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# Effects on gravity from non tidal sea level variations in the Baltic Sea

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## Abstract

The main purpose of this paper is to investigate numerically the effects of non tidal sea level variations in the Baltic Sea on gravity with special emphasis on the Swedish stations in the Nordic Absolute Gravity Project.

To calculate the ocean loading effect on gravity the method described by Farrell (1972) is widely used. This method is based on convolution of a Green's function for gravity with the ocean load, but does not include the direct attraction depending on the height of the observation point. It is described how this effect is included in the Green's functions and how numerical integration is performed over a dense grid bounded by a very high resolution coastline. The importance of this high resolution is shown. The major part of the direct attraction for stations close to the coast comes from relatively small water masses close to the station. The total effect from the Baltic Sea, crustal loading and direct attraction, is calculated for twelve Swedish and one Finnish absolute gravity stations. The distance from the coast for these stations varies from 10 m to 150 km. It is shown that the total non tidal gravity effect is significant, easily reaching values of 2-3  $\mu\text{gal}$  for stations with high elevation close to the coast.

In modelling the Glacial Isostatic Adjustment (GIA), the relation between the change of gravity and the absolute land uplift ( $\dot{g}/\dot{h}$ ) contains information about the viscoelastic properties of the upper mantle. The Baltic Sea is located in the Fennoscandian postglacial land-uplift area and experience therefore a long term sea level decrease. It is also shown that the magnitude of this long term effect is not negligible for determination of the unknown part of  $\dot{g}/\dot{h}$ .

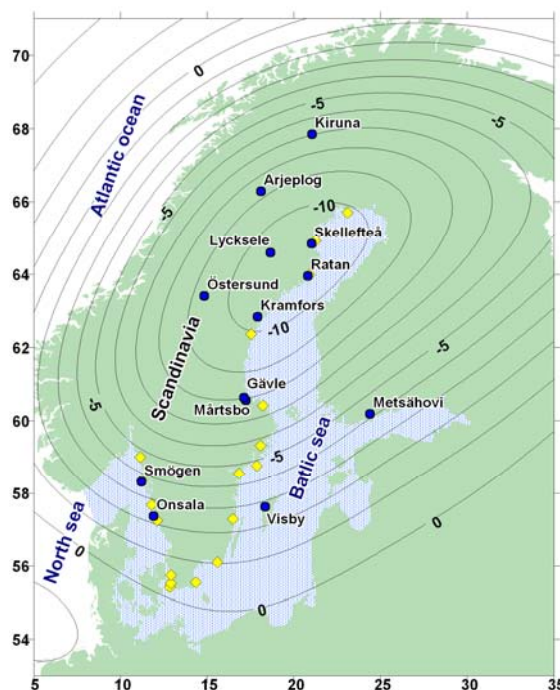
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**Keywords:** Green's function for gravity, non tidal ocean loading, Baltic Sea, Newtonian effect at height

## 1. Introduction

The Baltic Sea is unique in many respects. This 377 000 km<sup>2</sup> basin is connected to the North Sea in the Atlantic Ocean only via narrow straits between the Danish islands (Figure 1). This special condition makes the ocean tides small, less than 10 cm, but the non tidal sea level variations relatively large. Different wind conditions are the main cause of the large non tidal sea level variations in the Baltic Sea. Short term effects, e.g. over 24 hours, caused by strong south-west or north-east winds redistribute the water

masses within the Baltic Sea, tilting the sea surface, causing sea level variations in the range  $\pm 1$  meter. Longer term effects, e.g. on a scale of 2-4 weeks, caused by strong south-west winds over the North Sea in the Atlantic Ocean tend to transport water masses through the Danish straits, successively increasing the amount of water in the Baltic Sea. This effect may cause local sea level excursions in the Baltic Sea of up to 0.5 m (Samuelsson and Stigebrandt, 1996). Further, the Baltic Sea is located on the Fennoscandian Shield and therefore experiences a secular, apparent water decrease of magnitude 0-10 mm/yr, caused by the postglacial rebound.



**Figure 1.** Fennoscandia with isolines representing the postglacial absolute land uplift in mm/year (Milne *et al.*, 2004), Swedish tide gauges (yellow squares) and Swedish absolute gravity stations (blue circles). Metsähovi is a Finnish absolute and superconducting gravity station.

