Lantmäterirapport 2016:1

Reports in Geodesy and Geographical Information Systems

RG 2000

– status March 2016

Andreas Engfeldt

Gävle 2016

LANTMÄTERIET

LANTMÄTERIET

2016-03-29

Author Andreas Engfeldt

Typography and layout Rainer Hertel

Total number of pages 64

Lantmäterirapport 2016:1 ISSN 0280-5731

RG 2000

– status March 2016

Andreas Engfeldt

Gävle 2016

LANTMÄTERIET

Preface

I want to thank my Swedish colleagues Jonas Ågren, Per-Anders Olsson and Martin Lidberg for support and good advice, my Finnish colleagues Jaakko Mäkinen and Hannu Ruotsalainen for good support, my Polish colleagues Marcin Sekowski and Przemyslaw Dykowski for good cooperation during the five A-10 campaigns and my Danish colleagues Gabriel Strykowski and Jens Emil Nielsen for good cooperation during the measurements along the 56th degree gravity line. Finally I want to thank all old and deceased Swedish gravity experts for all their work and effort with the old networks.

Gävle, March 29, 2016

Andreas Engfeldt

Abstract

This report is written in order to get a good overview of which existing gravity observations that are usable for the new Swedish gravity system and gravity network, RG 2000, which will be defined in 2016. This report describes the situation today concerning existing and earlier gravity systems in Sweden, with focus on the latest, RG 82. In addition, the status of modern absolute gravity measurements in Sweden is described in detail. This means the FG5 measurements performed partially by foreign colleagues, partially by us with our FG5-233, as well as the A-10 measurements mainly performed in co-operation with IGiK (Poland). For those who are interested in reading about the plans for the further work with the new gravity network, the LMV report ”Preparations and plans for the new national gravity system RG 2000” by Andreas Engfeldt is recommended.

Sammanfattning

Denna rapport är skriven för att få en god översikt på vilka av de tyngdkraftsobservationer vi har som kan användas till det nya svenska tyngdkraftssystemet och tyngdkraftsnätet RG 2000, vilket kommer att definieras under 2016. Rapporten beskriver hur dagens situation ser ut beträffande befintliga och tidigare tyngdkraftssystem i Sverige, med fokus på det senaste, RG 82. Statusen för moderna absolutgravimetermätningar i Sverige beskrivs också detaljerat. Det innebär alltså de FG5-mätningar som utförts dels av utländska kollegor och dels av oss själva med vår FG5-233, samt de A-10-mätningar som främst utförts av IGiK (Polen) i samarbete med oss. Den som vill ta del av planer för hur det nya tyngdkraftssystemet ska realiseras, hänvisas till LMV-rapporten "Preparations and plans for the new national gravity system RG 2000" av Andreas Engfeldt.

RG 2000 – status March 2016 March 2016

RG 2000 – status March 2016

1 Introduction

The present gravity system in Sweden, RG 82, is based on four absolute gravity measurements from 1976 by an old Italian absolute gravimeter. The Zero Order Network of RG 82 consists of 25 sites spread all over Sweden, measured with two LaCoste & Romberg relative gravimeters in 1981-82. Today, almost 40 years after these absolute gravity measurements, the absolute gravimeters are at a completely different standard and uncertainty. Since the autumn 2006, Lantmäteriet owns an FG5 absolute gravimeter and measures regularly at 13 different places all over Sweden with a very low uncertainty.

Even if the level for the epoch 1982 set by the Italian instrument in 1976 looks better than what can be expected for such an instrument, the recent land uplift models and absolute gravity measurements would make a new gravity system more accurate and useful. There is also a need to harmonize the gravity system with the most recent height system (RH 2000) concerning epoch (Engfeldt 2014). This means that it is now rather urgent to establish a new gravity system (Ågren & Engberg 2010).

Some work has already been done for the new system. There is a seven year time span with Swedish FG5 observations at 12 sites. In addition, many of these sites were measured several times between 2004 and 2007 with another FG5 instrument, owned and operated by IfE (Institut für Erdmessung, Leibnitz University, Hannover, Germany). Furthermore, between 2011 and 2015, 95 old and new gravity sites evenly distributed over Sweden were measured with the portable outdoor absolute gravimeter A-10, owned and operated by IGiK (Institute of Geodesy and Cartography, Warsaw, Poland). In 2012, in connection with a NKG (Nordic Commission of Geodesy) project, 2 sites were measured by the Danish A-10, owned and operated by DTU Space (Copenhagen, Denmark).

In this respect all the background information about the present gravity system RG 82, older gravity systems and absolute gravity measurements in Sweden will be presented. These are all things that have already been made. The plans for the upcoming gravity system RG 2000 will be described in another report, ”Preparations and plans for the new national gravity system RG 2000”.

2 Current situation, relative gravity and old gravity systems

2.1 Old gravity observations and networks

The first Swedish gravity measurement was performed in 1741 at the Uppsala Observatory, when Anders Celsius determined the gravity difference between London and Uppsala using a pendulum-clock, which had been constructed in London especially for him. This pendulum-clock was in 1988 (Haller & Ekman 1988) still in operation in Uppsala and according to Martin Ekman (personal communication) it probably still is. Almost a century later, 1833, the gravity in the old observatory in Stockholm was determined by Jöns Svanberg.

Between 1889 and 1896 Per G Rosén observed the gravity differences between five stations (Haparanda, Härnösand, Uppsala, Stockholm and Lund) along a line with a north-south direction through Sweden. This was performed with the Sterneck pendulum and resulted in the system RG 1896, which was tied to a reference value in Vienna using a connection via Potsdam to Lund.

A complete first order network, also known as the First Fundamental Gravity Network of Sweden, was developed by Bror Wideland between 1941 and 1948. The used instrument was the recently invented Nørgaard gravity meter. The final network, RG41, contained 34 stations (Pettersson 1967) and was connected to Potsdam by the Baltic Geodetic Commission (Haller & Ekman).

2.2 RG 62

In 1959, Rikets Allmänna Kartverk (RAK) acquired a Worden Master gravity meter. That instrument was acquired in order to connect as many stations as possible in the old network (the 34 stations from 1943-48) to the international gravity loop Copenhagen-Oslo-Stockholm-Copenhagen and the international gravity line Stockholm-Kiruna-Bodø. The measurements were done by Lennart Pettersson and were carried out according to the plans in 1960-61. At the same time it was considered advisable to further extend them into a complete first order gravity network. The network was completed in 1966 and was called RG 62 or the Second Fundamental Gravity Network of Sweden. Totally it contained 185 stations in Sweden and was connected to several stations in Norway and a few in Finland. It was also connected to Potsdam via the European Calibration System 1962 (ECS 62). The same value for Potsdam was used as for RG 41. Later this network was also "temporary" connected to IGSN 71 (International Gravity Standardization Net

1971). It was ten years later verified that the poor gravity value of Potsdam led to that the absolute level of the whole RG 62 network was biased by more than 14,5 mGal and also that it was measured, mainly due to the instrument, so badly that there were several shifts where the values were more or less incorrect.

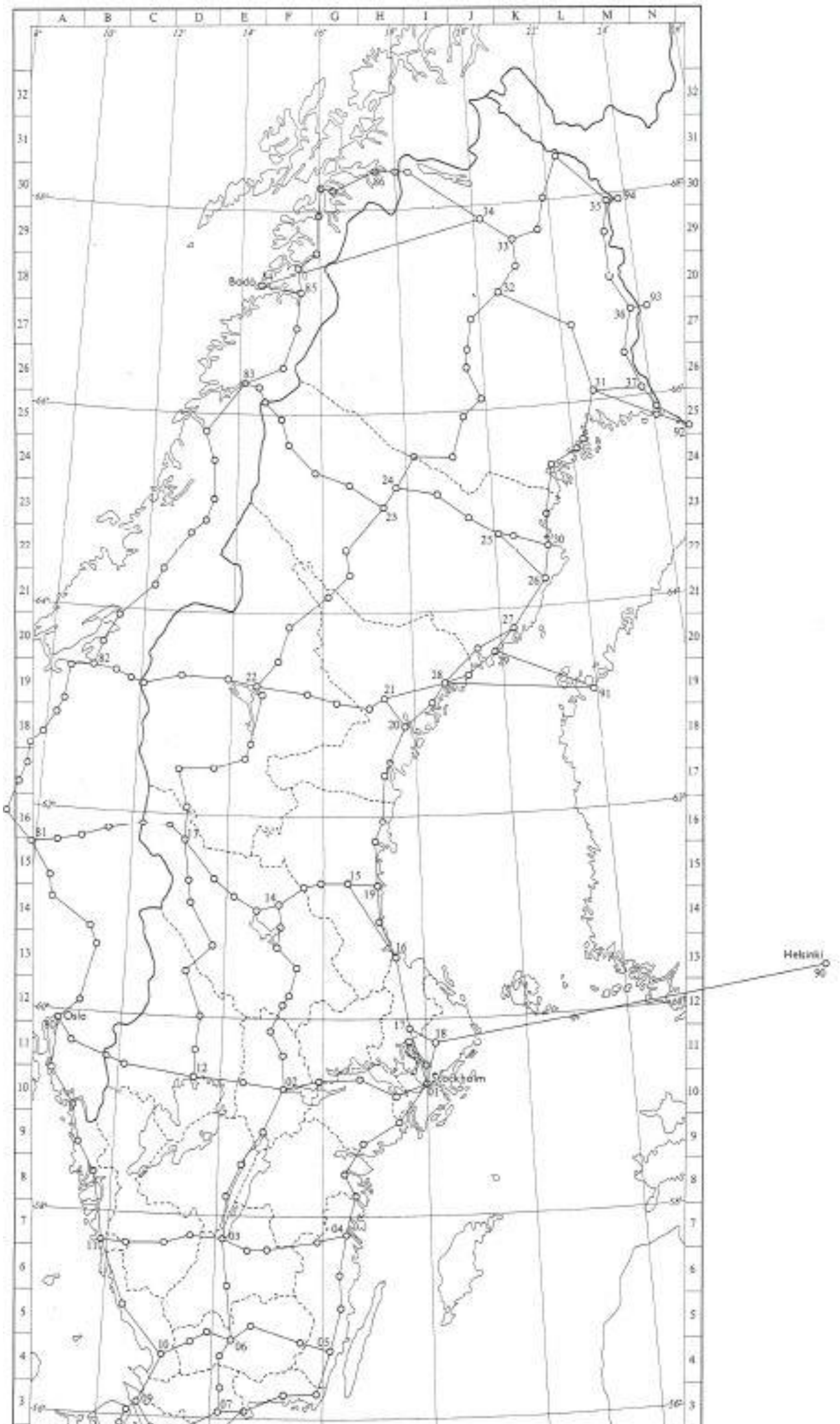


Figure 2: The RG62 Network (from Pettersson 1967)

Still it must be pointed out that the effort of making this network was an enormous step forward regarding gravity measurements in Sweden at that time. The stations form 23 loops. Ten of the junction stations are on the European Calibration Line and there are five connections to the Finnish first order gravity net which were measured during almost the same period.

The general measurement sequence was like:

A-B-A-B-C-B-C-D…

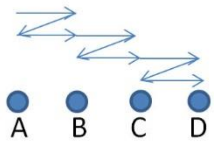


Figure 1: The measurement sequence of RG 62.

The distances between the stations were in general around 40-60 kilometres. Despite RG 62 covered Sweden, there were a lot of big gaps in the coverage, where the nearest site was more than 100 km away.

Of the 185 stations, only 23 were marked with a benchmark, so they could be identified. Many of the stations are situated on church steps, but for very few of them the place on the step is described better than "in the middle of the stone slab in front of the tower" or "on the uppermost step outside the tower entrance".

How the network was calculated is described in Pettersson (1967).

2.3 Land uplift lines

The Fennoscandian land uplift has been an object of scientific interest since the end of the 17th century (Ekman 2009). In 1743 Anders Celsius estimated the sea level change close to Gävle to 13 mm per year, based on an etching he did in 1731 in a seal rock. However, his theory was that the sea level change was either because of evaporation or a hole in the sea. First in 1865, the Scottish scientist Thomas Jamieson suggested that the land uplift is related to unloading due to the melting of the large ice sheet during the last Ice Age.

The first studies on how the land uplift can be determined by gravity observations were done in 1965 by Tauno Honkasalo (Finnish Geodetic Institute (FGI), Masala, Finland). He argued based on two simple models that 1 mm land uplift lowers the gravity somewhere between 0,17 and 0,31 µGal (Mäkinen et al 1986). In order to measure how much, the Finnish Geodetic Institute established three stations along the 63rd degree latitude. The gravity differences between these stations (Vaasa, Äänekoski and Joensuu) were measured in 1966 by Aino Kiviniemi. The following year the line was extended to Sweden and Norway. Observations on this line were performed from 1966 to 2003. The whole line was measured about every fifth year and the Finnish part of the line was measured several more times (Mäkinen et al 2005). A second line, along the 65th degree latitude was measured in 1975 and 1980-81. A third line, along the 61st degree latitude was measured in 1976 and 1983. A fourth line, along the 56th degree latitude was measured in 1977, 1984 and 2003. In Joensuu a calibration line, including four extra points was established, in order to check the instruments in connection with the measurements.

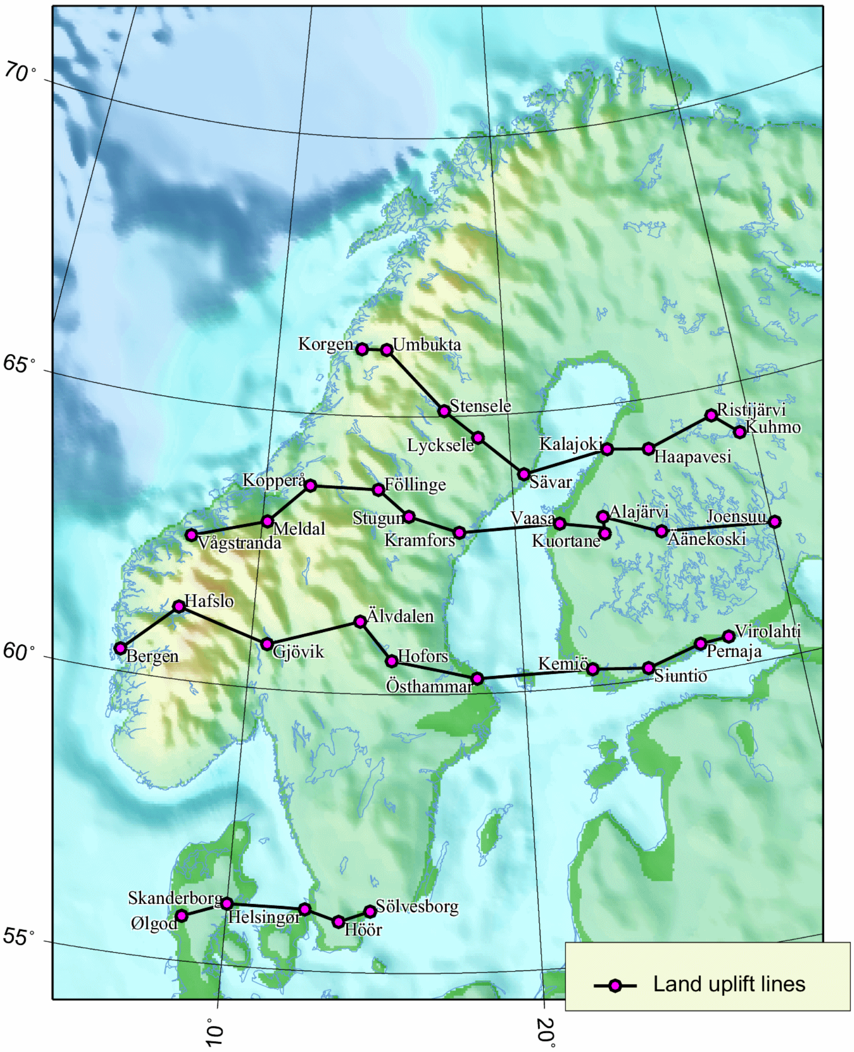


Figure 3: The four land uplift lines

For these measurements, only LaCoste & Romberg D- and G-models were used. In total, about 20 instruments participated in one or more of these measurements.

