiles) have been combined with various estimates of the uplift (levelling, continuous GPS, GIA models), which gives ratios between −1.6 and −2.0 nm/s² per mm.

Table 4 contains gravimetric trends measured by IfE together with BIFROST GPS height rates as published by Lidberg et al. (2007). Both kind of temporal variations have been merged to derive the proportionality factor between gravity and height rate for the single stations. Only the eight sites with a clear uplift signal have been considered. Assuming a geographically constant ratio for Fennoscandia an average value of −1.63 nm/s² per mm (±0.20) is obtained as a weighted mean. This result is in a good agreement with the estimates given in Mäkinen et al. (2005), and with the approximation provided by Wahr et al. (1995).

(Table 4)

7. Summary and Conclusions

With respect to the FG5-220 absolute gravity surveys since 2003, the achievements in Fennoscandian land uplift area may be described as follows:

- the whole uplift network includes more than 40 absolute gravity stations mostly co-located with permanent GPS points. From 2003 to 2008, the IfE absolute gravimetry team performed 84 gravity determinations at 34 different stations;
- the results from the IfE absolute gravimeter FG5-220 have been compared with results from international comparisons, and from other in the Fennoscandia uplift project participating instruments, as well as with results from repetition measurements at the German reference station in

Bad Homburg. An overall accuracy of approximately ±30 nm/s² is indicated for a single station determination with FG5-220. This empirical estimate includes not only the instrumental errors but also residual errors from uncertain reduction models (tides, polar motion, and atmospheric mass movements). Subsurface water variations may cause gravity changes of a few times 10 nm/s² or even more than 100 nm/s² at some special stations over a year which is not considered in the given accuracy estimate;

- a check of the instruments by parallel and reference measurements is essential. Especially for projects with highest accuracy demands over large areas, e.g. the Nordic Absolute Gravity Project, more than one absolute gravimeter should be employed to increase the reliability of the results and to detect instrumental offsets. This procedure improves the absolute accuracy of the whole network;
- based on comparisons with predicted rates from geophysical modelling, the FG5-220 absolute gravity measurements 2003/2004−2008 delivered reasonable and reliable gravity trends and accuracy estimates. The predicted rates and the observational trends agree within 3.8 nm/s² per year (r.m.s. difference);
- a mean proportionality factor $\dot{g} / \dot{h}$ = 1.63 nm/s² per mm (±0.20) has been deduced from gravimetric and GPS observations. The result agrees well with the assumption of a Bouguer plate approximation with a mass increase (~3300 kg/m^3) in the upper mantle;
- absolute gravimetry has shown its capability to observe the secular gravity variations in the Fennoscandian PGR area within a time span of 4 to 5 years.

Acknowledgements

We appreciate the cooperation and the great efforts of the Nordic Geodetic Commission (NKG) and its Working Group on Geodynamics. We gratefully acknowledge the essential support of a number of colleagues from the Nordic countries and from Germany. The following institutions are participating in the joint project: Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences (Ås); Federal Agency for Cartography and Geodesy (Frankfurt); Finnish Geodetic Institute (Masala); Norwegian Mapping Authority (Hønefoss); Onsala Space Observatory, Chalmers University of Technology; Swedish Mapping, Cadastre and Land Registration Authority (Gävle); Technical University of Denmark, National Space Institute (Copenhagen). The research has been supported generously by the German Research Foundation (DFG) through the research grants MU 1141/3-1, 3-2, and 3-3 ("Geotechnologien").

References

Ågren, J., and Svensson, R., Postglacial land uplift model and system definition for the new Swedish height system RH 2000, Reports in geodesy and geographical information systems (Lantmateriet, Gävle 2007).

Bilker-Koivula, M., Mäkinen, J., Timmen, L., Gitlein, O., Klopping, F., and Falk, R., Repeated absolute gravity measurements in Finland, In Terrestrial Gravimetry: Static and Mobile Measurements (TG-SMM2007), Proceed. Int. Symp. (ed. Peshekhonov. V.G.) (Elektropribor, St. Petersburg 2008) pp. 147−151.

Boedecker, G., and Flury, J. (1995), International Absolute Gravity Basestation Network IAGBN, Catalogue of stations and observations, Report of the IAG International Gravity Commission, IGC-Working Group 2, "World Gravity Standards", available at the Bureau Gravimetrique International, Toulouse.

