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Preface

I want to thank my Swedish colleagues Jonas Ågren, Per-Anders Olsson, Martin Lidberg and Holger Steffen 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

The purpose of this report is to describe the preparations that have been done so far for the new Swedish gravity system, RG 2000, and also to describe the plans and strategy to finish the work. Different strategies how to realize the network are described and discussed. The present status of gravity observations, which might be included in RG 2000, is also described.

Sammanfattning

Syftet med rapporten är att beskriva planerna för slutförandet av det nya svenska tyngdkraftssystemet RG 2000. Olika alternativa upplägg för att genomföra realiseringen beskrivs och diskuteras. Nuläget för tyngdkraftsobservationer som skulle kunna komma att användas för RG 2000 är också beskrivet.

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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 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 a 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).

The earlier gravity system, RG 62, was temporary connected to Potsdam via the European Calibration System 1962 (ECS 62). This resulted in that the level of the whole RG 62 network is biased by more than 14,5 mGal. The overall quality of the system is rather bad, mainly due to the instrument (Worden Master). Despite these facts, RG 62 is still used by many organisations in Sweden. One purpose with a new gravity system would be to facilitate for these users to change to a better modern system. Much more information about RG 62, RG 82 and modern absolute gravity measurements in Sweden can be found in Engfeldt (2016).

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 also measured by the Danish A-10, owned and operated by DTU Space (Copenhagen, Denmark).

The reference epoch for the new gravity system will be the epoch 2000.0. This is the same epoch as for the national height system, RH 2000, and very close to the epoch for the 3D national reference system, SWEREF 99 (1999.5). The measurements will be reduced to the reference epoch by means of a land uplift model. For RH 2000 the model NKG2005LU, developed by Ågren & Svensson (2007), was used. Right now an updated model is on the way. Concerning the definition of RG 2000, it is also decided that RG 2000 will be a zero tide system.

2 System definition of RG 2000

Here some different ideas are discussed before. After that, a number of decisions are presented in Section 2.4.

2.1 Discussion about where to refer the g-values

At 13 locations in Sweden there are repeated FG5 absolute gravity observations (see Table 1 in Appendix 1 and Map 3 in Appendix 2). All of these are co-located with permanent GNSS stations in the SWEPOS™ network. At 97 other locations there are absolute gravity observations measured by the instrument A-10 (see Table 6 in Appendix 1 and Map 4 in Appendix 2). The uncertainty of FG5-measurements is about 2-3 µGal while the uncertainty of A-10-measurements is about 10 µGal (Micro-g LaCoste 2006 and Micro-g LaCoste 2008).

One thing to decide is if the g-values refer to the top of the marker or to a place close to the reference height of the instrument, which means at 1,20 m for FG5 and at 0,70 m for A-10. From start the option that the g-values will be referred to the top of the marker was the first choice, since that is how it was done in RG 82 and also when we have done similar missions abroad (Serbia, Former Yugoslav Republic of Macedonia and Bosnia-Hercegovina). This option means that the gravity gradient will be used to reduce the observations from the sensor height of the different gravimeters to the top of the marker. The disadvantage is that the uncertainty of the gradient determination will be added to the FG5 observational uncertainty (Engfeldt 2016). The advantage is that any relative gravimeter easily can use the site for densification or any kind of mission.

The other option is to give the gravity value where it can be presented with its lowest uncertainty, i.e. to keep the g-values very close to the reference height of the FG5 (or A-10), where the free-fall observation takes place. This is at moment the option which is considered as our choice for the FG5 sites. Since all FG5 sites are situated indoors and a key is needed to enter, no one but staff from Lantmäteriet can measure at them. There are ideas to determine sites right outside of the FG5 gravity huts using relative gravimetry and if that would be done, this option would probably be the best one. Even if the present gradient determinations are good at our FG5 stations, they are probably possible to improve, which leads to better reductions of the gravity value to the desired height (on the ground) for future realizations of RG 2000. Notice that the FG5 stations are mostly marked by a drawn marker directly on the piece of concrete.

2.2 Land uplift model for the system

As is well known, in Fennoscandia the post glacial rebound results in gravity changes over time. Therefore, all gravity values in the new system must refer to a certain epoch. All observations included must consequently be transformed to the chosen epoch by means of a land uplift model. The epoch 2000.0 has been chosen in order to harmonize RG 2000 with the most recent systems in height, RH 2000 (epoch 2000.0), and in 3D, SWEREF 99 (epoch 1999.5). There are different options for how to correct the observations to the chosen epoch, either by using a land uplift model or by using the trend of the gravity change directly from the FG5 observations.

After the FG5 observations with our absolute gravimeter were evaluated in the spring 2015 (Olsson et al 2015a), we decided that these observations were at moment too uncertain to be used for making an extrapolation of the g-values to the year 2000 for the 13 sites in question. Therefore, the present choice is to use a land uplift model. The FG5 observations will be used for setting the absolute level for the middle of the observation period, e.g. the year 2010, from where the land uplift model will be used for the extrapolation.

When choosing a land uplift model, there are also other choices to make, e.g. which type of land uplift model to use. There are basically two kinds of models, referred to as GIA models (Global Isostatic Adjustment) and empirical models, respectively. With a GIA model the rate of change of gravity ($\dot{g}$) is predicted by means of theoretical assumptions about the physics of the Earth and models of the ice history. With empirical models we here mean a model based on observations, typically land uplift ($\dot{h}$). Using an empirical land uplift model presently means that we also need to estimate the relation between $\dot{g}$ and $\dot{h}$ in order to transform the empirically determined land uplift values to gravity change (Olsson et al, 2015b). The chosen model will be applied for all FG5 and A10 measurements before the adjustment of the sites only measured by relative gravimetry.

2.3 Preferred definition in view of the international development

The work with a new Finnish network started in 2010 and the work with a new Norwegian network started in autumn 2011. In Norway less has so far been performed compared to in Finland and Sweden. In the Nordic and Baltic countries, we all have height systems with the epoch 2000, which are well-connected and close to identical to each other.

In a way, it would be preferable if all the countries could use the same reference epoch and the same land uplift model. In Finland it has been decided not to wait for a better model and to use “NKG2005LU”. If the same model should be used in Sweden, the advantage is just that we will have an identical level as Finland in our new gravity system. The disadvantage is that in good time before the work with RG 2000 is finished, a new empirical model for the land uplift is available. It is therefore decided that we will test both the models to investigate which one is the best for a first realization.

Work is right now going on in IAG for “The global absolute gravity reference system” (IAG Resolution No 2 for the establishment of a global absolute gravity reference system, 2015). We believe that the definition of RG 2000 will be in accordance with this international system, but since the realisation of that global system is still at least a few years ahead, we cannot of course say this for certain.

2.4 Definition and realization

The definition of RG 2000 is that RG 2000 is a zero tide system with the post glacial land uplift epoch 2000.0. This system is then realized by the gravity values and the standard uncertainties determined for the sites of the network. This realisation should not be viewed as closed. It will be possible to determine new sites in the future. Of course, this will require that we take care of the land uplift effect with sufficient accuracy, but as the models in question will improve with time, this is not expected to be a significant problem. As a consequence, none of the stations in RG 2000 is regarded as perfect (free from errors). It will further be possible to include new absolute gravity stations in the future. Possibly, the latter might be more accurate than the present ones. The land uplift model which will be chosen for the initial realization is planned to be decided during the second half of 2016.

3 Discussion about the need of gravity networks

Traditionally, a gravity network consists of points on the ground with determined g-values in a certain area, which are used as starting points for relative measurements. Is there a need for such gravity networks? Yes, of course there is. There are many institutions/companies in Sweden who need accurate gravity data and which perform relative gravity measurements and consequently need accurate gravity stations in a well-defined national gravity system. Apart from Lantmäteriet, the Swedish Geological Research (SGU) and the company Boliden are two big users of accurate gravity data. SGU needs accurate data for mapping of the gravity field for geophysical purposes and prospecting in particular, in the whole of Sweden. For them, it is a big advantage if the network is as homogeneous and as accurate as possible. When calculating a new geoid model (as Lantmäteriet do as a part of the geodetic infrastructure) it is important with a homogeneous and accurate network in order to get the best possible geoid model. The quality of the geoid model directly affects the uncertainty of height measurements with GNSS. Also, when calculating geoid models across the borders, it is of great importance to have accurate gravity data in a similar epoch for all participating countries. For minor tasks, like getting the g-value correct for a scale, it is though not of the highest priority to have an accurate and homogenous network. However, gravity sites with verified uncertainty are needed also for such applications.

4 Status today

Today two different gravity systems/networks are still in use in Sweden, RG 82 and RG 62. To start with, the oldest, RG 62 was measured with a Worden Master gravimeter by Lennart Pettersson in 1960-66 and was also called the Second Fundamental Gravity Network. It contains totally 185 sites 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 "temporarily" connected to IGSN 71 (International Gravity Standardization Net 1971). Due to the poor gravity value of Potsdam, the absolute level of the whole RG 62 network was more than 14,5 mGal wrong. Furthermore, it was found that RG 62 was measured, probably due to the instrument, so badly so that there were several shifts where the values are more or less incorrect. 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".

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 of which two sites were in Sweden, Gävle (later on renamed Mårtsbo A / AA) and Göteborg A. In Fennoscandia also Hammerfest, Sodankylä, Vaasa and København were measured. The IMGC measurements in Gävle/Mårtsbo, Göteborg, Sodankylä and København became the foundation of the new system RG 82. The foundation sites together with the 12 Swedish sites on the Fennoscandian land uplift gravity lines were the first parts of the new fundamental network of 25 stations, referred to as the Third Fundamental Gravity Network, and also called the Zero Order Gravity Network. The 11 remaining sites were established and measured in 1981-82 by Lennart Pettersson and Lars Åke Haller 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 already established or added a few years later. RG 82 was in 1994 included in the UEGN94 (Unified European Gravity Networks 1994), which covered 11 countries and included 499 stations.

The First Order Network of RG 82 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. It was measured by Lars Åke Haller, Andreas Engfeldt and Håkan Skatt, consists of 149 points and was finished in 2002. The purpose of it was to get one point every 50 kilometres, preferably close to towns where accommodation exists, which is very practical as they were meant to be used as starting points for relative gravity densification for geoid modelling purposes.

The reason for bothering about these old networks is the large amount of existing data based on them. Since both RG 82 and RG 62 are in use today, we need good transformations between the old systems and RG 2000, so that the users can transform their data without degrading the accuracy too much. In the year 2000, two different transformations between RG 82 and RG 62 were calculated (see 7.1), but the transformations are based on only 28 points and today we have almost the double number of common points to use for a new transformation. Consequently, a new transformation will be calculated in the RG 2000 project.

