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An Accuracy Assessment of Absolute Gravimetric Observations in Fennoscandia

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Abstract. *We compare a suite of absolute gravimeters used to monitor the temporal changes of gravity at a number of sites in Fennoscandia. Direct comparisons are made from simultaneous observations at selected sites within and outside of the postglacial uplift region. We also compare results at sites visited by two instruments with some separation in time. We conclude from four years of data that gravity differences are obtained within an rms error of ± 3 μGal. The data reveal no systematic biases between the instruments, but occasional shifts from one year to another are noted. We consider that annual instrument comparisons are required to ensure data integrity in a regional observing program that extends over more than a decade.*

1 Introduction

Time series analyses of positions derived from permanent GNSS observing stations reveal both vertical and horizontal movements of the Fennoscandian crust, caused by the postglacial rebound phenomenon (Milne et al. 2001, Scherneck et al. 2003). The geographical distribution of vertical velocities is similar to previous results derived from multi-epoch precise leveling and tide gauge records (Ekman and Mäkinen 1996). A maximum uplift of ~10 mm/year is observed in the northwest part of the Gulf of Bothnia. This geometric height change suggests a gravity change approaching –2 μgal/year. The velocity field decays towards no vertical uplift in all directions away from the maximum uplift area. The oval shaped uplift area has its major axis oriented in azimuth direction ~35° (i.e. approximately northeast). The linear extension is 1,750 km along the major axis and 1,000 km along the minor axis.

A multi-national cooperation of terrestrial absolute gravimetry was initiated in 2003 to survey the geographical distribution of gravity change in Fennoscandia (Müller et al. 2003, Timmen et al. 2006, and Bilker-Koivula et al. 2008). The observational effort is coordinated under the auspices of the Nordic Geodetic Commission, thus maintaining cooperation between university groups and the national mapping agencies. The entire absolute gravity network presently consists of more than 30 observing sites located adjacent to or in the vicinity of permanent GPS stations. In coastal areas there are also tide gauges near many of them. Annual campaigns employing three absolute gravimeters each year have visited more than 20 sites annually. The sites have been prepared and established by the national mapping agencies in Denmark, Finland, Norway, and Sweden. New sites have been added during the course of this ongoing project. For the purpose of instrument comparison, some sites have been visited by more than one instrument, either simultaneously or successively during the same observing season. This paper assesses the accuracy obtained during the first four years of the project (2003–2006) by discussing various approaches to intercomparing results from the instruments.

2 Observing program

In 2003 observations were made with FG5-220, FG5-221, and FG5-301. In 2004, 2005, and 2006 observations were made with FG5-220, FG5-221, and FG5-226. In general, one observation set consisted of 50 or 100 drops of the test mass. Several sets were collected at one hour intervals. A complete observation lasted 1–2 days. Marks on the concrete floors allowed the instruments to be centered and oriented in the same way. Post processing was made using final values of Earth axis polar motion from IERS bulletin B and empirically determined gravity gradients for each site.

Various approaches may allow assessment of the consistency of observational results obtained with these instruments. The most direct method is to compare simultaneous observations with two instruments at the same site. This approach minimizes differences in observing conditions since results for a particular monument are separated by only one day for the two instruments. These events are identified in Table 1. Two monuments at the same site allow two instruments to be mounted next to each other. Observations are typically made for about one day. The instruments then change monuments and a new observing series is made.

An indirect comparison may be made from non-simultaneous observations at the same site with two instruments. The occupation may be separated in time by weeks or months. This situation occurs when the observing plan brings more than one instrument to a site during the same observing season. These events are identified in Table 2. Local geophysical changes (e.g. in the ground water level) may cause real variability in the gravity value, which will cause a larger observed gravity difference than that caused by the instruments alone.

For sites with no uplift or with the temporal gravity change determined empirically, data from adjacent years may in principle be compared as well. We have collected a test sample (Table 3) to investigate the usefulness of such long time separation for comparison purposes.

3 Results and discussion

3.1 Simultaneous observations

Direct comparison of observational results for pairs of instruments that measured simultaneously at the same site, may be made from the data in Table 1. Each site produced gravity differences for two monuments, identified by a two-letter designation. Bad Homburg, Germany has been included as a reference site outside of the Fennoscandian uplift area. It has a well-observed history of absolute gravimetry extending more than a decade (Wilmes et al. 2004). In Fennoscandia, simultaneous comparisons have been made at Metsähovi and Vaasa in Finland, and at Onsala, Sweden in 2003–2006.

