The first absolute gravity measurements in The Netherlands

Period 1991 - 1999

Marc Crombaghs
Erik de Min
Govert Strang van Hees

NCG Nederlandse Commissie voor Geodesie Netherlands Geodetic Commission

Delft, March 2002

The first absolute gravity measurements in The Netherlands. Period 1991 - 1999
Marc Crombaghs, Erik de Min, Govert Strang van Hees
Publications on Geodesy 50
ISBN 90 6132 275 8
ISSN 0165 1706

Published by: NCG, Nederlandse Commissie voor Geodesie, Netherlands Geodetic Commission, Delft,
The Netherlands
Layout and corrections by: The Office of the Netherlands Geodetic Commission, Delft, The Netherlands
Printed by: Optima Grafische Communicatie, Optima Graphic Communication, Rotterdam,
The Netherlands
Cover: The FG5 absolute gravimeter (left) and Light interference in an absolute gravimeter (right)

NCG, Nederlandse Commissie voor Geodesie, Netherlands Geodetic Commission
P.O. Box 5030, 2600 GA Delft, The Netherlands
Tel.: +31 (0)15 278 28 19
Fax: +31 (0)15 278 17 75
E-mail: ncg@citg.tudelft.nl
Website: www.ncg.knaw.nl

The NCG, Nederlandse Commissie voor Geodesie, Netherlands Geodetic Commission is an institute of
the Royal Netherlands Academy of Arts and Sciences (KNAW).

Table of contents

Introduction

The determination of the earth's gravity field is done for various reasons:

- From gravity measurements the geoid can be computed. The geoid is the equipotential surface of the earth at mean sea level. The geoid enables 'levelling with GPS' (Global Positioning System).

- Absolute movements of the earth surface can be detected from gravity changes in time, while conventional levelling yields only relative height changes. With absolute gravity changes one can distinguish land subsidence from sea rise. This is a crucial question in low-lying Netherlands.

- Gravity is interesting from a geophysical point of view because deep tectonic fracture zones can be detected in combination with seismic measurements. This is important for the exploration of oil and gas.

- In oceanography gravity is important because ocean currents can be detected. The combination of gravity observations with satellite altimetry reflects sea topography and large-scale ocean circulation, like the warm Gulf Stream.

This report describes in detail the first high precision absolute gravity measurement in The Netherlands. The measurements were carried out by the Survey Department of Rijkswaterstaat and by the Delft University of Technology, Department of Geodesy (former Faculty of Geodesy). The measurements from 1991 and 1993 were performed with financial support from the Netherlands Geodetic Commission (NCG).

The gravity units microgal and milligal are used frequently in this rapport. One milligal = 1000 microgal = 1×10^{-5} ms^{-2}. The worldwide mean gravity value equals 980000 milligal (9.80 ms^{-2}), with variations up to 5000 milligal. In The Netherlands gravity values increase from south to north with about 1 milligal per kilometer. Smallest values occur in Limburg (981100 milligal), while the largest values occur in Groningen (981350 milligal). Local variations are limited to 1 milligal over some kilometers.

1. Principles of absolute gravity measurements

Gravity measurements can be done in a relative and in an absolute sense. Absolute measurements can be done with two different methods. The pendulum method is based on measuring the pendulum time T of a pendulum with length l very accurately. The accuracy of this observation is increased by observing the pendulum during a long time. The gravity value g is found with the relation:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

The length of the pendulum and the influence of the suspension point need to be known very precisely. With a pendulum it is possible to determine absolute gravity values with a precision of some milligal. After 1975 the pendulum method was superseded by the 'free fall method', which is based on a falling prism in a vacuum tube. The basis formula for the free fall method yields:

$$z = z_0 + v_0 t + \tfrac{1}{2} g t^2$$

In this formula z is the fall distance, t is time and z_0 and v_0 are distance and velocity at $t = 0$ ($t = 0$ is a time epoch shortly after the start of the fall; figure 2). For a fall distance of 30 cm the time interval is about 0.25 seconds. If we want to determine g with an accuracy of 1 microgal, the accuracy of the observation of t should be 0.25 nanoseconds, and the accuracy of z should be 0.3 nanometer (nano is 10^{-9}). This can only be achieved by measuring t with an atomic clock and by measuring z with light interference.

Measuring z with light interference is an ingenious method, illustrated in figure 1. A laser transmits light of very stable wavelength. This light is sent through a semi-pervious mirror to a falling prism A and to a fixed prism B. Prism B is fixed to a so-called super-spring. This is a spring that does not transit any vibrations from the ground. The returned light from both prisms is brought together by mirrors, resulting in light interference.

If the difference in the traversed paths of both bundles of light is equal to an integer wavelength, the light is intensified. If this difference is half a wavelength, the light is dimmed. The falling prism changes the traversed path continuously, resulting in the interfered light continuously changing on and off. By counting the number of changes in the interfered light, the fall distance can be measured with a precision of one hundredth of a wavelength.

Because there is always a small remainder of air in the vacuum tube, the falling prism is enveloped by a small box. This box is driven by a servo motor in such way that it falls together with the prism, without disturbing the fall of the prism. This way the air in the box falls together with the prism, resulting in a prism falling without friction of motion. The box has two small openings in order to let through the light bundles.

By averaging about 3000 fall experiments, a precision of 1 - 2 microgal can be reached for the absolute gravity value.

There is one complication with the above set-up: gravity is not constant during a fall. There is a vertical gravity gradient dg / dz of about 3 microgal per cm. If a linear gradient is assumed, the differential equation describing the free fall yields:

$$\frac{d^2z}{dt^2} = g(z) = g_0 + \frac{dg}{dz}(z - z_0)$$

with g_0 gravity at the location of the start of the timing. The vertical gradient dg / dz can be solved from this equation, but this method is inaccurate. A better and independent way to determine the vertical gradient is by using relative gravimeters, measuring at several heights along the fall trajectory of the absolute gravimeter.