A normal measurement sequence for the 63rd degree line was according to the following:

A-B-C, C-D, D-E-F-G, G-H-I

Where A=Joensuu, B=Äänekoski, C=Vaasa, D=Kramfors, E=Stugun, F=Föllinge, G=Kopperå, H=Meldal, I=Vågstranda

This sequence took four days to complete and was normally done three times forward and backwards, which means that it took 24 days to complete the fieldwork. For the 61st degree line it took five days to complete a normal measurement sequence. This was because of the bad and slow roads between the sites, especially in Norway but also partly in Sweden, and the long ferry boat journey between Sweden and Finland.

Figure 4: Andreas Engfeldt measuring the site Höör B at the 56th degree land uplift line in 2003. Photo: Gabriel Strykowski.

The strategy for how to choose the sites was very different in Sweden and Finland. In Finland, the sites were established in rural areas, very close to houses. This was because they thought the people living nearby would feel responsibility for the sites, which would lead to that the sites would not be destroyed. In Sweden, on the other hand, the sites were established in very remote areas, if possible far away from the closest house. This was because it was thought that at those places nothing ever would be built and the sites would then not be destroyed. Still, one of the Swedish sites along the 61st degree line was destroyed in 1996, when a shooting range was built over the site Hofors A. Luckily, the reserve site is still there. The Finnish strategy was equally good/bad concerning losses of sites, since also there (at least) one of the sites is destroyed – the second most important site in Joensuu, K4, at the end of the calibration line. These different strategies led to that the Finnish sites are all quite easy to access, while two of the Swedish sites are situated at very awkward places, Älvdalen A (and even more the reserve site Älvdalen B) and Stensele A.

All raw data from the measurements between 1966 and 1984 are published in Mäkinen et al (1986). The raw data from the measurements between 1985 and 2003 are not yet published, but conclusions based on them can be found in Mäkinen et al (2005).

2.4 RG 82, the Zero Order Network

In the late 1970´s it gradually became clear that RG 62 no longer met the state-of-the-art requirements on a basic gravity network. First, the uncertainty was too high. Second, the stations were not marked and some thirty percent of the stations were destroyed. Finally, after the Italian IMGC instrument had visited Sweden it was ascertained that the absolute level in RG 62 deviated very much from the correct value, with an offset of more than 14,5 mGal from the Italian measurements. Consequently, a new network was needed.

In 1976-77, the Istituto di Metrologia G Colonnetti (IMGC, Turin, Italy) performed 25 absolute gravity measurements at 17 stations in Europe in order to improve the world gravity standard (Cannizzo et al, 1977). The uncertainty of the measurements was in the order of 10 μGal, which was about 20 times better than the uncertainty of IGSN 71. IMGC measured two recently established sites in Sweden, Gävle (later renamed Mårtsbo A / AA) in July, August and September 1976 and Göteborg A in September 1976. In the Nordic countries also Hammerfest (Norway, August 1976), Sodankylä (Finland, August 1976), Vaasa (Finland, August 1976) and København (Denmark, September 1976) were measured. The IMGC measurements in Gävle/Mårtsbo, Göteborg, Sodankylä and København became the foundation of the new system. It was planned to include also Vaasa, but due to a suspected gross error seems it was excluded.

The two absolute gravity sites together with the 12 Swedish sites on the Fennoscandian land uplift gravity lines were the first parts of the new supreme network of 25 stations, the Third Fundamental Gravity Network, also called the Zero Order Gravity Network. The 11 remaining sites were established in 1981-82. Many of the earlier measurements on the Swedish side of the Fennoscandian land uplift gravity lines were used for this network. The remaining measurements were performed in 1981-82 by Lennart Pettersson (northern half) and Lars Åke Haller (southern half), using the two LaCoste & Romberg gravimeters G54 and G290. In addition to the 25 main sites, a number of 29 additional sites, situated nearby the main sites as spares, were established.

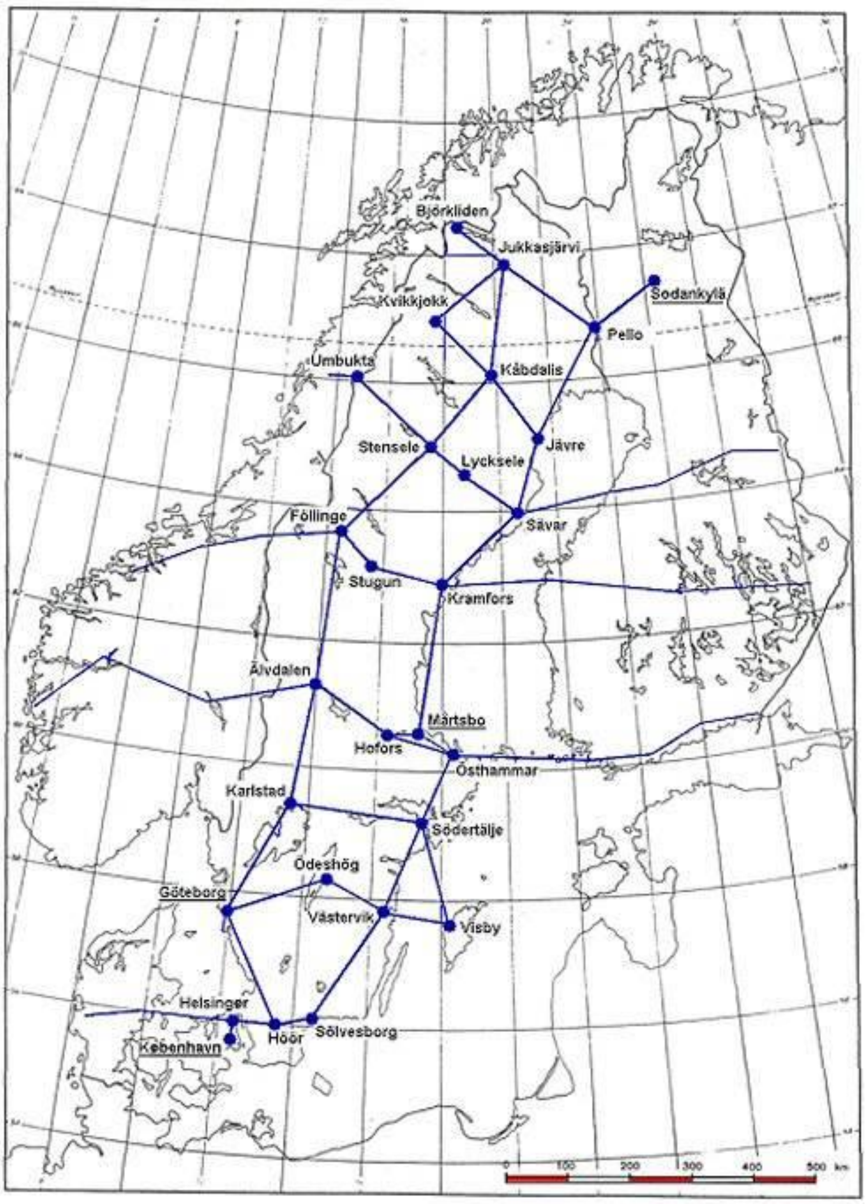


Figure 5: The Zero Order Network of RG82, from Haller & Ekman (1988).

The sites were normally measured according to the sequence:

A-B-B-A, B-A-A-B.

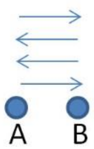


Figure 6: The measurement sequence of the Zero Order Network.

The Third Fundamental Gravity Network, RG 82, was in 1994 included in the UEGN94 (Unified European Gravity Networks 1994), which covered 11 countries and included 499 stations. Between 1998 and 2002, the project UNIGRACE (Unification of Gravity Systems in Central and Eastern Europe) took place and it resulted in UEGN02, where no Swedish stations are included (Boedecker et al. 2005). Since both of these European systems included only parts of Europe, they never came to any significant use. Today, the need for large-area gravity systems has decreased due to that modern absolute gravity measurements can easily be performed whenever needed.

Table 1: The Zero Order Network of RG 82

Name	Year of establishment	Included in a land uplift line?	Main site 1982	Best site 2011	g-value, RG 82 (µGal)
Björkliden NA	1981	N	Y	N	982362245
Björkliden NB	1981	N	N	Y	982365553
Jukkasjärvi NA	1981	N	Y	Y	982361917
Jukkasjärvi NB	1985	N	N	N	982362156
Pello NA	1981	N	Y	Y	982362461
Pello NB	1982	N	N	N	982365580
Kvikkjokk NA	1981	N	Y	N	982269111
Kvikkjokk NB	1985	N	N	Y	982268767
Kåbdalis NA	1981	N	Y	Y	982270445
Kåbdalis NB	1985	N	N	N	982268958
Jävre NA	1981	N	Y	Y	982269347
Jävre NB	1985	N	N	N	982268824
Umbukta A	1975	Y, 65	Y	Y	982191175
Umbukta B	1975	Y, 65	N	N	982191341
Stensele A	1975	Y, 65	Y	N	982191189
Stensele B	1975	N	N	Y	982191124
Lycksele A	1975	Y, 65	Y	Y	982191124
Lycksele C	1988	N	N	N	982191137
Sävar A	1975	Y, 65	Y	Y	982191088
Sävar B	1975	Y, 65	N	N	982191060
Föllinge A	1979	Y, 63	Y	Y	982075771

Föllinge B	1981	Y, 63	N	N	982075738
Stugun A	1967	Y, 63	N	N	982076474
Stugun B	1967	Y, 63	Y	Y	982075728
Stugun C	1967	Y, 63	N	N	982075670
Stugun D	1972	Y, 63	N	N	982075942
Kramfors A	1967	Y, 63	N	N	982076644
Kramfors B	1967	Y, 63	N	N	982077100
Kramfors C	1967	Y, 63	N	N	982075573
Kramfors D	1972	Y, 63	Y	Y	982075783
Älvdalen A	1976	Y, 61	Y	Y	981908201
Älvdalen B	1976	Y, 61	N	N	981908200
Hofors A	1976	Y, 61	Y	N, destroyed 1996	981908210
Hofors B	1977	Y, 61	N	Y	981908224
Mårtsbo A	1976	N	Y	Y	981923484
Mårtsbo B	1975	N	N	N	981923646
ÖsthammarA	1976	Y, 61	Y	Y	981908210
Östhammar B	1976	Y, 61	N	N	981908206
Karlstad NA	1981	N	Y	Y	981828158
Karlstad NB	1984	N	N	N, destroyed 1992	981828082
Södertälje NA	1981	N	Y	Y	981828128
Södertälje NB	1984	N	N	N	981828024
Göteborg A	1976	N	N	N	981718749
Göteborg NB	1981	N	Y	Y	981718370
Ödeshög NA	1981	N	Y	Y	981718430
Ödeshög NB	1984	N	N	N	981718473
Västervik NA	1981	N	Y	Y	981718574
Västervik NB	1984	N	N	N	981718453
Visby NA	1981	N	Y	Y	981719266
Visby NB	1984	N	N	N	981718567
Höör A	1977	Y, 56	Y	N	981580437
Höör B	1977	Y, 56	N	Y	981580438

Sölvesborg A	1977	Y, 56	Y	Y	981580437
Sölvesborg B	1977	Y, 56	N	N	981580443

2.5 RG 82, the First Order Network

The First Order Network is not a network in any real meaning, since only 15 points have been measured from more than one starting point. However, it is still a densification of the Zero Order Network and consists of 149 points. The purpose of it was to get one point every 50 kilometres, preferably close to towns with accommodations. The latter was an important requirement since they were meant to be used for densification for geoid purposes and in those days all measurements for the geoid were performed by staff from a part of Lantmäteriet in Gävle, which later developed into Metria.

The work with the first order network was not given the highest priority in the beginning, which is indicated by the number of sites established each year. In the end of year 2000, because of the work with a new Nordic geoid, it got priority. This led to that the network was finished in October 2002.

Table 2: Number of new sites per year

Year	Number of new sites	Gravimeters used	Operator
1984	5	LCR G54 and LCR G290	Lars Åke Haller
1985	10	LCR G54 and LCR G290	Lars Åke Haller
1990	12	LCR G54 and LCR G290	Lars Åke Haller
1992	9	LCR G54 and LCR G290	Lars Åke Haller
1996	5	LCR G54 and LCR G290	Lars Åke Haller
2001	34	LCR G54 and LCR G290	Andreas Engfeldt
2002	43	LCR G54 and LCR G290	Andreas Engfeldt
2002	31	LCR G54 and LCR G290	Håkan Skatt

With a few exceptions, the sites were measured in a loop back and forth like the following sequence:

A-B-C-D-E-A, A-E-D-C-B-A

Or

A-B-C-D-A, A-D-C-B-A

Or

A-B-C-A, A-C-B-A

Or

A-B-A, A-B-A

Where A is a Zero Order site and the rest of the letters are First Order sites.

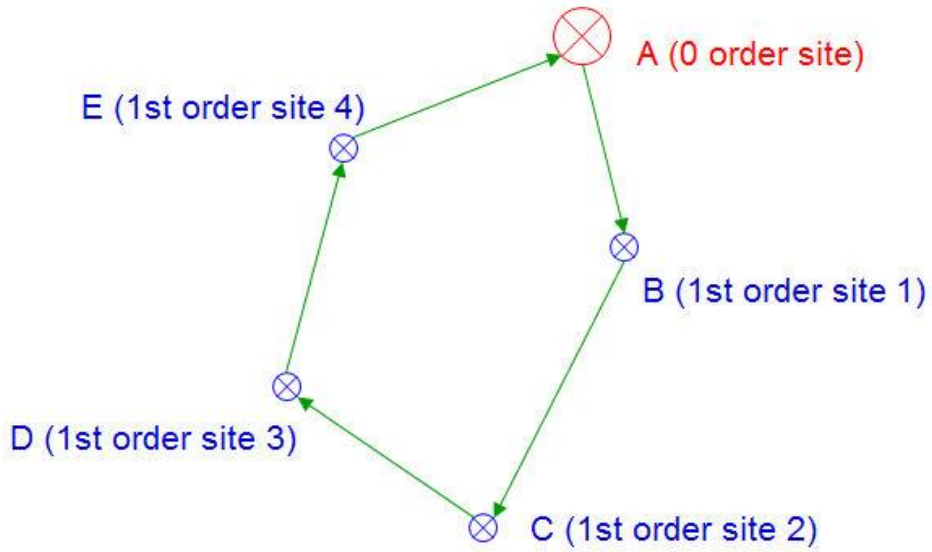


Figure 7: Measuring the First Order Network of RG 82. Illustration of a normal sequence.

All measurement sequences included started on a Zero Order site. Most ended on the same site, but there were a few exceptions. As found out during the calculations in 2001, parts of the Finnish calculation software could not handle sequences of measurement starting and ending at different points in a totally correct way, which behind the reason that almost no such measurements were performed in 2002.

All the measurements were recalculated by Andreas Engfeldt in 2002, in the Finnish software Gred2 (written by Jaakko Mäkinen, FGI) and adjusted in the Finnish software Gadjd32 (written by Jaakko Mäkinen) and in Excel. In the adjustment, all the Zero Order sites were fixed and a correction for linear drift of the instrument was applied.

During the preparatory work for RG 2000 it was discovered that the instrument specific files which arrived with the software from Finland had the incorrect calibration factors for both the Swedish instruments, which means that everything calculated in 2002 was wrong. Everything has now been recalculated in the same software by the author. The correct calibration factors are 1,00075 for G54 (1,0009 in the software, where this value came from is nowhere to be found) and 1,00083 for G290 (1,0012 in the software), which are the factors derived through the adjustment of the Zero Order Network in 1982. The factor for G54 is still valid, which was proved by calibration measurements between LMV AA and Husby-Ärlinghundra AA in October 2015. Table 3 shows the difference between the old values and the new correct values in µGal.

