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Review of current and near-future levelling technology

– a study project within the NKG working group of Geoid and Height Systems

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Preface

Levelling is a discipline in physical geodesy. Combined with gravity we calculate geopotential differences. In contrast to GNSS, referring to complicated reference systems realized in reference frames, the geopotential differences refers simply to defined geopotential values in one (or more) fundamental point(-s), and has as such an easy defined physical meaning, and gives valuable knowledge about this feature of the earth.

A height reference frame, or vertical datum, is obtained by following given standards and conventions on how to calculate heights from these geopotentials, and we get normal heights, orthometric heights or other types of heights.

It is important to see levelling in this context, to have focus on the physical quantities rather than the height system and vertical reference for maps. This physical information about the earth is valid and useful for geodesy studies beyond heights and height references.

We should focus on the accurate observations and the consistent net of observations covering the whole Fennoscandian area with connection to Europe and Russia. And we should focus on all the thousands of benchmarks to which these observations are connected. The measurements and the benchmarks, those are the important results of 20–30 years of work and what should be taken care of for the future.

This document gives a detailed documentation on how the measurements have been done. We hope the document will be useful in the future, when underlying detailed information is required to understand the observations.

Table of contents

Review of current and near-future levelling technology

1 Background

The purpose of this study project is to make a literature and experience-based review that sums the current levelling methods and capacities in the Nordic countries, identifies promising areas for further study and development, and, if it finds reason for that, propose a focused continuation project with concrete actions in them.

The motivation for the project is to secure that the knowledge of the current methods in precise levelling, on the practical level, is documented for the future.

To keep the scope manageable, GNSS/geoid height determination has been kept out of the project.

The review mainly deals with the practical work regarding the latest precise levellings in the Nordic countries, resulting in a common calculation of the networks in Denmark, Finland, Norway and Sweden.

In order to get a stronger connection to the United European Levelling Network (UELN), measurements from the Baltic countries, Poland, the Northern part of Germany and Holland were included in the calculations called the Baltic Levelling Ring (BLR).The epoch for BLR is year 2000.

In addition to that, a new common land uplift model, NKG2005LU, could be calculated for the whole area. This work could be done since precise levellings was carried out in all the Nordic countries fairly at the same time.

In 1982, the NKG working group for Height determination worked out a proposal for common guidelines for precise levelling in the Nordic countries. The guidelines were accepted by the working group in 1984. In all the Nordic countries precise levellings were about to start, or were already going on at that time, and were thus facing the same problems. The guidelines included most of the operations connected to e.g. benchmarks, measurements and controls.

The measurements for the latest precise levelling projects in the Nordic countries took many years to complete, and the original guidelines were slightly modified in all countries during the projects. The guidelines are enclosed as *Appendix 1.* The major differences in handling the various items concerning the precise levellings are shown in this document.

The review also contains a list of literature on items mainly connected to practical issues regarding precise levelling.

Throughout the years the working group had a very good cooperation, all the way from levelling to implementation of the new height systems in the Nordic countries. This cooperation was to a great extent conducive to the good result that was achieved in the Nordic countries as a whole.

The third precise levelling in Denmark was carried out in 1982 – 1994, and the third precise levelling in Finland in 1978–2006. In Norway there have not been different precise levelling projects, but all measurements from 1917–2013 defines the network. Many lines have been measured again one time or more throughout the years. The third precise levelling in Sweden was carried out in 1979–2003. The levellings on Gotland were made in 2007 and then connected to the network, *(Lilje et. al. 2007).*

In Iceland the conditions are somewhat different due to volcano activities, which make it difficult to establish lasting reference systems. Measurements started in 1992, and are still ongoing. However, the first version of the Icelandic vertical reference system ISH2004 was published in 2011, (*Valsson et.al, 2011)* and *(Valsson, 2012),* based on measurements made in the period 1992–2009.

2 Benchmarks

An important issue connected to precise levelling is the handling of the benchmarks. A sustainable result from precise levelling requires as solid benchmarks as possible. The result from the measurements is in fact stored at the markers in the terrain. Therefore it is important to use appropriate markers, adapted to the conditions at each location, in order to preserve the result from the measurements. Precise levelling is a fairly expensive measuring technique, and the value of the investment will decline concurrently with the dislocation or destruction of the benchmarks.

The Danish levelling network consists of totally102 500 points. About 20 000 of them are damaged or removed, so the remaining number of benchmarks that have a DVR90 height is 80 000. Approx. 60 000 of the benchmarks is founded in buildings, and they are only for levelling. The last few years other types of benchmarks have been established, but all of them are suitable for levelling.

The Finnish precise levelling network consists of 6 000 benchmarks. The total number of levelling benchmarks in Finland is 54 000. Most benchmarks belong to the network of the National Land Survey. The length of a benchmark bolt is 15 cm, and the diameter of its spherical head is 38 mm. In the bolt there is a slit for a wedge in order to fasten it firmly in a borehole. The average benchmark interval is 1.5 km. In the southern parts of Finland the levelling lines are located along railroads. As a whole, around 50 % of the levelled kilometres were measured on railways.

The precise levelling benchmarks have been founded in bedrock (47 %), stone blocks (42 %), bridge foundation (8 %) or building walls (3 %).

The Icelandic levelling network consist of approximately 3 500 points. Some of the points are destroyed, mainly due to road construction. The benchmarks are preferably founded in bedrock, but that is not always possible.

58.9 % of the benchmarks are founded in bedrock, 15.4 % are temporary points, 13.7 % in stone blocks, 8.3 % in pipes, 1.6 % in buildings or concrete pillars and 2.1 % are not specified.

The Norwegian levelling network consists of approximately 31 000 points, but many of them are gone, overgrown or damaged. Height benchmarks are placed in many different substrates.

64.5 % of the benchmarks are founded in bedrock, 9 % in stone blocks or boulders, 2.5 % in concrete bridges, 2.5 % in other concrete constructions, 1.3 % in building walls, and 20 % are not specified, see figure 1.

The Swedish precise levelling network consists of totally 49 400 points, including Gotland. The conditions to establish solid benchmarks are varying over the country, but on average they are quite good. The most common marker is a bolt made of stainless steel with a spherical upper surface and a wedge or expander in the bottom of the bore hole to anchor the bolt to the foundation. The length of the bolt varies between 10 and 50 cm, depending of the hardness of the foundation.

When no sufficient foundation is accessible, a type of underground benchmark is used. Shortly it consists of a steel bar, that can be lengthened, that is worked down as far as possible, hopefully to the bedrock, using a pneumatic hammer.

35 % of the benchmarks are founded in bedrock, 53 % in stone blocks or boulders, 6 % in constructions as houses or bridges, and 4 % are underground benchmarks. 2 % of the points are temporary points with no permanent marker.

The benchmarks were normally set out one year before the measurements, so that benchmark descriptions and benchmark maps could be prepared during the winter before the levelling, *(Eriksson 2001).*

Figure 1: A Norwegian benchmark in bedrock.

2.1 Benchmark descriptions

It is for many reasons important to have clear and distinct descriptions over the benchmarks. It should be possible for the users to find the points even after many years. If a point cannot be found even if it is there, it is quite expensive and unnecessary to establish a new one. All points must also have a unique identification, in order to eliminate the risk for using the wrong point in case there is more than one point at the same location. This is a common reason for mistakes among the users.

A good benchmark description should contain:

- A unique identity number
- A short and clear text describing the location
- A sketch showing the point in the terrain with surrounding permanent details
- An extract from a map showing the point and the nearby ones
- Information about other identification numbers or names on identical benchmarks (e.g. older national points, local points)
- Information about other points in the nearness if any
- Information about date for establishment, measurements, recovery and updating
- Coordinates for the point
- Height in a given height system

All information about ***the Danish*** benchmarks is stored in a database. The sketches are available in digital form and in a format that gives a possibility to correct the information if needed. There are only sketches for benchmarks that have been renewed, and have 3d coordinates. Since the

90´s, efforts have been made to improve the location coordinates, down to the level of a few metres.

All benchmarks and descriptions of the points are now free of charge, and can be viewed from the internet. http://valdemar.kms.dk/valdemar

A benchmark description ***in Finland*** includes coordinates, type of levelling line (railway, road), surface material of the road or railway (asphalt, clay, gravel etc.), the distance of the benchmark from the middle of a road and its height above a road surface. In case of bedrock or stone, quality and size of the visible area of the bedrock or stone was reported. Type of soil is also shown in the description.

The description has a space for a sketch, where the surveyor typically added some reference distances from meaningful and permanent objects near the benchmark.

Since 2001 the benchmark's coordinates were measured with a handheld GPS receiver. Every benchmark has a unique name. The naming convention for a benchmark has five digits. The first two digits represent a setting year. The third digit denotes the code of a surveyor, and the last two digits are for an annual serial number of benchmarks.

All information about ***the Icelandic*** benchmarks is stored in an excel file and in a geodatabase. There is currently a work going on in order to create a new database for all benchmarks in Iceland.

All information about ***the Norwegian*** benchmarks is stored in a database, even the sketches if available in digitized form. Old benchmarks not visited since the 70's, may have very inaccurate coordinates.100 m off is not unusual.

Also ***in Sweden,*** all information about the benchmarks is stored in a database, and the benchmark sketches are linked to the database. When a description is viewed on a screen or printed out, all information is given on a form, and an extract from a map sheet showing the actual point and the neighboring ones. The coordinates for the benchmarks were originally digitized from a map in scale 1:50000 and are therefore not very accurate. Since the updating programme started in 2004 the coordinates are measured with a handheld GPS receiver.

3 Instruments and equipment

Precise levelling works have historically always been carried out using classical levelling on foot (FL) procedures. However, when the latest levelling projects were about to start in the Nordic countries, thoughts came up about how to speed up the levelling field work and still preserve the quality. For that reason the motorised levelling technique (ML) was regarded a possible alternative.

The motorised levelling technique was first developed in former East Germany at the Technical University in Dresden by professor Peschel and his collaborators. Jean-Marie Becker at Lantmäteriet made a study visit there in 1973, and then started to develop the technique further in Sweden, see figure 2 and 3. Test measurements were carried out in 1974–1975, and when the third precise levelling started in Sweden in 1979, the technique was fully operational.