The term $(z - z_0)$ is approximated by:

$$z - z_0 = v_0 t + \tfrac{1}{2} g_0 t^2$$

Using this, the differential equation can be written as:

$$\frac{d^2z}{dt^2} = g_0 + \frac{dg}{dz}(v_0 t + \tfrac{1}{2} g_0 t^2)$$

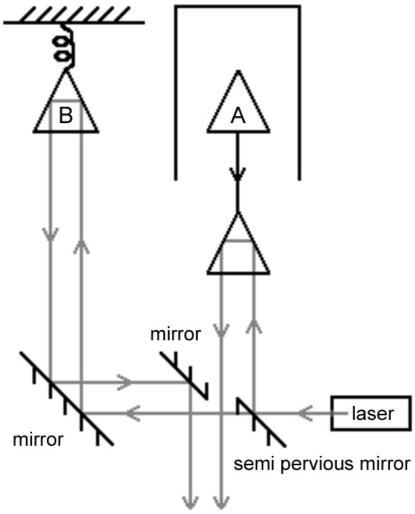


Figure 1: Light interference in an absolute gravimeter.

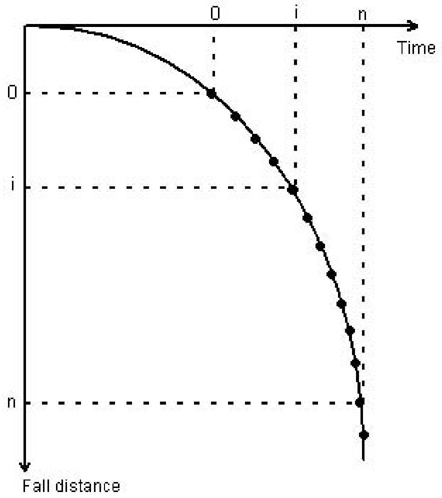


Figure 2: Measuring points during a fall experiment in an absolute gravimeter.

Integration over time t results in:

$$\frac{dz}{dt} = v_0 + g_0 t + \frac{dg}{dz}\left(\tfrac{1}{2} v_0 t^2 + \tfrac{1}{6} g_0 t^3\right)$$

$$z = z_0 + v_0 t + \tfrac{1}{2} g_0 t^2 + \frac{dg}{dz}\left(\tfrac{1}{6} v_0 t^3 + \tfrac{1}{24} g_0 t^4\right)$$

When this equation is filled in for every measuring point (some hundreds during a fall), the unknown parameters z_0, v_0 and g_0 can be solved in a least squares sense. Every fall experiment gives a value for z_0, v_0 and g_0 (figure 2).

After correction for tidal effect, the gravity values at height z_0 are converted to gravity values at the height of the surface on which the instrument is placed. This is done by using this formula:

$$g_{surface} = g_{z_0} + \frac{dg}{dz}\left(h_{z_0} - h_{surface}\right)$$

The precision of this reduction is about 1% of the gravity difference $g_{z_0} - g_{surface}$. This difference is instrument dependent, varying from 150 to 375 microgal. Therefore the precision of the reduction is 1 - 4 microgal.

For the sake of completeness a variant to the free fall method is mentioned here: the rise and fall method. This principle is slightly more accurate, but the construction of the instrument is more complex, and the measurements take more time.

Relative gravity measurements are based on a completely different principle: the elongation of springs with a small weight attached to them is measured. Taking measurements at different locations yields differences in elongation. These differences can be converted to gravity differences, on the condition that the instrument is calibrated on stations with known absolute gravity values. One relative measurement takes about 15 minutes, while a complete absolute measurement takes at least half a day. Well-calibrated instruments can measure gravity differences with a precision up to 5 microgal.

Absolute gravity measurements are necessary as a base for relative gravity measurements, for the calibration of relative gravimeters, and for determining the drift of relative gravimeters.

2. Precision measures for absolute gravity measurements

All absolute gravity measurements taken in the period 1991 - 1999 in the Netherlands are carried out using free fall absolute gravimeters. During a measuring campaign at a station, several series are measured, each of them consisting of numerous fall experiments.

2.1 Used precision parameters

The standard deviation of *n* fall experiments ('drops') in one series *j* ('set') yields:

$$\sigma_g(set\ j) = \sqrt{\frac{\sum_{i=1}^{n}(g_i - \bar{g}_j)^2}{n-1}}$$

with $\bar{g}_j$ the mean value of the set. If the *n* drops in a set are not correlated, the standard deviation of this mean value can be computed by dividing by $\sqrt{n}$:

$$\sigma_{\bar{g}}(set\ j) = \frac{\sigma_g(set\ j)}{\sqrt{n}}$$

At a station *k* several sets are measured consequently. For every set a $\sigma_g(set\ j)$ can be computed. The mean value of these $\sigma_g(set\ j)$'s is called 'drop standard deviation' or 'mean drop standard deviation':

$$\bar{\sigma}_{g_j}(station\ k) = \frac{\sum_{j=1}^{m}(\sigma_g(set\ j))}{m}$$

with *m* the number of sets measured at a station. The standard deviation of the mean values per set ($\bar{g}_j$'s) are called 'set standard deviation' (or 'series standard deviation'):

$$\sigma_g(station\ k) = \sqrt{\frac{\sum_{j=1}^{m}(\bar{g}_j - \tilde{g})^2}{m-1}}$$

with $\tilde{g}$ the mean gravity value from all *m*-sets together. If the *m* sets at a station are not correlated, the standard deviation of this mean can be computed by dividing by $\sqrt{m}$:

$$\sigma_{\bar{g}}(station\ k) = \frac{\sigma_g(station\ k)}{\sqrt{m}}$$

This standard deviation is a measure for the internal precision of a measurement. For the external precision of the resulting gravity value, systematic errors like ground water variations, tidal computations and remaining air pressure in the tube need to be considered (chapter 3).

2.2 Reflection of the suitability of the precision measures

The parameters from 2.1 are internationally in use for the description of the precision of absolute gravity measurements. A different way of computing the standard deviation of the mean of the sets at a station is:

$$\sigma_{\bar{g}}(station\ k)' = \frac{\sigma_g\,(m \cdot n\ \ drops)}{\sqrt{m \cdot n}}$$

In practice it turns out that drops correlate to one another, and that sets/series correlate to one another as well. Therefore this parameter is far too optimistic. But also parameters $\sigma_{\bar{g}}\,(set\ j)$ and $\sigma_{\bar{g}}(station\ k)$ are too optimistic.

