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THE FUNDAMENTAL GRAVITY NETWORK OF SWEDEN

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Abstract

The Swedish fundamental gravity net consists of 25 stations, including stations on the Fennoscandian land uplift gravity lines and absolute stations. It has been measured with high precision using LaCoste & Romberg gravimeters. Corrections are applied for earth tides, polar motion, land uplift, vertical gradient and air pressure. The adjustment gives gravity values with standard errors ranging from 4 to 11 µgals. To each gravity value there is also attached an estimated annual decrease due to the land uplift.

With the results of the fundamental network a new Swedish gravity system, RG 82, is introduced. It is defined by the following items: 1) The level and scale are determined from the corrected and weighted Italian absolute measurements in northern Europe. 2) The epoch is 1982. 3) The permanent tidal deformation of the Earth is retained whereas the permanent tidal attraction of the Moon and Sun is eliminated. In a final section comparisons between RG 82 and IGSN 71 are made.

Contents

1. Background

The first Swedish gravity measurement was made in 1741 at the Uppsala Observatory by Anders Celsius. He determined the gravity difference between London and Uppsala using a pendulum-clock constructed for him by Graham in London (Celsius, 1744). This pendulum-clock is still in operation in Uppsala. Nearly a century later, in 1833, Jöns Svanberg determined the gravity value of the Stockholm Observatory (Svanberg, 1834).

Taking advantage of the introduction of the Sterneck pendulum instrument, Per G. Rosén in 1889 - 1896 observed the gravity differences between five stations along a north-south line running through the whole of Sweden. He connected this line to Potsdam (Rosén, 1898).

A complete first order gravity network was built up by Bror Wideland in 1941 - 1948 using the then newly invented Nørgaard gravimeter (Wideland, 1946 & 1951). The number of stations was 33. The net was connected to Potsdam by the Baltic Geodetic Commission.

In 1960 - 1966 Lennart Pettersson measured a new first order network with a Worden gravimeter (Pettersson, 1967). It consists of 198 stations. The connection to Potsdam was made via the European Calibration System 1962 (ECS 62); later on the net was provisionally connected to the International Gravity Standardization Net 1971 (IGSN 71).

Today Pettersson's first order net does no longer meet the requirements of a basic gravity network. First of all, the accuracy is nowadays too low. Second, the stations are not marked. Third, some thirty percent of the stations are destroyed. Consequently a new net is needed.

As a first step a supreme network of 25 stations - the fundamental gravity network - has been established. It was measured in 1981 - 1982 by Lennart Pettersson and Lars Åke Haller, both using two LaCoste & Romberg gravimeters. In addition, measurements on the Fennoscandian land uplift gravity lines are used. Two absolute stations are included and connections are made to another two absolute stations in Denmark and Finland, all of which belong to the European set of stations measured with the Italian instrument IMGC. Furthermore, the measurements of the fundamental net have been sent for inclusion in the Unified European Gravity Network (UEGN).

2. Stations

The net consists of 25 stations, of which 12 also belong to the Fennoscandian land uplift gravity lines. Mårtsbo A and Göteborg A are absolute stations. In addition to these, the absolute stations Sodankylä in northern Finland and København in Denmark are included in the computation of the network. (So is also the Danish station Helsingør, used for the connection to København.) A fifth absolute station, Vaasa in western Finland, has been excluded because of a suspected error (Mäkinen & Haller, 1982).

The distances between the stations have been chosen to make it possible to drive from one station to a neighbour station and back again in one day. Furthermore, the stations have been located such that the gravity differences between them in the east-west direction are small (hundreds of μgals).