Boedecker, G., and Fritzer, Th. (1986), International Absolute Gravity Basestation Network, Veröff. Bayer. Komm. für die Internat. Erdmessung der Bayer. Akad. d. Wissensch., Astron.-Geod. Arb. 47, München.

Carter, W.E., Aubrey, D.G., Baker, T., Boucher, C., LeProvost, C., Pugh, D., Peltier, W.R., Zumberge, M., Rapp, R.H., Schutz, R.E., Emery, K.O., and Enfield, D.B. (1989), Geodetic fixing of tide gauge bench marks, Woods Hole Oceanographic Institution Report WHOI-89-31/CRC-89-5, Woods Hole, Mass., U.S.A.

Carter, W. E., Peter, G., Sasagawa, G. S., Klopping, F. J., Berstis, K. A., Hilt, R. L., Nelson, P., Christy, G. L., Niebauer, T. M., Hollander, W., Seeger, H., Richter, B., Wilmes, H., and Lothammer, A. (1994), New gravity meter improves measurements, EOS, Transactions, American Geoph. Union, Vol. 75, No. 08, 90−92.

Ekman, M. (1996), A consistent map of the postglacial uplift of Fennoscandia, Terra Nova 8, 158−165.

Ekman, M., and Mäkinen, J. (1996), Recent postglacial rebound, gravity change and mantle flow in Fennoscandia, Geophys. J. Int. 126, 229−234.

Francis, O., and van Dam, T., Analysis of results of the International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003, In International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003, Cahiers du Centre Européen de Géodynamique et de Séismologie 26 (eds. Francis. O., van Dam. T.) (Centre Européen de Géodynamique et de Séismologie, Luxembourg 2006) pp. 1−23.

Francis, O., van Dam, T., Germak, A., Amalvict, M., Bayer, R., Bilker-Koivula, M., Calvo, M., D'Agostino, G.-C., Dell'Acqua, T., Engfeldt, A., Faccia, R., Falk, R., Gitlein, O., Fernandez, Gjevestad, J., Hinderer, J., Jones, Kostelecky, J., Le Moigne, N., Luck, B., Mäkinen, J., McLaughlin, D., Olszak, T., Olsson, P., Pachuta, A., Palinkas, V., Pettersen, B., Pujol, R., Prutkin, I., Quagliotti, D., Reudink, R., Rothleitner, C., Ruess, D., Shen, C., Smith, V., Svitlov, S., Timmen, L., Ulrich, C., Van Camp, M., Walo, J., Wang, L., Wilmes, H., and Xing, L., Results of the European Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2007, In Gravity, Geoid and Earth Observation, IAG Symp. 135 (ed. Mertikas. St.) (Springer, Heidelberg 2010) pp. 31−36.

Gitlein, O. (2009), Absolutgravimetrische Bestimmung der Fennoskandischen Landhebung mit dem FG5-220, Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik der Leibniz Universität Hannover 281.

Gitlein, O., Timmen, L., Müller, J., Denker, H., Mäkinen, J., Bilker-Koivula, M., Pettersen, B.R., Lysaker, D.I., Svendsen, J.G.G., Wilmes, H., Falk, R., Reinhold, A., Hoppe, W., Scherneck, H.-G., Engen, B., Omang, O.C.D., Engfeldt, A., Lilje, M., Strykowski, G., and Forsberg, R., Observing Absolute Gravity Acceleration in the Fennoscandian Land Uplift Area, In Terrestrial Gravimetry: Static and Mobile Measurements (TG-SMM2007), Proceed. Int. Symp. (ed. Peshekhonov. V.G.) (Elektropribor, St. Petersburg 2008) pp. 175−180.

Hagedoorn, J. M., Wolf, D., and Martinec, Z. (2007), An estimate of global mean sea-level inferred from tide-gauge measurements using glacial-isostatic models consistent with the relative sea-level record, Pure Appl. Geophys. 164, 791−818.

Haas, R., Scherneck, H-G., and Schuh, H., Atmospheric loading corrections in geodetic VLBI and determination of atmospheric loading coefficients, In Proceedings of the 12th working meeting on European VLBI for Geodesy and Astronomy, Norway (ed. Pettersen. B.R.) (Hønefoss 1997) pp. 111−121.