Since 2003, annual absolute gravity measurements have been performed in Fennoscandia at more than 40 stations (Gitlein *et al.*, 2007) with the final purpose of computing the best possible Glacial Isostatic Adjustment (GIA) model. Nearly all absolute gravity stations are co-located with permanent GPS stations. Absolute gravimetry combined with geometrical methods makes it possible to separate vertical surface deformations and subsurface mass movements. The absolute gravity observations are corrected for tidal- and atmospheric effects according to the standard procedure for FG5 absolute gravimeters, i.e. with the “g”-software from Micro-g LaCoste Inc.. “g” includes the software ETGTAB and global ocean tide models, the atmospheric pressure corrections are handled with a barometric admittance factor. So far no corrections have been made for effects from hydrology or from non tidal sea level variations.

Non-tidal ocean loading effects on ground gravity measurements have been studied for example by Zerbini *et al.* (2004), Fratepietro *et al.* (2006) and Boy and Lyard (2008). In Virtanen and Mäkinen (2003) and Virtanen (2004) extensive investigations of the effect from the Baltic Sea on Metsähovi station in Finland have been carried out. The main purpose of this paper is to investigate numerically the effects of non tidal sea level variations in the Baltic Sea on twelve Swedish absolute gravity stations to get an idea of the order of magnitude of these effects. The Metsähovi station is also included for

comparison with the results from Virtanen and Mäkinen (2003). We extend our concerns to the secular change of water mass in the Baltic Sea as an effect of the land uplift, since this effect may bias the inference of earth structure in particular at those stations that have large vertical motion and happen to be located near the coast.

In Bos and Baker (2005) the error sources of ocean loading computations are assessed. Some of these error sources are critical for stations close to the coast. Since several stations in this investigation are located very close to the sea (10-1500 meters), it is clarified how these error sources (such as the direct attraction of water masses close to the station, the resolution of the loading grid and the coastline) have been handled.

## 2. Theoretical approach

The theoretical approach is based on the assumption of a spherically symmetric, elastic earth. The loading effect on gravity,  $\Delta g$ , is computed by convolution of a Green's function for gravity (Farrell, 1972) with the surface load

$$\Delta g = \iint_{\text{seasurface}} \Delta g_G(\theta) S(\bar{\theta}) \rho dA \quad (1)$$

where  $\Delta g_G$  is Green's function (Section 2.1),  $S(\bar{\theta})$  is the sea level deviation from MSL as a function of the spherical distance vector from the point of observation.  $\rho$  is the density of sea water. This approach is valid on the sphere, i.e. the load and the observation point are both located on the sphere. Since the gravity stations are all located on land with a certain height  $H$  above sea level there is an additional effect in terms of direct attraction from the water masses below the point of observation (Section 2.2).

### 2.1. Green's function for gravity

The Green's function is equal to the effect on gravity from a unit point load at spherical distance  $\theta$  from the point of observation (Farrell, 1972)

$$\Delta g_G(\theta) = \frac{G}{R^2} \sum_{n=0}^{\infty} [n + 2h'_n - (n+1)k'_n] P_n(\cos \theta) \quad (2)$$

where  $G$  is the gravitational constant,  $R$  is the radius of the spherical earth and  $h'$  and  $k'$  are load Love numbers for the PREM reference earth model (Dziewonski and Anderson, 1981). For comparison also load Love numbers from Gutenberg-Bullen earth model have been used (Farrell, 1972).

The first term in Eq. (2) represents the direct attraction from water masses, the second term represents the effect due to of the vertical displacement trough the gravity gradient and the third term the disturbance of the gravity field caused by redistribution of masses within the solid Earth.

### 2.2. Newtonian effect at height

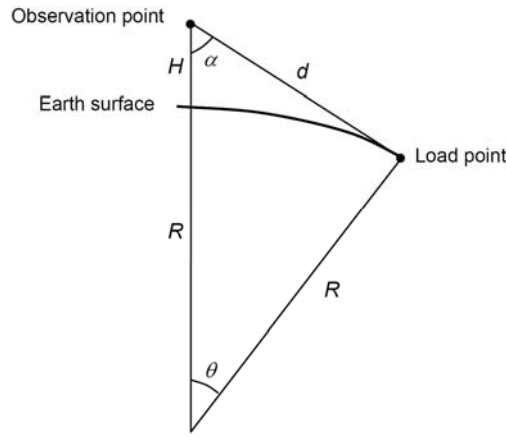
The Green's function for gravity in Eq. (2) assumes that the point of observation, as well as the loading point, is located on the earth surface approximated by a sphere. This is not the case for the Nordic absolute gravity stations that are located at some height  $H$  above sea level. This yields a total direct attraction from the water masses located below the point of observation of