All RG 82 sites which still exist could be included in the new network, but this is something to be decided later while making the calculations and checking the relative observations. The two main problems with RG 82 are the epoch and the absolute level of the system. The epoch is 1982.0, which is now more than 34 years ago, which adds considerable to the uncertainty of the gravity values in RG 82. Furthermore, it is very inconvenient that this epoch does not harmonize with the other reference frames in Sweden, which have the epochs 1999.5 and 2000.0. The big problem with the absolute level of the RG 82 system is that it is set by observations on four sites in Scandinavia by a very early Italian absolute gravimeter, when we today have a better instrument ourselves and many much better observations. So now, finally, we will establish a new gravity network based on our FG5 observations.

5 Realization of RG 2000 – in the perspective gravity network

In the 10 year plan "Geodesi 2010", it was stated that a new gravity network should be established before 2020. This led to that the work with RG 2000 started in 2011, even if many ideas were born long before that and even if many measurements usable for a new gravity network were performed decades before. For instance, it was earlier decided that RG 2000 will primarily be built based on absolute gravity observations. Something that was not decided until 2014 was how the last densification of the absolute gravity observations should be performed. The two possible alternatives were to densify by relative gravimetry or by using more A-10 measurements. This will be discussed in the present chapter as well as our ideas concerning FG5 absolute gravity measurements.

During the last decade, the necessity of having physically marked sites has been discussed a lot for other types of geodetic techniques. Many geodesists mean that such are not needed anymore after the GNSS-technique has become as robust as it is today. The exception is of course that a dense network of permanent reference stations for GNSS are needed. Otherwise, the GNSS solutions will not be good enough. Concerning physically marked gravity sites, things are different. Here the relative measurements have to start and end directly at a known marked site itself, it is not possible to get data from them connected by GSM/GPRS or satellite. Of course it is today possible to use an A-10 gravity meter to get the gravity value directly. However, such an advanced and expensive instrument is usually not available for this purpose. It is much more efficient to use relative gravimetry, and then marked gravity stations are required. The difficulties by using vaguely defined marked sites (like in RG 62) have been proved to yield bad results and confusion, and is thus not an option. If the user's new relative measured points need to be marked is totally up to the user and the purpose of the measurements, though. For example, for measurements used for geoid modelling all that is needed are good positions and heights. Of course, rather good gravity observations are also needed with a standard uncertainty lower than somewhere around 0,2-0,5 mGal. It is particularly important that there are no systematic errors, which will put high requirements on the gravity system, see Ågren and Sjöberg (2014).

5.1 Ideas concerning FG5 measurements

When the Swedish absolute gravimeter FG5-233 was purchased in the autumn of 2006, this was mainly motivated by two major reasons. The most important one was to observe the gravity change induced by postglacial rebound in Fennoscandia. It was also important to make FG5 measurements for a new gravity network. In Sweden, gravity *sites* for FG5 have been established in four different stages, between 1976 and 2007:

- 1976: For the IMGC campaign
- The early 1990s: For JILA-g and the first FG5 instruments
- 2003-04: For the Nordic absolute gravity project
- 2007: For the Swedish FG5 instrument.

The sites were established at 14 different locations of which one is no longer in use (Göteborg, replaced by Onsala in 1993). Even if we do not view any of the stations as completely free from errors, we still regard the FG5 stations as fundamental stations in RG 2000, as they have the lowest standard uncertainties they are as close to the truth as we can get at the present time. This means that we have 13 fundamental sites all over Sweden for RG 2000 (see Appendix 2, Map 3). At two of these locations, Mårtsbo and Onsala, more than one pillar for FG5 measurements exist and the best one (i.e. Mårtsbo AA and Onsala AA) is the fundamental site.

5.1.1 Observations in Sweden using Lantmäteriet's FG5

A lot can be read about the FG5 observations in Sweden with Lantmäteriet's FG5-instrument in Engfeldt (2016), but a few things will nevertheless be repeated here. In mid-October 2006, FG5-233 arrived in Sweden. It was purchased from Micro-g LaCoste INC in Lafayette, Colorado, USA. Between 2007 and 2014, the existing Swedish stations have been measured a minimum of four times. The exception is Borås AA which has been measured only in 2013 and 2014.

The Swedish procedure to measure absolute gravity can be summarized as follows:

- 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

How the instrument works is described in Engfeldt (2016) and in a more detailed way in either Niebauer et al. (1995) or in Micro-g LaCoste (2006). More about absolute gravity observations in Sweden by other instruments than FG5-233 can be read in 5.4.1.

5.1.2 FG5 comparisons

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 (see 6.1.1).

Lantmäteriet's FG5-233 has participated in several comparisons. Table 3 in Appendix 1 is a brief summary of these. At all international comparisons, the weighted average of the participating instruments set the level.

5.2 A-10 observations for RG 2000

A-10 is a "portable" absolute gravimeter for outdoor use from the same manufacturer as FG5, Micro-g LaCoste Inc. How the instrument works is described in Engfeldt (2016) or in a detailed way in Micro-g LaCoste (2008).

5.2.1 Ideas concerning A-10 observations and background

To use A-10 for the establishment of a new gravity network was an idea which started to grow after discussions with Ludger Timmen (IfE) in the spring of 2004. The original idea was to measure all Zero Order RG 82 sites (Engfeldt 2015) and where this is not possible, another site in the neighbourhood should be measured instead. The other site should later on be connected to the Zero Order site by relative gravity measurements. But due to limitations of the A-10 instrument, it was after some investigation understood that much less than half of them could be measured. The original idea was also to measure as many of the First Order RG 82 sites as possible. But here the limitations of the A-10 instrument meant the same as for the Zero Order RG 82 sites.

In 2009, Finland started to work with their new gravity network. Their ambition was to measure all sites in their old gravity network (from the 1960s) with A-10 and they hired Marcin Sekowski from IGiK and the Polish A-10 instrument to make the measurements. Based on the good Finnish experiences with A-10, it was in early 2011 decided that we should start the work with our new gravity network, RG 2000, and that the ideas above should be followed. The first step was that all Zero and First Order RG 82 sites should be reconnoitred (Engfeldt 2016), as well as all First Order RG 62 sites. During this reconnoitring, it was established which sites were appropriate for A-10 measurements or for relative measurements in a new network. All the sites which were found were also measured by the best possible GNSS-solution found at the time. The second step was to make a test tour with the Polish A-10 during the summer of 2011 (see 5.2.2).

An important issue to consider is if the observations by A-10 should be left as they are, after being corrected for the land uplift. After some consideration, we have decided that it is better to correct them according to the results from the two international comparisons this instrument has taken part in (ICAG 2013 and ECAG 2015) in the same way as our own observations will be corrected (see 6.1.1). Another option could have been to correct the observations according to what differences were shown from the known FG5 sites journey by journey. The option to correct them through relative measurements is sort of out of the question, since the uncertainty when measuring with any relative meter is significantly higher than the uncertainty of a normal A-10 observation. Still, relative measurements can be used to check for gross errors in the A-10 observations (see 5.2.8).

5.2.2 A-10 observations in 2011

In early 2011 it was decided that a test tour with A-10 would be performed during the summer. It was decided to both start and finish the measurements in Mårtsbo, on the FG5 site Mårtsbo AA, which is also one of the fundamental sites of RG 82. The purpose was to get a good idea of how well the A-10 performed both concerning the differences to the FG5 and the differences from the start to the finish of the tour. The instrument was owned by IGiK and operated by Marcin Sekowski (IGiK) with assistance of Andreas Engfeldt. The test measurements were conducted in the procedure that two orientations were measured (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 regarded as very satisfactory, so it was decided that more campaigns with A-10 should be performed in order to get connections to old networks and to cover Sweden.

5.2.3 A-10 observations in 2012 and 2013

In 2012 and 2013 totally four A-10 campaigns were performed, three longer campaigns with the Polish instrument and one shorter with the Danish instrument. In total, 73 sites were visited, of which three were the FG5 sites Mårtsbo AA, Onsala AA and Kiruna AA. These three sites were used for checking that the A-10 results were reliable. One of the sites, Boda Bruk, was also measured both during 2012 and 2013 due to an unexpected observation the first year, later found out to be a gross error which could easily be corrected. The results from the different years differed, after the corrections, less than 1 µGal.

In addition, in April 2012, the A10-019 owned by DTU Space (Copenhagen, Denmark) visited Sweden for measurements along the 56th degree land uplift line (see Engfeldt 2016). 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, Copenhagen) 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 the two Danish Scintrex CG5s were used.

5.2.4 More A-10 observations or many more relative measurements?

In early 2013, when the fourth A-10-campaign was finished, two very different approaches were considered concerning how to continue the work with relative measurements, namely:

Strategy a) To connect as many old points as possible to the new network

Strategy b) To connect as few old points as possible to the new network and instead measure more with A-10

At this point, the idea was that the Zero Order Network of RG 82 should be included in RG 2000 and regarded as third class sites (after FG5 and A-10 sites, see chapters 5.3 and 8). In order to make that possible, the old relative measurements between the Zero Order Network sites observed between 1981-82 will be included. It is still under investigation how many of the observations made on the land uplift gravity lines that will be used. All existing observations between Zero Order sites and FG5 sites, as well as all existing ones between Zero Order sites and A-10 sites should also be used. In total, 67 measured relative differences existed. The idea was also to connect most Zero Order sites to either a FG5 or an A-10 site, which at this time meant that 9 more differences should have to be measured relatively. This was meant to be done no matter if Strategy a or b was used.

In addition, as many as 221 other differences between existing gravity sites were considered as possibly useful for the new gravity network. These were for example differences between new A-10 sites and either First Order RG 82 or RG 62 sites nearby. Of these 221 differences, 83 were already measured, even if the uncertainty might be too high for some of them. These 221 differences were only meant to be measured if Strategy a is chosen.

5.2.5 Strategy a, many more relative observations

This strategy means to connect as many old sites as possible to the new network by relative gravimetry. By “old sites” we here mean sites in the Zero Order Network of RG 82 or in the First Order Networks of RG 82 or RG 62. All these connections, which mean measured gravity differences, would be measured by two relative gravimeters, if possible one LaCoste & Romberg gravimeter and one Scintrex gravimeter. All differences should be measured at least twice, which has been the approach when measuring all previous networks.

With the assumption that we would have to measure 150 differences in this way, two different approaches for how to measure will here be introduced.

Let us assume that it takes 30 minutes per stop (normally it takes slightly longer), when the site is measured by two gravimeters. Also assume it takes 60 minutes to travel between the sites (normally it takes shorter time, but sometimes longer). In that case it takes 2 hours to measure a single difference.

Assume further that five sites to measure are called A, B, C, D and E and that we measure in a net structure.

In case all differences are independent, 4 differences (A-B, B-C, C-D, D-A) can be measured in one day of fieldwork. But in case the differences are not independent, 5 (A-B-C-D-E-A) differences can be measured in one day of fieldwork. This leads to that we need 75 days respectively 60 days to measure all differences twice. But since the starting site is not in Gävle (where the Lantmäteriet main office is) every day the following must be added: The travelling time to the start site and end site from the hotel, the travelling time from Gävle to the start site and end site of the specific journey, and that some old and new differences probably need to be re-measured. This would probably lead to about 1 extra day per 6 days to measure, which means that 87,5 and 70 days were needed.