Table 3 The First Order Network of RG 82, with new recalculated values (from 2014) and old incorrectly calculated values (from 2002), all in µGal

Storruta		Site name	New value	Old value	Difference (New-Old)
2	C	Dalby	981565696	981565692	4
2	E	Simrishamn	981566983	981566979	4
3	C	Åstorp	981617389	981617398	-9
3	F	Johannishus	981612156	981612164	-8
4	C	Laholm	981653010	981653028	-18
4	D	Osby	981589559	981589562	-3
4	E	Urshult	981594626	981594630	-4
4	F	Emmaboda	981630169	981630182	-13
4	G	Torsås	981641380	981641360	20
4	G	Kastlösa	981624427	981624402	25
5	C	Torup	981676644	981676669	-25
5	D	Lagan	981612487	981612495	-8
5	E	Ör	981619310	981619285	25
5	F	Åseda	981638771	981638750	21
5	G	Blomstermåla	981658987	981658972	15
5	H	Borgholm	981650542	981650524	18
5	J	Grötlingbo	981654450	981654433	17
6	B	Veddige	981696092	981696087	5
6	C	Svenljunga	981666080	981666066	14
6	D	Hillerstorp	981643279	981643260	19
6	E	Sävsjö	981655112	981655095	17
6	F	Lönneberga	981680827	981680817	10
6	G	Misterhult	981682922	981682913	9
6	J	Garde	981695104	981695098	6
6	J	Gothem	981713380	981713379	1
7	C	Borås	981661340	981661324	16
7	D	Bottnaryd	981671655	981671643	12
7	E	Aneby	981669676	981669663	13
7	F	Kisa	981720426	981720427	-1
7	J	Bunge	981699582	981699577	5
8	B	Uddevalla	981760238	981760248	-10
8	C	Vara	981752395	981752404	-9
8	D	Dala	981719773	981719773	0
8	F	Motala	981760343	981760354	-11

8	G	Norrköping	981789066	981789044	22
8	G	Åtvidaberg	981736805	981736810	-5
8	J	Gotska sandön	981746220	981746227	-7
9	A	Tanum	981786195	981786213	-18
9	B	Dals Ed	981775957	981775959	-2
9	D	Mariestad	981774076	981774091	-15
9	E	Laxå	981787151	981787141	10
9	F	Ljusfallshammar	981785362	981785380	-18
9	G	Valla	981816565	981816574	-9
9	H	Nyköping	981801229	981801211	18
10	B	Årjäng	981819424	981819422	2
10	C	Säffle	981817088	981817086	2
10	E	Bofors	981804614	981804608	6
10	F	Örebro	981816750	981816748	2
10	G	Eskilstuna	981833477	981833479	-2
10	I	Jordbro	981822885	981822881	4
10	I	Solna	981829155	981829150	5
11	C	Arvika	981844497	981844503	-6
11	D	Munkfors	981826788	981826789	-1
11	E	Grythyttan	981819955	981819953	2
11	F	Lindesberg	981835343	981835345	-2
11	G	Hallstahammar	981838612	981838614	-2
11	H	Enköping	981856085	981856092	-7
11	I	Uppsala	981883699	981883691	8
11	J	Norrtälje	981857437	981857424	13
12	C	Torsby	981856177	981856186	-9
12	D	Ekshärad	981828050	981828052	-2
12	E	Fredriksberg	981841665	981841668	-3
12	F	Ludvika	981867441	981867453	-12
12	G	Avesta	981882716	981882709	7
12	H	Tärnsjö	981900879	981900877	2
13	C	Sysslebäck	981864112	981864121	-9
13	D	Stöllet	981819943	981819940	3
13	D	Malung	981840702	981840687	15
13	E	Vansbro	981861844	981861832	12
13	F	Borlänge	981907934	981907928	6
13	H	LMV	981935083	981935085	-2
14	D	Transtrand	981865727	981865717	10
14	E	Mora	981926203	981926208	-5
14	F	Rättvik	981923248	981923252	-4
14	G	Åmot	981935356	981935359	-3
14	H	Vallvik	981987890	981987908	-18
15	D	Särna	981897162	981897159	3
15	E	Tandsjöborg	981916293	981916295	-2
15	F	Voxna	981967513	981967524	-11
15	G	Arbrå	981992413	981992430	-17

15	H	Boda bruk	981998390	981998410	-20
16	C	Idre	981885374	981885368	6
16	D	Lofsdalen	981893790	981893786	4
16	E	Sveg	981957940	981957953	-13
16	F	Laforsen	982011074	982011096	-22
16	G	Hybo	982020411	982020435	-24
16	H	Gnarp	982030299	982030327	-28
17	C	Tännäs	981907262	981907261	1
17	D	Hede	981948373	981948383	-10
17	E	Rätansbyn	982013541	982013525	16
17	F	Alby	982039002	982038992	10
17	G	Torpshammar	982068551	982068549	2
17	H	Stavreviken	982082376	982082377	-1
18	E	Svenstavik	982030860	982030847	13
18	F	Stavre	982039059	982039049	10
18	G	Boda	982087991	982087992	-1
19	C	Ånn	981998659	981998640	19
19	D	Järpen	982028002	982027989	13
19	E	Krokom	982048528	982048521	7
19	G	Ramsele	982129966	982129980	-14
19	H	Sollefteå	982115690	982115700	-10
19	I	Åte	982122395	982122408	-13
20	F	Hallviken	982108242	982108253	-11
20	H	Gulsele	982138176	982138192	-16
20	I	Björna	982143374	982143392	-18
20	J	Bjurholm	982148102	982148091	11
20	K	Hörnefors	982150903	982150922	-19
21	F	Sved	982086297	982086302	-5
21	G	Hoting	982143693	982143713	-20
21	H	Åsele	982139883	982139870	13
21	I	Fredrika	982152311	982152301	10
21	J	Hällnäs	982165441	982165435	6
22	E	Gäddede	982122804	982122818	-14
22	G	Vilhelmina	982144115	982144103	12
22	H	Vinliden	982151769	982151760	9
22	K	Burträsk	982206184	982206167	17
22	L	Lövånger	982223260	982223249	11
23	E	Stekenjokk	982065366	982065335	31
23	F	Saxnäs	982093903	982093879	24
23	G	Strömsund	982178148	982178144	4
23	I	Malå	982217407	982217414	-7
23	J	Norsjö	982190257	982190257	0
23	K	Lidträsk	982203153	982203136	17
24	F	Tärnaby	982153959	982153949	10
24	H	Sorsele	982217522	982217529	-7

24	J	Arvidsjaur	982216748	982216734	14
24	K	Älvsbyn	982299355	982299363	-8
24	L	Bergnäset	982298900	982298908	-8
25	F	Hemavan	982165914	982165892	22
25	G	Ammarnäs	982198716	982198717	-1
25	H	Arjeplog	982237394	982237406	-12
25	L	Hundsjön	982329626	982329642	-16
25	M	Kalix	982316642	982316654	-12
25	N	Haparanda	982321264	982321278	-14
26	H	Jäkkvik	982242229	982242253	-24
26	J	Jokkmokk	982347400	982347420	-20
26	K	Edefors	982340067	982340085	-18
26	L	Lansån	982349906	982349903	3
26	M	Övertorneå	982326908	982326899	9
27	J	Porjus	982319832	982319821	11
27	L	Hakkas	982356510	982356508	2
27	M	Korpilombolo	982345628	982345623	5
28	K	Gällivare	982345267	982345263	4
28	L	Junosuando	982397682	982397691	-9
28	M	Pajala	982372864	982372867	-3
29	K	Vittangi	982402958	982402968	-10
30	J	Torneträsk	982378769	982378774	-5
30	K	Sopporo	982375837	982375841	-4
31	L	Karesuando	982425006	982425023	-17
RMS:					12

So what does this mistake mean in practice? To start with, the transformation from 2001 between RG 62 and RG 82 (see 2.6) is not affected at all, since no new observations were used for it. Some of the sites have been used as starting sites for geoid measurements by Lantmäteriet. These are not so many, the magnitude of the change is very small compared to the required uncertainty of geoid measurements and it is easy to change these values. For example, for all the geoid points measured in 2001 which used Burträsk as the starting site, 17 µGal should be added. Some of the sites have also been used by the Swedish Geological Research (SGU) as starting sites for their gravity measurements. In their case, however, the relative uncertainty is much more important than the absolute one. Since the magnitude of the difference between the wrong and the correct values is small, this should be no big issue for them either. The maximum is 31 µGal in Stekenjokk and the minimum is -28 µGal in Gnarp.

2.6 Transformations between RG 62 and RG 82

The Second Order Network (also known as the Gravity Detail Network) includes more than 25000 gravity observations in Sweden of very different quality. This network is meant to be used for geoid modelling and gravity interpolation and a majority of the measurements were originally done in RG 62. In 2001, all data in the Swedish gravity database (where all First and Second Order RG 62 sites were included) needed to be transformed to RG 82 from RG 62, because of the work with a new Nordic geoid model. At the time two transformations were derived in the software Gtrans, one in the form of an inclined plane (A) and one in the form of a second degree polynomial function (B). All gravity numbers below are in mGal:

A

$gt=gf+Co+Cx*xf+Cy*yf-vg$

$Co=-15,15787533900 = 95,51*S(Co)$

$Cx=0,00000004627 = 1,61*S(Cx)$

$Cy=0,00000012380 = 1,68*S(Cy)$

$S\ (Co)=0,158705$

S(Cx)=0,028821 PPM

S(Cy)=0,073583 PPM

Max Abs (vg) = 0,100 (for Kiruna kyrka)

RMS (vg) = 0,047011

B

$p=(xf-Txf)/700000$

$q=(yf-Tyf)/700000$

$gt=gf+a0+a1*p+a2*q+a3*p^2+a4*p*q+a5*q^2 \ldots -vg$

RMS (vg) = 0,036798

Max ABS (vg) = 0,1038 (for Pello skola)

$a0 = -14,621826673201040$

$a1=2,996196260037513E-002$

$a2=8,911710021952457E-002$

$a3=-1,009511673561099E-001$

$a4=5,538504466532544E-002$

a5=6,4604338016794 86E-003

These were based on 28 observations of which 25 were in Sweden and 3 were in Norway (see Table 4). Notice that none of these values were based on the calculations in the Finnish software performed in 2002.

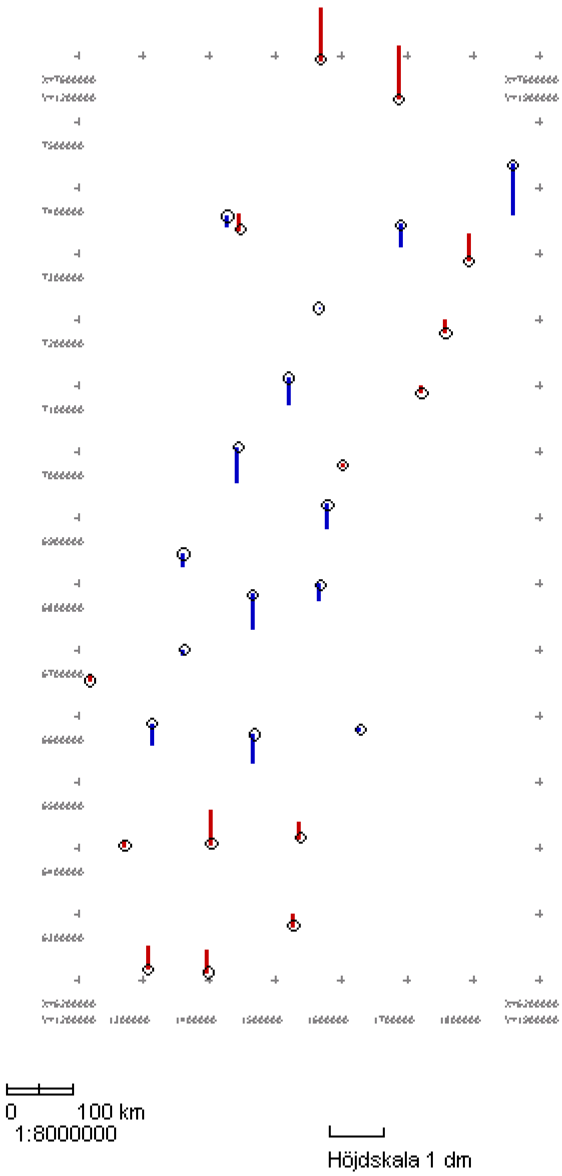


Figure 8: Residuals of the transformation between RG 62 and RG 82 as an inclined plane. The residuals of Kiruna, Pello and Narvik were indicated as outliers by the statistical test in Gtrans.

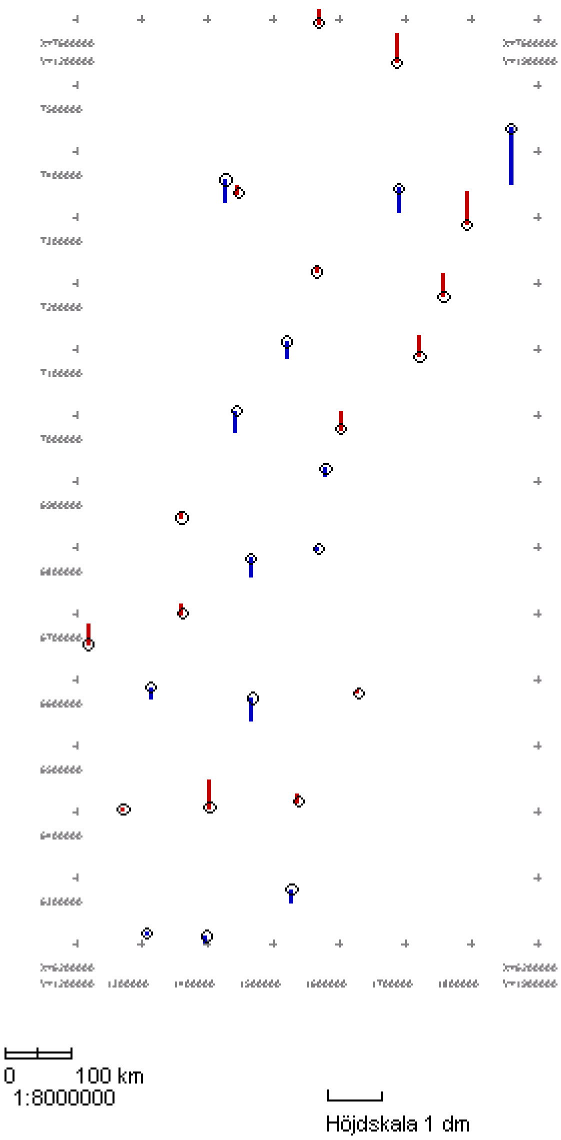


Figure 9: Residuals of the transformation between RG 62 and RG 82 as a second degree polynomial function.

16 of the 28 observations give a lower value for the residuals in g (*vg*) of the polynomial function than of the inclined plane. Generally speaking, the polynomial function gives a better agreement for the southern half of Sweden, but a worse result for the northern half of Sweden except the mountainous areas.

Table 4: Differences between RG 82 and RG 62 (in mGal) used to estimate the inclined plan and the polynomial function.