Gravity differences between individual instruments are plotted in Fig. 1. No systematic time dependency is apparent in the data. The average gravity difference is 0.4 ± 2.7 μGal between FG5-220 and FG5-221, 1.9 ± 2.5 μGal between FG5-220 and FG5-226, and 0.9 ± 2.6 μGal between FG5-220 and FG5-301. Within these errors, no significant biases may be identified between the instruments.

In Table 1 we have also included comparisons at Bad Homburg to FG5-101. In Fig. 1 these data are not distinguished from comparisons with FG5-301 at the same site. This is motivated by the average gravity difference between FG5-301 and FG5-101 of –0.5 ± 1.8 μGal, derived from 11 comparisons 2004–2006 (Wziontek et al., 2007).

We note that three of the instruments in Table 1 also took part in the Walferdange instrument comparison in November 2003 (Francis and van Dam 2006), following the field campaigns in Fennoscandia earlier that year. In particular, FG5-220 and FG5-221 had simultaneous occupations at Metsähovi and Vaasa, 2½ months before Walferdange. The gravity difference averaged –2.4 ± 1.9 μGal in Fennoscandia, and –2.7 μGal at Walferdange. A week after Walferdange, FG5-220 and FG5-301 made simultaneous observations at Bad Homburg, Germany. The gravity differences were +3.6 and +3.8 μGal, compared to –0.1 μGal at Walferdange.

Furthermore, FG5-220 and FG5-226 made individual comparisons to FG5-101 at Bad Homburg in 2006. These two occupations were separated by 4 months (April and August 2006). We derive gravity differences between 220 and 226 of 1.6 and 3.0 μGal from these data. In October 2006 these two instruments observed simultaneously at Onsala and obtained gravity differences of 0.6 and 5.1 μGal. Within errors, we conclude that comparisons at Fennoscandian sites produce consistent results with comparisons made outside of the Fennoscandian uplift region.

Similar behaviour is noted in a smaller dataset for 1993–1995, when absolute gravimetry was made by FG5-101, FG5-102, and FG5-111 (Wilmes et al. 2004).

Table 1. *Gravity differences (μGal) for two instruments simultaneously at the same site.*

Site	Date	220–221	220–226	220–301	Remarks
Bad Homburg AA	10.02.2003			+2.5	
Bad Homburg AA	11.11.2003			+3.8	
Bad Homburg AA	08–09.04.2005			–3.8*	* = 220-101
Bad Homburg AA	20–21.04.2006			+1.0*	* = 220-101
Bad Homburg AA	23.08.2006				–0.6 : 226-101
Bad Homburg BA	11.02.2003			–0.4	
Bad Homburg BA	10.11.2003			+3.6	
Bad Homburg BA	06–07.04.2005			–1.4*	* = 220-101
Bad Homburg BA	19–20.04.2006			+1.6*	* = 220-101
Bad Homburg BA	24.08.2006				–1.4 : 226-101
Metsähovi AB	19.08.2003	+0.5			
Metsähovi AB	12–15.05.2004	–0.3			
Metsähovi AB	05–07.05.2005	+2.9			
Metsähovi AB	16–18.08.2005	+4.1			
Metsähovi AB	14–17.08.2006	–0.5			
Metsähovi AC	18.08.2003	–3.1			
Metsähovi AC	12–14.05.2004	+4.1			
Metsähovi AC	08–09.05.2005	+0.8			
Metsähovi AC	18–19.08.2005	+4.1			
Metsähovi AC	14–17.08.2006	–2.2			
Onsala AS	25.10.2004		+0.5		
Onsala AS	28.10.2004	+0.3			
Onsala AS	11–13.10.2005		+4.5		
Onsala AS	07–10.10.2006		+0.6		
Onsala AN	26.10.2004		–1.4		
Onsala AN	27.10.2004	+1.5			
Onsala AN	11–13.10.2005		+2.2		
Onsala AN	07–10.10.2006		+5.1		
Vaasa AA	22.08.2003	–3.4			
Vaasa AB	24.08.2003	-3.5			
Vaasa AB	17–23.05.2004	+0.2			
Average ± std.dev.		0.4±2.7	1.9±2.5	0.9±2.6	