In case all differences would be measured three times, we would need 112,5 days and 90 days respectively to finish (the extra days not included, see above), with the addition of that about 50 differences would have to be measured once more. The long time for this compared to the time frame for the project meant that this option was cancelled directly without further consideration.

Summary: This strategy means a lot of field work, which will be too time consuming and expensive.

5.2.6 Strategy b, additional A-10 sites

This strategy means to measure more A-10 sites. There are a few options also how this could be done. One way is to have a similar coverage with A-10 and FG5 sites all over Sweden with about 50-80 kilometres between the stations, by filling all gaps by new A-10 observations. An exception could be in mountainous areas, where no suitable sites exist, neither levelling points nor church steps, and other areas without roads. Another way is to densify even further, so there will be one A-10 site every 50 kilometres.

The first option means to add between 5 and 12 new sites. The second option means to add about 50 more sites all over Sweden. Due to the limitations of the A-10 instrument, there was only one more site from the old networks which could be added in areas with gaps in the coverage. This means that the rest of the 4-50 new sites would have no connection to the old networks. This also means that unless the A-10 sites should be alone standing sites, which meant that RG 2000 would be no network in a real meaning, a lot of relative measurements would be needed for the second option. In order to verify the A-10 measurements and in order to get connections to the old network, these sites would in that case each have to be measured relatively from one old site or from another A-10 site. Anyway, the option about having one A-10 site every 50 kilometre was excluded since the main reason for densifying with more A-10 measurements is to avoid making so many relative measurements. The first option is good, though, and this choice was made.

In addition to this choice, it has been decided to make sure that every single A-10 site is checked for gross errors (see 5.2.8). In Table 7 (in Appendix 1) it is shown which A-10 sites are already checked for gross errors and from which site it has been checked or will be checked. In total there are 97 A-10 sites of which 74 have already been checked and 23 that are still not checked (March 2016).

The new relative measurements will be performed by 2 gravimeters, if possible one LaCoste & Romberg (G54) and one Scintrex CG5 (1184). Both the instruments should measure according to A-B, B-A. The main purpose with these measurements is not to decrease the uncertainty in the network, since the uncertainty normally is regarded to be higher for A-10 measurements than for the relative measurements. Still, many of these measured differences will be included in the network. This is for getting more connections between the new system and the old systems and for tying them together in a better way, which means improving the transformation between RG 82 and RG 2000 (see chapter 7).

Summary: This strategy could also mean a lot of field work, but when choosing the first option above, the field work days are minimized. This also means that every A-10 site will be checked for gross errors by performing relative gravity measurements between them and the nearest appropriate FG5 or RG 82 site. The remaining fieldwork started during 2015.

In order to get more transformation connections between RG 2000 and the older systems, it would have been preferable to measure more old (RG 82 and RG 62) sites with A-10. But if excluding all old sites within a distance of 20 kilometers from a previously measured A-10 site, only one more RG 82 or RG 62 site was suitable to measure with that instrument (as judged when the campaign in 2013 was finished). So instead, where more connections are needed, relative measurements will be performed. Concerning A-10 observations there could have been one more option, namely to observe some old sites which are located longer than 15 meters from the parking place, which is the maximum distance to keep the electronics in the van due to the length of the cable. In that case the observations per site take four hours longer than normal, which means in total about six hours. However, there are very few such possible sites, since the normal limit is the surface and not the distance to the parking place. None of these are in the areas where there were gaps in the coverage. So it was decided not to make any measurements at any such site.

5.2.7 A-10 observations in 2015

After strategy b and option 1 were chosen (see 5.2.6), it was decided in 2014 that one supposed last A-10 journey would be performed during the first half of 2015, where two kinds of sites would be measured: Some new sites and a minimum of five of the previously measured ones. The reasons why a few previously measured sites were measured again were to make some samples to ensure that no gross errors occurred and to investigate the repeatability of the instrument. Here the sites with the largest difference from the two orientations were the first choices. This time Przemyslaw Dykowski (IGiK) operated the instrument, with assistance of Andreas Engfeldt. In total 14 new A-10 sites (of which one was a First Order RG 82 site) and 7 previously measured A-10 sites were measured during this trip. When passing Säffle, it was discovered that the previously measured site Säffle AA had been partially destroyed when a roundabout was built. This will not affect RG 2000 in any other way than that this site is missing, since A-10-measurements, gradient measurements and all needed other measurements (like geoid measurements, starting from the site) already were performed and since it was not necessary to connect the site to the old network because it was a first order RG 82 site from start.

5.2.8 Verifying the A-10 observations

The uncertainties of a FG5 measured site and an A-10 measured site are specified to 1-2 µGal and 10 µGal , respectively. However, like for all kind of geodetic observations there is a risk of gross errors in all gravity observations, no matter of what the specification says. The FG5 observations in Sweden are verified by repeated observations at the same site during several years. However, before the journey in 2015 with one exception, the new A-10 sites had only been observed by A-10 one time. During the five tours with the A-10 in Sweden, 1-2 FG5 sites have been measured during the tour, which has proven that the instrument works and that the measured gravity value is not so far away from the "known" expected value. Relative measurements between the A-10 sites and either a FG5 site or a RG 82 site, give a good indication if there is a gross error in the measurement or not. In June 2015, the plan for these measurements was finished and the first new relative measurements for RG 2000 were then performed. The plan means making relative measurements between each one of the still not connected A-10 sites and the closest FG5 or RG 82 site (see Table 7 in Appendix 1). Notice that in case of a gross error is detected by relative measurements between an A-10 site and a First Order RG 82 site, it is most likely that the RG 82 site is the one which has the wrong g-value. This means that if a gross error is found, the next step is to re-measure the

A-10 site from the closest FG5 site or from the closest other A-10 site. Another way to verify an A-10 site is to re-measure it, but this is a more expensive option and not our choice. By doing these verification measurements we gain two other things. Most of them can be used for another purpose, to strengthen the connection between RG 2000 and RG 82, when making relative measurements between the new A-10 sites and RG 82 sites. This means that almost all A-10 sites will get a value in RG 82 and that there will be sufficient number of connections between RG 2000 and RG 82 for a good transformation. The same thing is valid for the connection between RG 62 and RG 82. Most RG 62 sites that are measured by A-10 will here be measured relatively from the closest RG 82 site, which gives the RG 62 sites values in RG 82. In connection to this, also a few additional relative measurements between RG 82 and RG 62 sites are performed, in order to get a better transformation between these systems.

5.3 What to do with the old networks

During 2011, all gravity sites from the First Order Network of RG 62 and the RG 82 Networks (both the Zero and First Orders) were reconnoitred in order to investigate which old sites were still available and usable for a new network (Engfeldt 2016).

It has been decided to let most of the relative measurements for the Zero Order Network of RG 82 also be included in RG 2000. Some relative measurements along the 63th degree land uplift line measured after 1982 will also be included. Even if all Zero Order sites of RG 82 will get a new value in RG 2000, it does not mean that all of them are recommended to use for further densification for other purposes. Instead, sites like Älvdalen B and Stensele A, which both are awkwardly situated, probably will be recommended not to be used. The measured differences between absolute gravity sites and Zero Order RG 82 sites will also be included, since that is the way the RG 82 sites will be connected to the new network. The Italian absolute gravity observations from 1976 will of course not be included. All of this will be re-calculated and re-adjusted. A software to make the calculation and the adjustment in, will either be written by Lantmäteriet or purchased from another company. Most of the relative measurements for the First Order Network of RG 82 might also be included. This decision will be taken during the calculations. It is also decided that no relative measurements from the First Order Network of RG 62 will be included, since their uncertainty is too poor. All First Order sites of RG 62 will though get a new value in RG 2000, some from relative measurements done to establish the connection between RG 62 and RG 82 and some after transformation (see 7.1). All points in our detail gravity base used for geoid modelling will get their RG 2000 values by transformation.

5.4 Summary of available stations and observations

In Appendix 1, the seven Tables 4 and 6 to 11 can be found, where all available observations are listed. This means all FG5 observations, all A-10 observations, all relative observations between the Zero Order RG 82 sites, all relative observations between FG5 sites and Zero Order RG 82 sites, all relative observations between A-10 sites and Zero Order RG 82 sites and finally all relative observations between FG5 sites and A-10 sites. The tables show the situation of available and suitable observations at the moment. The idea is to use all these observations in the adjustments, but some of them might be removed if the calculation shows gross errors.

5.4.1 Useful FG5 observations in Sweden performed by other organisations than Lantmäteriet

In Sweden, totally ten absolute gravimeters have observed gravity and seven of them are FG5s. Apart from the Swedish instrument, the FG5 from IfE is the one which has made, by far, most observations in Sweden. In case the results are handled correctly, the IfE observations will help to strengthen the Swedish observations on the Swedish AG stations (see 6.1.3).

The Norwegian FG5, belonging to NMBU (Norges miljø- og biovitenskapelige universitet, Ås, Norway), had its first measure season in 2004 when it measured at Smögen AA, Onsala AN and Onsala AS. During 2005 it measured at the same places in Sweden and if we want to extend the series in Smögen with 4 years, these observations could be used for RG 2000. The measurements in Onsala were comparisons to the IfE gravimeter, which can provide us with a factor between the instruments. NMBU also measured in Kiruna and Östersund in 2007 and Kiruna, Östersund and Arjeplog in 2008.

The Finnish FG5, belonging to FGI (Finnish Geodetic Institute, Masala, Finland), has only measured in Sweden during a few comparisons, which means that these observations are of no interest for RG 2000. In 1992, the predecessor of FG5, JILAg, owned by FGI, visited Sweden and measured in Skellefteå AA, Mårtsbo AA, Göteborg A (as a last step to abandon the site) and in between Onsala

AN and AS. Some of these measurements could be interesting for the gravity trend lines, despite having larger uncertainties.

In 1993, 1995, 1998 and 2003, BKG (Bundesamt für Kartografie und Geodäsie, Frankfurt, Germany) visited Sweden and measured Mårtsbo AA, Skellefteå AA, Kiruna AA (only 2003), Onsala AN and Onsala AS. If it is possible to get the history of the used instrument, these measurements might be interesting for RG 2000. The same goes for NOAA (National Oceanic and Atmospheric Administration, Boulder, Colorado, USA), which measured the same sites in Sweden as BKG did (including Kiruna AA), in 1993 and 1995.

How to combine different instruments is at moment discussed on Nordic basis within NKG (Nordic Commission for Geodesy) and an article about this is in preparation.

5.5 Remaining observations

The most accurate sites in the new RG 2000 network will be the FG sites. In one way one might say that they define RG 2000, since they have the lowest standard uncertainties. All observations on these sites have been checked for gross errors since we have measured there several times. All A-10 sites will also be included. Most of the relative observations for the Zero Order Network of RG 82 are still good and should be included. Also most of the relative observations for the First Order Network of RG 82 are still good and should be included. Relative measurements between FG5 sites and RG 82 sites are needed to be included here and a few more such observations will be performed in 2016.