Jachens, R.C. , The gravity method and interpretive techniques for detecting vertical crustal movements, In Applications of Geodesy and Geodynamics, Int. Symp., Reports of the Department of Geodetic Science 280 (ed. Mueller. I.I.) (Ohio State University 1978) pp. 153−155.

Johansson, J.M., Davis, J.L., Scherneck, H.-G., Milne, G.A., Vermeer, M., Mitrovica, J.X., Bennett, R.A., Jonsson, B., Elgered, G., Elósegui, P., Koivula, H., Poutanen, M., Rönnäng, B.O.,and Shapiro, I.I. (2002), Continuous GPS measurements of postglacial adjustment in Fennoscandia, 1. geodetic results, J. Geophys. Res. 107, B8, ETG 3, 1−27.

Kaufmann, G., Wu, P., and Li, G. (2000), Glacial isostatic adjustment in Fennoscandia for a laterally heterogeneous Earth, Geophys. J. Int. 143, 262−273.

Klemann, V. (2004), Linear gravity variations for the IfE absolute gravity stations in Fennoscandia predicted by geophysical GIA modelling, The computations were based on solution algorithms developed by Martinec (2000) and Hagedoorn et al. (2007) and use a global ice model with SCAN-II (Lambeck et al., 1998a) for Fennoscandia, Personal communication, Deutsches GeoForschungsZentrum (GFZ), Potsdam.

Lambeck, K., Smither, C., and Ekman, M. (1998a), Tests of glacial rebound models for Fennoscandinavia based on instrumented sea- and lake-level records, Geophys. J. Int. 135, 375–387.

Lambeck, K., Smither, C., and Johnston, P. (1998b), Sea level-change, glacial rebound and mantle viscosity for northern Europe, Geophys. J. Int. 134, 102−144.

Lambert, A., James, T. S., Liard, J. O., and Coutier, N., The role and capability of absolute gravity measurements in determining the temporal variations in the earth’s gravity field, In Global Gravity Field and Its Temporal Variations, IAG Symp. 116 (eds. Rapp. R.H., Cazenave. A.A., Nerem. R.S.) (Springer, Heidelberg 1996) pp. 20−29.

Lambert, A., Courtier, N., Sasagawa, G. S., Klopping, F., Winester, D., James, T. S., and Liard, J. O. (2001), New Constraints on Laurentide Postglacial Rebound from Absolute Gravity Measurements, Geophys. Res. Letters 28, 2109−211.

Lidberg, M., Johansson, J. M., Scherneck, H.-G., und Davis, J. L. (2007), An improved and extended GPS-derived 3D velocity field of the glacial isostatic adjustment (GIA) in Fennoscandia, J. of Geodesy 81, 213–230.

Mäkinen, J., Engfeld, A., Harsson, B. G., Routsalainen, H., Strykowski, G., Oja, T., und Wolf, D., The Fennoscandian Land Uplift Lines 1966-2003, In Gravity, Geoid and Space Missions GGSM2004, IAG Symp. 129 (eds. Jekeli. C., Bastos. L., Fernandes. J.) (Spinger, Heidelberg 2005) pp. 328–332.

Mäkinen, J., Amalvict, M., Shibuya, K., and Fukuda, Y. (2007), Absolute gravimetry in Antarctica: status and prospects, J. of Geodyn. 43, 339−357.

Martinec, Z. (2000), Spectral-finite element approach to three-dimensional viscoelastic relaxation in a spherical earth, Geophys. J. Int. 142, 117–141.

Micro-g Solutions Inc. (1999), Operator’s manual, FG5 absolute gravimeter, Erie, Colorado.

Milne, G.A., Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Johannson, J.M., Vermeer, M., and Koivuly, H. (2001), Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia, Science 291, 2381−2385.

Nakiboglu, S.M., and Lambeck, K., Secular sea-level change, In Glacial isostasy, sea level and mantle rheology (eds. Sabadini. R., Lambeck. K., Boschi. E.) (Kluwer Acad. Publ., Dordrecht, Bosten 1991) pp 237−258.