Site name	g (RG 82)	g (RG 62)	Difference	Comments

Pello skola*	982366,820	982381,310	-14,490	
Kiruna kyrka*	982315,410	982330,110	-14,700	
Luleå domkyrka 1	982295,510	982310,160	-14,650	
Kåbdalis kapell*	982271,240	982285,810	-14,570	
Bureå kyrka	982225,530	982240,160	-14,630	
Umbukta 1*	982201,970	982216,640	-14,670	
Umeå kyrkogård*	982188,270	982202,900	-14,630	Probably destroyed
Stensele kyrka*	982174,940	982189,570	-14,630	
Hoting hållplats	982135,840	982150,430	-14,590	Destroyed
Gudmundrå kyrka	982105,510	982120,150	-14,640	
Sundsvall Gustaf Adolf kyrka*	982069,920	982084,520	-14,600	
Östersund kyrka*	982044,150	982058,740	-14,590	
Söderhamn kyrka*	981993,290	982007,910	-14,620	
Furudal	981929,510	981944,110	-14,600	Probably destroyed
Särna nya kyrka*	981905,990	981920,640	-14,650	
Norra Ny kyrka 1	981843,150	981857,820	-14,670	
RAK 2	981831,110	981845,760	-14,650	Destroyed
Karlstad kyrka 1	981828,310	981842,960	-14,650	
Örebro slott	981819,990	981834,610	-14,620	
Göteborg Kristine kyrka*	981727,120	981741,830	-14,710	
Tjust motell*	981720,250	981734,950	-14,700	Probably destroyed
Jönköping Sofia kyrka	981705,860	981720,610	-14,750	
Dörby kyrka	981653,090	981667,790	-14,700	
Helsingborg Maria kyrka	981609,660	981624,410	-14,750	
Kristianstad kyrka*	981591,310	981606,050	-14,740	
Narvik Grand* (N)	982436,900	982451,610	-14,710	
Mo i Rana* (N)	982308,840	982323,460	-14,620	
Oslo A* (N)	981912,580	981927,290	-14,710	

** The observation data of these measurements were found in 2016 and has been recalculated (see Table 5).*

However, all g-values in RG 82 were rounded numbers in tens of µGal for the transformations. About half of the observation data was found in old protocol books in 2016 and recalculated (See Table 5). At the same time observation data for several other RG 62 sites were found and calculated to RG 82 (see Table 6).

The year after the transformations were calculated, a few more observations in the system RG 82 on old RG 62 sites were found (see Table 5). One of these observations, Norra Ny, was at the same site as one of the included observations, but the new one fits better with the surrounding observations and is regarded as better than the old one. The sites Luleå domkyrka and Umbukta were also remeasured in 2015, but here the observations agree better. In some areas there was a need for more connections between the systems, e.g. north of the Arctic Circle where the largest residuals were found (see Figure 8 and 9). If it is not already handled, it will be handled during the upcoming year, when some additional measurements will be done. The new connections (Table 5 and Table 6) will together with some of the old ones (the observations in Table 4, not marked with an asterisk) form a better transformation between the systems and for the lowest possible uncertainty it would be preferable to calculate a new transformation. It is then recommended to test and apply an interpolation method that is more suitable for the purpose, for instance least squares collocation or Kriging.

Table 5: New differences between RG 82 and RG 62 (in mGal), from the calculations in 2016.

Site name	g (RG 82)	g (RG 62)	Difference	Comments
Pello skola	982366,817	982381,310	-14,493	
Kiruna kyrka	982315,417	982330,110	-14,693	
Kåbdalis kapell	982271,236	982285,810	-14,574	
Umbukta 1	982201,953	982216,640	-14,687	
Umeå kyrkogård	982188,275	982202,900	-14,625	Probably destroyed
Stensele kyrka	982174,939	982189,570	-14,631	
Sundsvall Gustaf Adolf kyrka	982069,942	982084,520	-14,578	
Östersund kyrka	982044,145	982058,740	-14,595	
Söderhamn kyrka	981993,335	982007,910	-14,575	
Särna nya kyrka	981905,993	981920,640	-14,647	
Göteborg Kristine kyrka	981727,117	981741,830	-14,713	

Tjust motell	981720,249	981734,950	-14,701	Probably destroyed
Kristianstad kyrka	981591,306	981606,050	-14,744	
Narvik Grand (N)	982436,905	982451,610	-14,705	
Mo i Rana (N)	982308,833	982323,460	-14,627	
Oslo A 1 (N)	981912,579	981927,290	-14,711	

Table 6: New connections between RG 82 and RG 62 (in mGal). These were measured between 1976 and 2015 and were not included in the old transformations.

Site name	g (RG 82)	g (RG 62)	Difference	Comments
Pajala kyrka	982379,327	982393,870	-14,543	AE 2015
Jokkmokk nya kyrka	982346,984	982361,560	-14,576	AE 2015
Vassijaure station	982341,643	982356,360	-14,717	AE 2014
Gällivare kyrka	982341,220	982355,800	-14,580	AE 2015
Luleå domkyrka 2	982295,524	982310,160	-14,636	AE 2015
Arvidsjaur kyrka	982216,120	982230,680	-14,560	AE 2015
Umbukta 2	982201,949	982216,640	-14,691	AE 2015
Hörnefors kyrka	982149,958	982164,570	-14,612	AE 2015
Vilhelmina kyrka	982131,863	982146,460	-14,597	LÅH 1992
Ragunda kyrka	982129,237	982143,820	-14,583	AE 2015
Sollefteå kyrka	982123,719	982138,340	-14,621	AE 2015
Granbergets hållplats	982119,589	982134,220	-14,631	LÅH 1992, Destroyed
Ström kyrka	982108,316	982122,920	-14,604	LÅH 1992
Stugun kyrka	982088,116	982102,700	-14,584	AE 2015
Bollnäs kyrka	981994,609	982009,140	-14,531	AE 2015
Skutskär kyrka 1	981934,655	981949,200	-14,545	LP 1976
Skutskär kyrka 2	981934,622	981949,200	-14,578	LÅH 1976
Skutskär kyrka 3	981934,616	981949,200	-14,584	AE 2015
Älvdalen kyrka 1	981920,306	981934,920	-14,614	LÅH 1996
Älvdalen kyrka 2	981920,295	981934,920	-14,625	AE 2015
Stora Tuna kyrka 1	981907,283	981921,840	-14,557	LÅH 1976
Stora Tuna kyrka 2	981907,254	981921,840	-14,586	LP 1976

Norra Ny kyrka 2	981843,224	981857,820	-14,596	LÅH 1996
Ljusnarsberg kyrka 1	981836,826	981851,460	-14,634	LÅH 1976
Ljusnarsberg kyrka 2	981836,824	981851,460	-14,636	LP 1976
Norra Råda kyrka	981831,802	981846,400	-14,598	LÅH 1996
Karlstads flygplats 1	981829,583	981844,210	-14,627	LÅH 1976, Destroyed
Karlstads flygplats 2	981829,542	981844,210	-14,668	LP 1976, Destroyed
RAK 4 1	981827,984	981842,620	-14,636	LÅH 1976, Destroyed
RAK 4 2	981827,962	981842,620	-14,658	LP 1976, Destroyed
Turinge kyrka	981826,621	981841,240	-14,619	LÅH 1981/82
Silbodal kyrka 1	981820,138	981834,840	-14,702	LÅH 1976
Silbodal kyrka 2	981820,075	981834,840	-14,765	LP 1976
Varberg Appelviksåsen	981694,870	981709,580	-14,710	AE 2013
Oslo A 2 (N)	981912,585	981927,290	-14,705	LÅH 1976
Oslo A 3 (N)	981912,583	981927,290	-14,707	LP 1976

AE = Andreas Engfeldt (G54 and CG5-1184 in 2015; G54 and CG5-740 in 2013; CG5-740 in 2014); LP = Lennart Pettersson (only G290); LÅH = Lars Åke Haller (only G54 in 1976, the other years G54 and G290).

3 Current situation, absolute gravity

3.1 Modern absolute gravimeters

During the last decades, absolute gravity measurements have been performed in Sweden with FG5 instruments (Lantmäteriet owns FG5-233 since 2006) and during the last decade also with A-10 gravimeters. The predecessor of FG5 was the JILAg instrument. JILAg was based on Faller's ideas/principles (Niebauer et al 1995). Six instruments were manufactured and JILAg was thereby the first absolute gravimeter to be produced in a series. They had an uncertainty and repeatability of 3-5 µGal. One of them was purchased by FGI (Finland).

In 1993 the first two FG5's were manufactured. The design was based on the JILAg, but some technical improvements in reliability and operation had been implemented (Niebauer et al 1995). They looked quite different from how FG5 looks today, but the principles are the same and some of the features are also still the same.

The FG5 operates by using the free-fall method. An object is dropped inside a vacuum chamber (called the dropping chamber). The descent of the freely-falling object is monitored very accurately using a laser interferometer. The free-fall trajectory of the dropped object is referenced to a very stable active-spring system, called a superspring. The superspring provides seismic-isolation for the reference optic to improve the noise performance of the FG5. The optical fringes generated in the interferometer provide a very accurate distance measurement system that can be traced to absolute wavelength standards. Very accurate and precise timing of the occurrence of these optical fringes is done using an atomic rubidium clock that is also referenced to absolute standards. The fact that the measurement is directly tied to absolute standards kept at all national and international laboratories around the world is the reason why the FG5 is called an absolute gravimeter. Absolute standards of length and time together with absolute gravity comparisons provide the means to achieve a calibrated gravity value that does not drift over time.

The most recent development of FG5 is that the design of the dropping chamber has been changed completely and the instruments with the new dropping chamber are called FG5X. The new dropping chamber is made of glass and is also transparent, which means that the falling mass and the elevator lifting it up can be seen, even if the mass is falling too fast for the eye to really see clearly. The first prototype of FG5X was manufactured in 2011. Lantmäteriet has decided to upgrade our FG5-233 in connection with the next planned service will take place, which means probably around autumn/winter 2016.

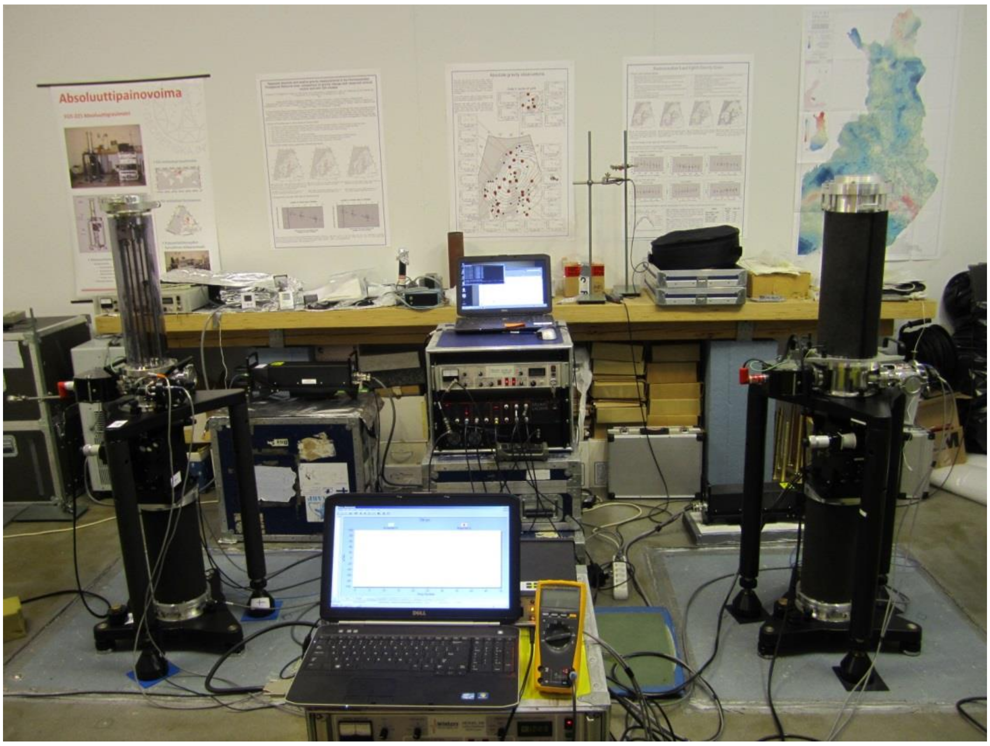


Figure 10: Comparison measurements in Metsähovi 2014. FG5-233 is on the right side and FG5X-221 is on the left side

FG5 is manufactured by Micro-g LaCoste and is partly operated through the software g, which runs on a PC. The present version of the g-software is 9.0.

A-10 has been on the market since the mid 2000s and is an absolute gravimeter which is optimized for fast data acquisition. It is designed by Micro-g LaCoste for easy use, to be portable and specifically for outdoor applications. According to the manufacturer, it allows true field operation in harsh field condition on open outdoor sites in sun, snow and wind. However, in reality, major problems occur if the sun is shining directly on it or if it is raining and the uncertainty increases significantly if it is standing directly in wind. Because of that, a tent is needed to get the best possible results.

The operation of A-10 is very similar to the operation of FG5. A test mass is dropped vertically by a mechanical device inside a vacuum chamber, and then allowed to fall an average distance of 7 cm. The A-10 uses a laser interferometer, long period inertial isolation device and an atomic clock to determine accurately the position of the free-falling test mass as it accelerates in the gravity field. The acceleration of the test mass is calculated directly from the measured trajectory (See Micro-g LaCoste 2008).

A-10 is using the same software, g, as FG5. One difference is that the measurements are made in two different laser modes, which are called “blue” and “red”. The average of the two laser modes gives the observed value of g.

Figure 11: A-10 measurements at the First Order RG 82 site Valla in 2012

3.2 The Nordic absolute gravity project

In the winter 2002-03 there was an initial meeting in Göteborg of a Nordic Absolute Gravity project. The initiative came from Ludger Timmen (IfE), who had applied for funds to measure the land uplift with absolute gravity connected to a project about NASA’s satellite mission GRACE (Gravity Recovery and Climate Experience). Apart from the measurements in 1976 by the Italian instrument, measurements in the region had also been performed in the 1990s. To start with, FGI purchased one JILAg absolute gravimeter in the early 1990s and apart from measuring a few stations regularly in Finland, Jaakko Mäkinen measured Mårtsbo AA and the new station Skellefteå AA once, in 1992. In the same year it was decided by Lars Åke Haller to abandon the Göteborg A site for Onsala. Jaakko Mäkinen then measured both these stations to get the connection between them. However, the site measured in Onsala was later decided not to be used. Instead on the same block of concrete, two new sites (Onsala AN and Onsala AS) were established and the measured site was in between those. During 1993 the first FG5s were constructed and two of them visited Scandinavia, NOAA (National Oceanic and Atmospheric Administration, Boulder, Colorado, USA) twice (1993 and 1995) and BKG (Bundesamt für Kartografie und Geodäsie, Frankfurt, Germany) three times (1993, 1995 and 1998). They measured Mårtsbo AA, Skellefteå AA and the new stations Kiruna AA (only NOAA), Onsala AN and Onsala AS.

The participants in the new project (2002-03) were:

- The three instrument owners:
  - IfE
  - BKG
  - FGI
- The three Nordic Mapping Authorities, who mainly were the station owners in respective country:
  - Lantmäteriet
  - KMS (later DTU Space)
  - Statens Kartverk (Hønefoss, Norway)
- The universities:
  - Chalmers Institute of Technology / Onsala Space Observatory (owners of the gravity station Onsala)
  - NMBU (The Norwegian Agriculture University, Ås, Norway)

At the meeting it was decided that the project should start and that the Nordic Mapping Authorities and FGI should establish a few more gravity stations in their respective countries in order to get a denser and more evenly spread network of absolute gravity stations in the area. At the next meeting in Copenhagen in March 2003, in connection to the NKG Geodynamics Working Group meeting, it was decided which new stations should be established and which stations the instrument owners should measure during the following year. In Sweden the stations Arjeplog, Östersund and Kramfors were established after this meeting. The first two were co-located with permanent GNSS, as all the other existing AG-sites in Sweden have. Kramfors got permanent GNSS in 2005 and was established in order to replace the Zero Order site on the 63rd gravity land uplift line in the long run. In Norway, the Vågstranda station was established in order to replace the site on the other end of the Swedish-Norwegian part of the 63rd gravity land uplift line. This site was measured by BKG in 2003. BKG also measured a few other stations in Norway, as well as the stations they measured in the 1990's in Sweden plus Kiruna. IfE measured most of the available stations at the time, except Mårtsbo, Kiruna and Vågstranda. The old station Göteborg was not measured since it was not convenient to use in this project (remark: it was decided to be moved in 1992, see above). IfE also measured the new station Borås, established at SP (Technical Research Institute of Sweden) not in coordination to the project. Borås was only measured one more time by IfE (2008).

