Accuracy Assessment of Absolute Gravity Control in Fennoscandia

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Introduction

Time series analyses of GPS positions derived from permanent observing stations reveal both vertical and horizontal movements of the Fennoscandian crust caused by 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 levelling and tide gauge records (Ekman, 1996). A maximum uplift of 10 mm per year is observed in the northern part of the Bay of Bothnia. An almost symmetrical reduction to 0 mm per year takes place over a distance roughly corresponding to the present western coastline of Norway. The oval shaped uplift area has its major axis oriented in azimuth direction $\sim 35^\circ$ (i.e. approximately northeast). The linear extension is 1750 km along the major axis and 1000 km along the minor axis.

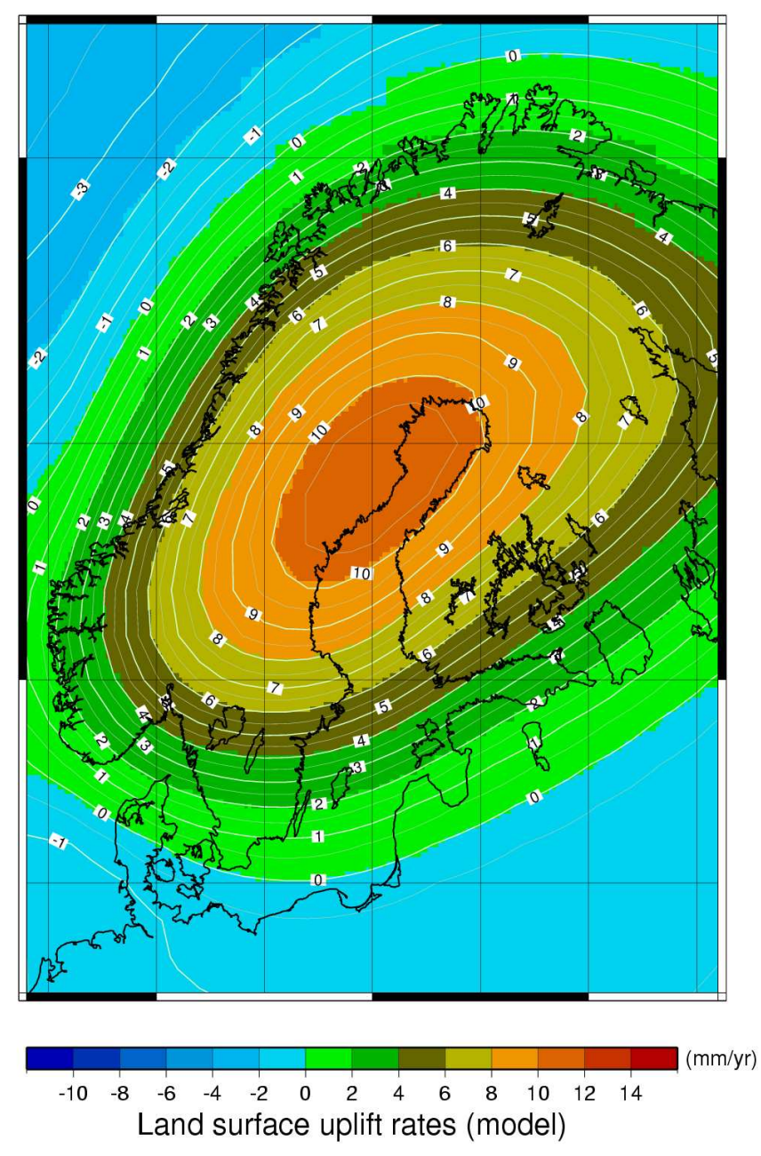

Figure 1: Model rates from BIFROST (Milne *et al.*, 2001)

The geometric height change in the centre area suggests a gravity change of -2 μgal/year for a footprint of diameter a few hundred km, implying a geoid rise of 0.6 mm/year. The time derivative of the geoid height N is

$$\dot{N} = \frac{R}{4\pi\gamma}\iint_{\sigma} H(\psi)(\dot{g} + \frac{2\gamma}{r}\dot{h})\mathrm{d}\sigma, \qquad (1)$$

where $\dot{N}, \dot{h}, \dot{g}$ are temporal change of geoid height, ellipsoidal height, and gravity, respectively (Hotine, 1969). GPS and absolute gravimetry allows detection of this phenomenon, but may require time series of several years to determine accurate values of the derivatives. Starting in 2002, data for a time series of geoid change is being collected by the dedicated satellite gravimetry mission GRACE. *In-situ* observations may thus be used for a future validation of the space mission results.