The A-10 sites that are not yet verified (see chapter 5.2.7) will be connected to RG82 sites. As for all previous connections, these connections shall be measured with two instruments, to get the measurements independent. If possible these instruments should be of two different brands, which means one Scintrex CG5 (1184) and one LaCoste-Romberg (G54) (see Table 7 in Appendix 1).

During the work with investigating the measured relative differences between all the sites, which will be included in the network, some discrepancies were discovered. This means that new observations must be made, either between the same sites (with the discrepancies in the measured relative differences) or between one of these sites and another better determined one nearby, which for example is measured by A-10.

6 Realization of RG 2000 – in the gravity system perspective

At the FG5 sites we have time series with repeated absolute gravity observations. At A-10 sites, with eight exceptions, we have only single observations. What does that mean for the realization of RG 2000? In fact, it does not mean especially much. The time series of the FG5 sites give us a good verification of that there are no gross errors in the observations, while we have the verification by relative gravity for the A-10 sites (see 5.2.8). Estimates of $\dot{g}$ (the gravity change over time) from observations depend a lot on how the instrument FG5-233 is treated in different years (Olsson et al 2015a). It also depends on if we will use observations by other instruments, like the instrument from IfE. If the IfE observations are used, the connection between the instruments is of huge importance (see 6.1).

The longer we need to extrapolate outside the observation time range (which is 2007-2015 for most FG5 sites with FG5-233 or 2004-15 including also observations with FG5-220), the larger the effect from errors will be due to errors in the applied gravity change $\dot{g}$. Today, if $\dot{g}$ is estimated by the FG5 observations themselves, then large errors will be obtained in $\dot{g}$. This means that the result (gravity value) for e.g. a FG5 site in 2010 will be much better than the result for the same site in 2000. For $\dot{h}$ (change in height over time = land uplift) there are other geodetic techniques which can be used with a more certain result than what at moment can come out of repeated FG5 observations. Previously, the land uplift has been calculated through repeated levelling and through the time series in tide gauges along the coast. However, the most accurate observing technique is to use the time series of SWEPOS™, the Swedish network of permanent reference stations for GNSS. So, we have measured the land uplift in different ways during the years and can estimate the gravity change from an empirical land uplift model with a relation between $\dot{g}$ and $\dot{h}$.

When we get longer time series for the FG5 stations, we get better data for the determination of $\dot{g}$. Does that mean that we would get a better realization of RG 2000 if we would wait some more years to specify it? That is a good question. As long as the instrument would be free from errors and if the influence from other error sources, e.g. the hydrography, would be known and the instrument never would get a new absolute level while being on service, then we would get a better realization for a specific station the more times we visit the station in question. Then we would also be able to calculate $\dot{g}/\dot{h}$ in a better way, for every station we observed. But that is not the reality. Here we are handling so small quantities, so all small errors and unknown biases together make the certainty not as high as we would wish. The epoch we are realizing the system in is before the FG5 observations started and every new FG5 observation we make is further away from that epoch, which leads to that the model to transfer the gravity value back to 2000 is becoming more and more important.

So the answer is that now is the right time to make a first realization at the FG5 stations. We already have enough data to get a good value for e.g. the year 2010 for every FG5 station and we also have good enough models for the land uplift to use for extrapolating the gravity values back about 10 years to the year 2000. Future realizations will use more data and better models and we could perhaps gain 1-4 µGal at some of the FG5 stations, but unless a gross error occurs somewhere the changes in future realizations will only be very small quantities, within the standard uncertainties.

Let us assume that we have an insecurity of $\dot{h}$ of about 0,5 mm per year in the land uplift model. What would that lead to if we use it to go back 10 years in time with the gravity value? It means that in total the error will be 5 mm and that corresponds to 0,815 µGal if we use the factor 0,163 µGal/cm (Olsson et al 2015b) to get the µGal from the height. This is a very small error, which is well within the standard uncertainty.

6.1 Chosen network and observations

In this section we discuss which observations will be used for RG 2000.

6.1.1 The difference between the levels of FG5-233 before and after the services

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 significant bias was introduced, a shift of more than 4 µGal. This has been confirmed at all comparisons the instrument has taken part in since then, but what caused it is still unknown. If something happened with the absolute level during the other three services is still under investigation, but if something happened the change was much smaller, which means that it is very difficult to detect it in a significant way. This matter is discussed in Olsson et al (2015a).

In order to deal with the suspected offsets, different absolute levels for the instrument between the services can 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 ECAG2007, the level of the observations performed between autumn

2008 and winter 2009 should have an absolute level according to ICAG2009 etc.

If we instead should assume that only one shift has occurred (the obvious one after 2009), the probably best way to derive that shift would have been to use the IfE instrument as reference. The following observations give us the difference (Timmen et al 2014).

Table 1: Differences between FG5-233 and FG5-220. CRVs: Comparison Reference Values as defined by all participating gravimeters (ICAG, ECAG) or by the reference gravimeters (RICAG); statistical values are partly not available

Site and time	Difference (µGal) FG5#233-CRVs	Difference (µGal) FG5#220-CRVs	Difference (µGal) FG5#233-#220
Mårtsbo May 2007			-2,1
ECAG November 2007	+1,0	+2,4	-1,4
ICAG September 2009	+1,0	+1,7	-0,7
RICAG November 2010	+5,8	+3,3	+2,5
ECAG November 2011	+4,7	+1,8	+2,9

The first three rows in Table 1 are from before the service in 2009/10 and the last two rows are from after the service. Just as an example, in the simplest of ways it could be derived this way: If all these are given the same weight, the difference between LM and IfE was -1,4 µGal before the service and +2,7 µGal after the service. This means that shift for FG5-233 after the service here would have been 4,1 µGal and the factor we would have been added to all observations performed between 2006 and 2009 with FG5-233. But so we will not do.

6.1.2 Chosen absolute gravity observations

The chosen absolute gravity observations for setting the absolute level for the most accurate FG5 stations (Class A, see 8.1) in the network could be the ones in Table 4 (in Appendix A), except the Finnish observations which do not improve the values, since they were only measured during comparisons. The chosen absolute gravity observations could also be only the Swedish observations in Table 4. In case we add several observations from IfE and one observation from NMBU, we need the connections/ differences from year to year between the instruments. These connections will in this case be taken from different ECAG/ICAG or from direct comparisons, see the next subsection.

6.1.3 Connections between the used instruments

As stated in 5.4.1, several absolute gravimeters have observed gravity in Sweden during the years. In order to combine the observations from different absolute gravimeters that have measured in Sweden, we need the differences from year to year between the instruments. This is at moment investigated on Nordic basis and an article is in preparation (Per-Anders Olsson, personal communication).

The instrument FG5-220 from IfE is the single instrument which apart from our own FG5 has measured by far the most in Sweden. The data from their measurements can be useful in order to get longer time series, but they will only be useful if we treat the data in a correct way.

In 2003, the gravimeter from IfE might have had a quite different absolute level than later, despite that it was not on service during the years it measured in Sweden. It is not completely resolved to what extent the low values from 2003 came from the groundwater conditions or if it was from a loose component of the laser, which was discovered at ECAG in Walferdange in November that year. These observations were removed from the gravity trends in Olga Gitlein's PhD thesis (2009) and these observations should not be used in any realization by us either. Most of the observations between 2004 and 2008 for IfE could be used, though, as long as observations were conducted in the same way. Table 1 (in 6.1.1) can also be used for deriving the difference between the IfE measurements and the first LM measurements. However, this is when IfE used both north and south orientations, which means for most sites during the years 2005-2008. In Gitlein (2009) it is shown that the average value for north respective south orientation differs 1,0 µGal, where north is higher. However, in 2004 IfE measured only in the south orientation at quite many sites and at some specific sites the observations were performed in unusual orientation angles. One option for the sites where observations in south orientation were performed, is to use half the factor between the north and the south orientation which IfE had derived through their measurements, but that would be a somewhat dangerous approach.

The 2005 observations in Smögen with the NMBU instrument are interesting in order to increase the observation series by 3 years. Right after the measurement in Smögen, the NMBU instrument was compared in Onsala to the IfE instrument. The result was that NMBU was 3,3 µGal lower than IfE. However, the comparison took place in south orientation only. How to handle this is still under consideration.

6.1.4 Chosen relative gravity observations

All relative measurements which were performed in 1981 and 1982 for the zero order network of RG 82 should be used also for RG 2000 no matter if the measured site is appropriate for RG 2000 or not. The sites that are not appropriate or does not exist anymore, should not be included in the network, though. In addition, many of the measurements performed on the Swedish parts of the land uplift lines should also be used for RG 2000. The only exceptions known right now are the measurements with the Swedish instrument in 1998 (gross errors occurred) and the Danish instruments in 2003 (the instruments were behaving strange). However, the rest of the measurements must be further checked in order to decide whether any gross error occurs there as well.

In addition, the measurements between zero order RG 82 sites and absolute gravity sites should be included, where both FG5 sites and A-10 sites are counted. Here the measurements with G290 in 2004 might be removed right away. The instrument behaved strangely during these measurements and was reported as broken when it was about to be used some months later.

In addition, most of the measurements between A-10 sites and RG 82 sites will also be included. Whether some of them will be excluded due to gross errors will be decided during the calculations.

Table 4 and Table 6 to 11 (in Appendix 1) show the available observations/ measurements.

6.2 Computation software and weighting

After deciding which observations that shall be included in RG 2000, the next step is to find a suitable adjustment software. First, it will be investigated if any fellow geodesists in other countries have such a software. If this cannot be solved in this way, we will write our own software. However, another option could be to use e.g. the old Lantmäteriet software for levelling adjustment, m9, where gravity should be used instead of height. In that case, m9 needs to be modified so that the weighting is done differently than for levelling (1 divided by the length of the distance between the sites).

Since, during a field trip, we usually know if something strange has happened with the instrument, or if the weather conditions were poor, all the observations with a certain instrument should not always get the same weights in the adjustment. Exactly how the weighting should be done is right now under investigation. In the adjustment of RG 82, both used relative instruments had the same weight. Another difference for RG 2000 is that the absolute gravity observations are of two different kinds. The FG5 observations will most likely be very close to fixed in the adjustment, while the A-10 observations will be given a weight so they are a little less fixed, depending on the chosen a priori standard uncertainties.

Before any adjustment starts, it is important to correct all observations for the land uplift. This means, both the absolute observations and the relative observations.

6.2.1 Another idea about weights

In a diploma work from 1990 (Jansson & Norin) the Zero Order Network was recalculated and after some analysis the a priori standard uncertainties of the two used instruments were changed from 12 µGal (both) to 10,5 (G54) and 13,8 (G290) after a proposal from professor Lars E Sjöberg (KTH, Stockholm). If these results should have been used, the g-values for RG 82 would have changed between -8 and -1 µGal. Since the same measurements will be used also for RG 2000, the proposal concerning the weights is something to consider.