After that, technical improvements were made step by step as a result from the experience gained through the measurements made with ML, both in Sweden and in other countries, like France, Holland and Germany, (*Becker 1984, 1985*) and (*Widmark and Becker 1984*).

Also in Denmark and Norway the motorised levelling technique (ML) was introduced. The reason to use ML was to increase the production, and by that decrease the costs. This was a necessity with such a huge task ahead. Moving between the setups was faster, and also the very measurements, thanks to the suitable instrument NI002. The operators do not have to leave the cars except when connecting to benchmarks. This technique made it possible to work during almost all weather conditions. It also increased the production rates and the quality of the results.

ML uses three cars (one instrument car and two rod cars) and four persons (two in the instrument car and one in each rod car) for all levelling operations.

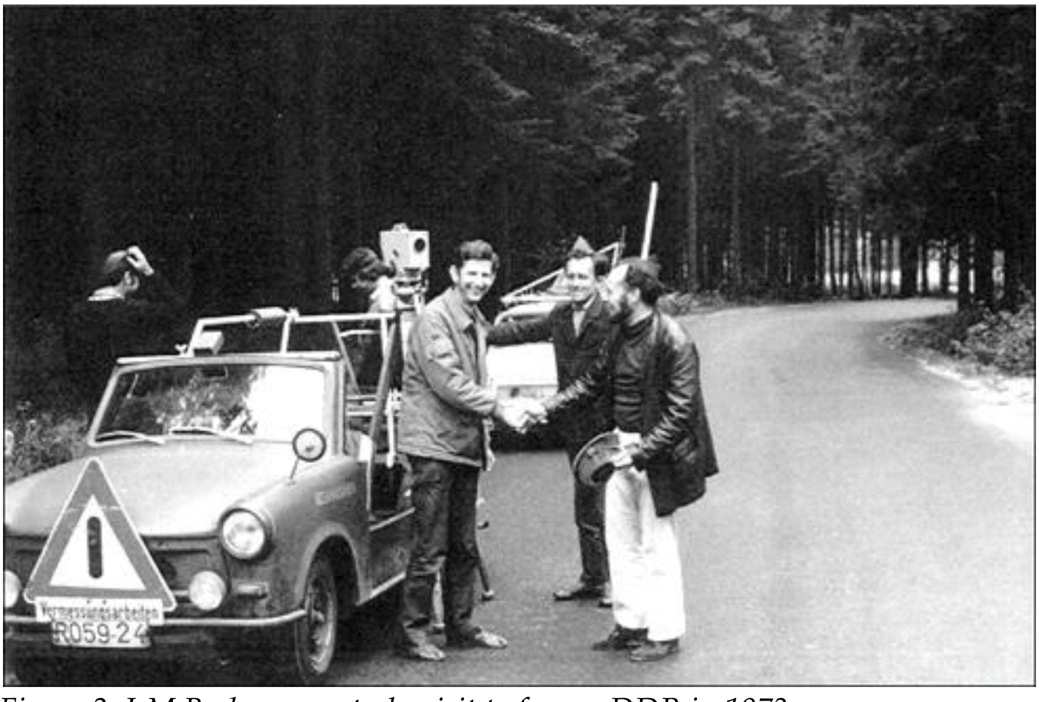

Figure 2: J-M Becker on a study visit to former DDR in 1973.

Figure 3: A motorised levelling team at work in former DDR in 1973.

3.1 Instruments

Until the middle of the 1970`s the dominating instrument for precise levelling was Wild N3 from Heerbrugg Switzerland. This is a very accurate instrument with a standard deviation of 0.2 mm for 1 km double run. Readings are given down to 0.1 mm, and estimations can be done to 0.01 mm. The instrument also has a tilting screw with graduation, which makes it useful for long distance measurements e.g. water crossings. N3 is a spirit tubular level, and is therefore a little slow to operate, see figure 4.

In 1973 a new precise levelling instrument was introduced, NI002 from Carl Zeiss Jena in former East Germany. NI002 is a compensator instrument. The accuracy is the same as Wild N3, but a unique advantage with NI002 is the reversing mirror compensator, that makes it possible to take readings in both the initial and the reverse position of the compensator. The mean of the two readings thus gives a "quasi-absolute horizon". This eliminates in practice the collimation error, and the need to keep the backsight and foresight lengths equal is not crucial. The instrument is also equipped with a rotating eyepiece, allowing measurements 360 degrees around. It also has the hair cross placed in the objective lens, which eliminates the parallax error.

All these improvements compared to Wild N3 made the NI002 very suitable for motorised levelling. A new model of NI002 was launched in 1988, called NI002A. This was in practice the same instrument as NI002, but with a slightly different design, see figure 5 and 6.

Figure 4: Wild N3 from Heerbrugg.

Figure 5: Zeiss NI002 from Jena.

Figure 6: Zeiss NI002A from Jena.

The factory and the service laboratory in Jena was closed down in 1992 and moved to Zeiss in Oberkochen. At the same time the manufacture of NI002 was also closed down.

In 1990 the first digital level, Leica NA2000 was introduced, see figure 7 and four years later Zeiss introduced their first digital level, DiNi10, see figure 8. Leica have improved their digital levels several times, and today's model for precise levelling is DNA03, see figure 9.The successor to DiNi10, designed for precise levelling, DiNi11 was released in 1996.

Figure 7: Leica NA 2000.

Figure 8: Zeiss DiNi 10.

Today´s model for precise levelling from Zeiss is Trimble DiNi12/DiNi0.3, see figure 10. The standard deviation for these instruments is specified to 0.3 mm for 1 km double run. There are a number of other brands on the market, specified for both precise levelling and lower order measurements, but in the Nordic countries DiNi11 or DiNi12/DiNi0.3 has been mostly used.

Figure 9: Leica DNA 03.

Figure 10: Trimble DiNi 0.3.

The ML technique in combination with NI002 was used ***In Denmark*** during the whole third precise levelling (1982–1994), and even until 1999 in lower order networks. ML and NI002 were taken in use as early as in 1980.

From 1996–1998 KMS tested a lot of digital instruments, and in 1999 Zeiss DiNi11 was taken in use for the production of ML. The invar rods were extended with 0.5 m in the bottom in order to lengthen the sight lines which increased the production. In 2000 the production was increased by approximately 20 % and the Ni002 has not been in use for production since. However, the levelling instruments have been upgraded with new models since then.

ML was never used ***in Finland***. The first levelling instrument used in the Third Precise Levelling was the automatic level Zeiss Ni002. The spirit level Wild N3 was used during the period 1984–2000. In 2001 the digital level Zeiss DiNi12 was taken into use.

In Iceland the entire network was measured using levelling by foot (FL), and Leica Na 2000, Leica Na3000 or Zeiss DiNi12.

In Norway foot levelling was the only technique in use until 1980 when ML took over. Where ML was not suitable, foot levelling was done. Wild N3 was the dominant instrument for foot levelling. For ML the Ni002 instrument from Zeiss Jena was used. Sometimes this instrument was used for foot levelling as well. ML was used in Norway until 1996. From 1997 only foot levelling with digital equipment has been performed.

Taking in use the digital equipment increased the production significantly compared to the traditional foot levelling with Wild N3. Compared to ML, however, the production was the same. The motivation for closing down the motorised levelling was the economy. A major investment in new cars was not necessary any more since the new digital technique could take over without any decrease in the production. The digital instruments used from 1997 to 2013 are: DiNi10, DiNi11, DiNi12 and DiNi0.3.

In Sweden the entire network was measured using ML and Zeiss Jena NI002/NI002A. A few water crossings were made using Wild N3 in the beginning of the project, see figure 11. Later on Leica total stations were used for that purpose. A few lines in the mountains were measured with good result in 1990, using MTL (Motorised Trigonometric Levelling), with three pieces of Kern E2 + DM503 total stations, see figure 12. The reason for those measurements was to connect between some long lines in the mountains towards the Norwegian border.

It was an advantage to be able to carry out the entire field production with the same type of equipment all through the project, even if e.g. the digital levels were accessible from the middle of the 1990´s. This made the whole work equivalent and homogeneous. However, for densification and updating of the network DiNi12 and DiNi0.3 have been used since 2004.

Figure 11: Trigonometric water crossing over Öresund between Kronborg and Pålsjö klint in 1981, using Wild N3, a joint project between KMS and LM.

Figure 12: "MTL" using ATV vehicles in the Swedish mountains near the Norwegian border in 1990.

3.2 Rods

The rods should be handled with the same care as the levelling instruments. A slight error on a rod can have as much influence on the result as an instrument error.

Precise levelling requires calibrated invar rods. For Wild N3 and NI002 double scale rods with 0.5 or 1 cm graduation were used. Traditionally the rod frames were made of wood. A problem with those rods was that the frames could expand slightly during a levelling season, due to damp from rain and humidity in the air. The invar band is connected to a spring fastened in the rod frame, that should take care of this expansion, but in spite of that, a 3 m invar band can expand with 0.1 – 0.2 mm during a field season. Modern invar rods have frames of aluminium which almost eliminates this problem.

Digital levels require bar code rods. This means that the invar tape has a bar code instead of a cm graduation. Otherwise they are constructed in the same way as standard rods. Those rods have frames of aluminium.

The rods are normally 3 m, but sometimes shorter rods (1 or 2 m) are required in order to connect points where a 3 m rod is too long, e.g. under a roof , inside a building or along a railroad with conductor.

In Denmark 3.5 m rods were normally used in ML, and some 3 m and 2 m for benchmark connections. After introduction of the digital level some changes had to be made. The rods had to be extended with 0.5 m, since the invar barcode rods only was available in the length of 3 m. The extension was made of aluminium, with a small expansion coefficient. This is monitored during the survey campaign. The same type of barcode rod is normally used for benchmark connections. This rod can have a length of 2 or 3 m.