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

Scherneck, H.-G., Johansson, J., Koivula, H., van Dam, T., and Davis, J. (2003), Vertical crustal motion observed in the BIFROST project, J. of Geodyn. 35, 425−441.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., and Watkins, M.M. (2004), GRACE measurements of mass variability in the Earth system, Science 305, 503−505.

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

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., and Forsberg, R., Observing Fennoscandian Gravity Change by Absolute Gravimetry, In Geodetic Deformation Monitoring: From Geophysical to Engineering Roles, IAG Symp. 131 (eds. Sansò. F., Gil. A.J.) (Springer, Heidelberg 2006) pp.193−199.

Timmen, L., Gitlein, O., Müller, J., Strykowski, G., and Forsberg, R. (2008), Absolute gravimetry with the Hannover meters JILAg-3 and FG5-220, and their deployment in a Danish-German cooperation, zfv - Zeitschrift für Geodäsie, Geoinformation und Landmanagement 3/2008, Jg. 133, 149−163.

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

Torge, W. (1993), Gravimetry and tectonics, Publications of the Finnish Geodetic Institute (Geodesy and Geophysics) 115, 131−172.

Van Camp, M., Williams, S.D.P., Francis, O. (2005), Uncertainty of absolute gravity measurements, J. Geophys. Res. 110, B05406.

Wahr, J. M., DaZhong, H., und Trupin, A. (1995), Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic earth, Geophysical Research Letters 22/8, 977–980.

Wahr, J., and Velicogna, I. (2003), What might GRACE contribute to studies of post glacial rebound, Space Science Reviews 108, 319−330.

Wiehl, M., Dietrich, R., and Lehmann, A., How Baltic sea water mass variations mask the postglacial rebound signal in CHAMP and GRACE gravity field solutions, In Earth observation with CHAMP (eds. Reigber. Ch., Lühr. H., Schwintzer. P., Wickert. J.) (Springer, Heidelberg 2005) pp 181−186.

Williams, S.D.P., Baker. T.F., and Jeffries, G. (2001), Absolute gravity measurements at UK tide gauges, Geophys. Res. Letters 28, 2317−2329.

Wilmes, H., and Falk, R. , Bad Homburg – a regional comparison site for absolute gravity meters, In International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003, Cahiers du Centre Européen de Géodynamique et de Séismologie 26 (eds. Francis. O., van Dam. T.) (Centre Européen de Géodynamique et de Séismologie, Luxembourg 2006) pp.29−30.

Wilmes, H., Falk, R., Klopping, F., Roland, E., Lothhammer, A., Reinhold, A., Richter, B., Plag, H.-P., and Mäkinen, J. (2004), Long-term gravity variations in Scandinavia from repeated absolute gravity measurements in the period 1991 to 2003, proceedings (CD publ.) of the IAG symposium Gravity, Geoid and Space Missions, Porto.

Wolf, D. (1993), The changing role of the lithosphere in models of glacial isostasy: a historical review, Global and Planetary Change 8, 95−106.

Wöppelmann, G., Martin Migues, B., Bouin, M.-N., and Altamimi, Z. (2007), Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide, Global and Planetary Change 57, 396−406.

