One Year with Our Absolute Gravimeter

Mikael LILJE, Jonas ÅGREN, Andreas ENGFELDT and Per-Anders OLSSON, Sweden

ABSTRACT

In 2006 Lantmäteriet (the National Land Survey of Sweden) bought an absolute gravimeter (Micro-g Lacoste FG5) together with a relative spring gravimeter (Scintrex CG5). Since then the absolute gravimeter has been used in the Nordic Area, on a consultancy basis in Serbia as well as in the international comparison ICAG2007 in Luxembourg. The main reason behind the investment is to determine better models for the post glacial rebound in the Nordic area (Fennoscandia), which eventually will make it possible for us to maintain our reference systems for a longer time. The purpose of this paper is to present our experiences from owning and using an absolute gravimeter as well as our long term plans for the future.

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WHY DOES LANTMÄTERIET NEED TO DETERMINE THE GRAVITY?

The main tasks for the geodetic research division at Lantmäteriet (the National Land Survey of Sweden) are to develop, monitor and maintain the national reference systems and frames in all dimensions (3D, horizontal, height) as well as gravity so that the need of the society is satisfied. This also includes the determination of various transformation formulae as well as geoid models. Lantmäteriet also has an important role to make sure that GNSS can be used efficiently in Sweden, which means that we have developed our National CORS network called SWEPOS™. Many of our projects are done in close co-operation with our Nordic colleagues as well as other international bodies.

Lately, several different Nordic institutions as well as other international actors have observed gravity with absolute gravimeters in the Nordic and Baltic area. These efforts have been co-ordinated through the working group of geodynamic within NKG (Nordic Commission of Geodesy). The main purpose of these measurements has been to detect the change of gravity over time, mainly caused by the post glacial rebound. Other techniques to contribute to this are permanent GNSS, repeated levelling and tide gauge observations. An important contribution from absolute gravimetri is that the technique makes it possible to determine the effect from post glacial rebound on the gravity field of Earth, both direct on the gravity as well as indirect on the geoid. The observations also contribute to the investigation on mass distribution within the Earth. Another aim of the observations during the last years has been to calibrate GRACE. Involved organisations have been using either *Micro-g Lacoste FG5* or *JILAg* gravimeter. The first mentioned instrument can be considered as the state-of-the-art. Lantmäteriet bought a Micro-g Lacoste FG 5 during 2006 from the company Micro-g LaCoste Inc (USA).

In Sweden we have introduced a new generation of reference systems during the last decade. These are SWEREF 99 (3D as well as horizontal), RH 2000 (height) and geoid model(s) attached to them. To secure their quality over time we need to model phenomena as post glacial rebound and to do this we need long time series of observations of gravity and GNSS. This is the main reason for continuous absolute gravity measurement and the need will remain for long period for Sweden as well the Nordic Area. To make sure that we are not relying too much on others as well as to develop our own knowledge, Lantmäteriet decided to invest in this field.

Lantmäteriet has measured gravity for many years. Lantmäteriet are responsible for the national gravity system. Historically, international colleagues have been measuring our fundamental points with an absolute gravimeter and Lantmäteriet has been to densify our networks measuring relative from these. Our second order network has a density of one point every 5 km.

Some of the main reasons for gravity determination can be summarized as follows:

- To develop geoid models
- To calculate heights above sea level e.g. orthometric heights
- To determine the gravity change over time as an input for the determination of a model of the post glacial rebound.
- For Geophysical purposes
- To calibrate various instruments

CONSEQUENCES OF THE INVESTMENT

It is a big stage to buy an absolute gravimeter. The instrument in itself is very expensive, requires a lot maintain and calibration. It also requires extensive personnel investments both when it comes to skill development, continuous management as well as measurements. It is not worth while to buy such an instrument if one does not have sufficient personnel or knowledge or can allocate the resources. During the last years Lantmäteriet has participated at other organisations' measurements. This meant that one person at the Geodetic Research Division at Lantmäteriet already could measure with an absolute gravimeter. After the purchase, approximately five persons can now more or less handle the instrument on its own. The major development however has come on the theory side, where a number of employees have improved their knowledge on gravimetry. Lantmäteriet has also made it possible for one person to start his ph. d. focused on absolute gravimetry and its error sources.

It should be made clear that the investment of an absolute gravimeter of course does not eliminate the need for relative gravity measurements. It is even so that the investment of the absolute gravimeter forced us to invest also in a relative gravimeter. Measurement with absolute gravimeter requires that the vertical gradient is decided with high precision. This is suitable done with a relative gravimeter. The vertical gradient describes how the gravity varies in height at the observation site. Lantmäteriet purchased the most appropriate relative gravimeter for this purpose, namely a Scintrex CG-5 from Scintrex Limited (Canada).