Between 2004 and 2007, IfE continued to measure many stations in Scandinavia. Lantmäteriet supported them in 2004 and 2005 when Andreas Engfeldt joined Ludger Timmen for totally 60 days.

In 2004, NMBU got funds to purchase a FG5 and started to measure, mostly in Norway. Two sites were measured in Sweden, though, in 2004 and 2005, when Andreas Engfeldt joined them for measurements in the new station Smögen and a comparison with the IfE instrument in Onsala. NMBU also measured in Kiruna and Östersund in 2007 and Kiruna, Östersund and Arjeplog in 2008.

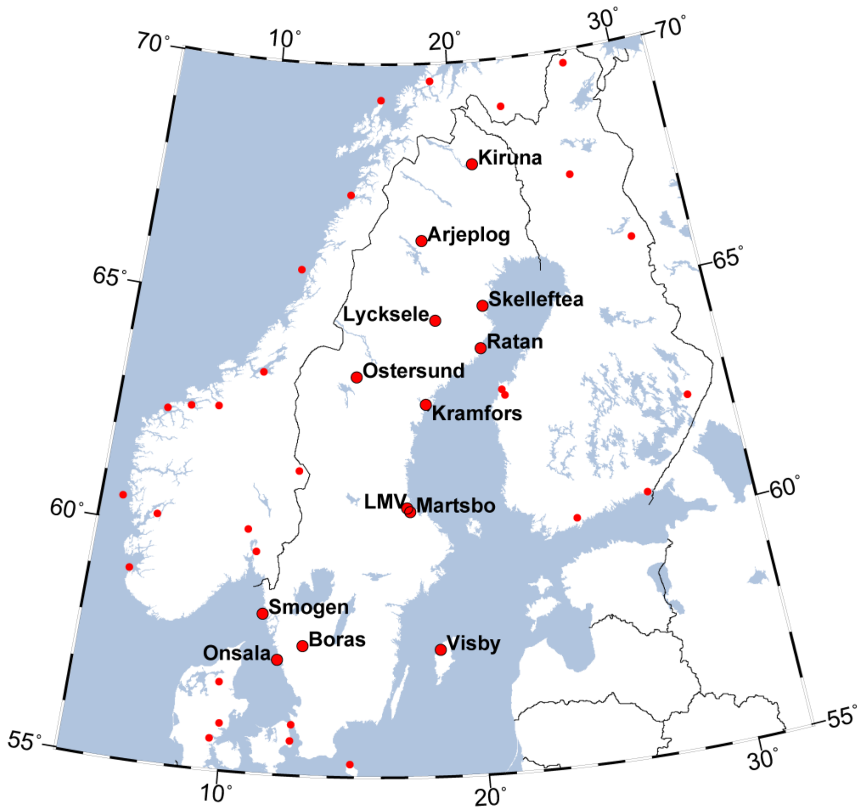


Figure 12: The FG5-stations in Fennoscandia

In October 2006 Lantmäteriet purchased an FG5 and from 2007 it became the instrument in the area that measured the most and it still is (see chapter 3.3). In 2009 Olga Gitlein (IfE), who measured with Ludger Timmen in 2003 and subsequently performed about 50% of the IfE measurements, finished her PhD studies and published her thesis about this project (Gitlein, 2009). From start approximate coordinates were typed into the g software and IfE did a splendid work at every site, levelling the gravity pillar every time from between three to five benchmarks with heights in the national height system (RH 2000), surrounding the GNSS pillar. IfE had from Lantmäteriet received sketches of the benchmarks and the height values of them. In the PhD report even better sketches were drawn in an Appendix, including the mean difference in height between the different benchmarks and the gravity pillar. Unfortunately it was forgotten to calculate the correct height of the gravity pillar. This was instead performed in 2013 by Andreas Engfeldt, who found this small error.

Table 7: The Swedish FG5 sites

Name	Latitude	Longitude	Height (RH2000)	Year of establishment
Arjeplog AA	66,318	18,1249	454,967	2003
Borås AA	57,7159	12,8895	176,076	2003
Kiruna AA	67,8776	21,0602	466,593	1995
Kramfors AA	62,8754	17,9277	122,824	2003
LMV AA	60,66647	17,13139	13,78	2006
Lycksele AA	64,6276	18,666	218,778	2007
Mårtsbo AA	60,595	17,259	43,695	1976
Mårtsbo AB	60,595	17,259	43,695	1976
Onsala AA	57,3964	11,9259	7,5	2009
Onsala AC	57,3964	11,9259	7,5	2009
Onsala AN	57,3956	11,9276	6,143	1993
Onsala AS	57,3956	11,9276	6,143	1993
Ratan AA	63,99	20,82	49,619	2007
Skellefteå AA	64,8792	21,0483	56,300	1992
Smögen AA	58,3535	11,218	5,789	2004
Visby AA	57,6539	18,3673	52,511	2004
Östersund AA	63,4428	14,8581	455,964	2003

IfE's observations from 2003 show a lower g-value than expected compared to later observations. It is not determined if the low values from that year are due to external effects, e.g. groundwater conditions, or if they are related to the instrument (at ECAG in Walferdange in November that year it was e.g. discovered that the laser had a loose component). Olga Gitlein excluded these data in her calculation and we have also decided to exclude these data in any kind of calculations.

3.3 Swedish FG5 measurements

In mid-October 2006, FG5-233 arrived in Sweden. It was purchased from Micro-g LaCoste INC in Lafayette, Colorado, USA. Some weeks in advance, a space on the D1 floor at Lantmäteriet in Gävle was allocated to be used as our new gravity laboratory and as a new absolute gravity site. The room itself was a part of an old "bomb shelter" and has a thick concrete floor. The first measurements with the instrument on Swedish ground therefore took place at this new gravity site, called LMV AA. Lots of measurements, mainly for test and practicing purposes, took place there before the instrument was transported to Mårtsbo in mid-December for measurements at an "old" site for the first time. During 2007, the instrument measured all Swedish FG5-sites existing at the time, except Smögen AA and Borås AA, including the two sites which were established in spring/summer 2007, Ratan AA and Lycksele AA. During 2007, the instrument also measured in four other countries, Finland (Metsähovi), Norway (Trysil and Vågstranda), Serbia (Grgeteg, Gradac and Sicevo) and Luxembourg (Walferdange, comparison). Between 2008 and 2015 the existing Swedish stations were measured at least four times. The only exception is Borås AA which was first measured in 2013 and 2014. Between 2008 and 2015 many sites in foreign countries were also measured: Finland (Metsähovi, 3 times), Norway (Trysil, 2 times and Vågstranda), Denmark (Tejn, 3 times and DTU in Copenhagen), Germany (Wettzell, 2 times), Luxembourg (Walferdange, 2 times and Belval), France (Paris), Former Yugoslav Republic of Macedonia (Ohrid, Valandovo and Skopje) and Bosnia-Hercegovina (Gomionica, Tavna, Sarajevo and Mostar).

The Swedish standard procedure to measure absolute gravity is according to the following:

- Two orientations, 24 hours in north orientation and 24 hours in south orientation
- 24 sets in every orientation (in 2007, 48 sets in every orientation)
- 50 drops (observations) per set
- All observations not within the 3 sigma level are regarded as outliers and are removed directly by the g-software

The frequency of the Rubidium clock has been calibrated regularly 2-3 times per year. The frequency used for computation is interpolated linearly between the measurements. In January 2009, Lantmäteriet purchased a GPS stabilised rubidium clock, which since then has been the most occurring reference to compare the FG5 clock frequency to. Before that, the clock calibrations were performed in Onsala where there is a hydrogen maser. When attending absolute gravity comparisons, the clock frequencies have been compared too and the reference frequency has then been supplied by the host of the comparison.

In 2009, Onsala Space Observatory, purchased a superconducting gravimeter. For the new instrument a new gravity building was built. In that building there is a room for the superconducting gravimeter and a room with three different pillars for FG5. The new FG5 stations are called Onsala AA, AB (so far, not measured) and AC. In 2013, the final measurements were performed in the old gravity building (Onsala AN and AS) and Onsala AA was also measured during the same stay. It is a wise choice to abandon the old sites, since there are some major heat problems in the old building, while the new building includes the best present gravity site(s) in Sweden.

3.4 Service and Comparison measurements

Just like all geodetic observations also absolute gravity observations are afflicted with errors, for instance errors related to the instrument, the software and/or the operator. These errors may occur as a random scatter or as a bias in the observed g-value and most of them tend to make the g-value lower (see e.g. Timmen et al 2014). It has been found that something, at least once, happened with the instrument during a service, introducing a new bias for the instrument (see below and Olsson et al. 2015). After a service, it is therefore very important to compare the instrument to an instrument with respect to which the difference was known before the service.

Lantmäteriet's FG5-233 has participated in several comparisons. Table 8 contains a brief summary of these. At all international comparisons, the weighted average of the participating instruments set the level.

Table 8: Summary of comparisons where FG5-233 has participated

Date	Location	Number of other instruments	Any specific instrument worth mentioning	Operator/s

February 2007	Metsähovi	1	FG5-221	JÅ, PAO
May 2007	Mårtsbo	1	FG5-220	AE, JÅ
August 2007	Trysil	1	FG5-226	AE, PAO
November 2007	Walferdange, ECAG2007	18	FG5-220, FG5-221, FG5-226, FG5-101, FG5-215	AE, PAO
April 2008	Trysil	1	FG5-226	AE, GL
September 2008	Metsähovi	1	FG5-221	GL, ML
September 2009	Paris, ICAG2009	20	FG5-220, FG5-221	GL, JÅ
September 2010	Onsala	1	FG5-226	PAO
November 2010	Wettzell, RICAG2010	4	FG5-220, FG5-101, FG5-301, FG5-215	AE
February 2011	Metsähovi	1	FG5-221	AE
November 2011	Walferdange, ECAG2011	21	FG5-220, FG5-221, FG5-301, FG5-215	AE, JÅ
May 2012	Mårtsbo	1	FG5-221	AE, FD
January 2013	Wettzell, RICAG2013	4	FG5X-220, FG5-101, FG5-301, FG5-215	AE, HS
May 2013	Mårtsbo	1	FG5-221	AE
November 2013	Walferdange, ICAG2013	22	FG5X-220, FG5X-221, FG5-101 or FG5-301, FG5-215	AE, JÅ
April 2014	Metsähovi	1	FG5X-221	AE
May 2014	Onsala	1	FG5X-220	AE
April 2015	Mårtsbo	1	FG5X-221	AE, HS
November 2015	Belval, ECAG2015	16	FG5X-220, FG5X-221, FG5-301, FG5-215	AE, PAO

AE = Andreas Engfeldt; FD=Fredrik Dahlström; GL=Geza Lohasz; HS=Holger Steffen; JÅ=Jonas Ågren; ML=Martin Lidberg; PAO=Per-Anders Olsson

FG5-101=BKG; FG5-215=Czech Republic; FG5-220=FG5X-220=IfE; FG5-221=FG5X-221=FGI; FG5-226=NMBU; FG5-301=BKG

FG5-233 has been four times on service at the manufacturer in USA, in the summer of 2008, after the field season in 2009, after the field season in 2011 and after the field season 2014. After the service in 2009/10, a new bias was introduced, a shift larger than 4 µGal. This has been confirmed by all comparisons the instrument has taken part in after that, but what caused it is still unknown. Whether something happened with the absolute level during the other three services is still under investigation, but if something happened the change was much smaller and much more difficult to determine with high significance. These issues are discussed in Olsson et al. (2015).

In order to deal with these suspected offsets, different absolute levels for the instrument between the services could be assumed, which e.g. means that the level of the observations performed between autumn 2006 and summer 2008 should have an absolute level according to the ECAG2007, the level of the observations performed between autumn 2008 and winter 2009 should have an absolute level according to the ICAG2009 etc. This is further discussed in Engfeldt (2016). How to use the data from other instruments in order to get a longer time series, like the FG5 measurements from IfE, is also discussed further there.

3.5 A-10 observations in Sweden

In July 2011 A-10-020 visited Sweden for measurements at 12 sites. This was performed as a test to see if A-10 measurements were suitable for determining our old outdoor sites (i.e. the RG 62- or RG 82-sites; see Engfeldt 2016). The instrument was owned by IGiK and operated by Marcin Sekowski (IGiK), with assistance of Andreas Engfeldt. The test measurements were conducted such that on each site two measurements were performed with the instrument oriented in two different directions (120 degrees in between, since with this instrument the influence of the Coriolis Force is not significant, according to Marcin Sekowski), four times in the blue laser mood and four times in the red laser mood per orientation. In case the results from the two orientations differed less than 15 µGal they were considered good enough, otherwise one more orientation was measured. The result from these measurements was very satisfactory, so it was decided that four more campaigns with A-10 should be performed, two in 2012, one in 2013 and one in 2015, in order to get connections to the old networks and to fill Sweden. In total, 98 sites were visited, of which three were the FG5-sites Mårtsbo AA, Onsala AA and Kiruna AA. These three sites were used as reference values to check that the A10 results were reliable. One of the sites, Boda Bruk, was measured both during 2012 and 2013 due to an unexpected measured value in 2012, later found to be a gross error which could easily be corrected. The Boda Bruk results from the different years were separated within 1 μGal. During the measurements in 2015, 8 more of the previously measured sites were re-measured, just as a check.

In addition, also another A-10 has been observing in Sweden. In April and June 2012, A10-019, owned by DTU Space, measured along the 56th degree land uplift line. Unfortunately it was not possible to measure the sites in Höör and Sölvesborg with an A-10. Therefore, new sites were established at Höör church and Sölvesborg church (the step outside the western door was included in RG 62, but this had to be the step outside the southern door, since the RG 62 step was not suitable for A-10) to be connected to the old sites by relative gravimetry. A-10-019 was operated by Jens Emil Nielsen (DTU Space) and the relative measurements were performed by Andreas Engfeldt and Gabriel Strykowski (DTU Space). For the relative measurements LCR G290 (just back from repair), Scintrex CG5-740 and two Danish Scintrex CG5s were used.