In Finland Zeiss Jena rods with 5 mm scale division and wooden frames were used during the period 1978–1997. Nedo aluminium rods have been used since then. The rods were usually 3 m long, but also 2 m long rods and rods with an enlarged rod scale have been used, see figure 13.

Figure 13: From the left Zeiss Jena 5 mm graduation rod with wooden frame, Nedo 5 mm graduation rod with aluminium frame and Nedo LD 13 bar code rod with aluminium frame. Photo: P. Lehmuskoski.

In Iceland 3m rods produced by Nedo have been used. Wild-GPCL3 was used for the Leica Na2000/3000 instruments and Zeiss LD13 for the DiNi12 instrument. Rod readings are usually not taken under 50 cm, except for special circumstances.

In Norway 3 m rods where in use for a very short period of time when ML was first implemented. After that only 3.5 m rods were used. The rods were produced by Nedo in cooperation with Zeiss Jena. There was no special third rod for connection to benchmarks, instead one of the two rods was designated for bench mark connection and marked with a red tape on top.

In Sweden a few 3 m rods from Wild were used in the very beginning of the project. With the ML technique the instrument height is roughly 2.1 m above the ground, and with a 3 m rod there was only 90 cm left to use in the upper end. So when the terrain was a little inclined, the maximum sight lengths became very limited. Therefore, 3.5 m rods were ordered for the rod cars in cooperation with Zeiss Jena, and they were specially produced by Nedo. All the Swedish rods had 1 cm graduation. In order to reduce refraction errors, the lowest 0.5 m of those rods had no scale and was not readable. The car rods were equipped with three bull's eye levels for permanent plumbing control during the measurements. A special 3 m rod was used for connection to the benchmarks.

3.3 Thermometers

In precise levelling it is necessary to correct the measurements for the thermal expansion of the invar band, even if the thermal expansion for invar is very small. For that reason the air temperature was measured both in Finland, Norway and Sweden.

In Denmark, the air temperature and the temperatures of the invar band and the asphalt was measured and used for every setup.

In Finland thermometers measured the air temperature and the temperature difference using sensors located 0.5 m and 2.5 m above the ground. The temperature readings were also used for refraction correction computations. The used thermometers were Delta Ohm HD 8704 (1990–1995, 1998–1999), Fluke 52 (1996–2000), and Fluke 54 II (since 2000). Before these models, specially designed thermometers were used. An old model was constructed by Kukkamäki for the Second Precise Levelling, and was later improved by Hytönen.

Thermometers were not always used ***in Iceland***. When it was not, the weather data was collected from the closest weather station.

In Norway a whirling thermometer was used. In the last period with ML the air temperature was measured with a temperature sensor equipped with a fan. Also ***in Sweden*** the air temperature was measured with a temperature sensor equipped with a fan, and could be read from inside the instrument car for each setup. Two temperature sensors were mounted on the invar tape of the car rods, measuring the temperature on the invar band at 0.6 and 2.4 metres above the ground. Those temperatures were stored for each setup. Information about weather conditions and road surface was also stored for each setup.

3.4 Change plates

When levelling between the backward and forward rod it is crucial that the rods are not sinking while the instrument is moved to the next setup, and the forward rod is turned to backward rod.

In Finland steel plates were mainly used as rod bases on asphalt roads. Wedge-like pins were used in sand, in forest and on new asphalt roads. Also steel pins, 50 cm long and 2 cm thick, were used in forest or swamp terrain. These were also used on sand beds along railways when the rail nails were considered to be too unstable.

Rail screws, springs, nails and steel rail clamps were used as rod bases along the railways. Rail screws attached the rails on wooden sleepers and rail springs correspondingly on concrete sleepers.

In Iceland and Norway pads with three big and quite widely spaced screw heads are used. The large screw heads makes the bearing surface larger and reduces the risk of sinking.

In Sweden the rods are set up on change plates with a steel pin looking like a marker on top. The plate should be tramped down on the ground to be stable before the rod is set up on it. If the plates are relatively heavy they are more stable. The change plates used in the Swedish ML are specially designed and have a weight of more than 5 kg. They can be hooked up on the drivers' door when moving to the next setup.

3.5 Transportation

When using the ML technique, a team consists of three cars, one instrument car and two rod cars. The cars are adjusted to some extent, see figure 19 and 20. The instrument car is a small pickup model with a loading platform, where the observer is working. On the floor of the platform there is a hole for one of the tripod legs. The other two legs are put on the outside of the platform. This means that the instrument is totally free from the car during the observations.

In Finland the ML technique or cars have not been used, but the bicycle and handcar trolley methods were in daily use in the beginning of the Third Precise Levelling. Since 1986, the levelling teams have moved only on foot, see figure 14 and 18. Using the bicycle method, all team members had a modified bicycle, see figure 15. A distance measurer had a bicycle with a distance meter and a bag for the rod base spikes and their pounding device. The rod men had bicycles with a rack for transporting a rod in a vertical position. The bicycle for the record keeper was equipped with a table needed for a recording and a rack for the differential thermometer. The observers bicycle had a rack for the instrument.

Figure 14: Adjustment of Wild N3 in 1996. The record keeper notes the rod readings on a Husky Hunter computer. As a part of the table there are temperature sensors 0.5 and 2.5 m above the ground.

Figure 15: Bicycle levelling in Hyvinkää 1979. Photo: S. Kora.

Using the handcar method along railroads, a levelling team had three vehicles. Two handcars were used for the rod men and one was in common for an observer and a record keeper. The handcars of the rod men had a rack for transporting the rod in the vertical position. The handcar of the observer was equipped with a table and racks for a level and a differential thermometer. A distance measurer walked along the rails and marked the locations for set ups and rod bases, see figure 16.

Figure 16: Handcar levelling in Inkeroinen in 1979. Photo: P. Lehmuskoski.

Cars have not been used for levelling ***in Iceland*** so far.

In Norway there was a person with a trolley with warning signs who followed behind the levelling team between 1980 and 1990. From 1991, the trolley was replaced with a separate car with a warning panel, see figure 17. When ML was taken in use, the instrument car and rod cars were equipped as described for Sweden and Denmark.

In Sweden and Denmark the instrument car is equipped with a Digitrip distance gauge in order to get equal backsight and foresight distances. The recording of data and other administration is handled by the driver. Communication between the observer and the driver is done with the use of microphones and speakers. There is also a possibility to set up a plastic roof and a wall over the platform as a shelter from rain and strong wind. Strong wind can cause vibrations in the long tripod legs.

The rod cars are small sedan cars, and have a divisible driver’s door so that the driver can operate the rod from the driver’s seat. On the roof a frame is mounted to hold the rod, and a device that also allows the driver to turn the rod from forward to backward. During the transportation between setups, the rod is fastened in a hook on the door. Also the rod cars are equipped with Digitrip distance gauges. It is an advantage to have small cars, so that they can pass each other on narrow roads.

Figure 17: A Norwegian FL team with a protection car in 2009.

Figure 18: A precise levelling expedition in Inari in 2002. Photo: M Poutanen.

Figure 19: A Swedish ML instrument car on the Öresund Bridge in 2000.

Figure 20: A Danish ML team in Sweden in 2010.

4 Fieldwork

4.1 Description of one setup

A setup means levelling the height difference between the back and forward rods.

In Finland, Norway and Sweden the BFFB observing method was used. This means that the readings on the staffs were made in the following order: Distance backwards measured on the distance threads in the reticle, backward reading on the left scale, distance forward on the forward rod correspondingly, forward reading on the left scale, forward reading on the right scale, and backward reading on the right scale. After that the height difference between the scales was compared.

In Denmark the method used in ML until digital level was introduced was called "**du pantalon rouge**"method. The principle was to always make the first observation to the same rod (the man with red trousers). In principle it was the BFFB method for the first setup, and then FBBF for the next one in rotation. The rejections limit used is described in the NKG Nordic levelling guidelines.

Later, when ML Digital Level was introduced, the principle was BF, but when precise levelling was performed, it was changed to BFFB. When a digital measurement is done, the instrument makes 3 readings for each sight, and the standard derivation may not exceed 0.12 mm.

In Finland a setup was re-measured if the difference between the height differences was more than 0.30 mm. During the period 1989–2000, a limit value of 0.45 mm was used. Barcode rods have only one scale, but the same BFFB procedure was applied.

In Iceland the BF method is used. The observer estimates the suitable distance for the setup. Max distance is 40 metres. The moving rod man paces the distance and makes a mark where the instrument should be. Then he paces the same distance and marks the position for the rod. The instrument makes three readings on each rod, and if the standard deviation is less than 0.3 mm, the measurement is approved.

Since the digital levelling took over ***in Norway*** in 1997, the BF method has been used. This method means sighting only one time each at the backward and forward rod. The instrument makes automatically three readings on each rod, and if the standard deviation is less than 0.15 mm, the measurement is approved.

In Sweden where ML was used, the instrument was set up at a distance of maximum 50 metres from the back rod. This distance was measured with Digitrip. The forward rod was then set up at the same distance in front of the instrument, also using a Digitrip device.

The readings were taken manually and reported to the driver who stored the measurements in a field computer. This made it possible to store and also perform automated field controls of all observation data. The difference between the scales was compared by the computer.

If the difference exceeded 0.4 mm the whole setup was remeasured. If also the new measurement exceeded the rejection limit the mean of the two measurements was compared, and if that mean did not exceed 0.2 mm, both series were used. Otherwise a third measurement of the setup had to be performed, using more equal distances. The maximum difference of the measured sight lengths forward and backwards for a setup was 5 %. For a section the maximum difference was 2 %.

4.2 Description of one section (between two benchmarks)

A section has a general length of 1 km, and is shorter in steep terrain in Iceland, Norway and Sweden. In Finland it is 1.5 km in average. A section normally consists of several setups. Sections between nodal points are a levelling line. Each section was always measured twice, one time in each direction. Then the two measurements were compared. This procedure is according to the guidelines, and was used in Finland, Norway and Sweden, *see appendix 1*. A rejection limit of *1 mm/√km* was used in Finland. In Denmark, Norway and Sweden it was *2 mm/√km*. In Iceland the rejection limit is *3.2 mm/√km*. If the rejection limit was exceeded in any of the countries, the interval was relevelled in both directions.