7 Connections to older systems

Today there are more than 25000 gravity points in the gravity data archive, measured in either RG 62 or RG 82. Since we want to use them and still want them to be accurate after introducing RG 2000, we need accurate connections between them. Since any transformation between different reference systems brings errors, the errors need to be minimized. This chapter will describe our ideas concerning how to get as good connections to the old systems as possible.

7.1 Transformations

In order to transform old gravity data to the new system RG 2000, good transformations between the systems are needed. The proposal is that the transformation between the systems RG 62 and RG 2000 goes via the system RG 82, which means a two-step transformation. This is a way to avoid getting different values of a site when transforming them in different ways – like directly between the systems and when transforming sites which already has been transformed to RG 82.

Figure 1: The two-step transformation between RG 62 and RG 2000.

7.1.1 Transformation between RG 62 and RG 82

The Second Order Network includes more than 25000 gravity observations in Sweden of different quality. This network is meant to be used for geoid calculations and almost all of the observations were originally measured 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 upcoming new Nordic geoid. At the time two transformations were derived, one with an inclined plane and one with a second degree polynomial function (Engfeldt 2016). These were based on 28 observations of which 25 were in Sweden and 3 were in Norway (see Table 12, Appendix 1).

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 Engfeldt 2016). This is mostly already handled, but during the upcoming year, a few more RG62 sites will get a RG 82 gravity value. According to the preliminary plan, there will be 11, namely Jämjö, Stenbrohult, Algutsboda, Mönsterås, Eksjö, Södra Fågelås, Skönberga, Arboga, Malung, Övertorneå and either Pustnäs or Uppsala. When Bollnäs got a RG82 value it was clear that something was strange (see Table 12 and Table 14), since the difference between RG 62 and RG 82 was 89 µGal less than in Söderhamn, 35 km away. Since everything seemed fine about the Bollnäs measurements, a gross error in the Söderhamn measurements was suspected. When finding the observations for Söderhamn in the archive and recalculating them, half of this difference vanished. Still 44 µGal is much for 35 km, why new observations between them and the same RG 82 site (Vallvik, which is situated close to both) will be performed during 2016. The new connections (see Table 13, Table 14 and the 11 mentioned sites above) will together with some of the old ones (the observations in Table 12, 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.

A question is whether it could cause any problems to change the transformation between the systems? In case a user has many observations directly in RG 62 and nowadays use RG 82, it can. But the problems will only occur if the old RG 62 values are thrown away. However, the difference between the transformations would be substantially less than 100 µGal at most places in Sweden.

7.1.2 Transformation between RG 82 and RG 2000

The transformation between RG 82 and RG 2000 will be based on two different kinds of connections, relative and absolute connections. The relative connections are relative gravity measurements between FG5 sites and RG 82-sites. The absolute connections are A-10 measurements on RG 82-sites.

There are 27 RG 82-sites which are measured by A-10/FG5. In order to get the best possible transformation between RG 82 and RG 2000, these 27 common sites are not sufficient. Because of that, more relative measurements are needed between A-10 sites and RG 82-sites. The verification measurements mentioned in 5.2.7 will be used for that (see Table 7, Appendix 1).

Like as for the old transformation between RG 62 and RG 82, both an inclined plane and a polynomial function will be calculated and the solution with the smallest residuals will be used.

Notice once more that there will not be a transformation connection directly between RG 62 and RG 2000. The old detail network should be transformed first to RG 82 and then to RG 2000. The RG 62 sites which are already measured by A-10 should though validate the transformations and the one between RG 62 and RG 82 in particular.

8 Documentation of RG 2000

8.1 Classes of RG 2000 sites

The RG 2000 sites are marked sites, which can serve as starting points for densification as for e.g. geoid measurements. They are divided into four different classes of sites:

Class A: Sites measured by FG5, of which one site per location serves as foundation site. These will also serve as carrier of the system.

Class B: Sites measured by A-10.

Class C: The Zero Order Network of RG 82, except the sites of the old network which fit the requirements of a Class A or a Class B site.

Class D: The First Order Network of RG 82, except the sites of the old network which fit the requirements of a Class B site. Also the so called "FAMOS sites" will be classified as Class D sites.

8.2 Site descriptions

The coordinates of all RG 2000 sites are measured with the best possible GNSS-solution. This means that most of them are measured with RTK. However, at some places it was not possible to get an RTK-solution and at a handful of places it was not even possible to get another position than an absolute one due to bad GSM connection. Luckily at most of these places, the height was known in advance since they were levelling sites in RH 2000. Luckily, since the height is the most crucial thing here. The remaining very few sites will be re-measured by GNSS.

For the gravity sites which are measured by absolute gravimeters or Zero or First Order sites in RG 82, the site descriptions will be available in the DGA ("Digitala Geodetiska Arkivet" – the digital geodetic archive) of Lantmäteriet. In DGA, a sketch of the site, the g-value in RG 2000, the planar coordinates in SWEREF 99, the height in RH 2000, the gradients (only Class A and B) and a few photographs of the site will be found. The text of the description shall be in Swedish, except for the "FAMOS sites" where the text shall be in English. For the Class B sites which are on church steps, it can be discussed if a phone number to the church expedition should be included or not.

All of the FG5 sites are though indoors and not available for other people than employees of Lantmäteriet, since they are in locked huts mostly in the forest. Because of that, it is recommended that at every FG5 station relative measurements between the FG5 station and a levelled bolt outside of the hut are performed.

9 Summary

RG 2000 is a zero tide system with the epoch 2000.0. For every realization a land uplift model will be chosen and this means that the g-values of every single site in the system will be given an uncertainty value.

RG 2000 consists of sites measured by the absolute gravimeter FG5, the absolute gravimeter A-10 and some relatively measured sites. These sites are all marked and divided into four different classes (A-D) and are all excellent to use for densifying Sweden with gravity points for geoid purposes.

The transformation between RG 62 and RG 2000 will go via RG 82 through a two-step transformation. A new connection between RG 62 and RG 82 and a connection between RG 82 and RG 2000 will be derived. These connections will be done via an interpolation method that is more suitable for the purpose than an inclined plane or a second degree polynomial, for instance least squares collocation or Kriging.

Several new relative gravity observations are needed before RG 2000 is finished and they are planned to be done during 2016.

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Appendix 1: Tables

Table 2: The Swedish FG5 sites = the Swedish Class A 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

Table 3: 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		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

Table 4: Available observations of the FG5 sites in Sweden

Name	Number of observations (1 observation = N+S)	Years with observations
Arjeplog AA	4 (+4 by IfE)	2007, 2009, 2011, 2013
Borås AA	2 (+1 by IfE)	2013, 2014
Kiruna AA	5 (+4 by IfE)	2007, 2008, 2010, 2012, 2015
Kramfors AA	4 (+4 by IfE)	2007, 2008, 2010, 2013
LMV AA	Many	2006-2016
Lycksele AA	6	2007, 2008, 2009, 2010, 2012, 2015
Mårtsbo AA	Many (+4 by IfE + 3 by FGI)	2006-2016
Mårtsbo AB	4 (+1 by IfE + 3 by FGI)	2007, 2012, 2013, 2015
Onsala AA	5 (+1 by IfE)	2009, 2011, 2013, 2014, 2015
Onsala AC	3 (+1 by IfE)	2009, 2014, 2015
Onsala AN	2 (+4 by IfE)	2010, 2013
Onsala AS	5 (+4 by IfE)	2007, 2009, 2010, 2011, 2013
Ratan AA	6	2007, 2008, 2009, 2010, 2012, 2015
Skellefteå AA	5 (+4 by IfE)	2007, 2008, 2010, 2012, 2015
Smögen AA	6 (+1 by NMBU)	2008, 2009, 2010, 2012, 2013, 2015
Visby AA	4 (+2 by IfE)	2007, 2009, 2011, 2013

Östersund AA	5 (+4 by IfE)	2007, 2008, 2009, 2011, 2015

Table 5: The Zero Order Network of RG 82

Name	Latitude	Longitude	Height (RH 2000)	Best site 2011	g-value, RG 82 (µGal)
Björkliden NA	68 23 58,9	18 41 37,5	387,843	N	982362245
Björkliden NB	68 26 35,8	18 36 16,4	377,809	Y	982365553
Jukkasjärvi NA	67 51 03,4	20 29 57,6	347,452	Y	982361917
Jukkasjärvi NB	67 51 10,4	20 29 32,8	348,610	N	982362156
Pello NA	66 47 49,8	23 53 35,7	93,209	Y	982362461
Pello NB	66 48 12,7	23 53 50,7	80,755	N	982365580
Kvikkjokk NA	66 57 06,2	17 43 00,0	310,699	N	982269111
Kvikkjokk NB	66 57 08,7	17 43 02,6	312,667	Y	982268767
Kåbdalis NA/AA*	66 06 22,8	19 55 24,9	350,877	Y	982270445
Kåbdalis NB	66 07 39,2	19 50 24,3	346,661	N	982268958
Jävre NA	65 09 41,0	21 29 36,8	30,221	Y	982269347
Jävre NB	65 08 27,6	21 30 10,5	28,693	N	982268824
Umbukta A	66 07 16,4	14 41 17,6	542,524	Y	982191175
Umbukta B	66 07 14,5	14 41 22,9	540,337	N	982191341
Stensele A	65 00 26,6	17 40 13,2	285,243	N	982191189
Stensele B	65 03 10,4	17 25 46,8	338,083	Y	982191124
Lycksele A	64 35 27,5	18 42 02,6	218,881	Y	982191124
Lycksele C	64 35 25,8	18 42 00,9	218,56	N	982191137
Sävar A/AA*	63 57 41,5	20 39 20,8	54,596	Y	982191088
Sävar B	63 57 46,3	20 39 28,8	54,952	N	982191060
Föllinge A	63 40 32,7	14 34 10,7	301,775	Y	982075771
Föllinge B	63 40 35,5	14 34 11,5	301,527	N	982075738
Stugun A	63 09 29,4	15 33 37,2	273,466	N	982076474
Stugun B	63 09 30,6	15 33 43,9	277,934	Y	982075728
Stugun C	63 09 22,2	15 33 28,4	277,414	N	982075670
Stugun D	63 09 22,1	15 33 28,0	276,114	N	982075942