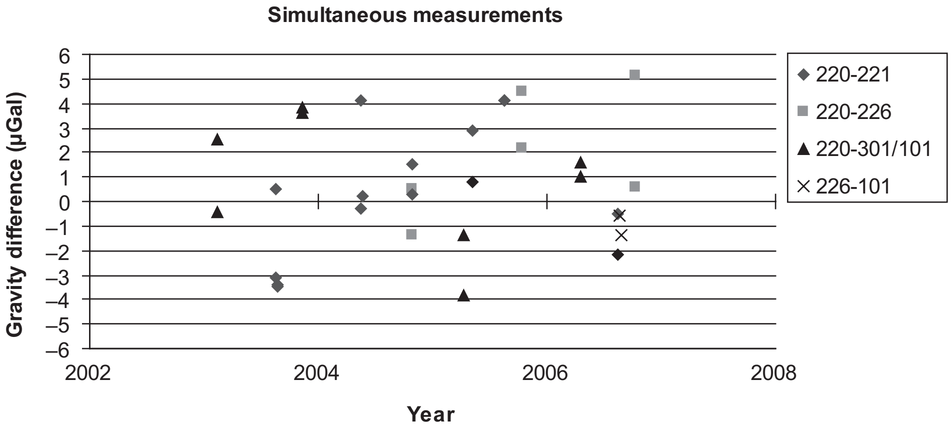

Figure 1. *Gravity differences between five instruments, obtained by simultaneous observations for pairs of two. The data are found in Table 1.*

Four observations at Onsala and Trysil in 1993 yielded a gravity difference of –2.5 ± 1.5 μGal between FG5-102 and FG5-101. Occupations at Trysil and Mårtsbo in 1995 yielded gravity differences of +3.5 and +2.4 μGal between FG5-111 and FG5-101. An instrument comparison in USA prior to the Fennoscandian campaign in 1995 (Klopping et al. 1997) yielded –0.7 μGal between F5-102 and FG5-101, and –0.9 μGal between FG5-111 and FG5-101. FG5-101 and FG5-102 were also compared in Paris in 1994 (Marson et al. 1995, Sasagawa et al. 1995).

3.2 Non-simultaneous observations

Indirect comparisons between pairs of instruments that have visited the same site within a time span of weeks or months (i.e. within the same observing season) may be made from Table 2. Column 2 lists the dates observed by FG5-220, while the dates pertaining to the other instruments are listed in column 6. The average gravity difference is 1.6 ± 2.8 μGal between FG5-220 and FG5-221. The annual averages (from only two observations!) are similar in 2004 and 2005, but a shift exceeding the error estimate is noted in 2006. The gravity difference is 1.8 ± 3.0 μGal between FG5-220 and FG5-226, and –0.1 ± 4.1 μGal between FG5-220 and FG5-301. The annual averages for the latter was –2.2 ± 2.6 in 2003 and +5.1 ± 0.5 in 2004.

We have also investigated the option of comparing results from the same site when observations by two instruments were separated in time by a full year or more. Ideally this should only be made for sites with very small (insignificant) vertical movement or for sites with known temporal gravity change so that the annual change may be corrected for. Sites along the west coast of Norway (Table 3) may be expected to experience small changes in gravity since they are located far from the maximum uplift region. The local geophysical conditions, however, may be very different one year apart. The average gravity difference from Table 3 is 2.1 ± 4.9 μGal (n=10). A dataset of 7 observations from 1993–1995 (Wilmes et al. 2004) yields 0.9 ± 4.2 μGal for the gravity difference as measured by FG5-102 (1993) and FG5-111 (1995).

Table 2. *Gravity differences (μGal) for sites observed non-simultaneously.*

Site	Dates (220)	220–221	220–226	220–301	Remarks
Onsala AS	13.06.2003			+1.1	301: 15.07.2003
Skellefteå	28.–30.08.2003			–3.0	301: 09.07.2003
Trondheim AA	14.–16.09.2003			–4.2	301: 29.06.2003
Trysil AC	23.–24.09.2003			–0.2	301: 24.06.2003
Hønefoss AC	27.–28.09.2003			–4.8	301: 22.06.2003
Ås	19.–20.03.2004		+2.2		226: 14.–24.04.2004
Honningsvåg	27.–29.08.2006		–0.4		226: 26.–28.06.2006
Kautokeino	01.–03.09.2006		–0.5		226: 01.–02.07.2006
Kiruna	05.–07.09.2006		+5.9		226: 03.–04.07.2006
Metsähovi AB	03.07.2004	+2.7		+5.4	221: 13.–14.05.2004
Metsähovi AC	04.07.2004	+3.0		+4.7	301: 12.07.2004
Vaasa AB	21–23.08.2005	+0.5			221: 27.–29.10.2005
Vaasa AB	19–21.08.2006	–0.7			221: 28.–30.07.2006
Sodankylä	25–27.08.2005	+5.8			221: 16.–18.07.2005
Sodankylä	23–25.08.2006	–2.0			221: 04.–06.08.2006
Average± s.dev		1.6±2.8	1.8±3.0	–0.1±4.1	