After this the procedure slightly deviates from country to country.

Since 2000 the measurements ***in Iceland*** always starts and ends with the same rod on the benchmarks, and then the rods are switched on the way back. If the distance between the benchmarks is very long or if the terrain is steep, temporary auxiliary points are used. The goal is not to have more than 20 setups between benchmarks or auxiliary points, and the daily work is always ended on a benchmark.

After the remeasurement ***in Norway***, all the four height differences were compared. If any of the single measurements is outside a 95 % confidence interval, it was rejected. If two measurements in the same direction are rejected, a third remeasurement was done. If there was a good reason to suspect either the forward or the backward measurement, only the suspicious one was measured again. If also this exceeded the rejection limit, also the opposite direction had to be remeasured.

When the digital levelling took over, a small notebook was used, to write down the measured height differences of the sections. It was then easy to compare forward and backward measurement, and the notebook also served as a log book for every day.

Some sections can be very long in areas where there are no suitable objects to set the benchmark in. Here temporary auxiliary points were used, to divide the sections into distances of 1 to 1.5 km. If no natural point was found, like a sharp edge on a stone, a 40 cm iron rod was hammered into the ground and served as an auxiliary point.

If also the new measurements exceeded the rejection limit ***in Sweden***, the mean of the two double runs were compared. If that mean was within the rejection limit *1 mm/√km*, all four single measurements were used. If not, a third double run was carried out and compared, in the first place to the ordinary rejection limit. If that did not work, the mean of the third double run was compared to the means of the first and the second double run. If the third double run together with one of those means could manage the limit $1\ mm/\sqrt{km}$, all four of those single measurements were used. The need for a third double run was very unusual.

In Sweden the aim was to have as independent measurements as possible. That means that the observer was always changed between the forward and backward measurement of a section. It was also desirable to carry out the forward and backward measurements of the sections under different weather conditions. Therefore the forward and backward measurements were preferably made on different days if possible. This made it harder to stay within the rejection limit for a forward and backward measurement, but the mean value should be more reliable. Between 5 and 10 % of the sections were relevelled per year throughout the years.

In Norway however, the aim was the opposite, that is, not to have as independent measurement as possible. The Norwegian philosophy was that systematic errors were the largest contributor to the difference between forward and backward measurement. To eliminate these in the mean, the conditions should be as equal as possible during these two measurements. This meant back and forth measurement the same day, under the same weather condition and preferable close in time. However, the first years with ML, 1980 to 1987, the normal procedure was to level in the opposite direction the next day or later.

4.3 Description of a normal day

In Denmark like in Sweden, it is possible to make survey under almost all whether conditions. Only in heavy rain and strong wind the production has to be stopped. The normal season starts in March and stops in the beginning of December. Every day the equipment is visually inspected, and every week the instruments are calibrated for collimations error. Every instrument has a digital log. The average daily production is between 10–20 km, depending on weather and terrain.

A daily levelling session ***in Finland*** begun in the morning about two hours after the sunrise and lasted for 3-4 hours. In the evening the measurements were done until one hour before the sunset. During a sunny day, especially in the middle of the summer, the weather conditions were not optimal for precise levelling due to the turbulence of warm air. This affected the planning of both annual and daily observation hours.

Two sections were measured per day, both sections in forward and backward directions. In spring the expedition usually had a break between the morning and evening sessions. On rainy days, and especially in the late autumn, the levelling team worked continuously without a midday break. In Southern and Central Finland, annual measurements were carried out in spring (May and June) and autumn (August, September and October). In Northern Finland, the levelling season was from June to September.

In Iceland a daily levelling session starts at 8:00 am. Road signs are set out for the planned distance to measure, in order to warn the oncoming traffic. The levelling starts in the middle of the planned distance, usually four to six sections. Before lunch levelling is done back and forth in one direction, and after lunch in the other. If the conditions are good, one or two sections can be added. The day ends at 7:00-8:00 pm. When the weather conditions are bad, but it's still possible to measure, only one section at a time is measured. On a good day the production is between 3–5 km double run levelling, depending on the terrain. However, due to weather conditions, the average production for one campaign is only 2.5 km double run per day. The sun is usually not an obstacle. If the wind is stronger than 8–10 m/s, or in heavy rain, no measurements can be done. Then benchmarks are set out and benchmark descriptions are made up instead. In the evening the data from the instrument is transferred to a computer, and it is also saved on a USB stick.

In Norway the levelling normally started near the middle of the total distance planned for the day. Before lunch back and forth in one direction from the starting point was measured, and after lunch in the other direction (as mention before, the procedure was different the first years of ML).

The daily production was depending on the terrain, but was normally between 7 and 12 km single run levelling for 8–12 working hours with the digital levelling equipment. With ML the production could be higher in flat terrain, but lower if the roads were steep.

In Sweden the ML technique made it possible to carry out the field operations under almost all weather conditions. In that sense almost all days were normal days. A new working day normally started where the work had stopped the day before. Every morning when the equipment was set up, the three bull's eyes of the rods were compared to a long constructions spirit level, and if necessary they were adjusted. At least once a week also the collimation error of the instruments was checked and stored in a register before the levellings started.

The measurements were normally carried out in one direction for a couple of days, and then the backward measurement was carried out. However, if remeasurements were required, they were normally made directly, due to efficiency reasons, *(Eriksson 2009).*

The average hourly progression for precise levelling during the whole project was around 2.2 km with average sight lengths of about 35 metres (maximum allowed 50 m). The total time used at each setup including the moving time, varied between 1.6 and 2.4 minutes, depending on e.g. the sight lengths. The gross average daily production was some 13 km single run, including 8 % relevelling, which means about 11.7 km daily net production. Statistics also shows that the effective measuring time using ML was about 5.5 hours per day in average.

All the raw levelling data from the three field computers was stored (see section *Developments and changes in the last 25 years*). Then a control programme matched the data in order to check that nothing was wrong concerning e.g. benchmark numbers, number of setups for each section, rod identities. After corrections of errors if any, a corrected result file from the day was stored together with the raw data files. In 1990 this control programme was transferred to PC, and each team could correct the daily measurements at the hotel in the evening. The corrected data was then transferred to a temporary local field database in the PC.

4.4 Traffic and safety

Both classical and ML precise levelling today is mostly carried out along roads. The roads can be heavily or low trafficked, depending on the need where to locate the levelling lines. In general the traffic is more intense nowadays than in the beginning of the 1980´s. Thus the demand for safety measures is also stronger today, which is a necessity. Regulations from the road authorities describe how the vehicles should be equipped with flash lights and traffic signs in order to warn the road-users and to protect the levelling team. The regulation also tells where and how to set out signs along the road, in order to inform the road-users that there might be an obstacle ahead. The demand for safety measures has increased also when levelling along railroads.

In Denmark all measurements are done along roads, and all personal in the team have the certificated "The road as a working place - license", given by the road authorities. Since 2006 measurements have also been carried out along high ways. Here it is done in cooperation with the road authorities, normally with a safety car behind, and sometimes the work is also done during night time. Sometimes permission has been given from the road authorities to close a bridge for some night hours, in order to avoid vibrations from the traffic on the bridge. During the normal day, every team member always remembers "safety first".

In Finland, when measuring on a road, the levelling team inserted the traffic signs to warn the oncoming traffic before the measurements started. On railways, safety persons from the railway company took care of the safety during the work.

In Norway a person with a trolley with warning signs followed behind the levelling team from 1980 to 1990. This could be tiring, especially when the headwind was strong.

The signs warned about work on the road and narrowing of the road. Warning in front of the levelling team was rarely used.

After 1990 a special car with warning panel on the roof was used. The levelling cars were also equipped with warning panels. Warning in front of the levelling team was more used, especially when the road was curved and hilly.

In Sweden the roads are classified depending on the traffic quantity, and the regulation is stronger the higher the traffic. The highest class today requires a heavy lorry with a Truck Mounted Attenuator (TMA) protection that should follow right behind the levelling team. The road authorities have regulations about warning signs and flashers on the cars, and also about warning signs on the road behind and in front of the team. All personnel in the levelling teams also must have a certificate from a course on "Safety at road work", given by the road authorities.

Today you are not allowed to stay on the railway embankment without a safety person from the railway company following the levelling team. The members of the team must also have a certificate from a safety course.

4.5 Formalities and permission from the road authority

In Denmark there is a permanent permission from the road authority to make surveys along the roads, but there is also a close dialog with the road authority during the survey season.

In Iceland the Road Administration Authorities take an active part in the levelling. They actually started the levelling of the national vertical reference network in 1992. The National Land Survey did not join until 1999. So they are always aware of where the levellings takes place. Warning signs and safety lights are used to mark the working areas. Sometimes it is quite dangerous to measure on the roads, because many drivers do not respect the warning signs. If it is possible, the measurements are located to horse tracks that are adjacent to the road.

Norway: Before 1990 a general plan concerning levelling on roads was approved by the national road authority. This plan covered the whole country and was valid for several years. After 1990 the plan is valid for one year only, and had to be approved by the regional road authorities.

Sweden: Before each season, a plan with a map was sent to the road authorities, showing the actual levelling lines and approximate timetable for each part of the area. There should also be a form describing e.g. the nature of the work, head of the field team, start and stop dates for the measurements. A sketch showing the traffic signs on the cars (different for instrument and rod cars) and how the traffic signs on the road was planned to be set out, should be attached to the documents. If there was no remark from the road authorities the plan was approved.

5 Data and data storage

5.1 Storing field data

During the first years of ML ***in Denmark,*** the observations were typed in on HP9915 or a Canon calculator. Later on, in the 90´s the first laptop was introduced, with self-developed software, see figure 22. This software and laptop has been modernized since, and are nowadays integrated with GPS, maps and many other procedures in order to reduce errors.