A multi-national cooperation in terrestrial absolute gravimetry has been initiated to address this problem (Müller *et al.*, 2003a,b). It is coordinated under the auspices of the Nordic Geodetic Commission, thus allowing the cooperation and support of the national mapping agencies. The entire absolute gravity network consists of more than 30 potential 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. The absolute gravity sites are connected by levelling to GPS stations using terrestrial surveying techniques, and to tide gauges by relative GPS between the gravity station and tide gauge. The local gravity gradient is determined with relative gravimeters to correct the measured results to a conventional reference height. Annual campaigns during the next several years will revisit up to 30 sites prepared by the national mapping agencies in Denmark, Finland, Norway, and Sweden. For the purpose of instrument comparison, some sites will be visited by more than one instrument. A few sites will also be monitored regularly throughout the year.

Observing program

In 2003 observations were made with FG5 # 220, 221, and 301. In 2004 observations were made with FG5 # 220, 221, and 226. 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 exist to validate the consistency of observational results obtained with the individual instruments. The most direct method is to obtain simultaneous observations with two instruments at the same site. This approach should minimize differences in observing conditions with results for a particular monument being separated by only one day for the two instruments. These events are identified in Table 1. The two instruments were mounted on each monument and observations were carried out for about one day. The instruments then swapped monuments and the observations were repeated.

An indirect comparison may be made from observations at the same site with two instruments, but separated in time by weeks, months or even a year. This situation occurs because the observing plan brings more than one instrument to some sites during each observing season. These events are identified in Table 2. For sites with no uplift and sufficient monitoring of local geophysical conditions, data from adjacent years may in principle be compared for consistency assessment as well (Table 3).

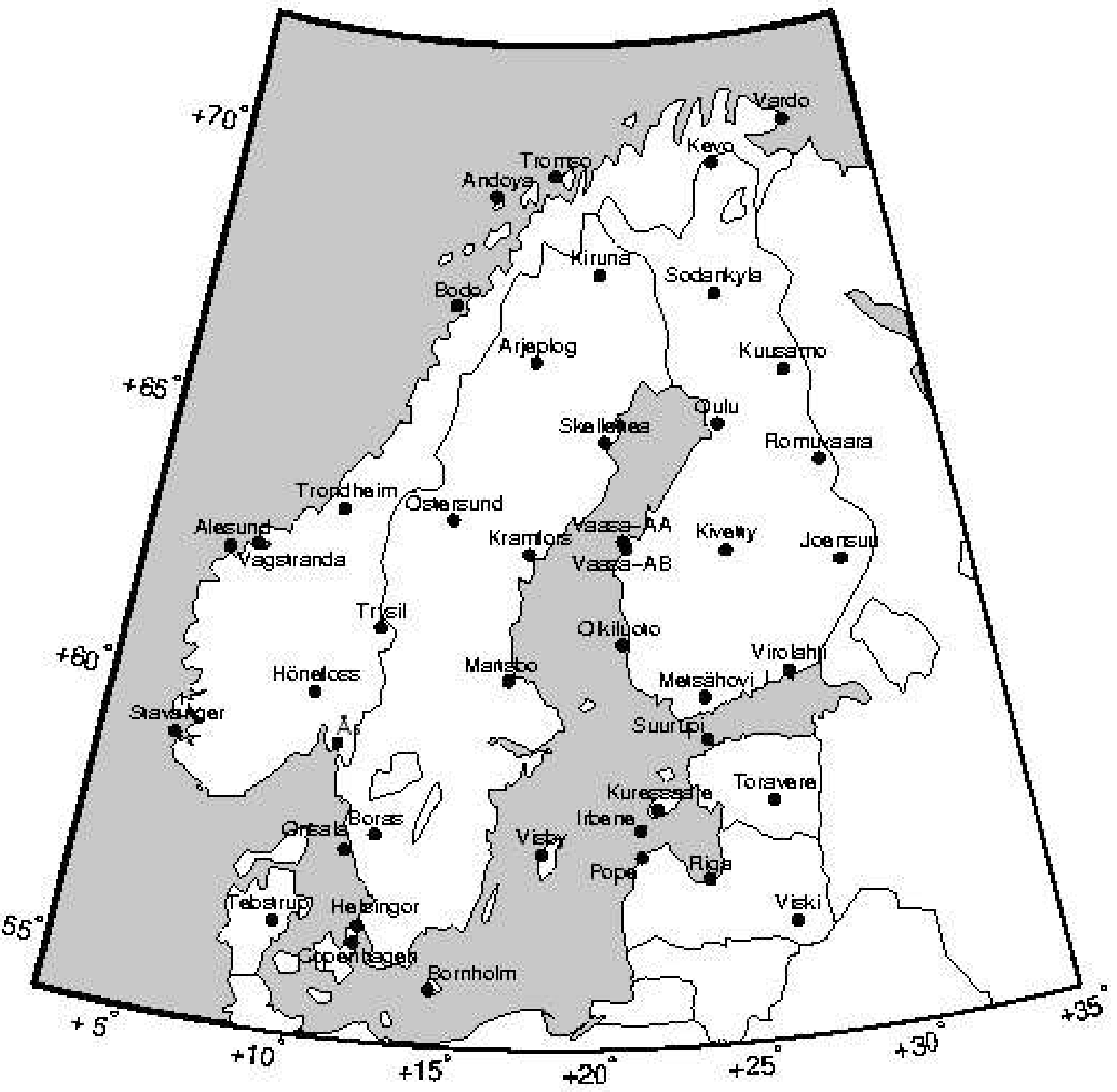

Figure 2: Absolute gravity sites in Fennoscandia

Results and discussion

Direct comparison of observational results for pairs of instruments that measured simultaneously at the same site, may be made from Table 1. Each site thus produces gravity differences for two monuments, identified by a two-letter designation. The sites Bad Homburg in Germany and Metsähovi in Finland have been visited more than once for comparison purposes.