DETERMINATION OF ABSOLUTE GRAVITY

Lantmäteriet acquired one absolute gravimeter of the type Micro-g LaCoste FG-5 with serie number 233. There are today approximately 50 more instruments in the world of this type. The cost of the instrument together with some extra equipment, a relative gravimeter, education and some more ended up to be approximately USD 420 000. Adding up, we also needed a new vehicle to transport the instrument.

The instrument, see figure 1, was delivered in seven boxes and weights together approximately 130 kg. To this is added at least equally amount of additional equipment and spare parts.

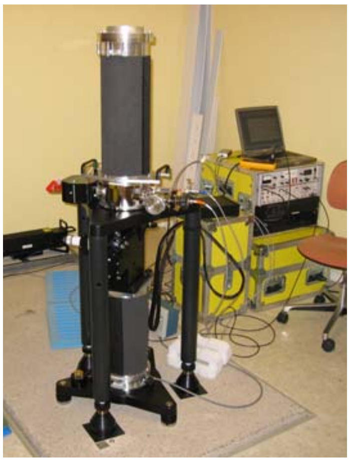

Figure 1: The Swedish instrument

The FG5 instrument is the most accurate type of absolute gravimeter ever constructed for practical applications and is capable of delivering a standard error of about 2 μGal. Absolute here means that the gravity is determined relative to absolute physical standards of time and length. This implies that the instrument has to be carefully calibrated against the standards kept at national and international laboratories around the world in order to achieve gravity values that do not drift over time.

The FG5 operates according to the ballistic or free-fall method, see figure 2. An object is dropped inside a vacuum chamber (called the dropping chamber). The trajectory of the freely falling object is accurately monitored using a Mach-Sender interferometer using laser light with very stable wavelength. The falling object is also accurately clocked by an atomic rubidium clock. The fall of the object is referenced to a stable active-spring system called the super spring, which provides isolation against micro-seismic disturbances and greatly improves the noise performance of the FG5. The main parts of the FG5 instrument are illustrated in Figure 2. The picture does not show the laser or the electronics box, which also contains the rubidium clock.

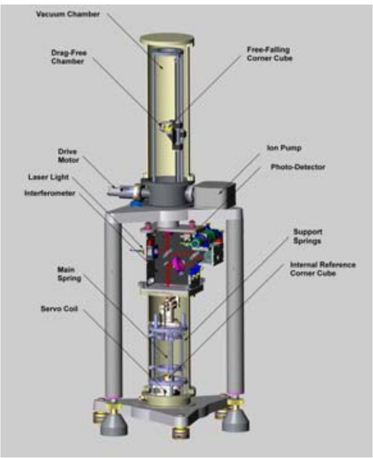

Figure 2: Schematic diagram of the FG5 instrument.

We have been using the following observation strategy:

- The observations are collected in two sessions (or set ups) with the instrument first oriented in the North orientation and then in the South orientation. In each session observations are collected during approximately 24 hours. The reason for choosing North/South orientations is to minimise the influence of the coriolis force on the falling object (Niebauer et al. 1995). To use two independent set ups also increases the reliability and reduces the influence of set up dependent error sources. The main reason for preferring 24 hour sessions is to reduce errors with this period, for instance ocean tide loading modelling errors.
- Each 24 hour session is divided into 48 sets with 50 drops each. One drop is made every 10 seconds, which means that each set is a little more than 8 minutes long. Furthermore, the time interval between the sets is 30 minutes. For 2008 we have decided to use 24 sets for every 24 hours instead.
- The levelling and the verticality of the instrument is checked and adjusted (if needed) once every 3-4 hours except during the night. The last check each is made at approximately ten o clock (local time) in the evening and the first check is made around eight in the morning. During the check the following items are also checked,

  - Current to the ion pump
  - Spring position
  - Fringe amplitude
  - Laser voltages
  - Temperature

The vertical gradient of gravity is needed both to compute the absolute gravity value from the time-distance pairs of the falling object and to reduce the computed absolute gravity value at 1.200 m down to the marker on the floor at height 0.000 m.

We have been observing the gravity difference between one point approximately 1.5 metres above the marker and another one as close to the marker as possible, both points having the same horizontal position. By accurately measuring the distance between the upper and lower points, the gradient can be derived. The gravity differences were observed using the Swedish relative gravimeter Scintrex CG-5 and the distance was determined using a levelling bar.

The Scintrex CG-5 is a relative spring gravimeter (Torge 1989) manufactured by Scintrex Limited (Canada), nowadays owned by Micro-g LaCoste Inc. It works according to the following principle: The gravitational force on a proof mass is balanced by a spring and a small electrostatic restoring force. The position of the proof mass is altered by a change in gravity, which is sensed by a capacitive displacement transducer. An automatic feedback circuit then applies DC voltage to the capacitor plates producing an electrostatic force on the mass which brings it back to the null position. In this way relative gravity differences can be observed with high accuracy; see Torge (1989) and Scintrex (2006).