The first recording system ***in Finland*** was a notebook, a pencil, and a calculator, which was needed in the computation of height differences. In a notebook was written information concerning the entire season, like a line number, an observer, team members and the serial numbers of the instrument and rods. During the measurements a record keeper noted weather observations, sighting distances, rod readings, air temperature gradients, the calculated height differences, and possible comments. At that time the observations were stored on punch cards after each field season. Data and results were stored in a computer at FGI, and the record books were stored in the data archive of the FGI. The final document of the entire levelling lines was computed at the office after the annual levellings.

Husky Hunter data loggers replaced the notebooks in 1987. Since 2001, the digital level Zeiss DiNi12 has been used. This instrument records, controls and stores the rod readings into a PC Card. The content of the PC Card was transmitted daily to the computer, as well as the data of the temperature logger Fluke 54II with an infrared link.

Iceland: The records from the digital instruments are stored on a PC Card during the measurements, and then transmitted daily to a computer and a backup. Earlier on diskettes, and later on a USB stick. The results are always written down in a field book.

During the first period of ML ***in Norway***, the observations were written on small programmable HP calculators. The data was printed out on thermal paper. In office the data was transferred to punch forms and then stored on punch cards. Later on, huge NORD computers took over from the punch cards. Finally the data was calculated on a computer at a control center outside the building.

In 1986/1987 Husky Hunter field books with new self-developed software were taken into use. After the observation was made, there was now a complete digital production line with no punching work

From 1990 to 1996, a small laptop replaced the Husky Hunter field book in ML. From 1997 digital levels took over and a totally new production line had to be developed.

The Swedish ML system is not just about the levelling technique. It is also a complete digital production line, from the readings in the instrument to the delivery of heights. A lot of data programs were developed in order to handle the big quantity of data.

In Sweden, the first field computer was taken in use in 1981. This was the first step in the digital production line. The observations were performed according to a strict measuring programme, and a lot of automatic controls were calculated for each set up, in order to eliminate the risk of introducing errors in the measurements, see figure 21.

Each set up had to pass the programme controls before the work could proceed. Complementary information was stored as well, e.g. identity of the observer, instrument number, rods identification, air temperature, type of weather and road surface, (*Lilje and Eriksson 2007).*

Figure 21: Interior from a Swedish ML instrument car 1995, with the data logger, Digitrip distance meter and air temperature display.

Figure 22: Interior from a Danish ML instrument car 2000, with the data logger, a computer and a Digitrip distance meter.

5.2 Format

In Denmark all raw information concerning the observations is stored in a specified format. The format is a plain ASCII text, but observations are also stored in a local SQL database on the laptop, so the error criteria for a double run can be checked quickly.

In Finland all the levelling data has been stored as text files. Most site descriptions have been digitized.

All levelling data ***in Iceland*** has been stored as text files. Data from the DiNi instruments are in the DiNi text format, but the binary files from the Leica instruments was converted into text format using software designed at the Road Administration Authorities. In the processing of the data, all data files were converted to a FGI ASCII format.

In Norway the raw levelling data from each setup was stored as text files (ASCII). The format has changed as the levelling technique has changed. The observed height difference between the benchmarks, including the corrections applied, was until 1997 stored on different text files. Then everything was copied into an Access database, where it was stored together with measurements done after 1997. The raw levelling data remains on text files. The database has later on been copied into an Oracle database.

The coordinates of the benchmarks are stored in the same database. Most of the sketches are still not digitized.

Also ***in Sweden*** the raw levelling data files are stored as text files (ASCII), and the levelling database was from the beginning MIDAS on a Pr1me computer. With the introduction of PC in 1990, the database was changed to Btrieve, and now it is Access. The information about the benchmarks was from the beginning stored in INFO, and was later changed to Access. Today this constitutes a part of LM's Digital Geodetic Archive (DGA) where Oracle is used. The benchmark sketches are in the PNG format, and they are linked to DGA, *(Lilje and Eriksson 1999)*.

5.3 What data is stored?

Denmark**:** All the raw observations are stored in the local raw observations files. Then they are transferred to the official database. The raw observations are corrected for rod calibration etc, and then only the main information is stored in the oracle data base. The main information is point number from and to, data, time, distance, height difference, journal page etc.

Finland: For every measurement a lot of data has been stored. The stored data includes for example benchmark number, distance, height difference (in mm and gpu), corrections and gravity values. For every setup the stored information includes: all rod readings, sighting distance and temperature gradient value e.g. temperature difference T(2.5 m)–T(0.5 m). Some weather information, like the intensity of the sun, cloudiness, and a remark in case of rain, was collected for every setup.

Iceland: All raw data is stored. This means height difference and distances for every setup. Information about rods and instruments is also stored. Afterwards temperature information is added.

Norway: From 1997, the observed height difference and all the corrections applied are stored in the database. For older data only the rod correction is stored. For observations done after 1980 instrument number and rod numbers are stored as well.

Sweden: The raw data files from the field computers are archived together with the corrected data files. The results from the measurements are stored in a database. The information in the levelling database is e.g. measured height differences, length of section, corrections, number of set-ups, observer, instrument nr, rod nr, type of road, type of weather etc. All the measurements are stored section by section in the levelling database. In total, 54 different items are stored for each section.

The benchmark database contains all information about the benchmarks. There are also other separate databases, e.g. for rod calibrations and results from field checks of the instruments.

6 Calibrations

6.1 Rod calibrations

The rods can be affected by errors, e.g. zero point error, graduation error and errors due to the temperature. For that reason calibration of the rods is necessary, so that the readings could be corrected for those errors.

When digital instruments are used, another type of equipment is required for calibration. The digital levelling technique differs from the optical level. The rod reading using the digital technique is obtained by electro-optical means, a CCD sensor instead of the human eye, and every rod reading represents a group of code lines instead of one graduation line.

In the measurement process with a digital level the whole system is involved. The scale value of the system is also influenced by the scale value of the level (e.g. aging effects of the CCD) and the behaviour of the system, which may change if the rod face is damaged (e.g. scratched code elements). Therefore "system calibration" has been considered the right technique to calibrate the level and the rods together.

Until 1993, all rods ***in Denmark*** were calibrated using a laser interferometer comparator in the house. Today the rods are sent to the manufacturer for calibration once a year.

In Finland the rods were calibrated before and after each field season using a vertical rod comparator at the Finnish Geodetic Institute. In the development work of the FGI, rod calibrations and construction of the rod comparators have played an important role. In order to calibrate a rod scale and to determine the thermal expansion coefficient, FGI constructed three laser rod comparators during the run of the levelling project.

The first version was a manual vertical-horizontal comparator used in the 1970´s. The next version was a vertical comparator in 1995. Since 2002, rods are calibrated using the system calibration comparator, which determines simultaneously the scales of a rod and an instrument, see figure 23.

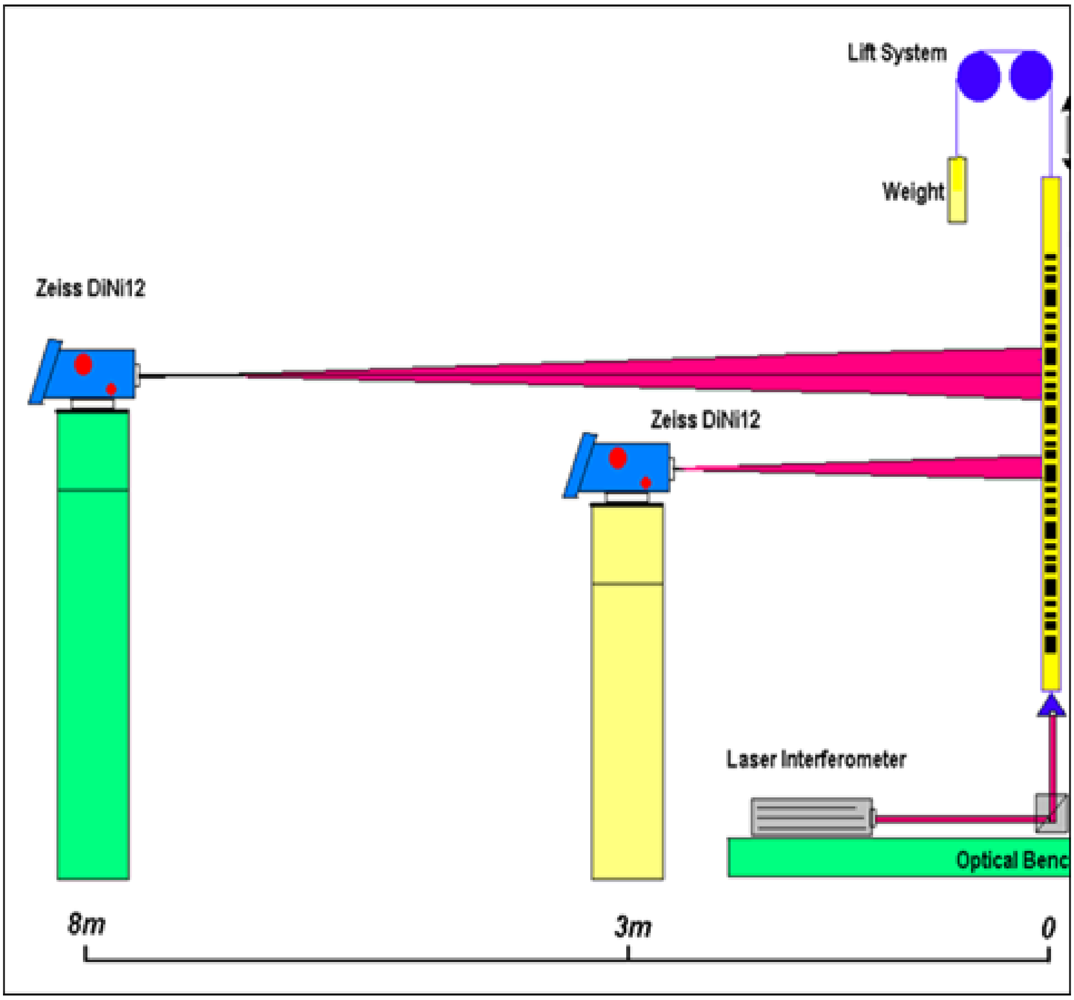

Figure 23: The principle of system calibration at FGI.