$$\Delta g_{\text{Newton}}(H, \theta) = \frac{Gm}{R^2} t^2 \frac{1 - t \cos \theta}{(1 - 2t \cos \theta + t^2)^{3/2}} \quad (3)$$

where  $m$  is the mass of the loading point and  $t = R/(R+H)$  (Figure 2). Eqs. (3) include the whole effect from the direct attraction, that is the part that comes from the height of the station as well as the first term in Eq. (2). By substituting the first term of Eq. (2) by Eq. (3) the total effect on gravity from a unit mass point load on spherical distance  $\theta$  from the point of observation becomes

$$\Delta g_m(H, \bar{\theta}) = \frac{G}{R^2} \left[ t^2 \frac{1 - t \cos \theta}{(1 - 2t \cos \theta + t^2)^{3/2}} + \sum_{n=0}^{\infty} [2h'_n - (n+1)k'_n t^n] P_n(\cos \theta) \right] \quad (4)$$

where we have included the height dependence of the secondary gravity effect mediated by  $k'_n$ .



**Figure 2.** Geometry for the Newtonian effect at height

### 3. Practical approach

To evaluate Eq. (1) in practise, the midpoint method of numerical integration is used. With  $\Delta g_m(H, \bar{\theta})$  Eq. (1) becomes

$$\Delta g = \sum_{\text{sea\_surface\_grid}} \Delta g_m(H, \bar{\theta}_i) S_i A_i \rho \quad (5)$$

where  $S_i$  is the sea surface height (above normal) at discrete points forming a grid and  $A_i$  is the area of the  $i$ :th grid cell. The infinite summations in Eqs. (4) and (5) are impractical. Below we discuss how this limitation is handled and how it affects the result.

#### 3.1. Green's function for small $\theta$

We have decided to use precomputed load Love numbers for the PREM (Jentzsch, 1997) and Gutenberg-Bullen (Farrell, 1972) earth models respectively. They are given as a sparse set with respect to degree up to a maximum degree 10,000. Values for infinite degree have been derived by Farrell (1972) from the limiting case of a point load on a homogeneous half-space. In order to carry out the infinite sum of Eq. (4) the numbers were interpolated. The sums including the high-degree tail can be expressed analytically utilizing that

$$h_n \rightarrow h_\infty, nk_n \rightarrow k_\infty \quad (6)$$

In the Kummer transform employed by Farrell (1972) the sums

$$\sum_{n=0}^{\infty} (h_n - h_{\infty}) P_n(\cos \theta) \text{ and } \sum_{n=1}^{\infty} \frac{nk_n - k_{\infty}}{n} P_n(\cos \theta) \quad (7)$$

are truncated at  $n=10,000$ . If one, unlike Farrell, distinguishes between the Love numbers at  $N$  and their infinite limit, a Gibbs's like phenomenon shows up for small  $\theta$ . We have verified empirically that the truncation error does not yield significant errors for the stations treated in this paper.

### 3.2. Loading grid

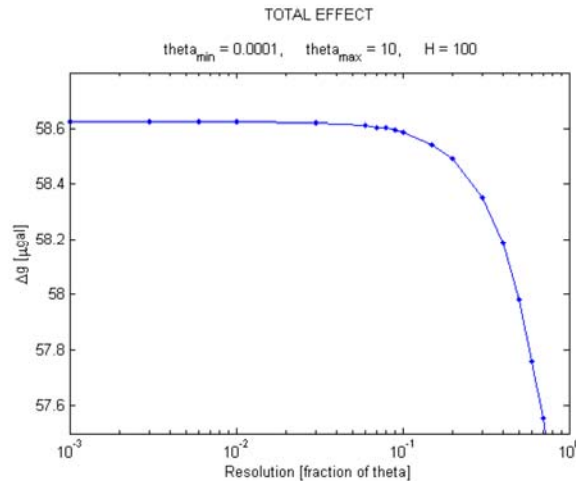
The surface load in Eq. (5) is represented by discrete values,  $S_i$ , in a grid. One important question is how dense the grid cells need to be to make the numerical integration sufficiently accurate. The resolution of the grid should be high enough to:

- avoid errors in the numerical integration
- represent the coastline accurate enough and
- represent variations in the load (sea level) accurately enough

We have found that these requirements are fulfilled by a grid with cell sizes that depends on the distance from the observation point  $\theta$ , as  $0.01 \cdot \theta$  in radial direction and  $0.02 \cdot \theta$  in azimuth. Below the choice of these numbers is discussed in more detail.