Kramfors A	62 51 13,5	18 05 32,4	95,254	N	982076644
Kramfors B	62 51 12,3	18 05 35,5	92,823	N	982077100
Kramfors C	62 52 20,2	17 56 15,0	118,785	N	982075573
Kramfors D/AB*	62 52 20,8	17 56 16,7	117,865	Y	982075783
Älvdalen A	61 20 25,4	14 01 25,2	346,023	Y	981908201
Älvdalen B	61 21 01,7	14 01 15,3	349,883	N	981908200
Hofors A	Destroyed	-	-	N, destroyed 1996	981908210
Hofors B	60 33 34,2	16 20 06,0	192,401	Y	981908224
Mårtsbo A/AA*	60 35 42,0	17 15 32,4	43,695	Y	981923484
Mårtsbo B	60 35 42,6	17 15 28,8	43,219	N	981923646
ÖsthammarA	60 16 23,2	18 18 47,3	15,813	Y	981908210
Östhammar B	60 16 02,5	18 16 47,0	9,911	N	981908206
Karlstad NA	59 22 03,8	13 28 37,6	54,110	Y	981828158
Karlstad NB	Destroyed	-	-	N, destroyed 1992	981828082
Södertälje NA	59 13 51,8	17 25 59,8	19,691	Y	981828128
Södertälje NB	59 14 44,9	17 26 50,8	27,096	N	981828024
Göteborg A	57 41 10,8	11 58 40,8	44,647	N	981718749
Göteborg NB	57 41 10,0	11 58 36,0	47,573	Y	981718370
Ödeshög NA	58 13 11,8	14 39 15,0	147,994	Y	981718430
Ödeshög NB	58 12 50,9	14 38 55,4	145,157	N	981718473
Västervik NA	57 49 16,1	16 25 43,6	31,012	Y	981718574
Västervik NB	57 49 36,8	16 29 25,6	18	N	981718453
Visby NA	57 39 50,1	18 19 40,9	42,450	Y	981719266
Visby NB	57 39 26,0	18 19 15,7	40,303	N	981718567
Höör A	55 58 56,6	13 32 59,2	140,302	N	981580437
Höör B	55 58 36,6	13 32 44,2	141,950	Y	981580438
Sölvesborg A	56 07 10,5	14 34 12,5	98,128	Y	981580437
Sölvesborg B	56 07 29,5	14 34 01,0	100,674	N	981580443

**Also measured by A-10/FG5.*

*Table 6: Available observations of A-10 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	-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	-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

Table 7: A-10 sites, closest RG 82-site or FG5 site and whether the difference is measured by relative gravity or not.

Site	Closest RG 82 site or FG5 site	Measured RG Y/N
Ljusnarsberg AA	Lindesberg	N
Arboga AA**	Hallstahammar	N
Tullinge AA**	Södertälje NA	N
Nyköping AA	First order site	Y
Valla AA	First order site	Y
Karlstad AA	Karlstad NA	N
Säffle AA	First order site	Y
Årjäng AA	First order site	Y

Fryksände AA	Ekshärad	N
Stöllet AA	First order site	Y
Vansbro AA	First order site	Y
Sundsvall AA	Stavreviken	Y
Ragunda AA	Stugun A	Y
Kramfors AA = Kramfors D	Zero order site	Y
Örnsköldsvik AA	Kramfors D / AA	Y
Sävar A	Zero order site	Y
Hörnefors AA	First order site	Y
Holmsund AA	Ratan AA (FG5)	Y
Bjurholm AA	First order site	Y
Åsele AA**	Gulsele	Y
Vilhelmina AA	Vilhelmina	Y
Stensele AA**	Stensele B	Y
Umbukta AA	Umbukta A	Y
Klimpfjäll AA	Saxnäs	Y
Sved AA	First order site	Y
Hammerdal AA	Östersund AA (FG5)	Y
Östersund AB	Östersund AA (FG5)	Y
Stugun AA	Stugun A	Y
Duved AA	Östersund AA (FG5)	N
Svenstavik AA	First order site	Y
Överturingen AA	Rätansbyn	N
Hede AA	Hede	N
Transtrand AA**	Transtrand	Y
Älvdalen AA	Älvdalen A	Y
Bollnäs AA	Arbrå	Y
BodaBruk AA**	First order site	Y
Simrishamn AA	First order site	Y
Maglarp AA	Dalby	N
Helsingborg AA	Åstorp	N
Veinge AA	Measured from Varberg/Veddige/Onsala AA,	Y

	since the closest one (Laholm) was regarded as destroyed	
Kärda AA	Hillerstorp	N
Ulricehamn AA	Borås AA	Y
Grinneröd AA	Göteborg NB	Y
Tanum AA	Dals-Ed	Y
Vara AA	First order site	Y
Mariestad AA	First order site	Y
Laxå AA	First order site	Y
Svinnegarn AA	Hallstahammar	N
Öregrund AA	Östhammar A	Y
Husby- Ärlinghundra AA	LMV AA (FG5)	Y
Norrköping AA	First order site	Y
Ljusfallshammar AA	First order site	Y
Västra Tollstad AA	Ödeshög NA	N
Eksjö AA	Sävsjö	N
Gamleby AA	Västervik NA	N
Misterhult AA	First order site	Y
Ljungbyholm AA	Emmaboda	N
Köpingsvik AA	Borgholm	N
Emmaboda AA	First order site	Y
Öjaby AA	Ör	N
Älmhult AA	Osby	N
Augerum AA	Johannishus	N
Sollefteå AA	Sollefteå	Y
Norsjö AA	Norsjö	Y
Sorsele AA	Stensele B	Y
Arjeplog AB	Arjeplog or Arjeplog AA (FG5)	N
Arvidsjaur AA	Arvidsjaur	Y
Kåbdalis NA	Zero order site	Y
Gällivare AA	Gällivare	Y
Tärendö AA	Pajala	Y

Karesuando AA	Karesuando	Y
Övertorneå AA	First order site	Y
Hundsjön AA	First order site	Y
Luleå AA**	Bergnäset	Y
Bureå AA	Skellefteå AA (FG5)	Y
Ljusdal AA	Hybo	N
Sveg AA	Sveg	N
Särna AA	Idre (since Särna is destroyed)	N
Leksand AA	Borlänge	Y
Fredriksberg AA	First order site	Y
Grytnäs AA	Avesta	Y
Norrtälje AA	Östhammar A	Y
Solna AA	Solna	Y
Rimforsa AA	Kisa	Y
Virserum AA	Åseda	Y
Falkenberg AA	Veddige	Y
Baltak AA	Dala	Y
Klöveskog AA	Dals-Ed	Y
Munkfors AA	First order site	Y
Voxna AA	Voxna	Y
Borgsjö AA	Torpshammar	Y
Junsele AA	Gulsele	Y
Älvsbyn AA	Älvsbyn	Y
Haparanda AA	Haparanda	Y
Härnösand AA	Kramfors D/AA	Y
Sölvesborg AA*	Sölvesborg A	Y
Höör AA*	Höör B	Y

** Measured by A-10-019 and not by A-10-020*

*** Measured twice by A-10*

Table 8: List of differences measured between sites in the Zero Order Network of RG 82, which are applicable for RG 2000. One of the sites, Hofors A, is destroyed but will function here as a "help site". 42 differences in total.

Site 1	Site 2	Year	Number of differences /number of gravimeters
Björkliden NA	Björkliden NB	1981	5/2
Björkliden NA	Jukkasjärvi NA	1981/82	8/2
Jukkasjärvi NA	Pello NA	1981/82	8/2
Jukkasjärvi NA	Kvikkjokk NA	1981/82	4/2
Jukkasjärvi NA	Kåbdalis NA/AA	1981/82	8/2
Pello NA	Jävre NA	1981/82	8/2
Kvikkjokk NA	Kvikkjokk NB	1981	5/2
Kvikkjokk NA	Kåbdalis NA/AA	1981/82	4/2
Kvikkjokk NB	Kåbdalis NA/AA	2001	2 /2
Kåbdalis NA/AA	Jävre NA	1981/82	8/2
Kåbdalis NA/AA	Jävre NB	2001	4/2
Kåbdalis NA/AA	Stensele A	1981/82	8/2
Jävre NA	Sävar A/AA	1981/82	8/2
Jävre NA	Jävre NB	1981	5/2
Umbukta A	Stensele A	1975/80/81	?/14
Stensele A	Stensele B	1976	3/2
Stensele A	Lycksele A	1976-83	?/14
Stensele A	Föllinge A	1981/82	8/2
Lycksele A	Sävar A/AA	1976/83	?/14
Sävar A/AA	Kramfors D/AB	1981/82	8/2
Föllinge A	Föllinge B	1981	6/2
Föllinge A	Stugun B	1976-2003	?/?
Föllinge A	Älvdalen A	1981/82	8/2
Stugun B	Kramfors D/AB	1976-2003	?/?
Kramfors D/AB	Mårtsbo AA	1981/82	8/2
Älvdalen A	Hofors A	1976/83	?/10
Älvdalen A	Karlstad NA	1981/82	8/2
Hofors A	Hofors B	1977	4/2

Hofors A	Mårtsbo AA	1981/82	4/2
Hofors A	Östhammar A	1976/83	?/10
Östhammar A	Södertälje NA	1981/82	20/2
Karlstad NA	Södertälje NA	1981/82	8/2
Karlstad NA	Göteborg NB	1981/82	8/2
Södertälje NA	Västervik NA	1981/82	10/2
Södertälje NA	Visby NA	1981/82	8/2
Göteborg NB	Ödeshög NA	1981/82	8/2
Göteborg NB	Höör A	1981/82	8/2
Ödeshög NA	Västervik NA	1981/82	8/2
Västervik NA	Visby NA	1981/82	16/2
Västervik NA	Sölvesborg A	1981/82	8/2
Höör A	Sölvesborg A	1977/84	?/9
Höör B	Sölvesborg A	2003	8/2

Table 9: List of differences measured between FG5 sites and Zero Order Sites of RG 82, which are applicable for RG 2000. 11 differences in total, of which three are listed in Table 11.

Site 1	Site 2	Year	Number of differences /number of gravimeters
Jukkasjärvi NA	Kiruna AA	2004	6/2*
Jukkasjärvi NA	Kiruna AA	2015	4/2
Kåbdalis NA/AA	Arjeplog AA	2004	6/2*
Jävre NA	Skellefteå AA	2004	6/2*
Lycksele A	Lycksele AA	2008	4/1
Lycksele A	Lycksele AA	2015	4/2
Sävar A/AA	Ratan AA	2015	4/2
Föllinge B	Östersund AA	2004	6/2*
Kramfors D/AD	Kramfors AA	2003	6 /4
Göteborg NB	Onsala AA	2013	4/2
Visby NA	Visby AA	2004	6/2

** G290 did not work especially well during 2004 and those observations might be removed here.*

Table 10: List of differences measured between A-10 sites and Zero Order Sites of RG 82, which are applicable for RG 2000. 31 differences in total, of which one is listed in Table 11.