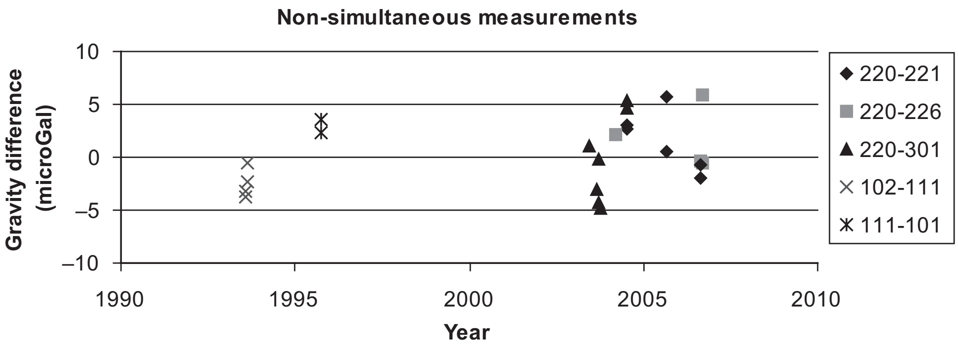

Figure 2. *Gravity differences between pairs of instruments occupying the same site, but separated in time by weeks or months. Data between 2003 and 2006 are from Table 2. Data from 1993 and 1995 are from Wilmes et al. (2004), see text for details.*

When non-simultaneous observations are taken within the same observing season (Table 2), average observed differences are of the same size as those of simultaneous observations (Table 1) and the scatter of 3.4 μGal is only slightly larger than the 2.5 μGal of simultaneous observations. When observations are separated by more than one year, the average differences as well as the scatter values become larger. Although vertical movements due to land uplift may be neglected at the stations in Table 3, local geophysical conditions differ from year to year, causing part of the observed gravity differences given in Table 3.

Table 3. *Gravity differences (μGal) for sites observed one year apart or more.*

Site	Dates (220/301)	220–226	220–301	301–226	Dates
Stavanger AA	301: 18.06.2003			–5.3	03.–05.11.2004
Ålesund	18.–21.09.2003	–0.7			20.–21.07.2004
Ålesund	18.–21.09.2003	–0.7			21.–24.05.2006
Vågstranda	301: 26.06.2003			+2.7	20.–21.05.2006
Trondheim AA	14.–16.09.2003	–8.1		–4.0	23.–26.06.2004
Bodø	28.–30.06.2004	+5.9			19.–22.07.2005
Andøya	23.–25.06.2004	+4.7			23.–25.07.2005
Tromsø AA	19.–20.06.2004		+6.5		03.07.2003
Tromsø AA	19.–20.06.2004	+6.3			04.–05.08.2005

4 Conclusions

In summary the present material yields average gravity differences between instruments as listed in Table 4. The last column contains the statistics for the entire data set.

Table 4. *Summary of gravity differences between individual instruments and type of observation. The number of observations are listed in parentheses.*

Type of obs.	220–221	220–226	220–301	226-301/101	All
Simultaneous	0.4±2.7 (15)	1.9±2.5 (6)	0.9±2.6 (8)	–1.0±0.6 (2)	0.7±2.5 (31)
Non-simult.	1.6±2.8 (6)	1.8±3.0 (4)	–0.1±4.1 (7)		0.9±3.4 (17)
Simult. & non-simult.	0.7±2.7 (21)	1.9±2.6 (10)	0.4±3.3 (15)	–1.0±0.6 (2)	0.8±2.8 (48)
≥1 year apart		1.2±5.6 (6)	6.5 (1)	2.2±4.3 (3)	2.1±4.9 (10)

Field comparisons at Fennoscandian observing sites reveal that the suite of instruments employed over several years produces an rms scatter of about ± 3 μGal. This refers to the gravity difference between two instruments and implies that the error estimate of each observation is correspondingly smaller. There appears to be no systematic biases between instruments exceeding that level, although larger differences are occasionally noted from one year to another (few observations). A similar result appears to hold for the suite of three instruments employed in Fennoscandia in 1993–1995.

Non-simultaneous occupations of the same sites produce useful data for monitoring instrument behaviour. The scatter of non-simultaneous observations taken within the same observing season is only slightly larger than the scatter of simultaneous observations. The scatter grows more when non-simultaneous observations are taken more than one year apart at stations with no vertical movements due to land uplift, as changes in the local geophysical conditions start playing a major role. As long as local geophysical conditions are not monitored or modelled, observations taken over such long intervals should not be used for instrument comparisons.

For a long term observing program, we conclude that annual comparison between instruments is an important and required activity to ensure the homogeneity of the data material for the entire (decadal) observing program.

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