The usual procedure when processing absolute gravity data is to remove 'bad' sets, and to use the remaining sets unweighted for the computation of the final gravity value. A least squares adjustment will however give more realistic results. The covariances have to be extracted from the data empirically. In the framework of this report, this theory is no further elaborated.

3. Gravity variations

Gravity depends on [Van Ree, 1991]:

Local effects

Position on earth	± 800 microgal per km along a meridian
Height on earth	± 3 microgal per cm height difference
Subbottom mass disturbance	

Gravity variations are the result of mass displacements because of:

Secular effects

Geological crust movement	0.1 - 1 microgal per century (no earthquakes)
Length of day variation	0.1 - 1 microgal per century
Sea rise (ocean loading)	0.5 - 2 microgal per 10 cm
Non-natural processes	5 - 20 microgal in 10 years (e.g. gas extraction)

Periodical effects

Polar motion	0 - 8 microgal per year
Ground water variations	1 - 10 microgal per day - per year (location-dependent)
Atmospheric pressure variations	0 - 20 microgal per some days / 3 microgal per season
Tides	100 - 250 microgal per day
Microseismic	2000 - 5000 microgal per 1 - 10 seconds

Gravimeters are built in such a way that microseismic is suppressed as much as possible (electronically or using super-springs). By repetition of measurements the residual microseismic noise can be removed. The same is valid for short periodic movements of the earth.

Microseismic in combination with the stability of the surface are of great importance for the success of an absolute gravity measurement. The magnitude of the microseismic at a location can be tested with seismic instruments, before the actual gravity measurement will take place.

In order to be able to compare measurements from different points of time, a number of mass displacements (tides, polar motion, length of day variation) are modelled, and corrected for. Effects like ground water variations and air pressure variations are difficult to model. Therefore it is tried to limit these effects during the gravity measurements, by combining the measurements of several days. The aim of the gravity measurements is to get insight in the other mass displacements, like land subsidence.

Gravity is also affected by incidents, like seismic from earthquakes or volcanoes, 'man made' seismic, shocks and gusts of wind. When these incidents occur, precise gravity measurements are difficult or impossible to carry out.

4. Gravity research in The Netherlands

The Netherlands played an important role in gravity research in the past. This is mainly due to Vening Meinesz who started with gravity measurements using pendulum instruments in 1915. Due to the instable bottom in The Netherlands the measurements were disturbed and Vening Meinesz designed a new instrument with a combination of three pendulums, by which the microseismic was eliminated. The instrument turned out to work very well. It could even be used at sea on board of a submarine. Vening Meinesz became world famous for his expeditions on the Atlantic, the Indian Ocean and near Australia and Indonesia. His gravity measurements at sea took place between 1920 and 1960.

After 1960 the gravity research was continued on land and at sea with modern instruments. A new sea gravimeter was purchased which could work on a normal ship. On board of Navy ships many expeditions were made worldwide between 1964 and 1990. Two special oceanographic survey ships (H.M. Tydeman and the Tyro) were built as well. These ships were specially equipped for gravity measurements.

On land a very detailed gravity network was measured by BPM (Shell) during the nineteen fifties. The results were published in the 'Atlas of The Netherlands'. In the years 1964, 1975, 1984 the Faculty of Geodesy of the Delft University of Technology measured a primary gravity network. After 1984 this network was extended and approved with new LaCoste & Romberg relative gravimeters.

The Survey Department of Rijkswaterstaat measured a primary gravity network in 1987 and 1990 as well. In 1993 this network was adjusted together with measurements from the period 1986 - 1992 carried out by the Faculty of Geodesy of the Delft University of Technology. The result is called the Nederlands Zwaartekrachtdatum 1993 (NEDZWA93) [De Min, 1995].

In the framework of NEDZWA93, absolute measurements needed to be done. As stated before, this is necessary to convert the gravity differences measured by relative gravimeters to absolute gravity values. Absolute measurements with free fall instruments were done in 1991 and 1993 at 4 points in The Netherlands. This was the first time in history that absolute gravity measurements with very high precision were done in The Netherlands. Before, points with known absolute values in Germany and Belgium were used. The measurements were performed with financial support from the Netherlands Geodetic Commission (NCG).

The NEDZWA93 results can be considered the first epoch of gravity values in The Netherlands for land subsidence research. The primary network consists of about 50 points distributed in The Netherlands. NEDZWA93 is also used to connect the secondary gravity network for the determination of the geoid for The Netherlands. This network is measured in the period 1990 - 1994 by the direction of the Survey Department of Rijkswaterstaat. The network consists of approximately 8000 points, with separations of about 2 kilometer. This high density was necessary in order to compute the geoid with centimeter precision [De Min, 1995 and 1996].

Despite the lack of a total planning of the measurements, the results are very acceptable. The precision of the NEDZWA93 gravity values is 5 - 6 microgal. The reliability of the network is good.

The second epoch of the primary gravity network (NEDZWA99) was prepared more thoroughly. [De Min, 1995] recommended to join the existing networks. The new network consists of 51 groups of points (figure 3). Design computations showed the potential of the network to give results with high and homogeneous precision and reliability [Crombaghs, 2002].