The distance from the observation point to the midpoint of the grid cell is crucial. If the resolution of the grid is too low, the resulting gravitational effect will be too low.

Figure 3 shows how the total effect (Eq. 4) from a load corresponding to one meter of water, distributed over a ring with inner radius  $0.0001^\circ$  and outer radius  $10^\circ$ , is affected by the radial resolution of the grid. This graph shows that a radial resolution higher than  $0.01 \cdot \theta$  does not improve the results on the  $0.01 \mu\text{gal}$  level. If the resolution is lower than  $\sim 0.08 \cdot \theta$ , the error introduced in the numerical integration will increase quickly.

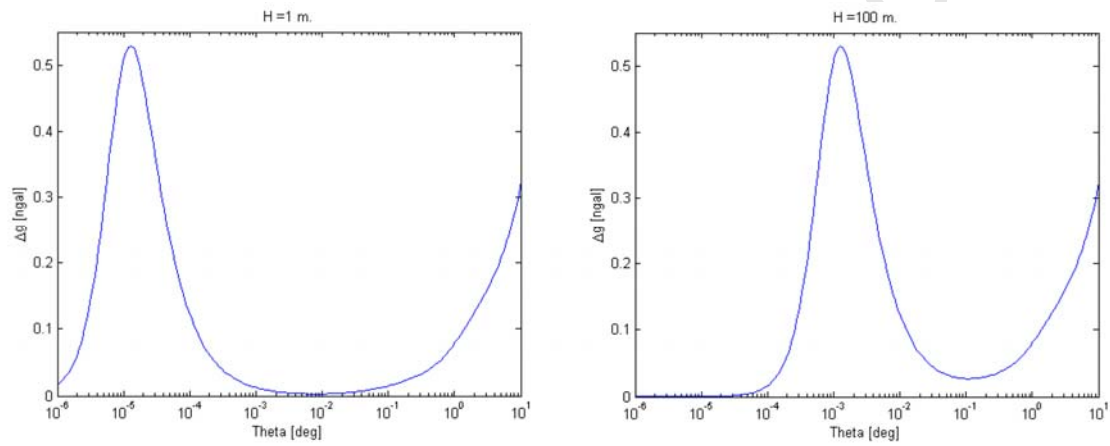


**Figure 3.** The effect on gravity, from a load corresponding to one meter of water distributed over a ring reaching from  $0.0001$  to  $10$  degrees from the observation point, as a function of the grid resolution

Another important issue concerning grid resolution is the ability to represent the coastline in an appropriate way. For a station like Smögen (c.f. Section 4 below) situated 10 meters from the coast and 6 meters above MSL, about 70% of the total effect comes from water masses within a radius of 100 meters from the station. This indicates that a high resolution coastline is crucial. We have used a coastline provided by Lantmäteriet (the Swedish mapping, cadastre and registry authority) with an average accuracy of about one



meter. The method chosen for the numerical integration is the midpoint rule. On average the number of midpoints located on land (and thereby not included in the grid) but with some parts of its cell on the sea side of the coastline should be about the same as the number of cells with its midpoint in the sea but with some parts of its cell in land. Therefore the amount of water should in average be close to correct. Of course, there might happen to be some overweight of cells wrongly defined as “only water” or “only land” and the size of the cells and the amount of load they represent is important. Figure 4 shows how big part of the total effect one cell at a certain distance from the observation point represents. This is never more than 0.5 ngal (normally much smaller), indicating that you need an overweight of more than 200 cells either on land or in the sea to achieve an error of 0.1  $\mu\text{gal}$ . Figure 4 also indicates that a grid cell size that depends linearly on the distance from the observation point is reasonable, since the effect from a single grid cell close to the observation point is in the same range as one grid cell far from the observation point.



**Figure 4.** Contribution to  $\Delta g$  from one grid cell at distance  $\theta$  and with sides  $0.01\theta \times 0.02\theta$ .

Finally it is important that the grid is dense enough to be able to describe the modelled sea level variations. With grid cell size  $0.01 \cdot \theta \times 0.02 \cdot \theta$  the sea level in the cells furthest away in the area of investigation (Figure 1) will be averaged over an area of about  $13 \times 26$  km which is sufficient considering the relative long wave nature of the modelling of sea level variations.