All stations (except Pello NA) are situated on bedrock. Thereby the influence of ground water variation on gravity is made negligible. With exception for the absolute ones all stations are outdoors, their sites being marked by bench

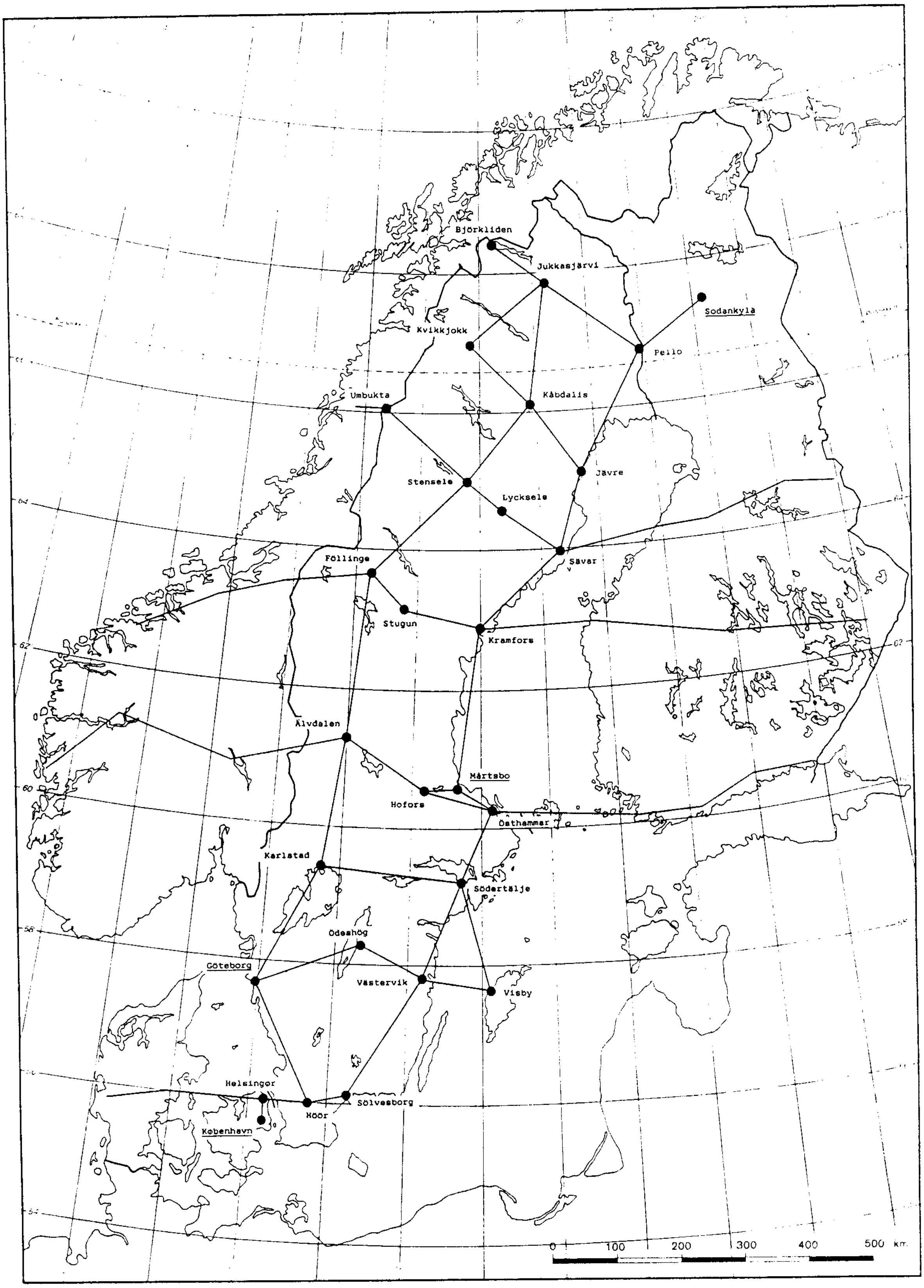


Figure 1. The fundamental gravity net of Sweden. The Fenno-scandian land uplift gravity lines are outlined. Names of absolute stations are underlined.