In Iceland the rods have been calibrated before the field seasons by FGI since 2000. Before that the rods of the Road Administration and the National Power Company were calibrated in 1992 and 1994–1997 by TUM in Munich.

During the period 1982 to 1996, ***the Norwegian*** rods were calibrated at Lantmäteriet (LM) in Sweden every spring and fall. However, these calibration data was not fully used for the period 1982 to 1992! Instead a field calibration every 2nd week based on a normal metre was applied. For the years 1993 to 1996, the calibration at LM has been applied. When digital equipment was taken in use in 1997, the Norwegian Mapping Authority established a calibration basis in the building, where benchmarks is placed on a wall and separated vertically approx. 30 cm.

This calibration basis was since 2004 checked twice a year with a rod calibrated at Finnish Geodetic Institute. This rod was used only for this purpose.

In Sweden double scale cm-graduated rods were used throughout the whole project. In 1981 an automatic laser interferometer comparator was constructed at LM. For each rod the temperature expansion coefficient was calculated and stored, and corrections of the measurements could be done depending on the temperature when the measurement had been carried out, *(Peterson 1981).*

Each graduation on the rods was calibrated before and after the field seasons. All this information was stored in a database, and the graduation corrections were interpolated in time between the two calibrations. So after the field season every rod reading could be corrected in that respect.

The zero point errors were avoided since the same rod was always used for connections to the benchmarks. However the zero point errors were investigated, and for all the 68 rods that were used in the project, the zero point error is varying between +0.2 and -0.2 mm for 66 of them. Two rods had a zero point error of respectively +0.3 and -0.3 mm.

The Swedish comparator cannot be used to do system calibrations or calibrations of bar code rods. In Finland a vertical laser interferometer comparator has been constructed at the Finnish Geodetic Institute (FGI), where system calibrations of digital systems can be made.

6.2 Instrument calibration

In Denmark the Ni002 instruments were adjusted at the Zeiss factory in Jena. From 1996 a local instrument dealer in Copenhagen found a German instrument mechanic, who was able to repair and make service on the instruments, until they were replaced by the digital instruments in 1999.

To check the collimation error ***in Finland,*** a surveyor checked the instrument once a week using the Kukkamäki method, *(Kukkamäki 1938 and 1939).* To use this method the rods are set up 20 m apart. First the instrument is set up in the middle between the rods and the height difference is measured. Then the instrument is moved to a position outside the rods, so that the distances to the rods are 20 m and 40 m, and then the height difference is measured again. The collimation error is the difference between the two height differences. The largest accepted error is 0.80 mm or 0.02 mm/m.

A surveyor was able to correct the error of Wild N3 by turning the wedge-shaped cover glass in front of the objective, but it was not possible to correct the error of Zeiss Ni002, so the instrument had to be sent for service. The error of Zeiss Ni002A was possible to correct in the field by adjusting the main level.

In Iceland the collimation error was checked using the Förstner method, at least once per survey day. This means that the rods are put up 45 m apart, and in the first setup the instrument is put 15 m from rod A and 30 m from rod B. Then the instrument is put up 30 m from rod A and 15 m from rod B. The corrections for the Leica instruments were usually bigger than for the DiNi instruments.

In Norway the Ni002 instruments were adjusted by an in-house instrument specialist when the pendulum was far out of alignment. Instrument control was taken every 14 day in the field, both for Ni002 and for the digital instruments.

In Sweden the collimation error of the NI002 instruments were checked at least once a week. The checks were carried out according to a strict schedule using a program in the field computer. All information from these checks was stored in a special designed database for this purpose, the instrument database.

Due to the reversing mirror compensator, the instruments were not sensitive to small collimation errors, and if the collimation error was too big the instrument was taken out of production and sent to Jena for repair. In Sweden there was no service firm that could service or repair those instruments. After the factory in Jena was closed down in 1992, a private firm in Copenhagen was engaged instead, when needed.

7 Corrections

In Denmark**:** From 1980 rod corrections and temperature corrections have been done. Corrections for refraction and earth tide have been done, *(Schmidt 2000).*

The corrections applied ***in Finland*** are tidal, magnetic, rod, and refraction corrections. Theory and computer programs for the temporal tidal correction are presented in (*Heikkinen 1978).* The magnetic field of the Earth influences the automatic level Zeiss Ni002. The magnetic correction is based on the results from (*Kukkamäki and Lehmuskoski 1984).*

The rod scale length was assumed to change linearly between the calibration epochs, but the coefficient of thermal expansion was assumed to be constant during the season.

Levelling observations are affected by atmospheric properties in the path of line of sight. Due to changes in the refractive index along the path of light, the observations have some refraction error. The refraction correction is based on the works of (*Kukkamäki 1938 and 1939)* and (*Hytönen 1967).*

In Iceland no refraction corrections have been made. Readings under 0.5m are usually not taken, except under very good circumstances. The earth curvature corrections are made automatically in the instruments.

In Norway only rod correction has been made from 1980 to 1989. From 1990 also temperature correction and earth curvature correction have been applied. Correction for refraction and earth tide has never been done.

In Sweden no refraction corrections have been made even if it should have been possible to do that. The reason for this decision was that the height of the instrument was 2.1 m above the ground, and no readings could be taken lower than 0.5 m above the ground. In that way it was considered that most of the refraction effect was avoided. Test measurements had also showed that it was hard to make temperature measurements accurate enough along the line of sight to calculate reliable corrections.

For the Swedish measurements corrections for graduation of the rods, temperature, earth curvature and earth tide has been applied, *(Olsson and Bergqvist 2003).*

7.1 Formulas

Sweden: Graduation corrections were applied to each rod reading, according to the tables from the rod calibrations, interpolated in time between the spring and autumn calibrations.

Temperature corrections were made using the expansion coefficient for the actual rods and the deviation of the measured temperature at each rod reading in the field from the reference temperature that is 20°C. Primary the mean of the temperatures on the rod thermometers were used, and if they were not available, the air temperature measured at the instrument car was used.

Earth curvature corrections were made using a standard formula, (*Jordan et al 1956, page 106).*

Tidal corrections were made using the LM program Tidal. The program is based on Longman: *Formulas for computing the Tidal Accelerations due to the Moon and the Sun*, Journal of Geophysical Research 64/12 (1959) and 66/9 (1961).

Norway.: Until 1992 the rod corrections were calculated as a scale error and applied to the observed height difference by multiplication. From 1993 to 1996 graduation corrections were applied like in Sweden. From 1997, when the digital technique was taken in use, correction for every 30 cm section of the rod has been possible.

8 Changes and development during the last 25 years

8.1 Description of the changes in instrument and techniques during the period 1980–2005

The precise levellings in the Nordic countries were huge projects that took many years to complete. Most of the activities took place in the period

1980–2005. During that time there was a violent development in many fields. That has also influenced the work with the ongoing precise levellings. The development of computers from 1980 to 2005 is amazing, and has made it possible to handle and store data in a much easier and safe way. That has changed the work to a great extent. The digital technique made it also possible to develop revolutionary new kinds of levelling instruments in the beginning of the 1990´s. But also the field routines have changed to some extent over the years by increasing experience, maybe mostly in the early years of the projects.

In Iceland the levellings has been done more or less in the same way since 1992.

In Norway the project started as motorised levelling in 1980 and ended up with foot levelling. The change happened in 1997 when the classical instruments were replaced with digital equipment. At the same time the rod readings changed from BFFB to BF resulting in significant reduced setup time and the yearly production could be kept at the same level.

The collection and storing of the observation data have changed a lot since 1980. A major step forward was when the electronic field book Husky Hunter was taken in use in 1986 and a fully digital production line was in place. Another step forward was the levelling database. It started as a database for benchmarks only, but was extended to a database for both benchmarks and observations in 1997. Without such a database it had been very hard doing the final adjustment of the levelling network in 2005.

Before ***the Swedish*** production work started in 1979, there were long discussions concerning how it should be done. It was early decided that if the network should be of the highest quality, the production work must be done in a homogenous way. That means in the same way throughout the whole project. Therefore, it was important to have a production line that was as correct as possible from the beginning. It was also decided that the production work should be done in a fully digital production line. The manual work should be reduced to a minimum.

This 25 year old production line is still working excellently, even if e.g. new computer systems throughout the years have opened up for improvements and simplifications of some parts of the process. The tools have changed dramatically, but the content of the production line has in principal been the same since the beginning, *(Lilje et al 2007)*.

Until 1990, all treatment of data was made during the winter, on a PR1ME computer at LM. The field data was originally recorded on a tape from the field computers using a data tape recorder. The big tape cassettes were sent by mail to Lantmäteriet once a week, and the content on the tapes was stored in the PR1ME computer until the end of the field season. Copies of the tapes were kept in the field as a backup. Then each team leader spent the winter seasons with error detection and corrections of more than 100 days of measurements in the field.

In 1990, portable PC: s was introduced, and then the data files could be stored in the PC from the field computer. Error detection and corrections could now be made in the evening after each day, see figure 24. This made the work much more effective. If a fault had been made, it was easier to correct it the same day than to wait until after the field season. Copies of the raw data files were stored on floppy disks, together with the corrected ones, as a back-up. Another copy was sent to Lantmäteriet once a week and stored in the PR1ME computer. The PR1ME computer was phased out in 1999, and all activities were moved to PC.

Through the years the field computers were worn out and had to be replaced. During the project three generations of field computers have been used. Unfortunately the programme language was changed every time, so the measuring programme had to be rewritten. However the programme has worked in exactly the same way all the time.

Also the handling of the benchmark descriptions and benchmark maps has been made easier and more effective due to the development of the digital technique. The development of GIS systems e.g. MapInfo made it possible to use digital maps, which was a huge improvement.

*Figure 24: Dumping the daily Swedish levelling data from the field computer to a PC **with a 35 Mb hard disc** at the hotel in 1990.*

9 Future

9.1 Capacity and plans for the near future

New national height systems have now been released in all the Nordic countries after many years of large-scale precise levellings. These were the biggest levelling projects ever carried out in the countries in question. Special routines were built up, and many people were involved in order to carry out the task. Now, when the new height systems are in place, the levelling activities will probably be scaled down in the Nordic area, at least for a foreseeable future. Therefore the precise levelling capacity will probably also decrease.