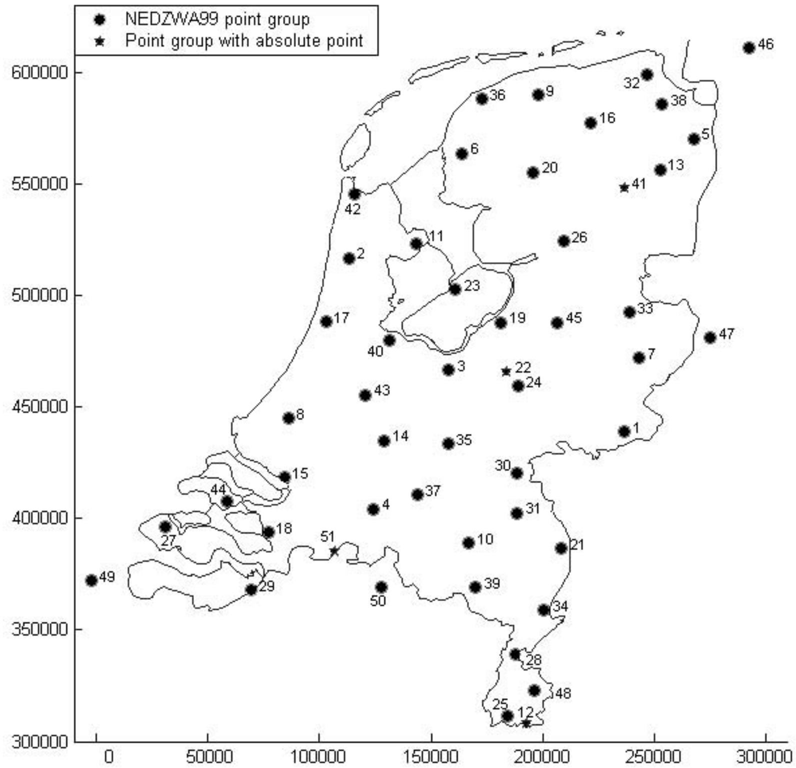


Figure 3: The point groups of NEDZWA99.

The relative gravity measurements for NEDZWA99 were carried out in the period 1996 - 1999 by the Faculty of Geodesy and the Survey Department of Rijkswaterstaat. Again, some absolute gravity measurements were made. All the absolute measurements carried out in the nineteen nineties are described in this report.

5. Absolute gravity measurements

5.1 Instrumentation

Due to the high costs of the instruments and the staff to keep the instruments running, no absolute gravimeters are purchased (and no will be purchased) in The Netherlands. Instruments and personnel from foreign institutes were contracted:

- Institut für Erdmessung, University of Hannover, Germany,
- Bundesamt für Kartographie und Geodäsie, Frankfurt (former IfAG, Institut für Angewandte Geodäsie),
- Royal Observatory of Belgium, Brussels.

The University of Hannover took measurements with the JILAG-3 absolute gravimeter. JILA is the name of the manufacturer: Joint Institute for Laboratory Astrophysics, Boulder, Colorado. Number 3 is the serial number. The instrument dates from 1986. In [Van Ree, 1991] an extensive description of the JILA instrument is given.

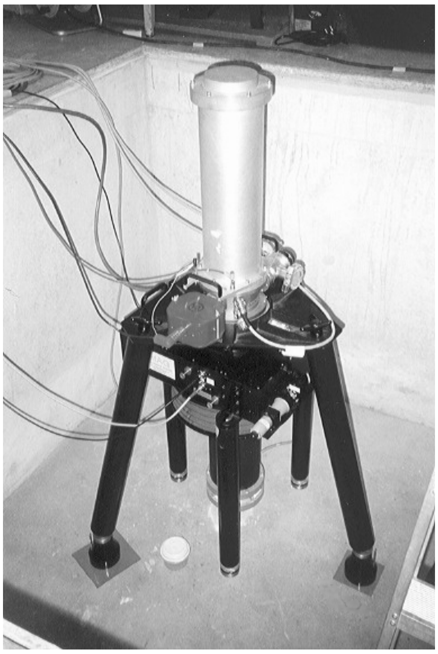


Figure 4: The FG5 absolute gravimeter.

The institutes of Frankfurt and Brussels measured with the FG5 absolute gravimeter. The FG5 is developed since 1990 by the American institutes NIST and NOAA together with IfAG. The FG5 is regarded as the improved successor of the JILA-instruments. The instruments are built by AXIS. The serial numbers of the instruments used in The Netherlands are 101 (Frankfurt) and 202 (Brussels).

Both the JILA and the FG5 gravimeters are based on the free fall principle. They both make use of an atomic clock, laser interferometry and a super-spring. The falling prism is lifted mechanically and dropped in a vacuum tube. The fall distance is about 20 cm, and the fall interval is about 0.2 seconds. The results are computed and stored in a computer. The JILA instrument weighs about 400 kg and is transported in 8 boxes. The FG5 instrument weighs about 350 kg and is transported in 6 large boxes.

After a period of warming up (about 1 hour) measurements take 1 to 2 days in order to be sure that at least one semi-diurnal tidal period is captured. In the software the measurements are corrected for tides, polar motion, air pressure and speed of light. No corrections are made for ground water variations.

In November 1997 all used instruments were compared in an international campaign in Sèvres, France (5th ICAG, International Comparison of Absolute Gravimeters). Each instrument was given an official correction for systematic errors that was published in 'Metrologia'. Correspondence with Olivier Francis (co-author of the official ICAG97-report) resulted in the correction values in table 1.

Instrument	Measured in	ICAG97-value (microgal)
JILAG-3	1991, 1993 and April 1997	+5.4
FG5-101	November 1996	-2.7
FG5-202	November 1997	+2.2
FG5-202	May 1999	-1.8

Table 1: ICAG97-corrections.

A positive ICAG97-correction means that the results of the instrument are systematically too high. For FG5-202 two corrections are given. In 1998 it turned out that this instrument was afflicted with a demonstrable systematic error of 4 microgal. The instrument is repaired, and the 1999 measurements are no longer affected with the offset.

The corrections for FG5-101 and FG5-202 (may 1999) are approximately the same. The difference is within the precision of the FG5-instruments (1 - 2 microgal). The JILAG-3 has an offset of about 7 microgal with respect to the FG5-instruments. This was already reported in 1996 by the Frankfurt group.

It can be concluded that systematic errors of absolute gravity instruments are below the level of 5 microgal. In The Netherlands measurements with different (types) of instruments are done in order to observe and level out all kind of discrepancies.