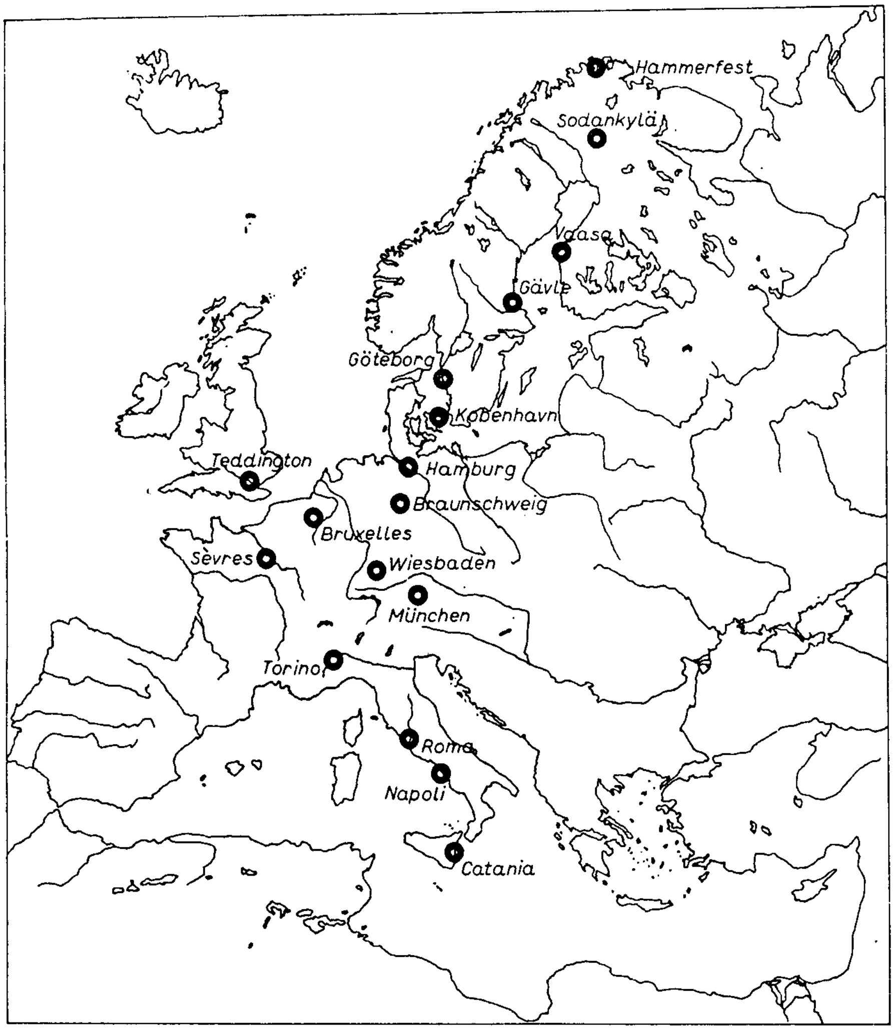


Figure 2. The European set of absolute stations measured by the IMGC instrument. (Note: Gävle = Mårtsbo A.)

marks. To every station there is at least one excenter (also on bedrock wherever possible), serving as a reserve station in case the main one is destroyed.

A map of the net is shown in Figure 1. The coordinates of the stations are given in the Appendix. Figure 2 shows the European set of absolute stations to which those of the net belong.

3. Measurements

The measurements have been carried out with two LaCoste & Romberg (LCR) model G gravimeters, no. 54 and no. 290. It would have been desirable to measure the net with a few more gravimeters but for economic reasons the number had to be limited to two. The observers have been Lennart Pettersson for the northern half of the network, and Lars Åke Haller for the southern half. All observations of the main stations were made in 1981 and 1982.

The measurements between neighbouring stations have been performed according to the scheme A - B - B - A, B - A - A - B. Each station is directly connected to two, three or four other stations in the net, except for one station in the far north (Björkliden) which has only one connection.

The gravimeters have been transported by car; for one station (Visby on the island of Gotland) also a quite long transportation by ferry boat was necessary. Considerable efforts were made to protect the gravimeters from mechanical shocks and sudden temperature changes. The instrument G-54 has been read using the microscope, G-290 using the galvanometer. The waiting time between unclamping and the first reading was usually four minutes. To avoid possible magnetic effects the gravimeters were oriented in the same way at almost all stations.