The ML technique was, and still is, a very effective levelling method, especially in large projects. However, it is quite expensive to keep all the equipment and personnel in shape. So when the levelling volume is not big enough, there is a possibility that this technique will be closed down. In Norway, the ML is closed down since many years, and in Sweden only one ML team remains, working on less than half its capacity. This team is run by Metria AB, a separate company owned by LM since May 2011.

In Denmark however, at KMS, there is a large-scale densification program going on. So for efficiency reasons, KMS have two teams working with full capacity, one team using ML and the other one Motorised Trigonometric Levelling (MTL).

In Norway, there is also a densification project going on, where levelling lines are measured to places where connection to the precise levelling network and the new height system is missing today. In this project both ML, carried out by Metria, and levelling on foot by Statens Kartverk (SK) is used.

In Sweden the levelling activities has decreased dramatically for natural reasons, since the third precise levelling was completed. The tasks today are mainly updating of the network, control measurements to mareographs and levelling of occasional densification lines.

9.2 The need for precise levelling

In order to preserve the high quality of precise levelling networks, we must be able to carry out densification, updating, maintenance and control measurements with the corresponding quality. Otherwise the networks and the height systems will gradually be undermined. Densification of the networks must therefore be carried out so that the height difference between new nearby points will get the same accuracy as the points in the original network.

Control measurement at mareographs is another example of short distance applications where the highest possible accuracy is needed.

Since precise levelling is, at least over short distances, still the most accurate height determination technique, we must continue to have the knowledge and the capability to carry out precise levelling, even if it will be in smaller projects than national precise levellings.

Precise levelling to GNSS points in order to validate geoid models will be important for the future. In rough terrain it is a challenge to make reliable gravimetrical geoid models, and GNSS/levelling points are needed for control or to serve as adjustment points.

Precise levelling is also an alternative technique to height determination using GNSS in combination with a geoid model. As always in the field of geodesy, it is good not to rely on just one technique. Comparison between different techniques makes it possible to carry out independent controls.

If we are defining new height systems in the future using GNSS and a geoid model, we will not have any GNSS/levelling geoid heights to compare with, since it will be the geoid model that defines the height system. But we will still be interested to evaluate the accuracy of that GNSS+geoid defined height system. This could be done for instance by using precise levelling on a number of randomly selected locations.

In the USA such a height system is about to be introduced, and there they have chosen a number of profiles where alternative measurements are carried out for evaluation, including precise levelling. This is another example of the need for precise levelling as an alternative technique in the future.

9.3 Developments of the levelling technique

The digital levels were introduced in the beginning of the 1990´s, and are today the only type of instrument used for classical precise levelling in practice. In combination with invar bar code rods, the accuracy is almost the same as for WILD N3 and Zeiss Jena NI002. According to the manufacturer of Wild N3 and Zeiss Jena NI002, the standard deviation for 1 km double run levelling is 0.2 mm. The correspondingly value for DiNi 0.3 is 0.3 mm according to Trimble. The manufacture of Wild N3 and Zeiss Jena NI002 instruments was closed down in the middle of the 1990´s.

Lantmäteriet carried out extensive field tests of the first generation of digital levels. Leica NA2000 and Zeiss DiNi10 were evaluated in 1990. The tests showed some general limitations for the digital instruments compared to NI002. E.g. the CCD camera could not work under poor light conditions and backlight. Connecting to benchmarks was harder, since the camera had to "see" a longer section of the rod, and not just a graduation line. This was a problem when there was an obstacle in the sight line between the instrument and the benchmark. However, the accuracy was regarded almost the same as NI002 under favorable conditions, and when the sight lines were shortened from 50 to 40 m. *(Becker and Andersson 1991).*

The decision at Lantmäteriet was to continue with NI002 and complete the measurements of the whole network with the same type of instrument.

Today's models of these instruments, Leica DNA03 and Trimble DiNi0.3, have been slightly improved. The digital levels are easy to operate, and the observations can be stored in the instrument if one of the standard measuring protocols is used. They are the main tools available for precise levelling today.

9.4 Proposals for further evaluation

Finally, we propose a few topics to investigate and possibly develop further in the field of height determination with accuracy comparable to what is possible with precise levelling.

9.4.1 Classical precise levelling

The criterion for precise levelling networks is a standard uncertainty below 1 mm/√km. The levelling networks in the Nordic area approximately fulfil this requirement with the levelling methods used, either ML or foot levelling.

Considering the accuracy, the two methods are equally good. The advantage with ML is that it is faster. On the other hand, it is more expensive to keep all equipment and personnel in shape. So, if we don't believe that there will be any large levelling projects ahead, the question is if it is worthwhile to maintain all the ML equipment and the special knowledge of the personnel.

However, it should be possible to develop the classical levelling method further in both cases, when it comes to accuracy. Most likely no new national levellings will be carried out in the future, but the precise levelling technique will still be needed. In many situations there is a need for extremely accurate measurements, e.g. smaller networks used in connection with construction of tunnels, bridges, controls of dam subsidence and other kinds of accurate monitoring.

For those reasons among other things, it might be useful to develop the classical precise levelling technique further. This could be done by raising the demands for the present method. For example, the maximum sight lengths could be shortened, more narrow limits for backward and forward sight lengths could be initiated, sharper rejection limits and a limit for the lowest sight line introduced, harder requirements not to carry out measurements in unfavourable weather and so on.

Of course, such changes will slow down the field work, which means that the costs will increase. But sometimes, in a smaller scale, when the demands for extreme accuracy are at hand, we ought to be able to respond to these demands.

9.4.2 Motorised Trigonometric Levelling

The MTL technique (see section *Instruments*) was developed and evaluated in Sweden in the middle of the 1980´s. The purpose was to see if this technique could be an alternative to ML, especially in hilly areas and in open landscapes. For this reason, measurement of some lines in different areas was done with both techniques.

It turned out that double run MTL gave a standard error of mean better than 1.0 mm/√km, and therefore could be used for precise levelling. The production capacity with three survey vehicles was about the same as ML, around 2 km/hour. However, a limitation for optimal production with MTL in Sweden was that the sight lengths became too short. In average they were less than 200 m, due to vegetation obstacles. The technique is also more advanced technologically, which makes it more vulnerable when it comes to field work. For instance, the telemetry, that was needed for transfer of data to the "control vehicle" in those days was not so well developed, and caused many problems, *(Becker and Lithén 1986)* and *(Becker et al 1988)*.

So the decision in Sweden at that time was to use only ML. However, the technique can be further developed, and has the potential to be used in precise levelling if the right conditions regarding e.g. the terrain are at hand, see figure 25 and 26.

The technique is since many years in full production ***in Denmark*** for lower order levelling. In 2009 a precise MTL technique using maximum sight lengths up to 400 m was tried out on The Faroe Islands with great success. Now there are plans in Denmark to try to use 1 sec. total stations on the cars

Figure 25: A Danish MTL car on the Öresund bridge in 2000.

Figure 26: A Swedish MTL team in the Sälen area in 1985.

9.4.3 Automatization of Motorised Levelling

At the moment motorised levelling is similar to traditional levelling on foot, except that the instrument and rods are moved using vehicles. In (*Saaranen 2013)* a vision of a motorised levelling system that is fully automatic was presented. In the method the observations are controlled by a computer, which has Bluetooth connection to the levelling instrument. A robot arm takes care of the rotation of the instrument and the movement of rods. In order to make a movement of a levelling expedition faster, an automatic method to determinate the sighting distances was studied. It turned out that by using MEMS motion trackers, it would be possible to determine the locations for the rods and instrument accurately. The automatic motorised levelling method would be very productive. An estimate for speed is 40 seconds per setup, and thus the daily single run distance could be 30 km. The real productivity would of course be dependent on the locations of the benchmarks, the length of sighting distances, and the measuring experience of a team.

9.4.4 Chronometric Levelling

Martin Vermeer at the Aalto University in Finland informs that relativistic levelling by precise clocks will be possible, if not in the near future, then within a decade or so.

Optical lattice clocks are soon reaching relative accuracies of 10^-18, which would allow levelling connections of +/- 1 cm standard uncertainty. Also experiments are ongoing to use the existing Internet optic fibre infrastructure for precise time transfer, at the same level of accuracy. This requires a modification to the amplifiers though, which is easy only for connections on dry land, (*Delva and Lodewyck 2013).*

His suggestion to the working group is that now is perhaps the time for the precise levelling community to start thinking about the following questions:

1) Where in the Nordic area are the centres of professional competence regarding precise timekeeping and optic fibre connections?

2) Does the Nordic community have to do anything now not to miss this bus?

3) How would precise relativistic vertical links be incorporated in the existing levelling networks and their adjustment?

Literature list

Denmark

Schmidt K. (2000): The Danish height system DVR 90. *Kort & Matrikelstyrelsen. Publications 4. series, volume 8.*

Finland

Heikkinen M. (1978): On the tide-generating forces. *Publications of the Finnish Geodetic Institute No.* **85**.

Hytönen E. (1967): Measuring of the Refraction in the Second Levelling of Finland. *Publications of the Finnish Geodetic Institute No.* **63**.

Kukkamäki T.J. (1938): Über die Nivellitische Refraktion. *Publications of the Finnish Geodetic Institute No.* **25**.

Kukkamäki T.J. (1939): Formeln und Tabellen zur Berechnung der Nivellitischen Refraktion. *Publications of the Finnish Geodetic Institute No*. **27**.

Kukkamäki T.J. and Lehmuskoski P. (1984): Influence of the Earth Magnetic Field on Zeiss Ni002 Levels. *Reports of the Finnish Geodetic Institute No*. **84:1**.