Site 1	Site 2	Year	Number of differences /number of gravimeters
Pello NA	Övertorneå AA	2002	4/2
Kvikkjokk NB	Kåbdalis NA/AA	2001	4/2
Umbukta A	Umbukta AA	2015	4/2
Stensele A	Vilhelmina AA	1992	2/2
Stensele B	Sorsele AA	2015	4/2
Stensele B	Stensele AA	2015	4/2
Lycksele A	Bjurholm AA	2002	4/2
Föllinge A	Sved AA	1992	4/2
Stugun A	Svenstavik AA	2001	4/2
Stugun A	Stugun AA	2015	4/2
Stugun A	Ragunda AA	2015	4/2
Kramfors D/AB	Örnsköldsvik AA	2015	4/2
Kramfors D/AB	Härnösand AA	2015	4/2
Älvdalen A	Vansbro AA	1996	2/2
Älvdalen A	Älvdalen AA	1996	2/2
Älvdalen A	Älvdalen AA	2015	4/2
Mårtsbo AA	Boda Bruk AA	2002	4/2
Östhammar A	Öregrund AA	2012	6/2
Östhammar A	Öregrund AA	2015	4/2
Östhammar A	Norrtälje AA	2015	4/2
Karlstad NA	Fredriksberg AA	1990	4/2
Karlstad NA	Säffle AA	1985	4/2
Karlstad NA	Laxå AA	1990	4/2
Karlstad NA	Munkfors AA	1985	4/2
Södertälje NA	Valla AA	2002	4/2
Södertälje NA	Nyköping AA	2002	4/2
Göteborg NB	Grinneröd AA	2013	4/2
Västervik NA	Misterhult AA	2002	4/2
Höör B	Höör AA	2012	4/4

Höör B	Simrishamn AA	2002	4/2
Sölvesborg A	Sölvesborg AA	2012	4/4

Table 11: List of differences measured between FG5 sites and A-10 sites, which are applicable for RG 2000. 9 differences in total, of which three are listed in Table 9 and one is listed in Table 10.

Site 1	Site 2	Year	Number of differences /number of gravimeters
Arjeplog AA	Kåbdalis NA/AA	2004	6/2*
Skellefteå AA	Bureå AA	2015	4/2
Sävar A/AA	Ratan AA	2015	4/2
Ratan AA	Holmsund AA	2015	4/2
Östersund AA	Hammerdal AA	2015	4/2
Östersund AA	Östersund AB	2015	4/2
Kramfors AA	Kramfors D/AD	2003	6 /4
Mårtsbo AA	Boda Bruk AA	2002	4/2
Borås AA	Ulricehamn AA	2014	4/2

** G290 did not work especially well during 2004 and those observations might be removed here.*

Table 12: Connections between RG 82 and RG 62 (in mGal) used for 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	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	982069,920	982084,520	-14,600	

kyrka*				
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 13).*

Table 13: 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	

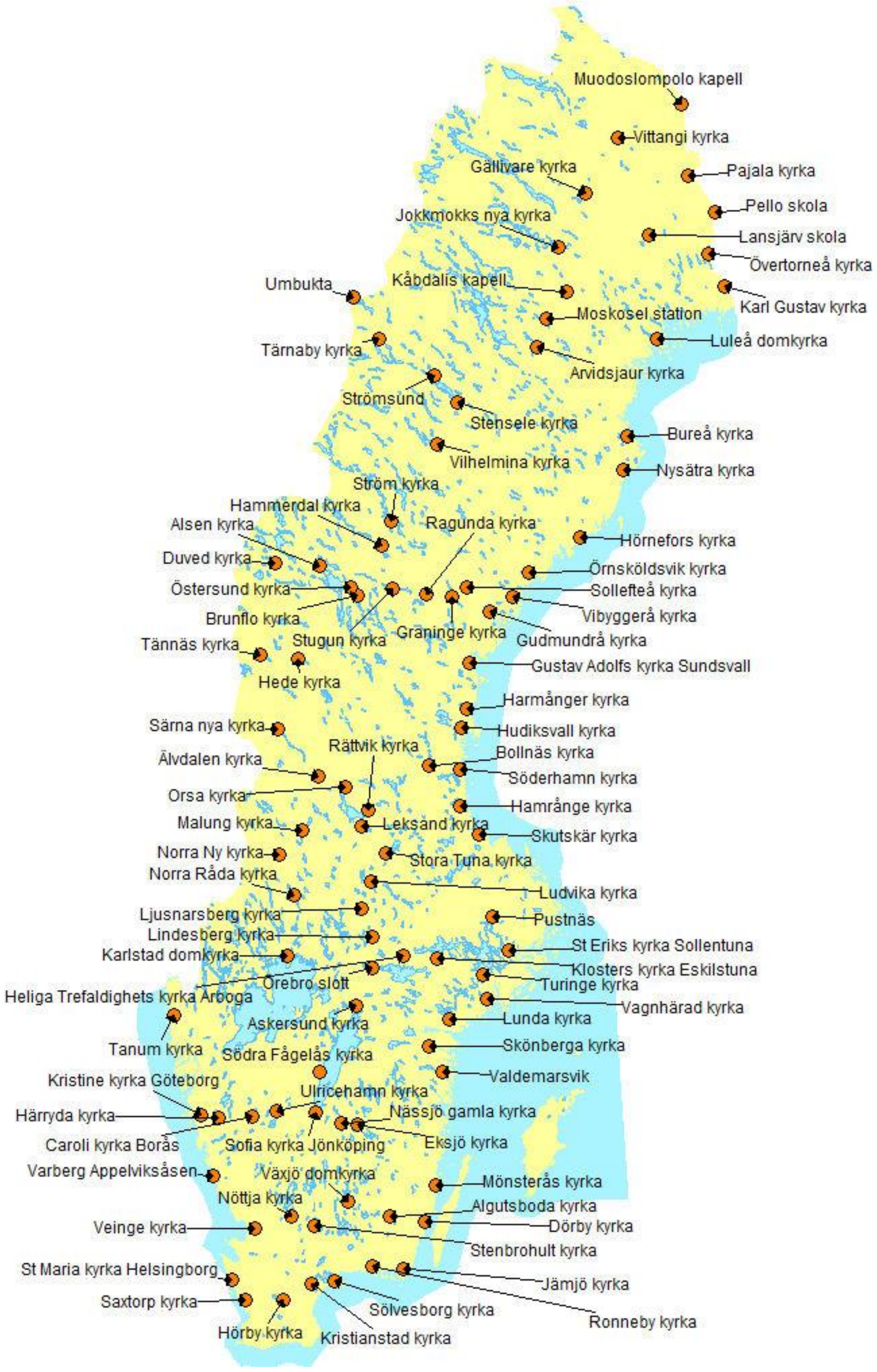
Table 14: New connections between RG 82 and RG 62 (in mGal). These were measured between 1976 and 2015 and were not included in the old transformations.

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

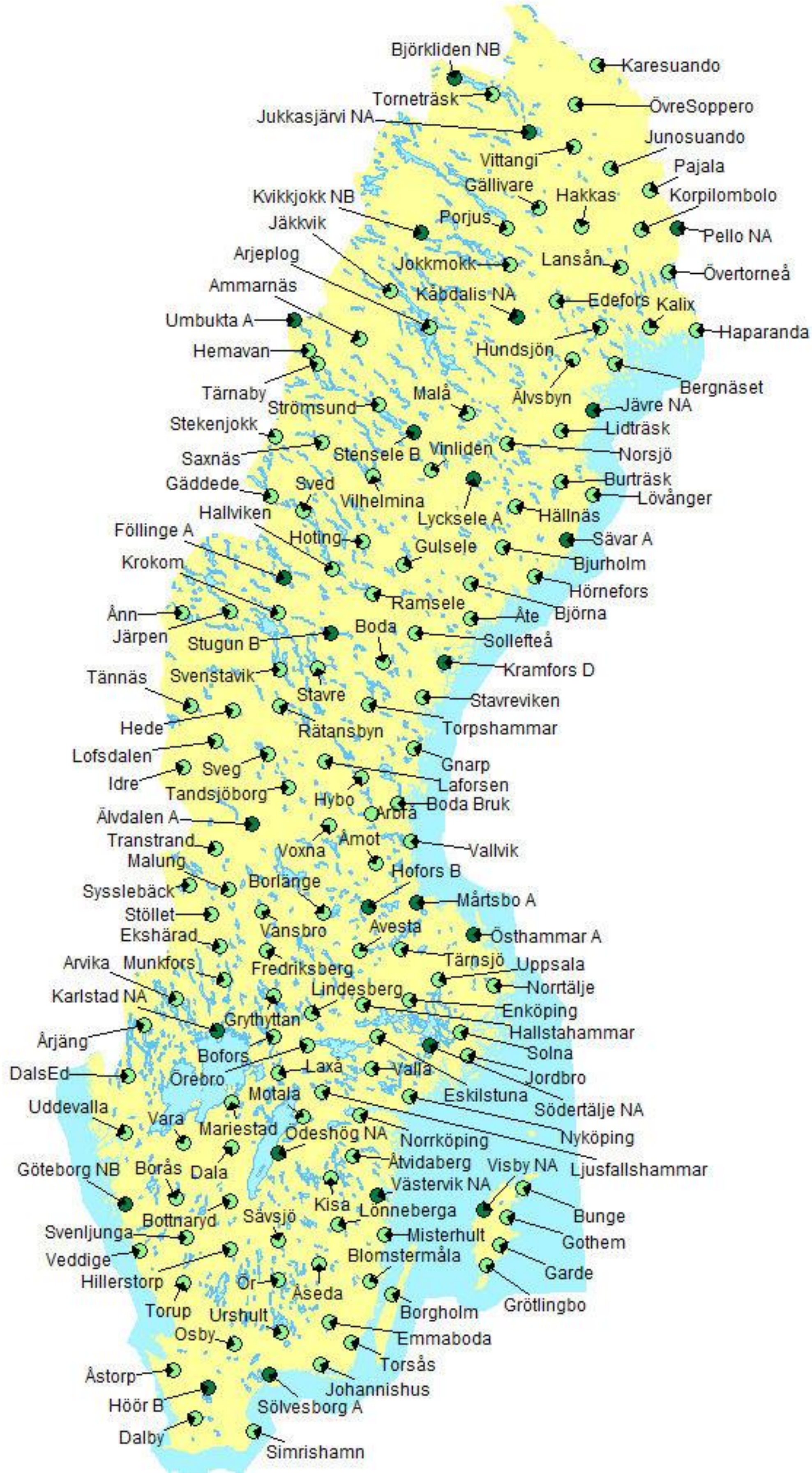
Skutskär kyrka 2	981934,622	981949,200	-14,578	LÅH 1976
Skutskär kyrka 3	981934,616	981949,200	-14,584	AE 2015
Älvdalen kyrka 1	981920,306	981934,920	-14,614	LÅH 1996
Älvdalen kyrka 2	981920,295	981934,920	-14,625	AE 2015
Stora Tuna kyrka 1	981907,283	981921,840	-14,557	LÅH 1976
Stora Tuna kyrka 2	981907,254	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).