For the land uplift lines the results from all participating gravimeters during the years 1977 - 1984 have been used (Mäkinen et al., 1986). The number of gravimeters is here between 8 and 10.

The connections to the absolute stations Sodankylä and København have been determined by 4 gravimeters. For Sodankylä results of the instruments no. G-55 and G-600 (communicated by J. Mäkinen) are used in addition to the Swedish measurements with G-54 and G-290. For København results of the instruments no. G-466 and G-495 (communicated by F. Madsen) are used together with the Swedish measurements. The very short connection to Göteborg A (from Göteborg NB) was measured with 3 gravimeters, the additional one being no. D-56.

The absolute stations themselves were measured in 1976 by two Italian institutes using their own instrument IMGC (Istituto di Metrologia G. Colonetti). Their results are published by Cannizzo et al. (1978). However, the values are not used as they stand but have been corrected for some effects as described later on. The station Mårtsbo A (= Gävle) was made one of the three European main stations (the other two being Sevres in France and Torino in Italy); it was measured at three different occasions.

4. Corrections

Before proceeding with actual corrections the LCR readings of each station occupation have been condensed to a single observation by taking the average value. The observations have then been corrected mainly according to the Nordic standard recently adopted for the computation of the Fennoscandian land uplift gravity lines; see Mäkinen et al. (1986). Corrections are applied as follows.

1. Earth tides: The computations were performed with the program of Heikkinen (1978), which gives the same results (within 0.1 µgal) as the method of Cartwright-Tayler-Edden. The elasticity factor δ = 1.16 and zero phase lag are used. Wahr's theory as recently amended by Dehant & Ducarme (1987) would give δ = 1.15 as a weighted mean of the factors for the tidal waves at the mid-latitude of Sweden (62^{o}).

The permanent tide can, in principle, be treated in three different ways: 1) according to Honkasalo (1964), agreeing with IGSN 71; 2) according to Heikkinen (1979), agreeing with the IAG resolution of 1979; 3) according to Ekman (1979) and Groten (1980), agreeing with the IAG resolution of 1983. This leads to gravity systems differing by small amounts depending on latitude; see further section 6. The last method - unlike in Mäkinen et al. (1986) - is adopted as the main one here.

2. Polar motion: The correction was made using a subroutine in Heikkinen (1978). The observation is reduced to the Conventional International Origin (CIO).

3. Postglacial land uplift: This correction has been introduced only for the absolute measurements, being made six years earlier than the net itself; se further Table 1.

4. Vertical gradient: Gravity is reduced to the top of the bench mark, applying the standard gradient of - 0.309 µgal/mm.

5. Attraction and loading of the atmosphere: The observation is reduced to the normal air pressure of the station, applying the factor - 0.30 µgal/mbar.

6. Influence of air pressure on the gravimeter: Only for the gravimeter G-54 there is a significant effect, amounting to 0.05 µgal/mbar. The observation is reduced to 1000 mbar.

Table 1. Corrected absolute gravity values. Unit: µgal.

	Sodankylä	Mårtsbo A	Göteborg A	København
(1)	982 362 206	981 923 528	981 718 774	981 549 602
(a)	- 47	- 39	- 35	- 32
(b)	- 2	- 2	- 3	- 3
(c)	- 9	- 10	- 3	0
(d)	+ 37	+ 7	+ 15	+ 17
(2)	982 362 185	981 923 484	981 718 748	981 549 584

(1) Absolute gravity value according to Cannizzo et al. (1978); for Mårtsbo A (Gävle) the mean of three values. Corrected for earth tides as in IGSN 71 and for vertical gradient using own gradient determinations.

(a) Elimination of permanent tidal attraction of Moon and Sun to obtain agreement with the IAG resolution of 1983. Cf. section 6.

(b) Correction for polar motion. To be consistent with (c) the reduction should really be made to the mean pole of 1982 instead of the CIO, but in our case this makes practically no difference (less than 1 µgal).

(c) Correction for land uplift. Reduction to 1982 using the approximate factor - 0.2 µgal/mm (cf. Ekman et al., 1987), and the following absolute land uplift values: Sodankylä 7.5, Mårtsbo A 8.0, Göteborg A 2.5, København < 1 mm/year.