No time dependency is apparent in the data of Table 1. All four instruments appear to perform similarly with respect to accuracy in 2003 and 2004.

Indirect comparisons between pairs of instruments that have visited the same site within a time span of weeks or months may be made from Table 2. Column 2 lists the dates observed by #220, while the dates pertaining to the other instruments are listed in column 6. Again, no time dependency is evident.

A third approach is to compare results from the same sites even when they were observed by two instruments separated in time by a full year or more (Table 3). A real instrument comparison can only be made for sites with very small vertical movement. Stavanger, Ålesund, and Tromsø are sites where vertical velocities may be estimated from time series produced by permanent GPS stations and from tide gauge records. Kristiansen (2003) obtained vertical velocities (relative to the mass center of the Earth) of 0.4, 0.9, and 0.8 mm per year from seven years of GPS data for Stavanger, Ålesund, and Tromsø, respectively. Archival tide gauge data from the Norwegian Hydrographic Office yields a sea level rise in Stavanger (1919-2004) of 0.2 mm per year, and in Ålesund (1961-2004) of 0.7 mm per year. In Tromsø (1952-2004) the sea level drops by 0.8 mm per year. The expected annual gravity change for these three sites is thus significantly less than 1 μGal.

Other sites, although with expected larger uplift rates, are Hønefoss, Trysil, and Trondheim, all of which were observed by two instruments in 2003 (see Table 2) and by a third instrument (#226) in 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 BA	11.02.2003			-0.4	
Bad Homburg BA	10.11.2003			+3.6	
Metsähovi AB	19.08.2003	+0.7			
Metsähovi AB	12-15.05.2004	-0.3			
Metsähovi AC	18.08.2003	-3.7			
Metsähovi AC	12-14.05.2004	+4.4			
Onsala AS	25-28.10.2004	+0.3	-2.3		
Onsala AN	25-28.10.2004	+1.5	-1.4		
Vaasa AA	22.08.2003	-3.2			
Vaasa AB	24.08.2003	-3.2			
Walferdange	3-7.11.2003	-2.7		-0.1	Francis *et al.* (2004)

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

Site	Date (FG5-220)	220-221	220-226	220-301	Date (FG5-XXX)
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
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	17.-19.05.2004	+1.4			221:21.-23.05.2004

Table 3: Gravity differences (μGal) for sites observed one year apart

Site	Dates 220/301	220-226	220-301	301-226	Dates
Stavanger AA	18.06.2003			-5.5	3.-5.11.2004
Ålesund	18-21.09.2003	-0.7			20.-21.07.2004
Tromsø AA	19-20.06.2004		+6.2		03.07.2003
Hønefoss AC	See Table 2	-2.6		+2.2	26.-31.05.2004
Trysil AC	See Table 2	-0.8		-0.6	01.-04.06.2004
Trondheim AA	See Table 2	-8.1		-3.9	23.-26.06.2004

Conclusions

Based on the currently available material the average differences between instruments are derived in Table 4.

The non-simultaneous comparisons apparently increase with increasing time difference between observations. For a time interval of many months to a year it is possible that seasonal effects at some stations contribute to the observed difference. A contribution from station motion may also enter for those stations that are not strictly zero uplift.

We identify the need to monitor the long term stability of each instrument by a continued repetition of simultaneous observations at quiet sites (e.g. Bad Homburg, Metsähovi, Onsala, Trysil). It will also be helpful to collect time series at some of these sites at a frequency of several observations per year. Hydrological data should be collected in order to develop future corrections for variable levels of groundwater. At coastal stations, especially in Norway, wind driven sea level variations affect the gravity results differently at different locations. Studies should be conducted to identify surges and correct for them. In conclusion it appears that a single instrument at a single site obtains an overall accuracy of ± 3 μGal or better, in accordance with the project goal to provide in situ gravity changes in Fennoscandia with sufficient accuracy to support the GRACE data evaluation.

Table 4: The average gravity differences (μGal) between instruments

Type of obs.	220-221	220-226	220-301	301-226
Simultaneous	-0.7 ± 2.7 (n=9)	-1.9 ± 0.6 (n=2)	1.9 ± 2.0 (n=5)	
Non-simultaneous	2.4 ± 0.9 (n=3)	2.2 (n=1)	-0.1 ± 4.1 (n=7)	
Annual		-3.1 ± 3.5 (n=4)	6.2 (n=1)	-2.0 ± 3.4 (n=4)

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