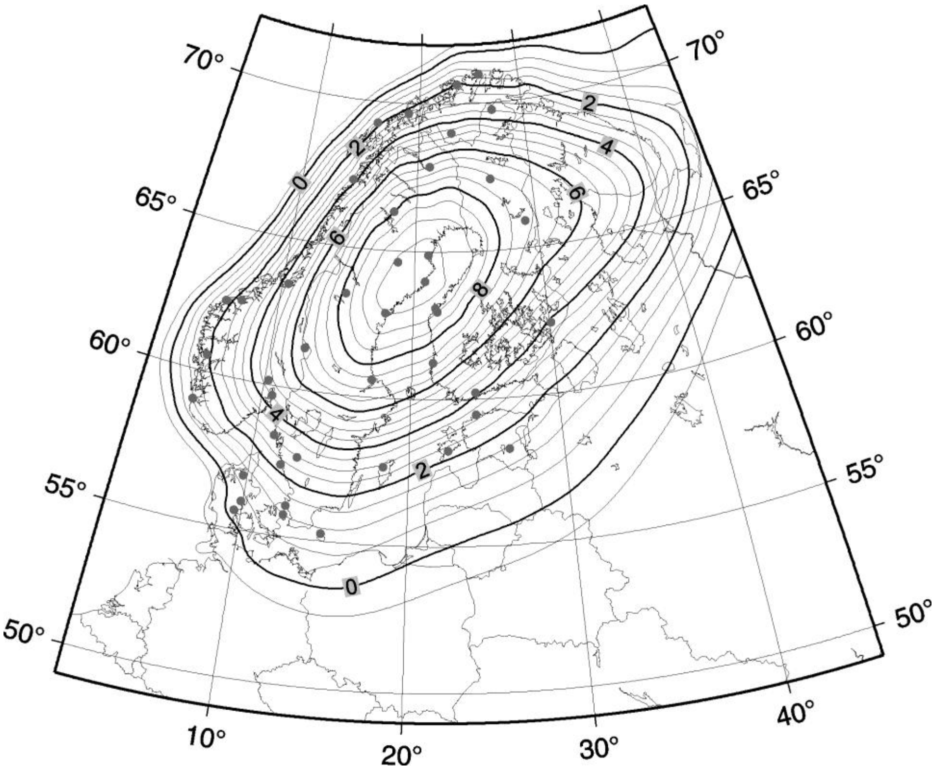

Figure 1

Map of the postglacial uplift of Fennoscandia in mm/year after Ågren and Svensson (2007) derived from model NKG2005LU, courtesy of Ågren. The dots indicate the positions of gravity stations of the Nordic absolute gravity project.

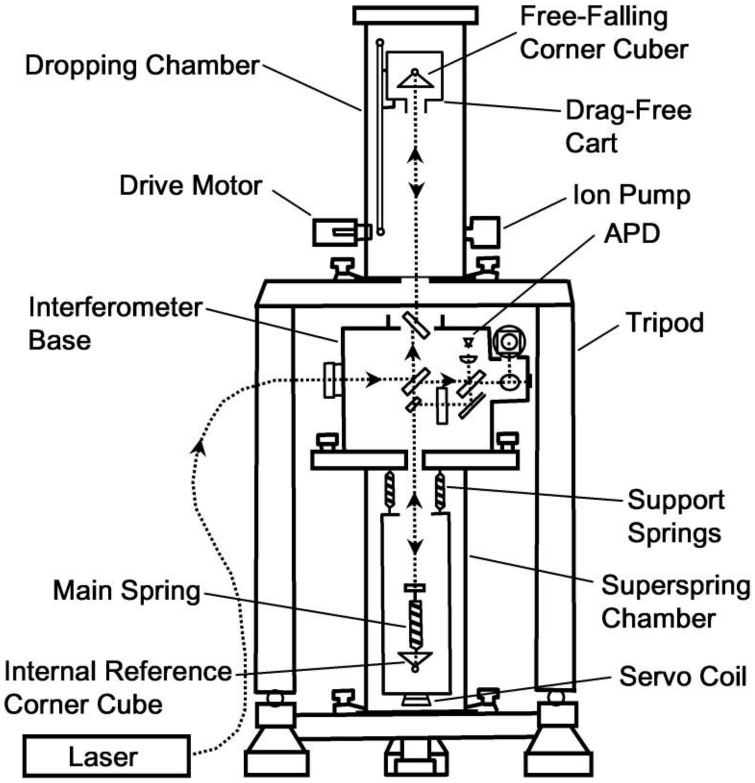

Figure 2

Schematic diagram of the FG5 absolute gravimeter, after Micro-g Solutions Inc. (1999), courtesy of Micro-g Lacoste, Inc.