(d) Correction for vertical gradient error. Gradients corrected to the following new values: Sodankylä 0.343 (Arnautov et al., 1982), Mårtsbo A 0.295 (not published before), Göteborg A 0.302 (estimated, cf. Torge et al., 1987), København 0.259 µgal/mm (Torge et al., 1987).

(2) Absolute gravity value corrected for the above effects. To be used in the adjustment.

7. Scale of the gravimeter: The correction factor to the manufacturer's scale factor table is determined within the adjustment. The periodic error for 1 reading unit (mgal) is not significant for any of the two gravimeters; the other periodic errors are unknown.

For details on corrections to absolute values we refer to Table 1.

5. Adjustment

The least squares adjustment has been performed with a computer program designed at the National Land Survey (Malmberg, 1986). It benefits from the statistical ideas of Förstner (1979) and Persson (1981).

There are three groups of input data: absolute measurements, relative measurements, and precomputed differences. They are weighted according to the following a priori standard errors.

An absolute measurement with the IMGC instrument is known to have a standard error of about 8 µgals (cf. Cannizzo et al. 1978). This value is used a priori for Sodankylä and København. For Mårtsbo A, being measured three times, the a priori standard error is put to 5 µgals. Göteborg A, lacking accurate information on the gravity gradient, is given a standard error of 12 µgals.

The relative measurements are those performed with the two gravimeters LCR G-54 and G-290. These are given equal weight. On the basis of long experience the standard error of one measurement (of a station, not of a difference of succesive stations) is put to 12 µgals (cf. Mäkinen et al., 1986).

The precomputed differences contain the results on the land uplift gravity lines. Each difference is the result from one gravimeter, with the standard error of the difference as given by Mäkinen et al. (1986). Normally this is between 5 and 8 μgals. A small group of differences, being determined with few degrees of freedom, was assigned conventional standard errors instead of those published. Also the results from gravimeters other than G-54 and G-290 on the connections to the absolute stations are included as precomputed differences, with a standard error of 5 μgals for Sodankylä and København (combined results of two gravimeters) and 8 μgals for Göteborg A (one gravimeter).

The adjustment gave a posteriori standard errors close to the a priori ones, showing the input data to be properly weighted. It should be mentioned that in order to check the absolute values also an adjustment with comparatively low weights for these values was made; it indicated nothing suspicious.

Measurements have been rejected on physical grounds only (like mechanical shock etc.). The adjustment indicated no remaining gross errors.

The drift of a gravimeter during transport is modelled as a linear function of time. When the gravimeter has not been transported (nights etc.) a shift of the reading level has been introduced.

6. Results

The final results are summarized in Table 2, showing the gravity values and their standard errors for all stations. It may be noted that the adjustment changed the gravity values of the absolute stations by only 1 μgal for Göteborg A and by nothing at all for Sodankylä, Mårtsbo A and København (cf. Table 1). In Table 2 is also given approximate time derivatives of the gravity values, described closer later on. The small Table 3 gives scale correction factors with standard errors for the two gravimeters.

The standard errors of the gravity values range from 4 to 11 μgals, the extremes being 4 μgals for the central absolute station Mårtsbo A and 11 μgals for the northern station Björkliden with only one connection. The accuracy of the Swedish fundamental net is thus about the same as that of the corresponding German net (Sigl et al., 1981), where the standard errors range from 6 to 12 μgals.

The gravity values of Table 2 constitute the Gravity System 1982 of Sweden ("Rikets tyngdkraftssystem 1982", RG 82). This system is defined by the following items:

1. The level and the scale of the system are determined from the corrected and weighted Italian absolute measurements at Sodankylä, Mårtsbo A, Göteborg A and København.

2. The epoch of the system is 1982.

3. The permanent tide is treated according to the IAG resolution of 1983, i.e. the permanent tidal deformation of the Earth is retained whereas the permanent tidal attraction of the Moon and the Sun is eliminated.