*Table 9: Available A-10 observations in Sweden, measured by A-10-020 except * measured by A-10-019.*

Date	Site	Lat	Long	H	Gradient
2011-07-21	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2011-07-21	Ljusnarsberg AA	59 52 37,6	14 59 52,2	176	-332,5
2011-07-22	Arboga AA	59 23 39,3	15 50 28,8	8,000	-305,8
2011-07-22	Tullinge AA	59 12 44,7	17 52 55,4	42,592	-343,7
2011-07-23	Nyköping AA	58 45 36,0	17 02 57,1	27,575	-337,9
2011-07-23	Valla AA	59 01 25,0	16 21 46,9	52,817	-334,2
2011-07-24	Karlstad AA	59 22 21,5	13 28 48,8	54,446	-325,4
2011-07-24	Säffle AA	59 07 35,7	12 52 58,2	73,812	-353,4
2011-07-25	Årjäng AA	59 23 24,0	12 07 55,7	116,634	-310,9
2011-07-25	Fryksände AA	60 08 15,6	13 00 50,4	105,5	-321,4
2011-07-26	Stöllet AA	60 28 13,0	13 18 11,0	299,529	-314,5
2011-07-26	Vansbro AA	60 30 54,6	14 16 03,5	246,433	-329,0
2011-07-27	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2012-06-05	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2012-06-05	Sundsvall AA	62 23 28,6	17 17 58,2	16	-282,9
2012-06-06	Ragunda AA	63 06 36,2	16 22 15,7	167,5	-335,7
2012-06-06	Kramfors D	62 52 20,2	17 56 15,0	117,865	-301,7

2012-06-06	Örnsköldsvik AA	63 17 37,5	18 42 44,3	47,907	-324,5
2012-06-07	Sävar A	63 57 41,5	20 39 20,8	54,596	-347,3
2012-06-07	Hörnefors AA	63 38 21,0	19 54 41,9	11,791	-351,8
2012-06-07	Holmsund AA	63 40 21,9	20 23 19,8	5,306	-325,9
2012-06-08	Bjurholm AA	63 55 47,4	19 16 09,3	233,531	-334,5
2012-06-08	Åsele AA	64 09 49,1	17 21 17,1	336,487	-342,7
2012-06-08	Vilhelmina AA	64 37 47,0	16 38 42,5	401,031	-376,5
2012-06-09	Stensele AA	65 03 55,1	17 09 52,5	332,596	-335,4
2012-06-09	Umbukta AA	66 08 06,2	14 35 27,7	526,516	-333,2
2012-06-11	Klimpfjäll AA	65 03 28,2	14 47 04,8	582,961	-294,8
2012-06-11	Sved AA	64 18 51,7	14 57 40,9	358,516	-329,2
2012-06-12	Hammerdal AA	63 35 42,3	15 21 51,1	308,92	-326,7
2012-06-12	Östersund AB	63 10 17,3	14 38 31,7	316,707	-282,4
2012-06-13	Stugun AA	63 09 58,7	15 36 57,5	223,619	-321,7
2012-06-13	Duved AA	63 23 34,6	12 55 45,2	401	-307,5
2012-06-14	Svenstavik AA	62 48 51,3	14 31 03,1	313,041	-314,2
2012-06-14	Överturingen AA	62 27 03,4	14 55 03,4	268,646	-327,9
2012-06-14	Hede AA	62 25 04,2	13 31 01,3	420,595	-295,6
2012-06-15	Transtrand AA	61 05 17,5	13 18 46,3	357,897	-288,2
2012-06-15	Älvdalen AA	61 13 34,1	14 02 28,4	241,9	-312,6
2012-06-16	Bollnäs AA	61 20 44,5	16 23 21,8	61,46	-304,8
2012-06-16	BodaBruk AA	61 32 03,0	16 55 25,0	65,942	-326,7
2012-09-11	Simrishamn AA	55 34 35,9	14 20 02,6	13,146	-314,1
2012-09-11	Maglarp AA	55 22 57,0	13 04 10,2	14,398	-328,0
2012-09-12	Helsingborg AA	56 04 51,7	12 41 08,5	44,463	-305,1
2012-09-12	Veinge AA	56 34 18,5	13 05 32,7	41,307	-320,2
2012-09-12	Kärda AA	57 10 21,3	13 55 06,1	179,337	-307,8
2012-09-13	Ulricehamn AA	57 47 27,0	13 24 45,5	183,536	-317,5
2012-09-13	Onsala AA	57 23 47,0	11 55 33,2	7,5	-316,0
2012-09-14	Grinneröd AA	58 11 26,3	11 57 17,4	87,905	-325,0
2012-09-14	Tanum AA	58 42 57,9	11 19 58,5	45,595	-309,5
2012-09-15	Vara AA	58 17 09,2	12 57 32,5	80,155	-326,9
2012-09-15	Mariestad AA	58 41 25,2	13 48 40,8	66,759	-322,9

2012-09-15	Laxå AA	58 58 56,5	14 37 31,9	104,944	-328,2
2012-09-17	Svinnegarn AA	59 35 17,2	17 00 02,7	9,25	-298,6
2012-09-17	Öregrund AA	60 19 41	18 24 09	6,46	-332,9
2012-09-18	Husby-Ärlinghundra AA	59 38 24,2	17 52 55,6	22,367	-305,8
2012-09-18	Norrköping AA	58 35 02,2	16 08 27,8	32,377	-325,2
2012-09-18	Ljusfallshammar AA	58 48 06,0	15 25 53,3	101,891	-336,6
2012-09-19	Västra Tollstad AA	58 16 39,8	14 39 20,1	104,48	-328,6
2012-09-19	Eksjö AA	57 40 01,9	14 58 17,0	212,25	-318,8
2012-09-20	Gamleby AA	57 53 45,1	16 23 56,6	20,144	-317,6
2012-09-20	Misterhult AA	57 26 34,5	16 34 13,9	14,053	-316,4
2012-09-20	Ljungbyholm AA	56 37 56,8	16 10 07,0	15,657	-310,6
2012-09-21	Köpingsvik AA	56 52 41,0	16 43 06,2	11,871	-309,6
2012-09-21	Emmaboda AA	56 37 22,4	15 34 50,3	126,785	-340,1
2012-09-21	Öjaby AA	56 54 25,5	14 44 24,7	167,946	-297,0
2012-09-22	Älmhult AA	56 33 11,1	14 07 44,0	145,547	-327,2
2012-09-22	Augerum AA	56 13 00,4	15 40 31,8	22,168	-315,8
2013-07-01	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2013-07-02	Sollefteå AA	63 09 44,0	17 17 01,8	53,258	-326,1
2013-07-02	Norsjö AA	64 54 52,3	19 28 34,3	310,055	-332,5
2013-07-03	Sorsele AA	65 32 30,6	17 30 53,5	345,874	-325,5
2013-07-03	Arjeplog AB	66 03 04,0	17 54 18,5	431,203	-332,6
2013-07-04	Arvidsjaur AA	65 35 44,6	19 10 01,7	387,473	-229,8
2013-07-04	Kåbdalis NA	66 06 22,8	19 55 24,9	350,877	-351,8
2013-07-05	Gällivare AA	67 07 56,0	20 39 34,1	365,483	-331,3
2013-07-05	Tärendö AA	67 09 24,2	22 38 09,8	176,343	-337,0
2013-07-07	Kiruna AA	67 52 39,4	21 03 36,7	466,593	-363,9
2013-07-07	Karesuando AA	68 26 30,2	22 28 51,7	330,435	-329,7
2013-07-08	Övertorneå AA	66 23 51,3	23 33 24,5	89,517	-320,6
2013-07-08	Hundsjön AA	65 56 33,9	21 49 37,6	28,219	-300,9
2013-07-09	Luleå AA	65 34 57,7	22 08 54,4	14,906	-323,1
2013-07-09	Bureå AA	64 37 05,7	21 12 11,7	11,019	-312,7
2013-07-11	BodaBruk AA	61 32 03,0	16 55 25,0	65,942	-326,7

2013-07-11	Ljusdal AA	61 49 41,3	16 04 19,7	135,065	-332,2
2013-07-12	Sveg AA	62 02 01,9	14 21 42,2	359,210	-321,0
2013-07-12	Särna AA	61 41 41,7	13 08 30,8	462,400	-312,7
2013-07-13	Leksand AA	60 43 51,6	14 58 57,4	176,950	-323,0
2013-07-13	Fredriksberg AA	60 08 18,8	14 22 47,5	298,497	-372,8
2013-07-13	Grytnäs AA	60 10 02,6	16 13 13,9	75,900	-297,9
2013-07-14	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2015-05-28	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2015-05-28	Norrtälje AA	59 43 36,7	18 51 30,1	4,281	-315,1
2015-05-28	Solna AA	59 21 10,5	18 01 26,4	14,5	-300,3
2015-05-29	Tullinge AA	59 12 44,7	17 52 55,4	42,592	-343,7
2015-05-29	Arboga AA	59 23 39,3	15 50 28,8	8,000	-305,8
2015-05-30	Rimforsa AA	58 09 19,0	15 40 48,6	88,179	-349,4
2015-05-30	Virserum AA	57 12 27,3	15 31 21,5	206,299	-354,7
2015-06-01	Falkenberg AA	56 54 07,5	12 29 21,2	9,4	-307,4
2015-06-01	Baltak AA	58 08 52,5	13 56 00,4	165,145	-318,3
2015-06-02	Klöveskog AA	58 38 40,4	12 36 56,3	67,3	-340,1
2015-06-02	Munkfors AA	59 51 22,7	13 35 41,0	157,939	-310,7
2015-06-03	Transtrand AA	61 05 17,5	13 18 46,3	357,897	-288,2
2015-06-03	Voxna AA	61 21 55,2	15 30 52,2	200,187	-313,1
2015-06-04	Borgsjö AA	62 32 23,8	15 54 23,7	131,5	-318,0
2015-06-04	Östersund AB	63 10 17,3	14 38 31,7	316,707	-282,4
2015-06-05	Junsele AA	63 41 32,1	16 54 00,4	232,740	-337,2
2015-06-05	Åsele AA	64 09 49,1	17 21 17,1	336,487	-342,7
2015-06-05	Stensele AA	65 03 55,1	17 09 52,5	332,596	-335,4
2015-06-06	Älvsbyn AA	65 42 24,3	21 04 35,7	72,787	-314,4
2015-06-07	Luleå AA	65 34 57,7	22 08 54,4	14,906	-323,1
2015-06-08	Haparanda AA	65 48 59,6	24 07 40,6	15,240	-329,0
2015-06-09	Härnösand AA	62 37 52,3	17 56 28,5	16,526	-322,0
2015-06-09	Sundsvall AA	62 23 28,6	17 17 58,2	16	-282,9
2015-06-10	Mårtsbo AA	60 35 42,0	17 15 32,4	43,695	-293,6
2012-04-16	Sölvesborg AA*	56 03 11,3	14 35 05,1	8,677	-289,0
2012-06-25	Höör AA*	55 55 52,2	13 32 59,0	72,2	-330,5

3.6 Gradient measurements

When using the measurements at our absolute gravity stations as a basis for relative gravimetry, the absolute gravity value normally has to refer to a bolt (or similar) on the ground. On the other hand, when measuring with and comparing different FG5 instruments, the gravity value is normally given 1,200 meters above the ground. In order to transfer the value from 1,200 meters to 0,000 meters as accurately as possible, one must measure the so called vertical gravity gradient. This is something which in its easiest form means measuring the gravity difference between as close to 0,000 meters as possible and as close to 1,200 as possible with a relative gravimeter

Figure 13: Andreas Engfeldt measuring the gradient in Skopje with LCR G54. Photo: Robert Odolinski.

In order to get the lowest possible uncertainty, one has to measure with several different setups and at different heights. This is the way gradient measurements are performed at our FG5 sites, but for the A-10 sites a different approach was used. Based on previous experience, the difference between doing e.g. three setups and one setup (close to the correct sensor height, which means around 70 cm for an A-10) is very small and usually negligible. So in order to save time, here the gradient measurements were performed only with one setup (which means measuring like the protocol in Appendix 2 shows). With two exceptions, all the A-10 gradient measurements were performed by Andreas Engfeldt and the instruments Scintrex CG5-740 (2011-2013) or Scintrex CG5-1184 (2015). At every site, twelve independent differences were measured. These differences were paired two and two (A-B, B-A) and a mean value was calculated. With this procedure the possible drift of the relative gravimeter is eliminated. The six mean differences had to be within 10 µGal. If not, more differences were measured. An example of a gradient protocol can be seen in Appendix 2. The gradient at the sites Höör AA and Sölvesborg AA were measured by Gabriel Strykowski and Jens Emil Nielsen with the two Danish Scintrex gravimeters.

The measured gradient at our FG5 stations is also used directly in the g software for transferring the absolute g value from where it is measured (at approximately 1,29 m, depends on the setup) to the referred used reference height (at 1,20 m). However, due to the small difference, for this application the quality in the gradient measurements is not as important as for transferring the g-value to the ground.

4 Reconnoitring of RG 62 and RG 82 sites

During 2011 most RG 62 and RG 82 sites were visited by Andreas Engfeldt, in order to investigate which ones were suitable for the upcoming RG 2000, e.g. which sites that still existed, how easy they were to access and in particular, which were possible to measure by A-10. During these visits, the sites were photographed and measured with the best possible GNSS solution. Unfortunately, at this point the Virtual RINEX technique was not considered since it had not yet been tested. This technique would have been excellent to use at many places where there was no existing GSM connection. This meant that more than 20% of the found sites which were considered usable only got an absolute GNSS position. For sites which consist of a levelled benchmarks (all the RG 82 sites are benchmarks, but a few of them are not levelled), this has no significance at all, but for the rest the degradation in height is quite large and it is recommended that the heights of these sites are measured again if they will be used for RG 2000.

4.1 Status of the RG 62 sites

91 of the RG 62 sites were found and considered usable. Additionally, 24 other RG 62 sites were found and considered unusable or destroyed. However, out of the destroyed ones, two (Karesuando and Norsjö) could be moved some 5-25 metres to very suitable places for RG 2000 and have later been measured with A-10 and will be included in the upcoming RG 2000 system.

13 of the 91 usable RG 62 sites only got an absolute GNSS-position. If they will be used for RG 2000, it is recommended that they are re-measured by a more accurate GNSS method.

Most of the RG 62 sites are located on church steps, but for many of them the site description did not make it clear exactly where on the church step the site was really situated. In these cases Andreas Engfeldt decided where the site shall now be situated and then measured two perpendicular distances to the sides of the stone slab. And in fact at all churches, new measurements were taken of the stone slabs.

10 of the sites were in airport buildings. None of them were visited, since the access to these places is very restricted and it is extremely unlikely that the sites still are there due to new construction works.

10 of the sites were at railway stations, either on the platform or on a step of the station building. Most of them were found destroyed and only one of them, Moskosel, was good enough for the new RG 2000

network. Still it was decided that there are better sites to use in that neighbourhood.

23 of the sites were coincided with benchmarks. 12 of them were found destroyed in one way or another. For example all sites which were on stones close to churches had been dug up. The steps at Ljungby church had just been renovated and when doing the reconnoitring Andreas talked to one of the workers. The worker said that he had put back the stone with the benchmark at another place, one step higher up than originally, something which also was very obvious when checking the site description.

4.2 Status of the Zero Order RG 82 sites

14 of the 49 Zero Order RG 82 sites found only got an absolute GNSS-position. All these sites are levelled benchmarks, so this has no significance at all.

Hofors A and Karlstad NB were previously reported destroyed (which was proved to be correct). Höör A, Västervik NB and Visby NB were not found despite long searches. The two first mentioned are probably still there, but under some decimetres of mouldered leaves. Because of the not so detailed maps and coordinates it was impossible to dig at the correct place.

Älvdalen B and Stensele A are found to be extremely unusable for further use. Göteborg A is situated at Chalmers and indoors, in a locked room filled with used furniture. The site description in Haller & Ekman (1988) was also bad, but in Cannizzo et al (1978) a much better site description exists. To find the bolt, lots of chairs and tables need to be moved. No key to the door can be found at Chalmers, but can be obtained from a property company. All these things together make this site also less suitable for RG 2000, something that goes well together with the decision by Lars Åke Haller in 1992 to abandon it for absolute gravity.

4.3 Status of the first order RG 82 sites

34 of the 137 first order RG 82 sites found only got an absolute GNSS-position. All first order RG 82 sites are levelled, so this has no significance at all.

Alby (in Medelpad) and Torsby (reported destroyed in 1995) were the only two of the RG 82 first order sites which were found destroyed (because of a new pipe line and because of making the road wider). Laholm, Lagan, Aneby, Tanum, Ludvika, Mora and Särna were not found. With the exception of Lagan, which was situated under a 5x5x2 m pile of wood, a quite long unsuccessful search was done for all of them. Särna and Tanum are not destroyed, though, but forestry has resulted in layers of soil that cover them and the measured distances on the site description were not accurate enough to find them. Laholm was found a few years later and is planned to be visited during 2016.

Figure 14: The First Order RG 82-site Arvika.

The two sites Gotska Sandön and Kastlösa were never visited and their status in 2011 is unknown. However, Kastlösa is planned to be visited in 2016. Fredrika, Åsele and Sorsele were found to be unusable by different reasons.

In 2013, Arvidsjaur was meant to be measured by the Polish A-10 absolute gravimeter (for the upcoming RG 2000 network). Unfortunately it was found that, after the reconnoitring in 2011, some big force (probably the snowplough car) had partly destroyed the bolt. This makes the site unusable. In 2015, Säffle, which was measured by A-10 in 2012, was partially destroyed after a new roundabout had been built nearby. In 2015, Rättvik was found destroyed.