5.2 Stations

The precision of absolute gravity measurements is strongly dependent on the choice of the location. Especially for the interpretation of long time series stable locations are required. Conditions for absolute gravity stations are:

- The location must be indoor, well accessible and on the ground surface (without underlying cellar). The point can also be located in a cellar. Preferably, the building has to be at least 10 years old. Air pressure must be stable. During the measurements the temperature must not vary more than 2 °C between 18 - 24 °C.
- The height of the room must be at least 2.2 meter, and the floor area must be at least 10 m^2.
- The measuring surface must be horizontal and must have a solid and stable under ground.
- Good lighting and a 220 V power supply are required.
- The observation platform must be stable: the environment has to be calm. The distance to busy streets has to be at least 100 meter, the distance to open water, water ways or channels has to be at least some kilometers. There must be no disturbance from people passing.
- The location must be suited for taking measurements comfortably and undisturbed during a full 24 hour day.
- The observation point must be easy to identify and to reconstruct.
- The observation point has to be available for several decades.
- The observers must have access to the location, also out of working hours and during night.
- The location must be accessible by car.
- There must be no magnetic radiation near the location.
- It has to be possible to monitor the ground water table.

Using these criteria the following stations have been chosen.

Westerbork

On the terrain of the Westerbork Astronomical Radio Observatory (Radiosterrenwacht) a special bunker was built for gravity measurements in 1997 (figure 5). Seismic meas-

Figure 5: The gravity bunker in Westerbork.

urements were done in order to determine the exact location. Inside the bunker is a concrete block of 3 m x 3 m x 3 m, which is free from the surrounding floor and the building. The block rests on a condensed pleistocene sand layer. The measurements in 1991 and 1996 were executed at different locations in Westerbork, but the gravity differences between these locations and the new bunker are carefully determined with relative gravimeters.

Kootwijk

Since 1991, the TU Delft Satellite Observatory in Kootwijk has a special concrete pillar for gravity measurements. Kootwijk is a very stable location, built on a pleistocene sand layer.

Epen (Zuid-Limburg)

In 1993 the Royal Netherlands Meteorological Institute (KNMI) built a new seismic observatory. The location was carefully chosen on a stable geological layer. The station is 6 meter underground, such that the measurement pillar is directly situated on the Carboniferous layer. Drawback of the station is the difficult accessibility (on foot through hilly lands). The gravity measurements showed that this station is very stable. According to German experts it is one of the most stable points in Europe. The location in the south of Limburg is well situated for the detection of a possible tilt of the Netherlands around the line Westerbork - Kootwijk.

Zundert

The location is inside the fire station of Zundert, south of Breda. After Epen it is the most stable gravity point in The Netherlands. The location is also favourable in order to detect a possible tilt of the Netherlands around the line Westerbork - Kootwijk.

At three proposed locations test measurements showed the unsuitability for performing absolute gravity measurements:

Utrecht

This station is in the cellar of the botanical garden of the Utrecht University. The location will not be used in the future because of poor accessibility, poor measuring circumstances and disturbing sources in the neighbourhood.

Delft

The first measurements in 1991 (with the JILAG-3) showed already that this station is not suited for precise absolute gravity measurements. The location near the coast and the highway and the weak bottom cause strong microseismic vibrations. Measurements in 1996 showed again that this point is not suitable.

Bergen (Noord-Holland)
Seismic measurements (1996) showed that this location is not suited due to strong vibrations from traffic and the sea.

5.3 Results

Table 2 summarizes the absolute measurements in The Netherlands in the period 1991 - 1999. Data processing is carried out by the institutions that did the actual measurements using home made software or using the software from the manufacturer of the absolute

Station	Date	Crew	Drops per set	Number of sets	Dropstd. $\bar{\sigma}_{g_j}(station)$	Setstd. $\sigma_g(station)$	$\sigma_{\bar{g}}(station)$
Westerbork	09-1991	Hannover	300	9	112.6	7.1	2.4
Kootwijk	09-1991	Hannover	300	9	93.5	7.4	2.5
Kootwijk	02-1993	Hannover	300	9	112.6	6.9	2.3
Epen	02-1993	Hannover	180/300	9	32.1	3.9	1.3
Westerbork	11-1996	Frankfurt	150	24	27.9	5.3	1.1
Kootwijk	11-1996	Frankfurt	150	24	34.8	4.6	0.9
Epen	11-1996	Frankfurt	150	24	13.4	1.5	0.3
Westerbork	04-1997	Hannover	250	27	128.1	7.8	1.5
Kootwijk	04-1997	Hannover	250/300	17	117.3	8.2	2.0
Epen	04-1997	Hannover	300	9	13.9	2.1	0.7
Utrecht	04-1997	Hannover	300	14	109.1	7.9	2.1
Zundert	04-1997	Hannover	300	15	86.6	8.1	2.1
Westerbork	11-1997	Brussels	100	14	26.6	8.2	2.2
Kootwijk	11-1997	Brussels	100	11	21.4	5.3	1.6
Utrecht	11-1997	Brussels	100	6	90.3	34.0	13.9
Zundert	11-1997	Brussels	100	13	21.1	5.4	1.5
Westerbork	05-1999	Brussels	200	9	19.1	2.1	0.7
Kootwijk	05-1999	Brussels	200	19	36.7	3.5	0.8
Zundert	05-1999	Brussels	200	13	28.7	6.1	1.7
Westerbork	11-1999	Brussels	200	21	15.4	4.1	0.9

Table 2: Characteristics of the absolute gravity measurements (microgal).

gravimeter. The table is compiled using the reports supplied by the German and Belgium institutions. All standard deviations are in microgal.

An explanation of the three standard deviations in table 2 is given in chapter 2. In the Hannover reports a different 'drop standard deviation' is given: the mean of $\sigma_{\bar{g}}\ (set\ j)$ instead of the mean of $\sigma_{g}\ (set\ j)$. A conversion is made by multiplication by the square root of the number of drops in a set (series).

Striking elements from the table:
- The Hannover drop standard deviations exceed the ones from the FG5. The set standard deviation and the standard deviation of the resulting gravity value however are on the same level as the other measurements.
- Standard deviations at Epen are significantly better than the ones at the other stations.
- Standard deviations in The Netherlands are very reasonable compared to the standard deviations from foreign measurements.

The final results are shown in table 3.