According to the earlier IAG resolution of 1979 the permanent tidal deformation should be removed to the extent allowed by the elasticity factor $\delta = 1.16$. The gravity values of Table 2 can be transformed to such a system by adding

$$c_1 = 4.9 - 14.6 \sin^2\varphi \quad \mu\text{gals} \qquad (1)$$

In IGSN 71, on the other hand, not only the permanent tidal

Table 2. Adjusted gravity values of the Swedish fundamental gravity network, including estimated annual decrease due to postglacial land uplift. Gravity system: RG 82. Unit: μgal. Stars (*) denote absolute stations.

Station	Gravity value	Standard error	Annual decrease
Björkliden NA	982 362 145	11	1.0
Björkliden NB	982 365 553	11	1.0
Jukkasjärvi NA	982 361 917	9	1.5
Jukkasjärvi NB	982 362 156	10	1.5
Pello NA	982 362 461	8	1.7
Pello NB	982 365 580	8	1.7
* Sodankylä	982 362 185	7	1.5
Kvikkjokk NA	982 269 111	10	1.4
Kvikkjokk NB	982 268 767	10	1.4
Kåbdalis NA	982 270 445	8	1.8
Kåbdalis NB	982 268 958	9	1.8
Jävre NA	982 269 347	8	2.1
Jävre NB	982 268 824	8	2.1
Umbukta A	982 191 185	7	1.1
Umbukta B	982 191 341	10	1.1
Stensele A	982 191 189	7	1.6
Stensele B	982 191 251	10	1.6
Lycksele A	982 191 124	7	1.7
Lycksele C	to be measured 1988		1.7
Lycksele B	destroyed		
Sävar A	982 191 088	7	2.0
Sävar B	982 191 060	8	2.0
Föllinge A	982 075 771	6	1.5
Föllinge B	982 075 738	7	1.5
Stugun B	982 075 728	6	1.6
Stugun A	982 076 474	7	1.6
Stugun C	982 075 670	7	1.6
Stugun D	982 075 942	7	1.6
Kramfors D	982 075 783	6	1.9
Kramfors A	982 076 644	6	1.9
Kramfors B	982 077 100	7	1.9
Kramfors C	982 075 573	7	1.9

Älvdalen A	981 908 201	5	1.5
Älvdalen B	981 908 200	7	1.5
Hofors A	981 908 210	5	1.5
Hofors B	981 908 224	7	1.5
* Mårtsbo A	981 923 484	4	1.6
Mårtsbo B	981 923 646	5	1.6
Östhammar A	981 908 210	5	1.4
Östhammar B	981 908 206	5	1.4
Karlstad NA	981 828 158	6	1.0
Karlstad NB	981 828 082	6	1.0
Södertälje NA	981 828 128	6	1.1
Södertälje NB	981 828 024	6	1.1
Göteborg NB	981 718 370	6	0.5
* Göteborg A	981 718 749	7	0.5
Ödeshög NA	981 718 430	7	0.7
Ödeshög NB	981 718 473	8	0.7
Västervik NA	981 718 574	6	0.5
Västervik NB	981 718 453	7	0.5
Visby NA	981 719 266	7	0.5
Visby NB	981 718 567	8	0.5
* København	981 549 584	7	-
Helsingør	981 580 371	7	0.2
Höör A	981 580 437	7	0.2
Höör B	981 580 438	9	0.2
Sölvesborg A	981 580 437	7	0.2
Sölvesborg B	981 580 443	8	0.2

Table 3. Scale correction factors for the Swedish gravimeters.

Gravimeter	Correction factor	Standard error
LCR G-54	1.00075	0.00002
LCR G-290	1.00083	0.00002

deformation but also the permanent tidal attraction are retained. To convert the gravity values of Table 2 to such a system one should add

$$c_2 = -30.4 + 91.2 \sin^2\varphi \quad \mu\text{gals} \tag{2}$$

Both formulae can be found in Ekman (1988); (1) is related to (2) through $c_1 = (1 - \delta)c_2 = -0.16\, c_2$. For the stations in Table 2 we have $5 < -c_1 < 8$ µgals and $32 < c_2 < 48$ µgals.