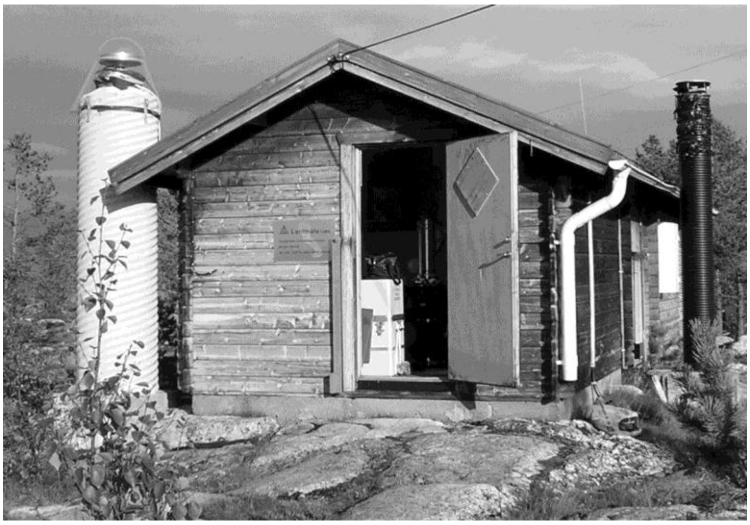

Figure 3

Station Skellefteå (Sweden) with an absolute gravity pier inside and a temperature stabilised pillar for continuous GPS outside.

Figure 4

Absolute gravimeter FG5-220 of IfE installed at station

Östersund.

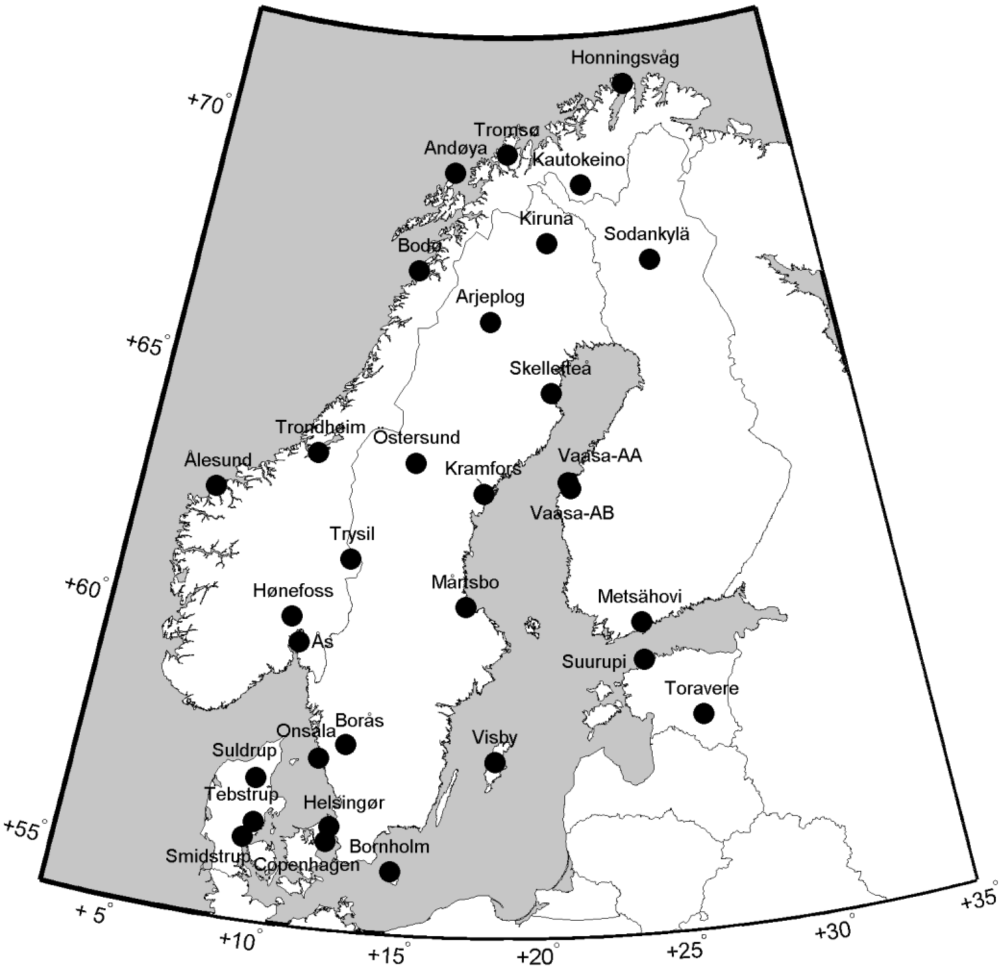

Figure 5

Absolute gravity stations in the Fennoscandian land uplift area occupied by the IfE gravimeter FG5-220 in the period from 2003 to 2008.