For highest accuracy one would have to consider at least also the second order term (derivative) for the reduction to the marker, but this component is much smaller and is therefore rejected in the present campaign. It should be pointed out, though, that the gradient is determined by taking the difference of two gravity values reasonably close in height to the points between which the reduction is made (0.000 m and 1.200 m). Due to this fact, it can be expected that the error of not considering the second or higher order terms is small.

The gravity differences were determined by the following strategy: Each CG-5 observation is made by continuously averaging over 60 seconds using the Seismic filter for reduction of micro seismic disturbances and earth tide corrections. The final gravity difference is obtained as the mean of six gravity differences, each determined by observing/averaging in the following way with the CG-5: 60 s down, 60 s up, 60 s up, 60 s down. The reason for observing in this order is to reduce the influence of a possible drift over time in the relative gravimeter.

The absolute gravity observations were processed using the g Absolute Gravity Processing Software version 7, which is a product of Micro-g LaCoste Inc. This g software is standard for processing of FG5 observations. It is used both to run the absolute gravimeter and for processing of the observations. In this project version 6 was utilised in the field, while version 7 was used for the final processing.

The g software fits a modified parabola to the observed time-distance pairs (601 for each drop) to obtain one gravity value per drop. Due to the fact that gravity varies along the fall, it is not sufficient to estimate a simple parabola. The variation of gravity with height is handled by introducing pre-determined vertical gradients in the observation equation. Corrections are then applied for the following effects; see e.g. Torge (1989) for more details:

- Polar motion.
- Earth tides.
- Ocean tide loading. The method of Farrell (1972) is used with a mass conservation correction.
- Atmospheric pressure. The internal barometer is used to observe the air pressure for each drop, which is then utilised to compute the correction.

The mean is then computed for each set and the session gravity is derived as the mean value of all sets. A number of statistical parameters are also computed. The “drop scatter” and “set scatter” are the estimated standard errors for the individual drops and for the individual sets, respectively. The drop scatter is estimated for each set from the corresponding drop values and the set scatter is computed using all set mean values for the session in question. Since the statistical standard errors are usually too optimistic due to the presence of systematic errors, another measure called the “uncertainty” is also computed. The latter quantity is derived by quadratic addition of a systematic component to the statistical standard error,

$$\text{Uncertainty} = \sqrt{\sigma_{statistical}^2 + \sigma_{systematic}^2} = \sqrt{\frac{(\text{scatter})^2}{N} + \sigma_{systematic}^2} \qquad (1)$$

where N is the number of observations used to compute the scatter. Note that the statistical standard error is here equal to the standard error of the mean. The systematic standard error $\sigma_{systematic}$ is in turn derived by quadratic addition of a number of standard errors for different factors like laser, system and set up. The uncertainty is used as a more realistic accuracy measure, but it should be noticed that insofar as the statistical standard error is small, it depends on the assumed standard errors for the factors just mentioned.

NATIONAL AND NORDIC PERSPECTIVES ON OUR OBSERVATIONS

We have already tried to describe why we consider the importance to perform absolute gravity observations. When it comes to geoid determination or to the development of a land uplift model it can easily be understood that Sweden is not enough as a geographical area. Our end products would not achieve the quality that is needed if we are only focusing on observations in Sweden. In order to decide the geoid model we need observations globally and for the post glacial rebound modelling, we need observations over at least the land uplift area. Absolute gravity observation at sites in Sweden has taken place since many years. The first observations in Sweden were done 1977. Since 2003, annual absolute gravity campaigns have been carried out in Fennoscandia. More than 30 stations covering Norway, Sweden, Finland and Denmark, se figure 3 has been observed more or less regularly. Five groups from Germany, Finland, Norway and Sweden with FG5 absolute gravimeters are engaged to survey the uplift by a mutually controlled procedure. Nearly all absolute stations are co-located with permanent GPS stations. Other techniques as tide gauges, VLBI, SLR and supra conducting gravimeter can also be found as various places (Lilje, 2008). Absolute gravimetry combined with geometrical methods allows separating vertical surface deformations and subsurface mass movements.

If we focus on the land uplift model, it is easy to realize that regular absolute observations are easier to carry out than more extensive relative campaigns. The absolute gravity observations are then used together with observations from e.g. permanent GNSS stations, mareografer and repeated weighing. It is not be enough here with a single gravity determination at a station since we are interested in gravity changes over time. If the country is rising this means that we are increasing the distance to Earth mass centre. The effect on the gravity is that it decreases over time. The change needs to be decided with high precision, approximately 0,1 µGal/years. It means that we need long time series before we from absolute gravity observations can determine the land uplift. We need moreover to have observations over the entire area why it is important to collaborate with our neighbouring countries. Today, there are absolute gravimeters similar as ours in Norway, Finland and several European countries. In the Nordic area, we have over 50 years of coordinated cooperation through the Nordic Commission of Geodesy (NKG).