5 Summary

The present gravity system in Sweden, RG 82, is based on four absolute gravity measurements from 1976 by an old Italian instrument. The Zero Order Network consists of 25 sites spread all over Sweden and was measured relatively with two LaCoste & Romberg gravimeters in 1981-82. Today, 40 years after these absolute measurements, the absolute gravimeters are at a totally different standard and uncertainty. Since autumn 2006, Lantmäteriet owns an FG5 absolute gravimeter (FG5-233) and measures regularly at 13 different stations all over Sweden with very low uncertainty (1-2 µGal). With one exception, we now have time series of at least 6 years only with our own instrument and if combining with other instruments we have even longer time series with good absolute gravity data. We also have measurements made with the absolute gravimeter A-10 at 97 other places all over Sweden, which has an uncertainty of about 10 µGal. 45 of the 97 sites measured by A-10 are included in either the present gravity network or a previous one. The new A-10 sites are with a few exceptions situated within 30 km from a RG 82 site. We also have relative measurements which connect the absolute gravity sites to the present and old networks. How to use the data in order to establish a new gravity system is described in Engfeldt (2016).

References

Boedecker, G. et al (2005): *Unified European Gravity Reference Network 2002 (UEGN02) – Status 2004*. IAG 2005, 286-291.

Cannizzo, L & Cerutti, G (1978): *Absolute-Gravity measurements in Europe*. Il Nuovo Cimento Vol 1C, N.1, January-February 1978, 39-85.

Ekman, M (2009): *The changing level of the Baltic Sea during 300 years: A Clue to Understanding the Earth.*

Engfeldt, A. (2014): *Status report from the ongoing work with the new Swedish Gravity System RG 2000.* NKG General Assemby, poster.

Engfeldt, A. (2016): *RG 2000 – further plans*. Lantmäterirapport 2016:2.

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

Haller, L. Å. & Ekman, M. (1988): *The fundamental gravity network of Sweden.* LMV-rapport 1988:16.

Micro-g LaCoste (2006): *FG5 User's Manual.*

Micro-g LaCoste (2008): *A-10 Portable Gravimeter User's Manual.*

Mäkinen, J. et al (1986): *The Fennoscandian land uplift gravity lines 1966-1984.* FGI report 85:4.

Mäkinen, J., Engfeldt, A., Harsson, B.G., Ruotsalainen, H., Strykowski, G., Oja, T., Wolf, D. (2005): *The Fennoscandian land uplift gravity lines 1966-2004.* In: Jekeli, C., Bastos, L., Fernandes, J. (Eds), Gravity, Geoid and Space Missions, vol 129 of International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, pp. 328-332.

Niebauer, T. et al (1995): *A new generation of absolute gravimeters,* Metrologia 1995, 32, 159-180.

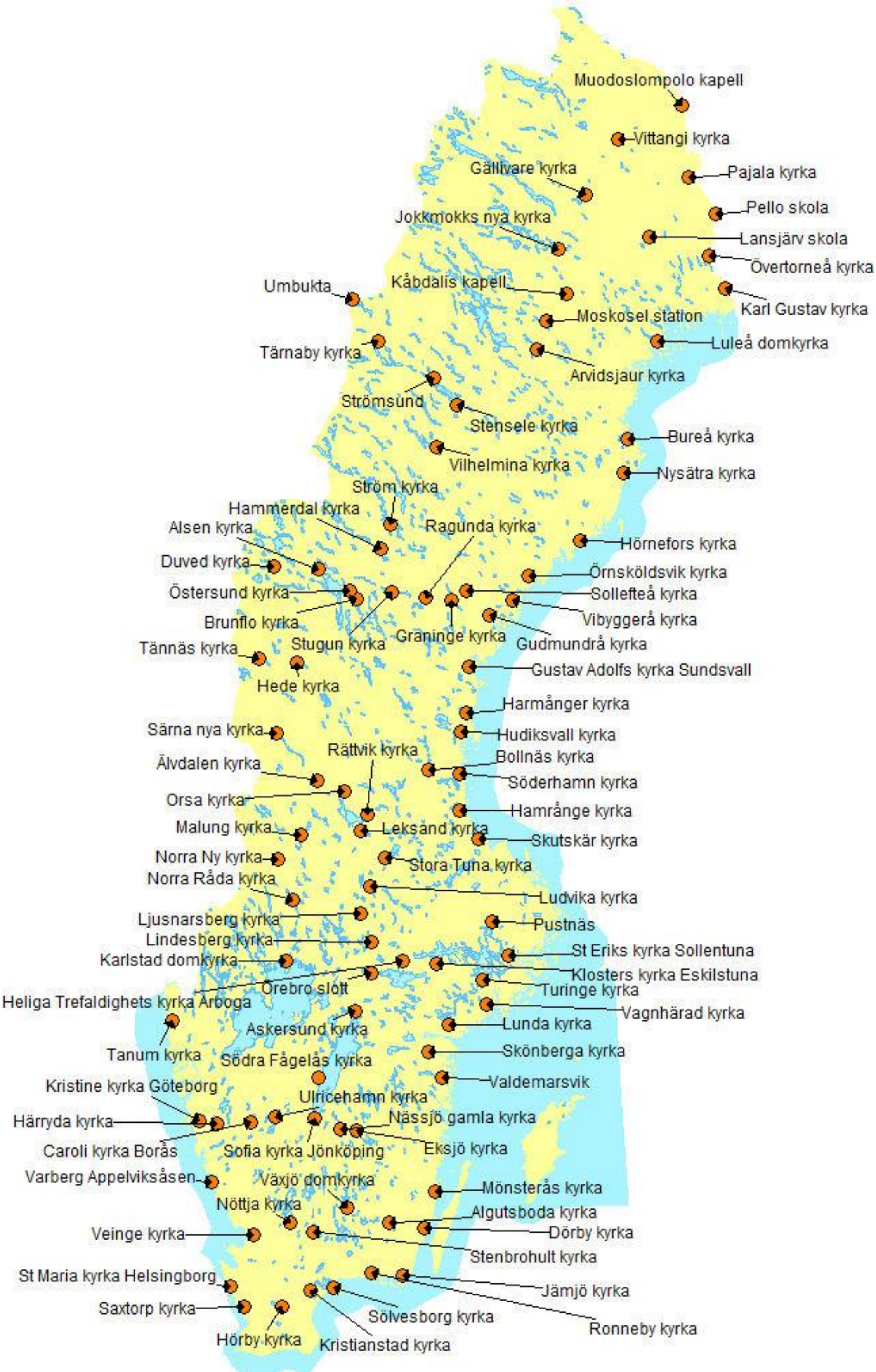
Olsson, P.-A. & Engfeldt, A. & Ågren, J. (2015): *Investigations of a suspected jump in Swedish repeated absolute gravity time series.* IUGG 2015, proceedings.

Pettersson, L. (1967): *The Swedish first order gravity network.* Rikets Allmänna Kartverk, Meddelande nr A 35.

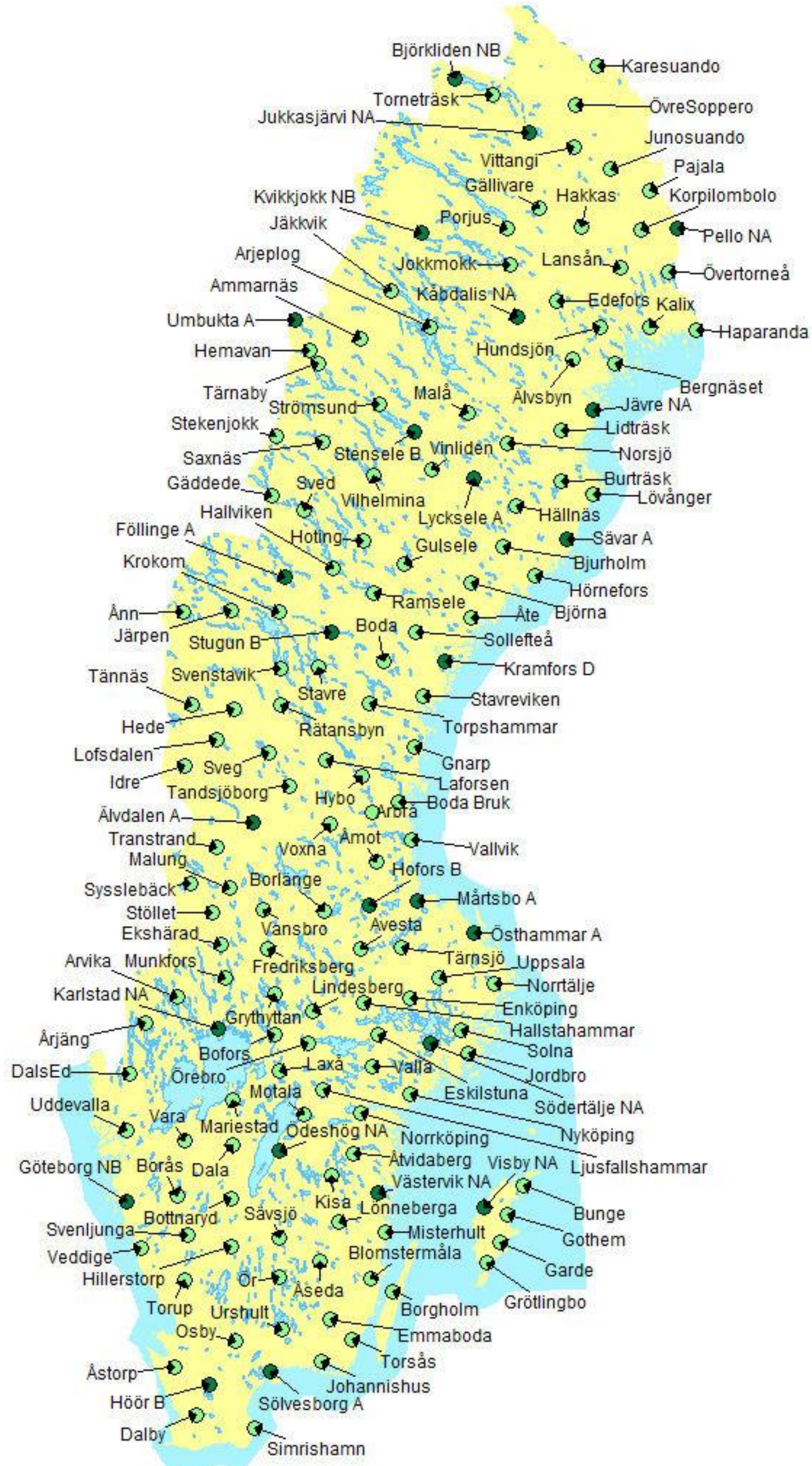
Timmen, L. & Engfeldt, A. & Scherneck H-G. (2014): *Observed secular gravity trend at Onsala station with the FG5 gravimeters from Gävle and Hannover.* NKG General Assembly, proceedings.

Ågren, J. & Engberg, L. (2010): *Om behovet av nationell geodetisk infrastruktur och dess förvaltning i framtiden.* Lantmäterirapport 2010:11.