Date	Crew	Westerbork	Kootwijk	Utrecht	Zundert	Epen
09-1991	Hannover	981309068.7	981250884.0	-	-	-
02-1993	Hannover	-	981250901.0	-	-	981100559.0
11-1996	Frankfurt	981309061.4	981250901.6	-	-	981100549.9
04-1997	Hannover	981309083.2	981250892.8	981252352.8	981196853.7	981100557.5
11-1997	Brussels	981309068.8	981250900.0	981252357.2	981196845.0	-
05-1999	Brussels	981309072.8	981250907.5	-	981196848.9	-
09-1999	Brussels	981309068.5	-	-	-	-
Mean value		981309070.6	981250897.8	981252355.0	981196849.2	981100555.5
Standard deviation		7.2	8.2	3.1	4.4	4.9

Table 3: Values from absolute gravity measurements (microgal).

The 1991 and 1996 Westerbork values are converted values. Only since 1997 the new bunker is used for the measurements. The measurements in 1991 and 1996 were executed at different locations in Westerbork, but the gravity differences between these locations and the new bunker are carefully determined with relative gravimeters (see table 4). Unweighted averages from all relative measurements available are used.

In table 3 epoch 11-1997 is already corrected for the 4 microgal-error (see 5.1). In table 5 the gravity values are corrected with the ICAG97-corrections from table 1.

Measured at	Observed g	Mean Δg with bunker (abs97)	g for point in bunker
abs91	981309119.0	50.3	981309068.7
abs96	981309175.9	114.5	981309061.4

Table 4: Conversion between the 3 absolute points at Westerbork (microgal).

Date	Crew	Westerbork	Kootwijk	Utrecht	Zundert	Epen
09-1991	Hannover	981309063.3	981250878.6	-	-	-
02-1993	Hannover	-	981250895.6	-	-	981100553.6
11-1996	Frankfurt	981309064.1	981250904.3	-	-	981100552.6
04-1997	Hannover	981309077.8	981250887.4	981252347.4	981196848.3	981100552.1
11-1997	Brussels	981309070.6	981250901.8	981252359.0	981196846.8	-
05-1999	Brussels	981309074.6	981250909.3	-	981196850.7	-
09-1999	Brussels	981309070.3	-	-	-	-
Mean value		981309070.1	981250896.2	981252353.2	981196848.6	981100552.8
Standard deviation		5.7	11.5	8.2	2.0	0.8

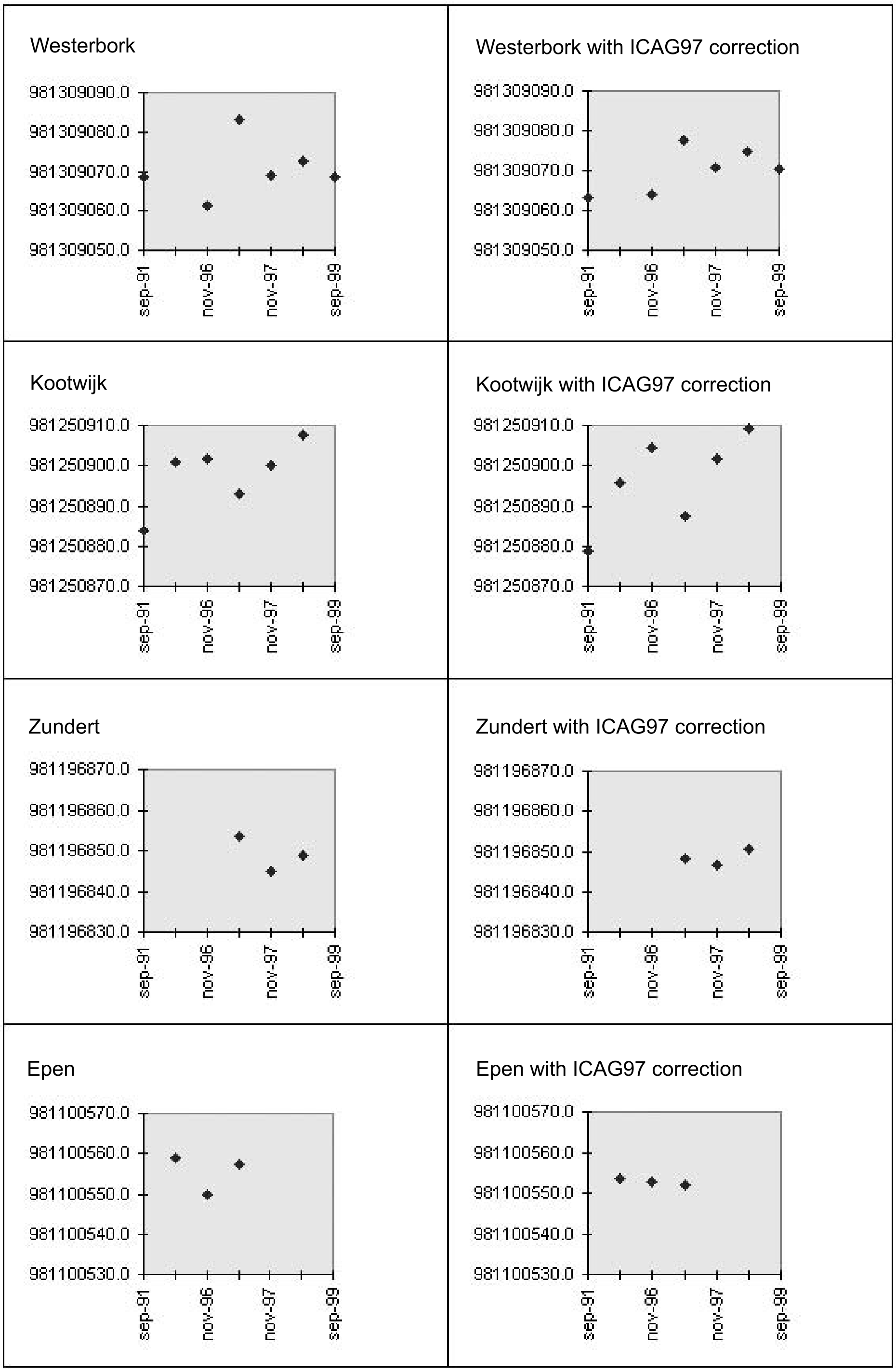
Table 5: ICAG97-corrected absolute values (microgal).