Table 1

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

FG5-220 External Comparison	**Remarks**	**Epoch**	**Δg [nm/s²] (FG5-220 − Mean g)**
ICAG2003, ECGS (Francis and van Dam, 2006, Tab. 16)	13 abs. meters, 14 points, 52 determinations	Nov. 2003	−19 std.dev. (single meter) 18
ICAG2007, ECGS (Francis et al., 2010, Tab. 3)	19 abs. meters, 16 points, 73 determinations	Nov. 2007	+24 std.dev. (single meter) 20
FG5-220 Internal Comparison	**Remarks**	**Epoch**	**Δg (FG5-220) [nm/s²] (Single − Mean g)**
Bad Homburg (gravimetry lab. of BKG, Wilmes and Falk, 2006)	Reference station for FG5-220 since 2003, point BA	Feb. 2003	+9
		Nov. 2003	−8
		Apr. 2005	+12
		Apr. 2006	+7
		Nov. 2007	+2
		Sep. 2008	−21

Figure 6

Parallel measurements with FG5-220 (IfE) and FG5-221 (FGI) at station Metsähovi in Finland.

Table 2

Gravity discrepancies in nm/s^2 from parallel measurements of FG5-220

with other FG5 meters participating in the Nordic absolute gravity project:

FG5-101/301 (BKG), FG5-221 (FGI), FG5-226 (UMB).

Bad Homburg		**Metsähovi**		**Onsala**		**Vaasa**	
Feb 2003	12	Aug 03	−10	Oct 04	−5	Aug 03, AA	−29
Nov 2003	37	May 04	19	Oct 04	9	Aug 03, AB	−30
Apr 2005	−26	May 05	18	Oct 05	34	May 04, AB	2
Apr 2006	13	Aug 05	42	Oct 06	29		
Nov 2007	7	Aug 06	−14				
Sep 2008	−19	Jul 07	22				
mean [nm/s^2]	4		13		17		−19
r.m.s.	21		23		23		24