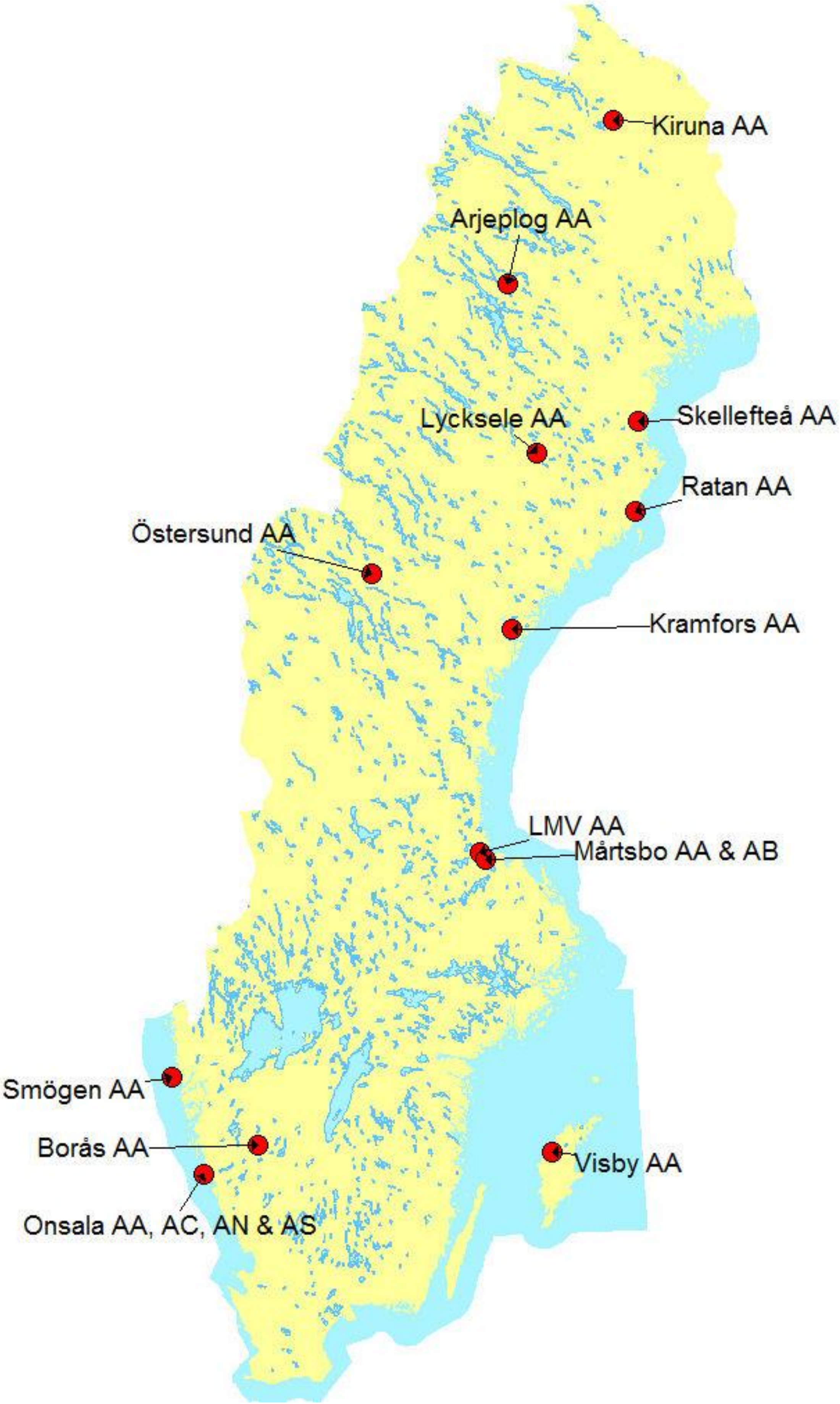
Appendix 2: Maps



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

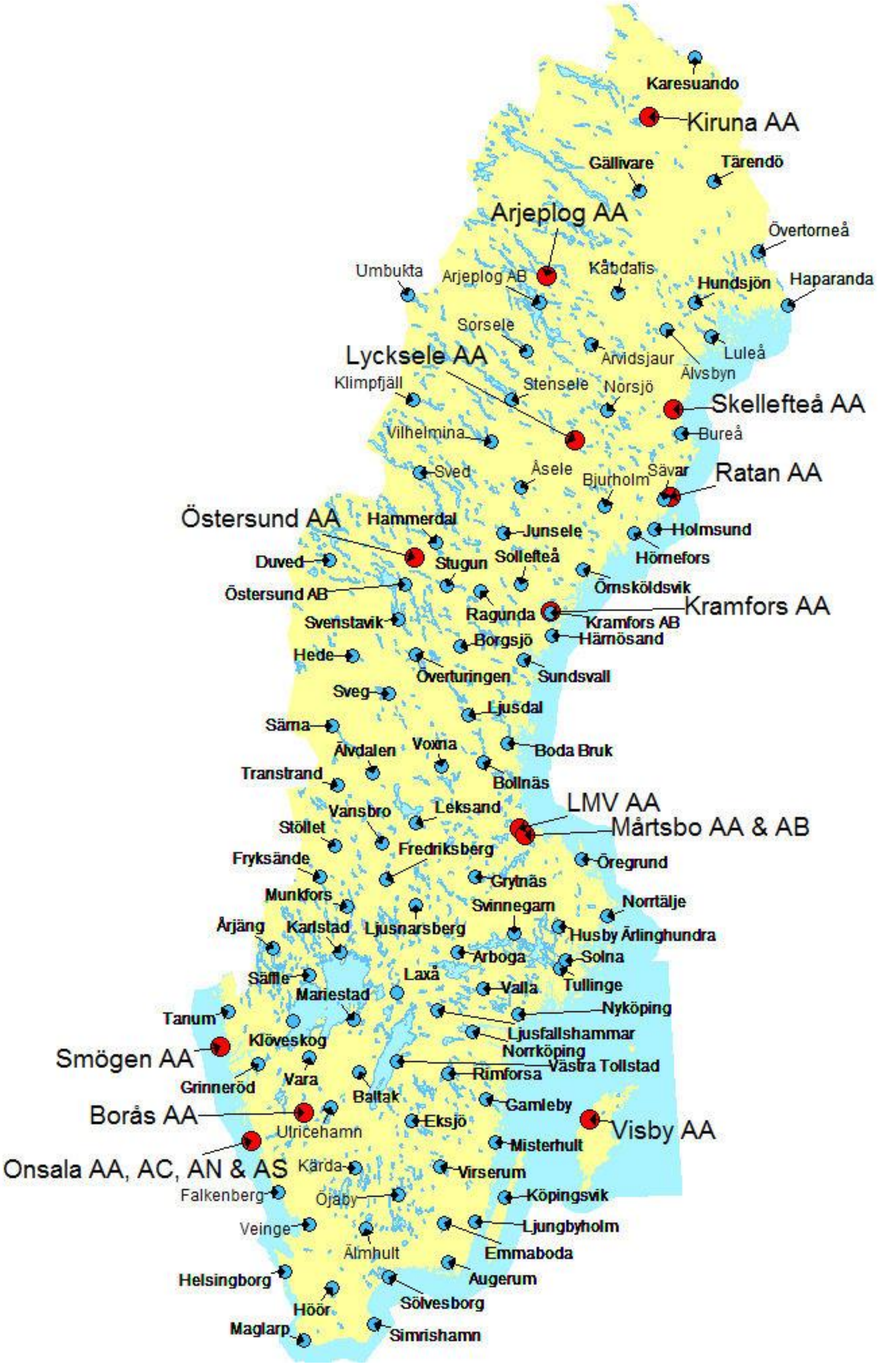


Map 2: Locations of the 25 main sites of the Zero Order RG 82-sites and the 131 still usable First Order RG 82-sites

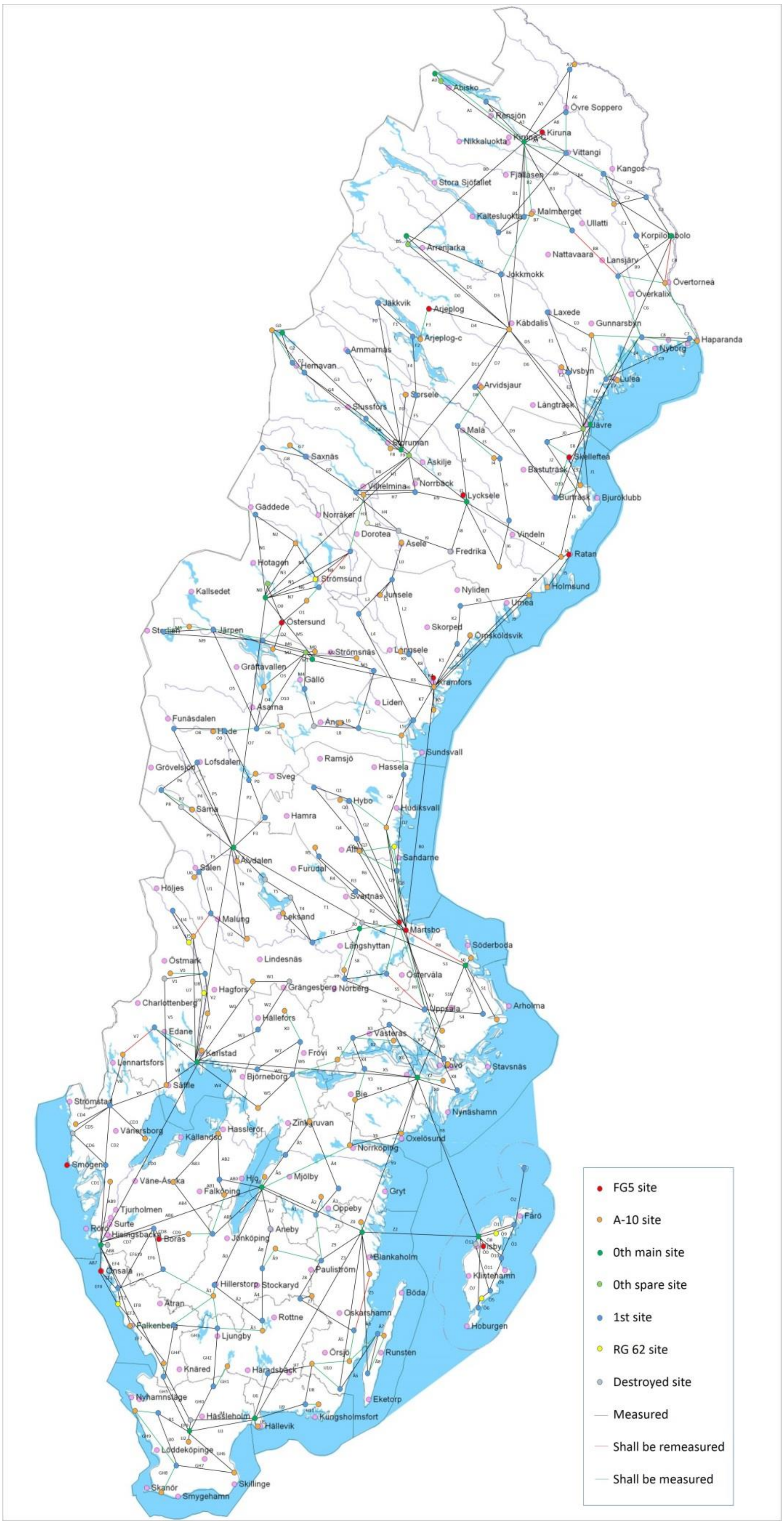


Map 3: Locations of the 13 FG5 sites

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

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.

2016:1 Engfeldt Andreas: RG 2000 – status March 2016.

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