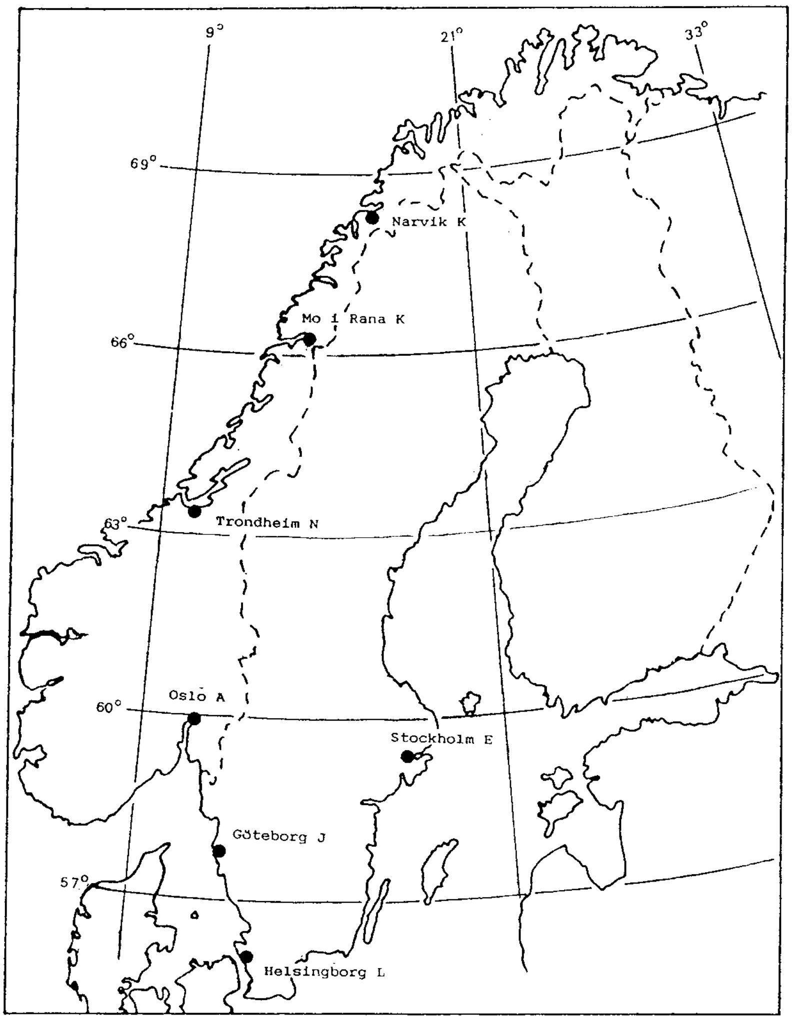
To allow the calculation of gravity values for some other year than 1982, an estimated annual gravity decrease due to land uplift is given in Table 2 for each station. The annual decrease has been estimated using the approximate factor 0.2 µgal per mm absolute land uplift, the absolute land uplift being the apparent land uplift corrected for eustatic rise of sea level and rise of the geoid. The most rapid decrease of gravity amounts to 2.1 µgals/year (at Jävre), corresponding to an absolute land uplift of 10.5 mm/year. Future research on the Fennoscandian land uplift gravity lines will, hopefully, give us a better knowledge of the land uplift factor.

7. Comparisons

From the Swedish fundamental network connections have been made to seven IGSN 71 stations in Norway and Sweden. For these stations gravity values are calculated in the system RG 82, allowing a comparison between the systems; see Table 4. The maximum discrepancy is about 100 µgals. A part of this originates from the permanent tidal attraction according to (2). Taking this into account, the maximum discrepancy decreases to 60 µgals, still leaving a discrepancy of 110 µgals in the gravity differences. These figures may be taken as measures of the true errors in IGSN 71. Comparisons with ECS 62 will be performed later.

Table 4. Comparisons between IGSN 71 and RG 82. Unit: mgal.
A = IGSN 71 - RG 82. B = IGSN 71 - RG 82 - (2).