In figure 6 time series from table 4 and table 5 are depicted. Conclusion about trends in time cannot be drawn yet. Therefore more epochs are needed. Moreover, from levelling a trend is expected not to exceed 0.1 microgal per year, corresponding to 5 cm per century. These small trends cannot be shown with the current short time series containing a comparatively large noise level.

What can be seen from figure 6 is the favourable influence of the ICAG97-corrections with respect to the spreading of the observations. This is especially valid for Zundert and Epen.

The rather large differences between the different measurements at a single station (up to 17 microgal at Kootwijk) can be explained by the large drop standard deviations [De Min, 1995].

It is internationally assumed that the repeatability of absolute gravity measurements is 1 - 8 microgal for a few days to a few year, and the precision is 5 - 8 microgal (mainly due to local varying microseismic noise and uncertainty in ground water variations). The figures from tables 1, 4 and 5 agree with these assumptions.



Westerbork

Westerbork with ICAG97 correction

Kootwijk

Kootwijk with ICAG97 correction

Zundert

Zundert with ICAG97 correction

Epen

Epen with ICAG97 correction

Figure 6: Time series from tables 4 and 5.

The four absolute gravity values from 1991 and 1993 are used in NEDZWA93 with a priori standard deviation of 10 microgal (except for Epen: 8 microgal). After adjustment, the results are:

- Westerbork (abs91):	981309119	(σ = 5 microgal)
- Kootwijk:	981250893	(σ = 4 microgal)
- Epen:	981100558	(σ = 4 microgal)

The other 16 values are used in the NEDZWA99-computations with a priori standard deviation of 5 microgal. This assumption did not give any conflicts in the adjustment. Standard deviations after adjustment are only 2 - 3 microgal.

In chapter 2 it is explained that vertical gravity gradients at the locations of absolute gravity measurements need to be determined in an independent way with relative gravimeters. The measured values are summarized in table 6.

Date	Crew	Westerbork	Kootwijk	Utrecht	Zundert	Epen
09-1991	Hannover	-299.0	-320.0	-	-	-
02-1993	Hannover	-	-320.0	-	-	-215.7
11-1996	Frankfurt	-299.9	-319.2	-	-	-214.3
04-1997	Hannover	-295.0	-319.8	-261.8	-299.3	-213.2
11-1997	Brussels	-295.0	-319.8	-261.8	-299.3	-
05-1999	Brussels	-295.0	-319.8	-	-299.3	-
09-1999	Brussels	-295.0	-	-	-	-

Table 6: Vertical gradients (microgal per meter).

The differences in gradient at Westerbork are explicable, because there are 3 different points (1991, 1996 and after 1997). The gradient at Epen is small. This is because of the underground situation. The ground layers around and above result in an upward attraction.

The gravity gradients will change very slowly with respect to the changes in gravity. That is why the gradients do not have to be determined during every absolute measurement campaign. It is however useful to check a gradient at least one time.

The absolute gravity points will be included in the IAGBN (International Absolute Base Station Network). From correspondence with Michel Sarrailh from BGI/CNES (the administration of IAGBN in Toulouse) it is learned that there are two IAGBN subsets:

- IAGBN-A is a closed subset of 36 stations to support both the needs of reference sites and studies on global changes, with the goal of achieving better than 10^{-7} m/s accuracy. For these reasons, many of these stations are located at space geodetic sites. In the IAGBN catalogue 20 IAGBN-A stations have already been included.
- IAGBN-B has been created as an open collection of stations where absolute gravity has been observed.

There is no institute to officially assign a label (A or B) to an absolute gravity station. Practically, at BGI, all the available absolute gravity reference stations are collected.

5.4 Confrontation with relative measurements

In most countries it is common practice to execute absolute gravity measurements repeatedly in time, usually with only one instrument. This method has a number of drawbacks. A better method is measuring absolute gravity with several instruments, and adding relative gravity measurements. Advantages of this combination are:

Blunder detection
Blunders in the absolute measurements can be found. This is impossible with 'stand alone' absolute gravity measurements. Vice versa blunders in the relative measurements can be found as well.

Insight into the quality of the absolute measurements
It is not possible to make any statement on the stochastic model of the absolute measurements without confrontation with relative measurements.

Improvement of absolute values
As long as the precision of absolute gravimetry is not at the level of 2 - 3 microgal the combination with relative measurements in a least squares adjustment results in a precision improvement of the absolute values. Errors in absolute and relative observations are spread evenly. The combination does introduce correlation. Therefore it is better not to use adjusted NEDZWA-values for an analysis of land subsidence. For this task all the available 'raw' absolute and relative measurements have to be used. The NEDZWA99-adjustment reveals a precision of 2 - 3 microgal for the precision of the absolute gravity stations after adjustment. Except one outlier, no absolute observations were rejected in the adjustment.

Spreading of risk
Observation points are subject to disturbances. They can even become unusable. Those risks are minimized when building a network with relative gravity measurements. In The Netherlands a network is built, consisting of 51 point groups (figure 3). Every group exists of 3 or 4 points. At only 5 of the 200 points absolute gravity measurements are

carried out (paragraph 5.3). The network design makes it possible to compute absolute gravity values for all 200 points in the network with a homogeneous quality.

An alternative measurement set-up is to do continuous relative measurements at the absolute stations. This way the periodical effects at these points are measured. With the present approach in The Netherlands, these periodical effects cannot be distinguished from the measuring precision of the absolute gravimeter. This alternative approach however gives a less representative view of The Netherlands. Besides, this approach is expensive, because several super-conducting relative gravimeters are needed.

This report does *not* compare the absolute measurements with the individual relative measurements. Instead, the absolute measurements are compared with the final results of NEDZWA93 and NEDZWA99, see table 7.