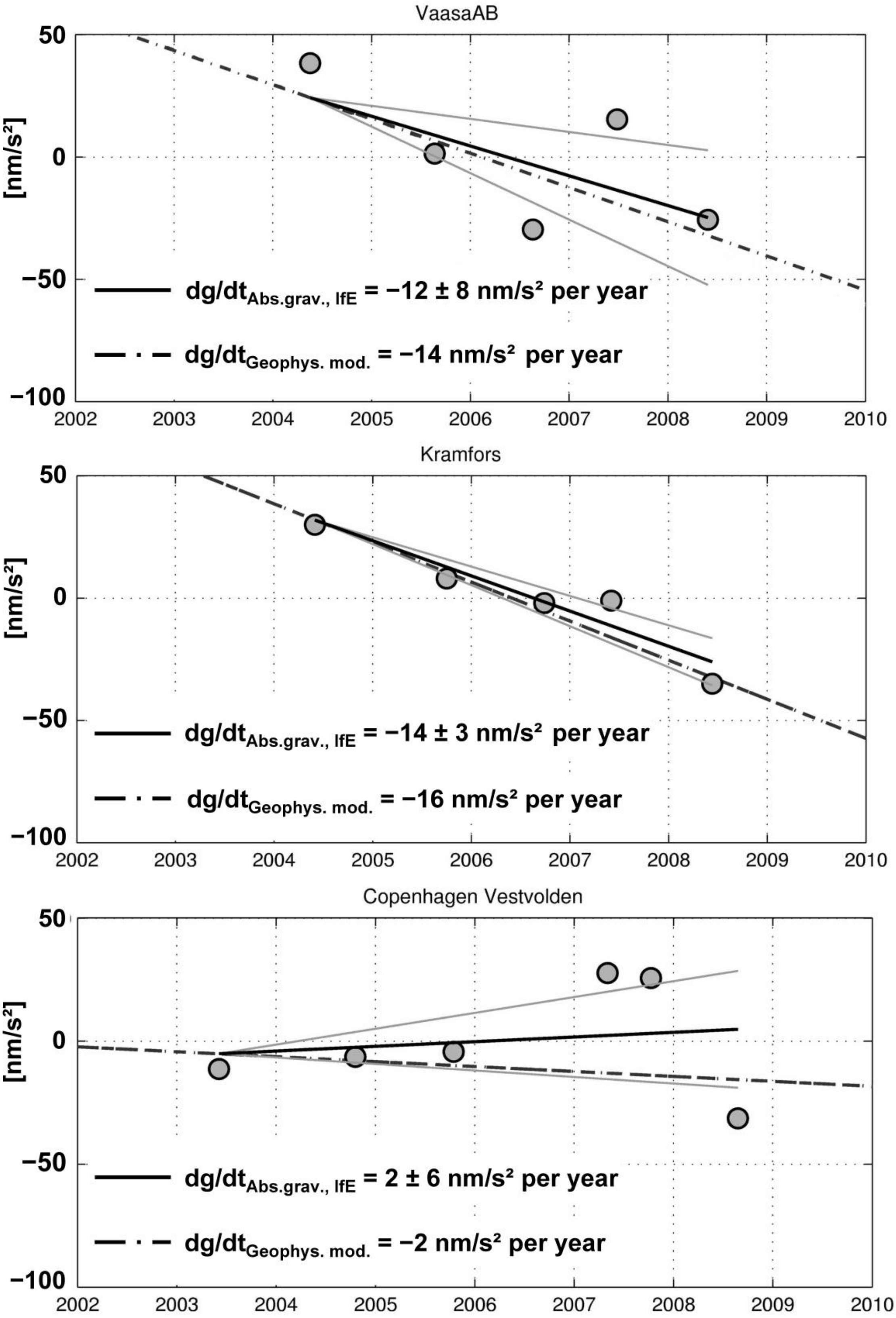

Figure 7

Linear gravity changes for three stations in Fennoscandia derived from absolute gravity measurements of IfE and compared with the trends from the model predictions provided by Klemann (2004). The grey lines beside the IfE trends indicate the standard deviation of the corresponding trend line.

Table 3

Comparison of gravity trends in Fennoscandia derived from IfE absolute gravity measurements AG (n: number of gravity determinations) and from the geophysical model predictions provided by Klemann (2004). The standard deviations (1-σ estimates) of the observational trends have been calculated from the single gravity determinations (equally weighted). Both results agree well with respect to the AG accuracy estimate.

Station	AG (FG5-220) [nm/s²/year]		n	Geophys. model [nm/s²/year]	Difference [nm/s²/year]
Arjeplog	−8.7	±2.4	4	−11.6	2.9
Copenhagen	1.9	±5.7	6	−1.9	3.8
Kiruna	−11.3	±11.0	4	−9.7	−1.6
Kramfors	−14.4	±2.7	5	−15.8	1.4
Mårtsbo	−15.6	±3.8	5	−11.7	−3.9
Metsähovi	−8.8	±5.2	7	−7.4	−1.4
Onsala	5.0	±5.7	6	−4.2	9.2
Östersund	−14.8	±10.8	5	−12.5	−2.3
Skellefteå	−18.8	±3.8	5	−16.6	−2.2
Vaasa AB	−12.2	±7.8	5	−14.4	2.2
mean diff.					0.8
r.m.s. diff.					3.8

Table 4

Proportionality factor $\dot{g}/\dot{h}$ from gravity and height rate. The BIFROST GPS results are from Lidberg et al. (2007). For the weighted mean and its accuracy, the standard deviations in the last column are used as weights.

Station	dg/dt (abs.grav.) [nm/s²/year]	dh/dt (BIFROST) [mm/year]	$\dot{g}/\dot{h}$ [nm/s²/mm]
Arjeplog	−8.7 ±2.4	7.7 ±0.2	−1.14 ±0.31
Kiruna	−11.3 ±11.0	6.4 ±0.3	−1.78 ±1.72
Kramfors	−14.4 ±2.7	10.2 ±0.5	−1.41 ±0.27
Mårtsbo	−15.6 ±3.9	6.7 ±0.2	−2.32 ±0.59
Metsähovi	−8.8 ±5.2	4.3 ±0.2	−2.07 ±1.21
Östersund	−14.8 ±10.8	8.3 ±0.2	−1.79 ±1.30
Skellefteå	−18.8 ±3.8	9.6 ±0.2	−1.95 ±0.40
Vaasa AB	−12.2 ±7.8	8.6 ±0.2	−1.41 ±0.91
mean (unweighted)			−1.73 ±0.14
mean (weighted)			−1.63 ±0.20