Vermeer M. (1983): Chronometric levelling. *Reports of the Finnish Geodetic Institute, No.* ***83*(2)*:1–7.***

Delva P. and Lodewyck J. (2013): Atomic clocks: new prospects in metrology and geodesy. http://xxx.tau.ac.il/pdf/1308.6766

Saaranen V. (2013): On the Automatization of the Motorized Levelling. *NKG Working Group of Geoid and Height Systems in Reykjavik, Iceland, March 14, 2013*.

Iceland

Valsson G. et.al (2011) and Valsson G. (2012): The Icelandic vertical reference system ISH2004.

Sweden

The following papers are available on the web-page of Lantmäteriet www.lantmateriet.se

Professional papers

LMV-RAPPORT 1984:1	Uppbyggandet av Sveriges nya riksnät i höjd *Becker J-M*

LMV-RAPPORT 1984:15	The Motorized Levelling Technique – the Swedish experience *Widmark J, Becker J-M*
LMV-RAPPORT 1985:7	The Swedish Experience with Motorized Levelling – new techniques and tests *Becker J-M*
LMV-RAPPORT 1985:8	Automatisering och motorisering av avvägningsarbeten – nuvarande teknik och framtidsutsikter *Becker J-M*
LMV-RAPPORT 1986:8	Motorized Trigonometric Levelling (MTL) & Motorized XYZ Technique (MXYZ) in Sweden *Becker J-M, Lithén T*
LMV-RAPPORT 1988:23	Experience of Motorized Trigonometric Levelling (MTL) – a comparison with other techniques *Becker J-M, Lithén T, Nordquist A*
LMV-RAPPORT 1991:15	Evaluation of NA2000 – a new digital level *Becker J-M, Andersson B*
LMV-RAPPORT 1997:2	Riksavvägningsarbeten I Sverige under perioden 1974–1995 *Becker J-M*
LMV-RAPPORT 1999:3	Geodesy and Surveying in the future – the importance of Heights *Lilje M* ed.
LMV-RAPPORT 2006:9	Systematiska effekter inom den tredje riksavvägningen *Shah A*
LMV-RAPPORT 2007:14	RH 2000 och riksavvägningen *Lilje M, Eriksson P-O, Olsson P-A, Svensson R, Ågren J*

Publications

1981-10-16	Beräkning av stånglängdskorrektioner *Peterson I*
1998-11-09	Tredje precisionsavvägningen *Becker J-M, Lilje M, Eriksson P-O*

2001-02-20	The production line used in the third precise levelling of Sweden *Lilje M, Erikson P-O*
2002-01-21	Kvalitetssäkring av riksavvägningsdata och förberedelser för införandet av ett nytt nationellt höjdsystem *Lilje M, Eriksson P-O, Olsson P-A, Svensson R*

Before the final calculation of the network there were two projects working with preparations of data and investigations of possible error sources. Project reports from those projects are archived at LM. In addition to that some documents of various kinds related to this matter were filed:

Archives in RA. The production line with special emphasis on the data capture and the structure of the archives used in the third precise levelling of Sweden
Lilje M, Eriksson P-O

FIG Brighton 1998. The establishment of the third precise levelling network of Sweden
Becker J-M, Lilje M, Erikson P-O

FIG Washington 2002: Validation and preparation of Data for the Computation of a New Height System in Sweden
Eriksson P-O, Lilje M, Olsson P-A, Svensson R

M70026 1991. Användarbeskrivning för handdatorn M700 och stackprogrammet
Nordquist A

Motorised levelling – the ultimate tool for production of classic national height networks
Becker J-M, Lilje M, Olsson P-A, Eriksson P-O

NKG Iceland 2001: Reqirements on the height benchmarks in the third precise levelling of Sweden
Eriksson P-O

NKG Iceland 2001: Underground bench marks
Eriksson P-O

Riksavvägningen-Slutberäkning. Delprojekt 2, Systemetiska effekter 2003
Olsson P-A, Bergqvist H

Riksavvägningen Lantmätaren. Ett nytt nationellt höjdsystem klart under 2004
Lilje M, Olsson P-A, Eriksson P-O

Uppdaterad arbetsinstruktion. 2009. Arbetsprocessen vid riksavvägningen
Eriksson P-O

Appendix

Appendix 1

Guidelines for Motorized 1. Order Precise Levelling

1984

Bilaga

NORDISKA KOMMISSIONEN FÖR GEODESI

Guidelines for Motorized 1. Order Precise Levelling

Drafted by
J.-M. Becker, Lantmäteriverket, Gävle, Sweden and
O. Bedsted Andersen, Geodætisk Institut, Copenhagen, Denmark

Accepted by
the Nordic Levelling Group at the Helsinki session, March 14, 1984

"A chain's weakest link is the measure of its strength"

A. The levelling network

1. The network shall consist of closed polygons.
2. The network configuration shall be homogeneous.
3. The polygon perimeters shall not exceed 400 kms.
4. Levelling lines should have bench marks at intervals of 1-2 kms along this length.
5. The distance between levelling junctions should be uniform throughout the network.
6. Levelling lines shall follow easily negotiable roads.

B. The bench marks

1. The sites of the bench marks shall represent the surrounding terrain and sub-surface structure.
2. The bench marks shall be clearly defined and allow the use of normal length staves.
3. All fundamental bench marks shall be of stable construction and have a well defined summit.
4. The levelling junctions shall normally consist of a group of bench marks.

C. The levelling procedure

1. The levelling method is that of geometric levelling with equal sight lengths.
2. The duration of the levelling period shall be short compared to the period between successive levellings.
3. All lines shall be measured twice, once in each direction.

4. None of the inter bench mark sections should be measured the second time unless all adjacent sections have been measured at least once or will be measured in immediate succession.
5. Errors due to weak connections at indispensable bench marks shall be isolated in branch lines at once.

D. The equipment

1. Precision Compensator instrument with quasi-horizon and revolving ocular; Ni002 or equivalent.
2. Precision staves with double graduated invar strip and centre ring.
3. Levelling vehicles with specially designed supports for the levelling instrument and staves.
4. Equipment which can resolve the distance driven to an accuracy of about 1 metre.
5. Temperature sensors on the invar strips.
6. Equipment for parallax free plumbing of the levelling staves.
7. Equipment for automatic data capture and validation.

E. Maintenance and supervision

1. Continuous maintenance and professional supervision of all items of equipment.
2. The levelling staves
   - 2.1. Regularly repeated calibration of staves including determination of zero error and coefficient of linear expansion.
   - 2.2. Each staff graduation shall be calibrated using a laser comparator.
   - 2.3. Calibration shall take place during the field season.
   - 2.4. Circular levels are to be checked daily.
3. The levelling instrument
   - 3.1. Regularly repeated calibration to determine the influence of magnetic fields.
   - 3.2 Weekly checks of the quasi-horizon; Collimation error shall be less than 2" of arc. Difference between mirror positions 1 and 2 shall be less than 15" of arc.
   - 3.3. Weekly check on the micrometer drum positioning.
   - 3.4. Circular levels to be checked daily.

F. The measuring routine

1. The same levelling staff shall be used for connections at fundamental bench marks and junction points.
2. The initial levelling of the instrument at each set up shall be done with the telescope directed towards the same staff.
3. The line of sight shall clear any object by at least 0.5 m.
4. The sight length shall be determined from the stadia intercept using the micrometer.
5. The instrument to staff sight distance shall not exceed 50 metres.
6. The maximum difference (Δs) between foresight and backsight (s) is given in the following table:

s	10	20	30	40	50	m
Δ s	5.0	3.5	3.0	2.5	2.0	m

7. The difference between accumulated foresight and backsight lengths shall be kept small and compensated within the inter fundamental bench mark section.
8. Reading sequence of height difference and sight distances:

8.1. 1 staff: stadia wire, centre wire (I)
2 staff: stadia wire, centre wire (II)

8.2. Rotate mirror position.

8.3. 2. staff: centre wire (III)
1. staff: centre wire (IV)

8.4. Tolerance:

A: $|(I - II) - (IV - III)| < 0.40$ mm
B: $|(I - IV)| < 0.40$ mm as well as $|(II - III)| < 0.40$ mm
taking the scale constant and collimation error into account.

8.5. The focusing shall be re-examined before each centre wire reading.

9. General observation data

9.1. Identification of observers and equipment involved.
9.2. Information on surroundings, temperature, wind, sun, shimmer.
9.3. Identification of levelling line and incorporated bench marks.
9.4. Date and time of start and finish of each section.
9.5. Accumulated height difference from the accepted measurements.
9.6. Control parameters which should be constantly improved.

10. The observer is permitted, and shall be able, to overrule any of the above rules and automatic data controls provided that such exceptions are always reported.

G. <u>Field control and evaluation of results</u>

1. The truncation limit shall be chosen to give optimal levelling performance. The current value is $2.5\sqrt{L}$ mm (L in kms) between backward and forward levelling. If this value is exceeded then the section shall be relevelled both forward and back.
2. At connections to bench marks on lines measured by other teams or after long interruptions both the stability and identification of the bench marks shall be verified by check levelling.
3. Any unusual effects such as systematic effects, difficult sections etc. shall be reported.
4. All records are valuable and shall exist in duplicate.
5. All levelling equipment is precision instrumentation and shall be treated as such, both whilst in use and when stored during weekends, holidays etc.
6. Traditional levelling of selected parts of the network shall be subject to the same procedures and directives as above and data recording systems shall be compatible with the specified computer system.

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

2009:1	Ågren Jonas: Beskrivning av de nationella geoidmodellerna SWEN08_RH2000 och SWEN08_RH70.
2009:2	Odolinski Robert & Sunna Johan: Detaljmätning med nätverks-RTK – en noggrannhetsundersökning.
2009:4	Fridén Anders & Persson Ann-Katrin: Realtidsuppdaterad etablering av fri station – ett fälttest med radioutsänd projektanpassad nätverks-RTK.
2009:5	Bosrup Susanna & Illerstam Jenny: Restfelshantering med Natural Neighbour och TRIAD vid byte av koordinatsystem i plan och höjd.
2010:1	Reit Bo-Gunnar: Om geodetiska transformationer (finns även på engelska med titeln *On geodetic transformations*).
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 possibility 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.

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