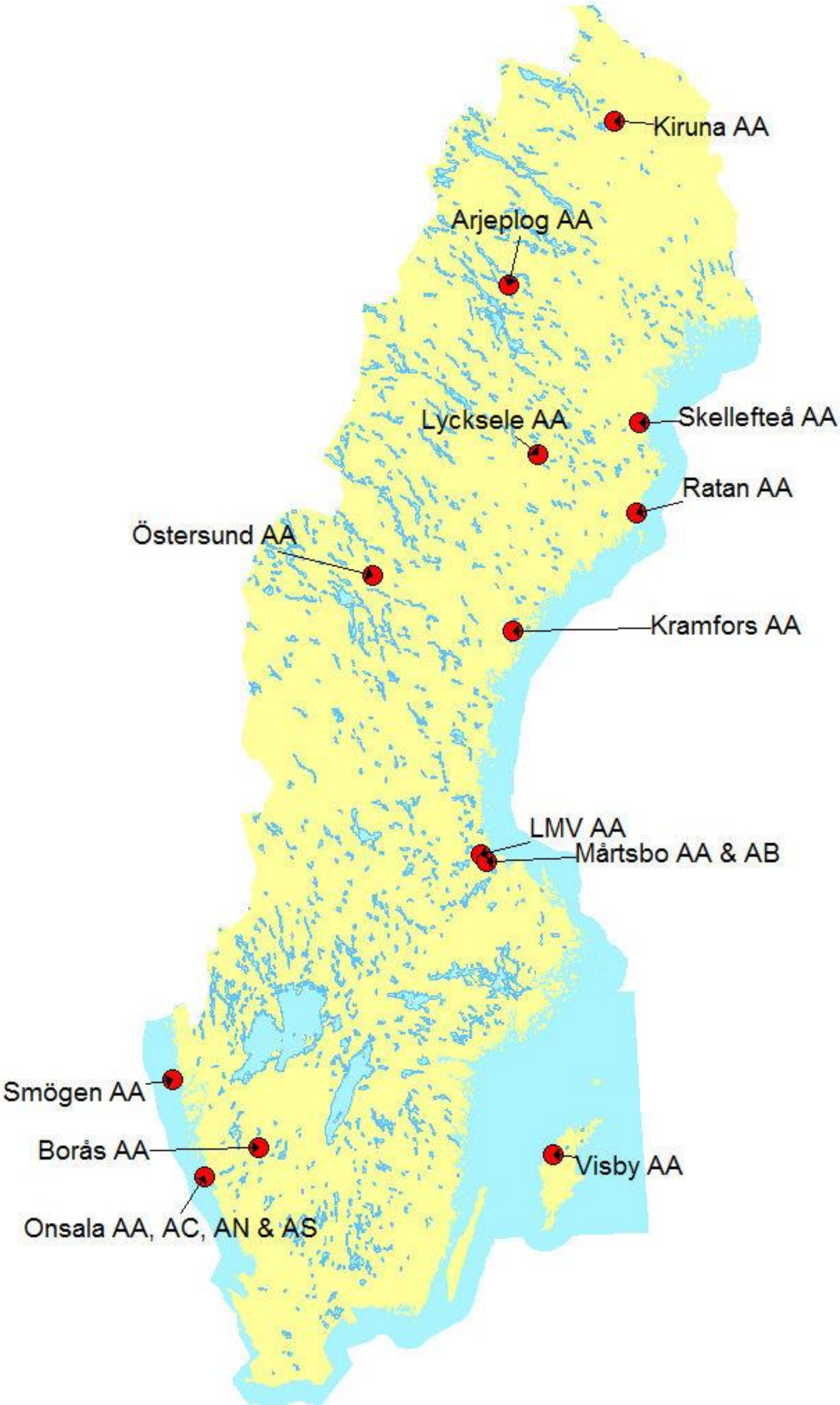
Appendix 1. Maps



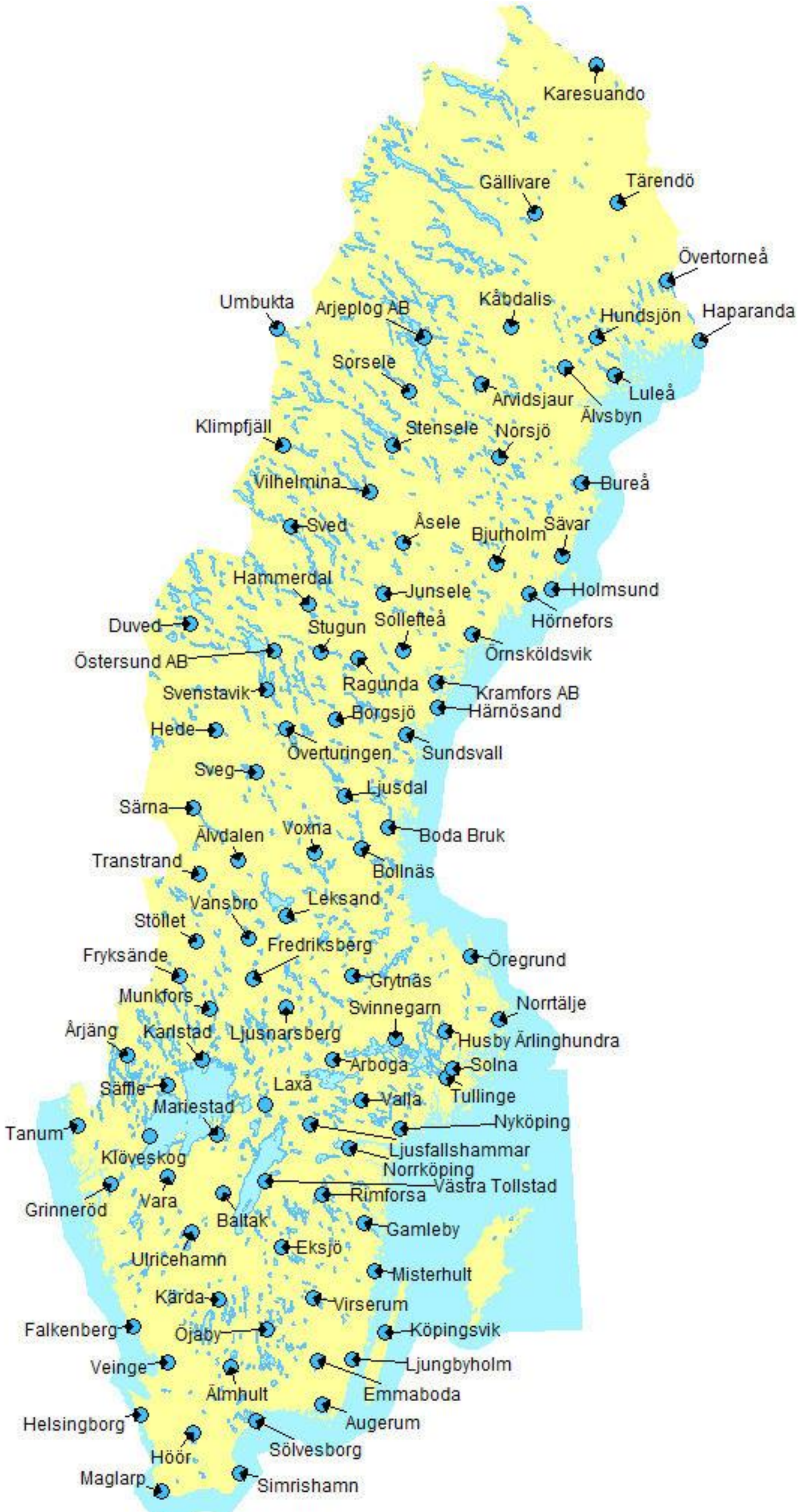
Map 1: Locations of the 91 still usable RG 62-sites



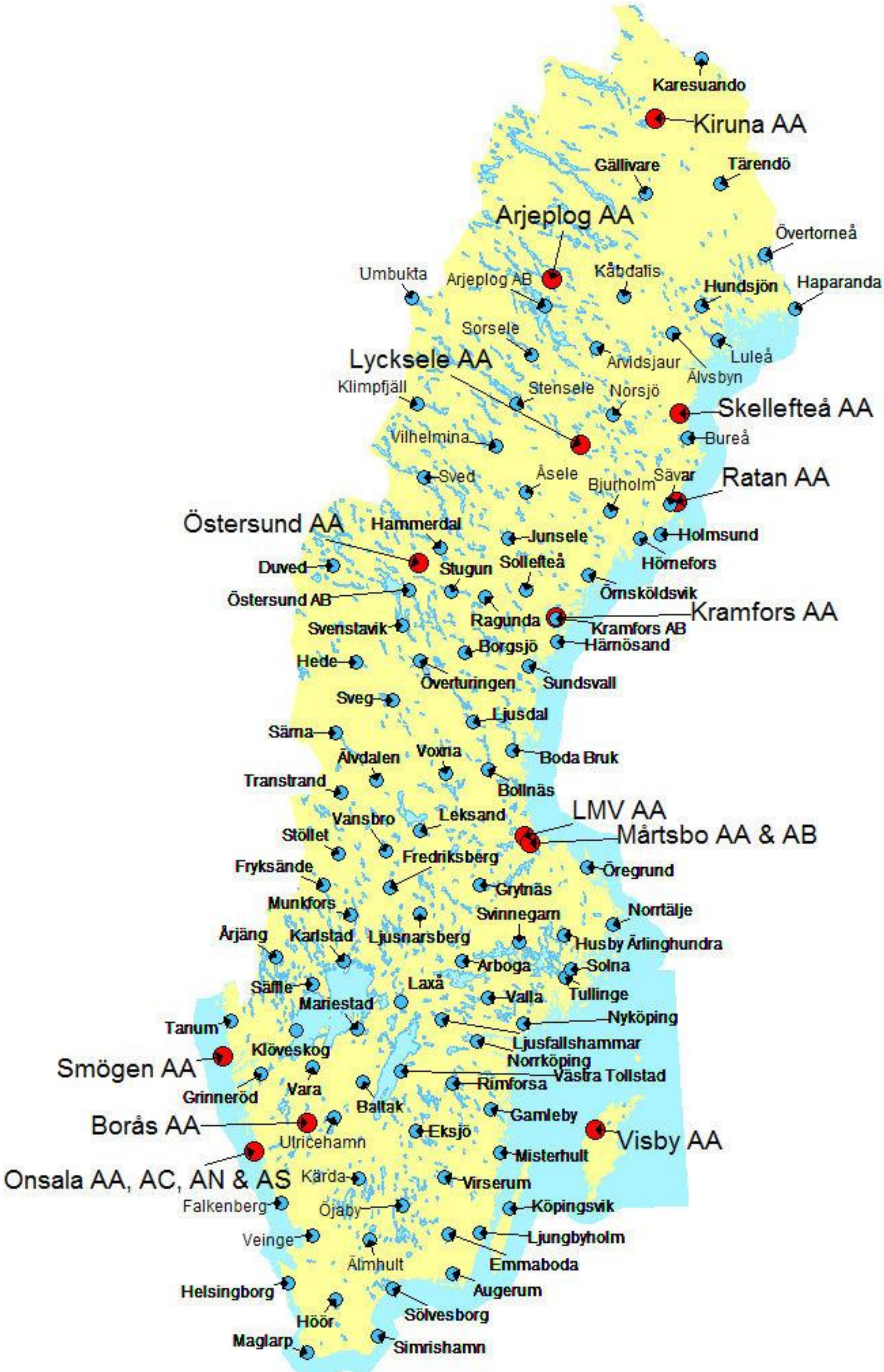
Map 2: Locations of the 25 main sites of the Zero Order RG 82-sites and the 131 still usable First Order RG 82-sites



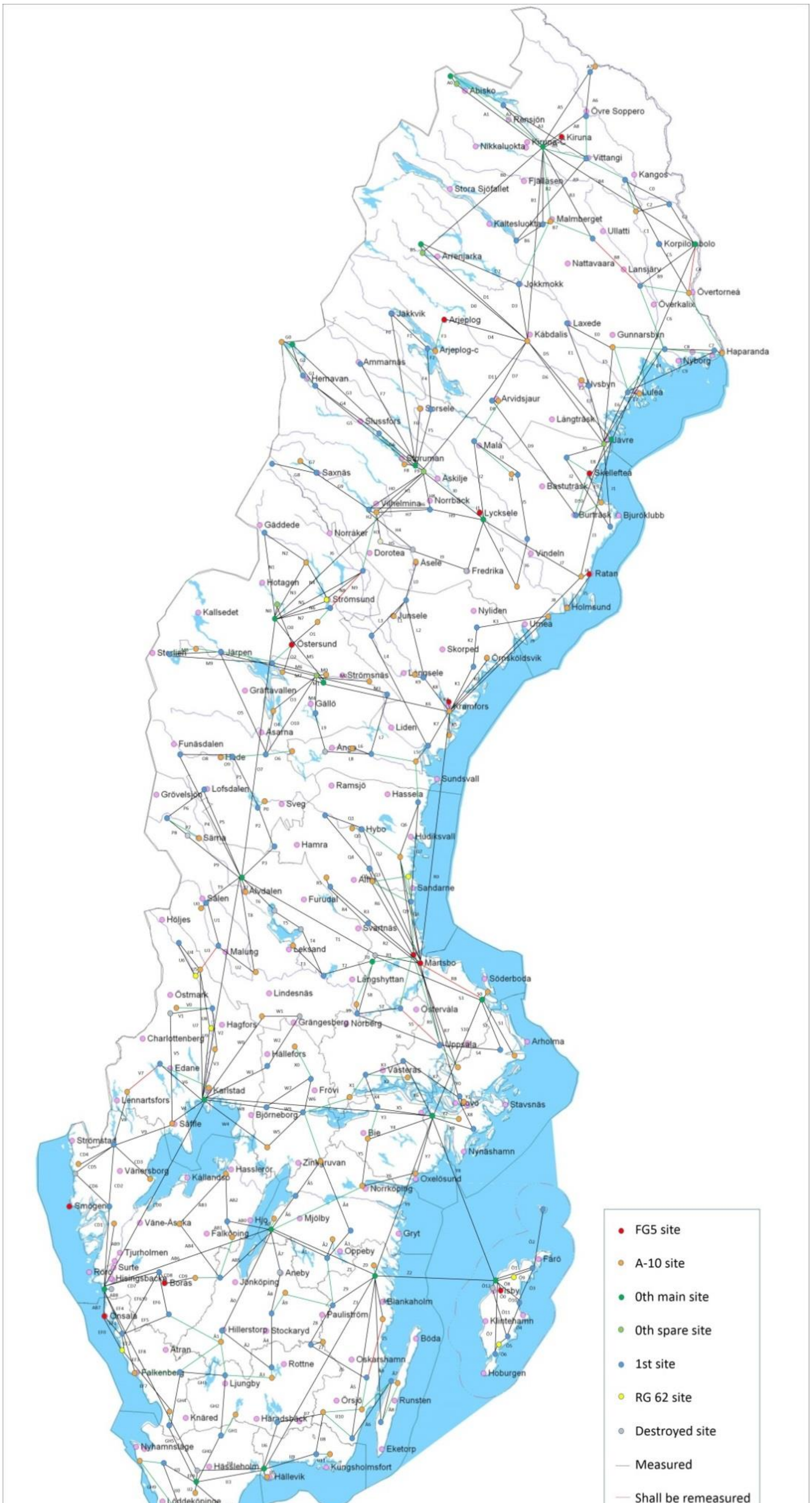
Map 3: Locations of the 13 FG5-sites



Map 4: Locations of the 97 A-10-sites



Map 5: Locations of all FG5- and A-10-sites



Map 6: The RG 2000 network as it will look in autumn 2016

Appendix 2. Gradient measurements for the A-10 sites

Example of a gradient measurement, in Arjeplog

Gradient Log Sheet, Scintrex

LANTMÄTERIET

		DATE (YYMMDD) 130912
		TEAM Lantmäteriet
		STATION NAME Arjeplog AB
		LATITUDE 66 03 04,0
OBSERVED BY Andreas Engfeldt	START TIME (UTC) 11:10	LONGITUDE 17 54 18,5
INSTRUMENT CG5-740	STOP TIME (UTC) 11:55	ELEVATION (m) 431,203

SITE	READING	σ	DIFF (UP-DOWN)	MEAN OF DIFFS (µgal)	MEAN OF MEANS	
DOWN 1	7093,160	0,024	-0,300	-297,0	UP - DOWN	-296,7
UP 1	7092,860	0,015				
UP 2	7092,864	0,026	-0,294		HEIGHTS (m)	
DOWN 2	7093,158	0,018			UP - DOWN	0,892
DOWN 3	7093,161	0,016	-0,297	-297,0		
UP 3	7092,864	0,021			UP - GROUND	1,326
UP 4	7092,866	0,015	-0,297			
DOWN 4	7093,163	0,019			DOWN - GROUND	0,434
DOWN 5	7093,161	0,013	-0,295	-297,5		
UP 5	7092,866	0,019			ADJ SENS HEIGHTS (+0.119 m)	
UP 6	7092,867	0,018	-0,300		UP - GROUND	1,445
DOWN 6	7093,167	0,017				
DOWN 7	7093,162	0,020	-0,295	-295,0	DOWN - GROUND	0,553
UP 7	7092,867	0,021				
UP 8	7092,869	0,024	-0,295		ORANGE FIELDS GOES INTO THE GRADIENT SOFTWARE.	
DOWN 8	7093,164	0,015				
DOWN 9	7093,165	0,015	-0,296	-295,0	STD DEV (1 OBS) (µgal)	
UP 9	7092,869	0,018			± 1,40	
UP 10	7092,869	0,025	-0,294		STD DEV (MEAN) (µgal)	
DOWN 10	7093,163	0,014			± 0,57	
DOWN 11	7093,167	0,017	-0,297	-298,5	SEISMIC FILTER IS	ON OFF
UP 11	7092,870	0,018			PRELIMINARY GRADIENT	
UP 12	7092,865	0,021	-0,300		GRAD= -332,6	
DOWN 12	7093,165	0,016				

Reports in Geodesy and Geographical Information Systems from Lantmäteriet (the Swedish mapping, cadastral and land registration authority)

2010:2 Odolinski Robert: Studie av noggrannhet och tidskorrelationer vid mätning med nätverks-RTK.

2010:3 Odolinski Robert: Checklista för nätverks-RTK.

2010:4 Eriksson Per-Ola (ed.): Höjdmätning med GNSS – vägledning för olika mätsituationer.

2010:5 Eriksson Per-Ola (ed.): Anslutning av lokala höjdnät till RH 2000 med GNSS-stommätning.

2010:6 Engfeldt Andreas & Odolinski Robert: Punktbestämning i RH 2000 – statisk GNSS-mätning mot SWEPOS.

2010:7 Lord Jonas: Test av GNSS-mottagare från DataGrid.

2010:11 Ågren Jonas & Engberg Lars E: Om behovet av nationell geodetisk infrastruktur och dess förvaltning i framtiden.

2011:2 Jansson Jakob: Undersökning av mätosäkerheten i det förtätade SWEPOS-nätet i Stockholmsområdet – vid mätning med nätverks-RTK.

2011:3 Liu Ke: A study of the possibilities to connect local levelling networks to the Swedish height system RH 2000 using GNSS.

2012:3 Lundell Rebecka: Undersökning av nätverks-RTK-meddelande tillsammans med olika GNSS-mottagare – vid nätverks-RTK-mätning i SWEPOS nät av fasta referensstationer.

2014:2 Vestøl Olav, Eriksson Per-Ola, Jepsen Casper, Keller Kristian, Mäkinen Jaakko, Saaranen Veikko, Valsson Guðmundur, Hoftuft Olav: Review of current and near-future levelling technology – a study project within the NKG working group of Geoid and Height Systems.

2014:5 Ohlsson Kent: Studie av mätosäkerhet och tidskorrelationer vid mätning med nätverks-RTK i SWEPOS 35 km-nät.

2015:1 Fredriksson Annika & Olsson Madeleine: Jämförelse av höjdmätning med olika GNSS-mottagare i SWEPOS Nätverks-RTK-tjänst.

2015:2 Norin Dan, Johansson Jan M, Mårtensson Stig-Göran, Eshagh Mehdi: Geodetic activities in Sweden 2010–2014.

2015:4 Andersson Bengt, Alfredsson Anders, Nordqvist Anders, Kilström Ronald: RIX 95-projektet – slutrapport.

2016:2 Engfeldt Andreas: Preparations and plans for the new national gravity system, RG 2000.

LANTMÄTERIET

Vaktmästeriet 801 82 GÄVLE Tfn 026 - 65 29 15 Fax 026 - 68 75 94
Internet: www.lantmateriet.se