Stations		Δg from absolute measurements	Carried out in	Δg from relative measurements	Computation	Difference
Kootwijk	Westerbork 017B0197	58234	09-1991	58225	NEDZWA93	9
Kootwijk	Westerbork 017B0218	58274	11-1996	58275	NEDZWA99	-1
Kootwijk	Westerbork 017B0217	58190	04-1997	58161	NEDZWA99	29
Kootwijk	Westerbork 017B0217	58169	11-1997	58161	NEDZWA99	8
Zundert	Westerbork 017B0217	112229	04-1997	112224	NEDZWA99	5
Zundert	Westerbork 017B0217	112224	11-1997	112224	NEDZWA99	0
Zundert	Kootwijk	54039	04-1997	54063	NEDZWA99	-24
Zundert	Kootwijk	54055	11-1997	54063	NEDZWA99	-8
Epen	Westerbork 017B0218	208626	11-1996	208636	NEDZWA99	-10
Epen	Westerbork 017B0217	208525	04-1997	208522	NEDZWA99	3
Epen	Kootwijk	150342	02-1993	150335	NEDZWA93	7
Epen	Kootwijk	150335	04-1997	150361	NEDZWA99	-26
Epen	Zundert	96296	04-1997	96298	NEDZWA99	-2

Table 7: Gravity differences from absolute and from relative gravity measurements (microgal).

The results in the column 'Δg from relative measurements' differ at most 1 microgal for the results from a first phase and from a second phase NEDZWA-adjustment.

The Utrecht station is not included in this table. At this point no more measurements will be done in the future. Also the measurements between the three points in Westerbork are not included.

The ICAG97-corrections do not have any influence on the gravity differences from absolute measurements, because absolute values from identical instruments are subtracted.

The large differences are caused by the absolute measurement at Kootwijk in April 1997. The other differences are certainly within the measurement noise of the absolute observations. Ground water variations and differences in air pressure between different points of time can play a role. These effects can be as large as 10 microgal.

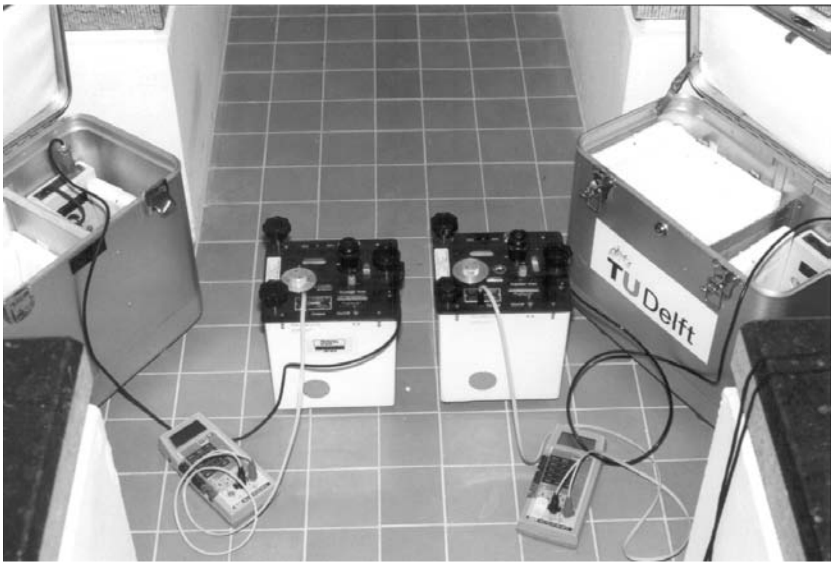


Figure 7: Relative measurements with two LaCoste & Romberg-gravimeters at the Epen absolute station.

6. Conclusions and recommendations

This report describes the first high precision absolute gravity measurements in The Netherlands. These measurements were carried out in the period 1991 - 1999. The measurements are important for future analysis of land subsidence in The Netherlands.

Due to the high costs of the instruments and the staff to keep absolute gravimeters running, no absolute gravimeters are purchased in The Netherlands. Instruments (JILAG and FG5) and personnel from three foreign institutes were contracted. The instruments operate according to the free fall principle.

Absolute gravity measurements have to be done indoor. Twenty campaigns were carried out on points in Westerbork (6), Kootwijk (6), Epen (3), Zundert (3) and Utrecht (2). Locations in Delft and Bergen (NH) turned out to be unsuitable. One campaign takes about one day. At this stage, insufficient measurements are available and insufficient time has expired in order to draw conclusions on trends in time.

Every campaign results in a gravity value for the station in question. Standard deviations for these values are only 1 - 2 microgal according to the reports from the institutes. From the NEDZWA-computations it can be seen that 5 microgal is a more realistic indication of the accuracy. After network adjustment with numerous relative gravity measurements a precision of 2 - 3 microgal for the adjusted absolute values is feasible.

Besides the precision improvement of the absolute values, the combination with relative measurements yields some other advantages: blunder detection, better insight into the quality of the absolute measurements and spreading of risk.

Recommendations

In order to be able to perform an analysis of land subsidence in about 20 years from now it is recommended to observe the primary gravity network in The Netherlands every 5 year. In Westerbork, Kootwijk, Epen and Zundert absolute measurements have to be done, simultaneous with the relative measurements, and preferably now and than in the years in between. It is preferable to use as many different (types) of instruments. This is especially true for the absolute gravity measurements.

The final analysis of land subsidence has to be done with all the available absolute and relative measurements, instead of using the absolute observations only or the adjusted NEDZWA-values. In the future better insight in the processing strategy might be available.

References

Crombaghs, M.J.E., 2002
Zwaartekracht in de 5^e NWP, de 2^e epoche van het Nederlands Zwaartekrachtdatum (NEDZWA99) ten behoeve van bodembewegingsonderzoek. MD-report MD-GAP-2002.10, 2002 (in Dutch).

Min, E.J. de, 1995
Het eerste orde zwaartekrachtnet van Nederland en het Nederlands zwaartekrachtdatum 1993 (NEDZWA93). Netherlands Geodetic Commission, publication 32, 1995 (in Dutch).

Min, E.J. de, 1996
De geoïde voor Nederland. Dissertation Delft University of Technology. Netherlands Geodetic Commission, publication 34, 1996 (in Dutch).

Ree, R.E. van, 1991
Absolute zwaartekracht in Nederland. Thesis Delft University of Technology, 1991 (in Dutch).