Station	IGSN 71	RG 82	A	B
Narvik K	982 436.99	982 436.90	0.09	0.04
Mo i Rana K	982 308.94	982 308.84	0.10	0.05
Trondheim N	982 138.43	982 138.35	0.08	0.04
Oslo A	981 912.61	981 912.58	0.03	- 0.01
Stockholm E	981 827.96	981 827.97	- 0.01	- 0.05
Göteborg J	981 727.10	981 727.12	- 0.02	- 0.06
Helsingborg L	981 609.70	981 609.66	0.04	0.01



Appendix

This appendix contains coordinates of the gravity stations. The coordinates are given in the national systems, for Sweden latitude and longitude in RT 90 and height in RH 70. Stars (*) denote absolute stations.

Station	Latitude	Longitude	Height
Björkliden NA	68 24 04	18 41 54	365
Björkliden NB	68 26 41	18 36 28	380
Jukkasjärvi NA	67 51 09	20 30 14	350
Jukkasjärvi NB	67 51 16	20 29 49	348
Pello NA	66 47 55	23 53 54	88
Pello NB	66 48 17	23 54 08	80.57
* Sodankylä	67 25 13	26 23 38	276
Kvikkjokk NA	66 57 10	17 43 13	308
Kvikkjokk NB	66 57 13	17 43 16	309
Kåbdalis NA	66 06 28	19 55 41	351
Kåbdalis NB	66 07 44	19 50 37	348
Jävre NA	65 09 45	21 29 52	30
Jävre NB	65 08 31	21 30 26	30
Umbukta A	66 07 22	14 41 30	535
Umbukta B	66 07 19	14 41 34	535
Stensele A	65 00 31	17 40 26	284
Stensele B	65 03 16	17 26 01	340
Lycksele A	64 35 32	18 42 17	220
Lycksele C	64 35 30	18 42 16	220
Lycksele B	destroyed		
Sävar A	63 57 50	20 39 36	54
Sävar B	63 57 45	20 39 42	53
Föllinge A	63 40 36	14 34 22	299
Föllinge B	63 40 39	14 34 22	299
Stugun B	63 09 34	15 33 55	277.66
Stugun A	63 09 33	15 33 48	273.19
Stugun C	63 09 26	15 33 40	277.14
Stugun D	63 09 26	15 33 40	275.84
Kramfors D	62 52 23	17 56 29	107
Kramfors A	62 51 17	18 05 46	102
Kramfors B	62 51 16	18 05 49	100
Kramfors C	62 52 23	17 56 31	108

	Älvdalen A	61 20 28	14 01 36	345
	Älvdalen B	61 21 04	14 01 26	348
	Hofors A	60 33 49	16 20 05	184.16
	Hofors B	60 33 37	16 20 17	192.16
*	Mårtsbo A	60 35 45	17 15 43	43.50
	Mårtsbo B	60 35 45	17 15 41	43.02
	Östhammar A	60 16 25	18 19 00	15.62
	Östhammar B	60 16 05	18 17 00	9
	Karlstad NA	59 22 06	13 28 48	53.89
	Karlstad NB	59 22 23	13 28 58	52
	Södertälje NA	59 13 54	17 26 12	19.52
	Södertälje NB	59 14 46	17 27 03	30
	Göteborg NB	57 41 11	11 58 45	47.46
*	Göteborg A	57 41 12	11 58 50	44.53
	Ödeshög NA	58 13 13	14 39 26	147.82
	Ödeshög NB	58 12 52	14 39 06	145
	Västervik NA	57 49 17	16 25 55	30.86
	Västervik NB	57 49 38	16 29 37	18
	Visby NA	57 39 51	18 19 53	37
	Visby NB	57 39 27	18 19 28	35
*	København	55 45 42	12 33 55	19
	Helsingør	56 02 44	12 34 48	32
	Höör A	55 58 57	13 33 09	140.21
	Höör B	55 58 37	13 32 54	141.86
	Sölvesborg A	56 07 11	14 34 23	98.04
	Sölvesborg B	56 07 30	14 34 11	100.59

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