The home of the absolute gravimeter is above all at Lantmäteriet where the Geodetic Research Division has installed a simpler test environment. The closest observation point is just outside Gävle and is called Mårtsbo. Here, we have two points, which make it possible to conduct comparisons with other instruments. We did this during last year when our German colleagues from Hannover were observing in Mårtsbo. In order to compare with the Finnish instrument and moreover to improve our own knowledge, we visit the Finnish geodetic station, Metsähovi. The station is situated just outside Helsinki.

Sweden has an important geodetic station outside Gothenburg. The station is called Onsala and belongs to Chalmers University of Technology. At this station other geodetic observing techniques as permanent GPS and VLBI (Very Long Baseline Interferometer) are present. During 2008, a supraconducting gravimeter will be installed. We conducted observations during March last year but gravity has been observed regularly since 1993 at this point. Among other Nordic stations that we visited during 2007 can also be mentioned the Norwegian stations Trysil and Vågstranda.

Figure 3: Stations in Fennoscandia for absolute gravimetry observations.

Lantmäteriet has the strategy of collocating geodetic observing techniques. Our gravity stations are almost every one collocated with permanent GNSS. Examples are the stations Visby (see figure 4), Östersund, Arjeplog and Kiruna.

Figure 4: Visby, a permanent GNSS station as well as absolute gravimeter

SWEDESURVEY MISSIONS

Lantmäteriet works international through the company Swedesurvey. A project is currently running in Serbia that includes some geodetic components. During 2007, three points were observed with absolute gravimetry. The three points (Grgeteg, Gradac and Sicevo) were decided in June and the observations were done during October. The result was over our expectation and our collaborative partner in Serbia was very pleased. Figure 5 and 6 shows one of the points.

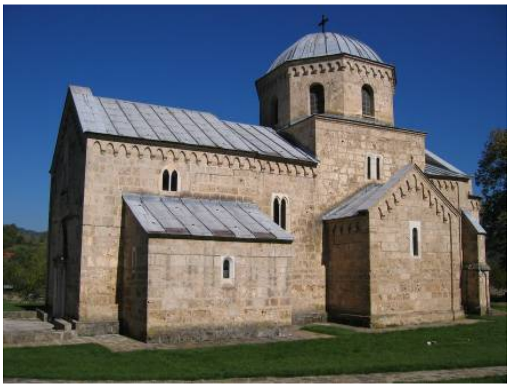

Figure 5: Gradac

Figure 6: The set-up at Gradac

COMPARISONS WITH OTHERS GRAVIMETERAR

The instrument is very sophisticated and delivers accurate results. To know the quality of the instrument is important, but not always easy to determine. To compare your instrument with other instrument is therefore an important method to show you how your instrument behaves. We have during 2007 compared our instrument with a German instrument in Mårtsbo, with a Finnish instrument in Metsähovi and with a Norwegian instrument in Trysil.

An organized international comparison campaign is conducted regularly in Luxembourg. A comparison took place in November, 2007. The campaign had the name ICAG2007. At the occasion, 19 instruments were gathered and the preliminary results that we have received so far were promising regarding our instrument.

CONCLUSIONS

One year with our absolute gravimeter has gone quickly. We have improved our level of knowledge significantly concerning gravimetry and how to handle the instrument. We have conducted 25 observations at 18 sited of which 7 are foreign stations.
To use absolute gravimetry at Lantmäteriet has just started but will need to be prioritized during a long time ahead. We will improve our models for post glacial rebound, and thereby extend the length of life for SWEREF 99 and RH 2000, as well as geoid model.

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BIOGRAPHICAL NOTES

Mikael Lilje

Mr Lilje graduated in 1993 from the Royal Institute of Technology (Stockholm, Sweden) as a land surveyor with emphasis on Geodesy and Photogrammetry. He is working at Lantmäteriet since 1994 with various topics, mainly at the Geodetic Research Division. He is since 2001 the head of a group working with reference frame and co-ordinate system questions.

Mr Lilje is chair of the Swedish Map and Measuring Technique Society and chair of the FIG Commission 5 Working Group on ”Reference Frame in Practice”. He has been involved in FIG since 1998 and worked as secretary for FIG Commission 5 during the period 1998 – 2002 and co-chair of working group during 2002-2006.

CONTACTS

Mikael Lilje
Geodetic Research Division
Lantmäteriet
SE-801 82 GÄVLE
SWEDEN
Email: mikael.lilje@lm.se
Web site: www.lantmateriet.se/geodesi