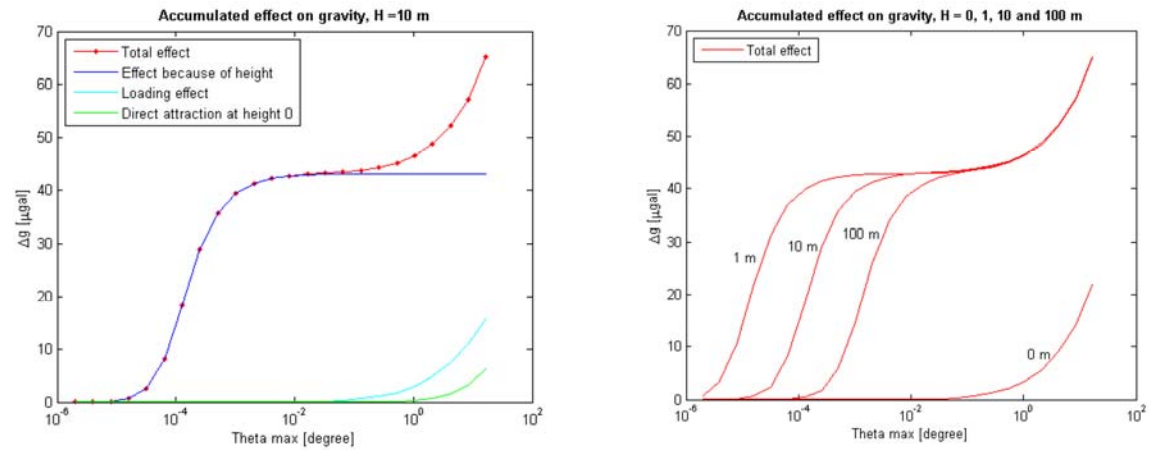
### 3.3. The dependence on height $H$

Figure 5 shows the accumulated effect on gravity for a theoretical case with a station surrounded by water from  $10^{-6}$  degrees ( $\theta_{\min}$ ) to  $\theta_{\max}$ . The load corresponds to one meter of water ( $\rho_{\text{water}} = 1030 \text{ kg/m}^3$ ) applied at MSL. The graphs show the accumulated effect on gravity for different station heights. The effect of the direct attraction from the water close to the station reaches  $\sim 43 \mu\text{gal}$ . The size of the area of influence depends on the station height. The major part of this effect is generated when

$$0.1H < \theta R < 10H$$

where  $H$  is the physical height of the station above MSL. By extending the upper limit to  $100H$  almost the whole effect is included. Within this area the resolution of the grid and the coastline is crucial (see Section 3.2 above).





**Figure 5.** The accumulated effect on gravity for a station at height  $H$  above sea level, surrounded by water from  $\theta_{\min} = 10^{-6}$  degrees to  $\theta_{\max}$ . The load corresponds to meter of water applied at MSL. To the left the total effect is separated in the direct attraction because of height, the direct attraction at height 0 and the loading effect. To the right is the total effect for four different station heights shown.

#### 4. Results

For twelve Swedish and one Finnish absolute gravity (AG) station (see Figure 1 and Table 1), the effects from the Baltic Sea and its transition to the North Sea (the blue area in Figure 1) have been calculated.

**Table 1.** Coordinates used (in most cases rough estimations (crucial for Smögen)).

Station	Latitude	Longitude	Height (RH2000)	Distance from coast [m]
Smögen	58.35354	11.21798	6	10
Kramfors	62.8755	17.9277	120	1 120
Onsala	57.3953	11.9255	6	170
Ratan	63.991	20.823	53	2 200
Visby	57.6539	18.3673	46	2 770
Skellefteå	64.8792	21.0483	55	1 360
Mårtsbo	60.5951	17.2585	44	7 380
Östersund	63.4428	14.8581	453	150 000
Metsähovi	60.2172	24.3958	56	16 400
Kiruna	67.8776	21.0602	466	154 000
Arjeplog	66.3180	18.1249	450	156 000
Lycksele	64.6276	18.6666	245	113 400
Gävle	60.6665	17.1314	14	2 720

For comparison, the effect from one meter of water all over the area is calculated and the results are presented in table 2. In column 2-8 load Love numbers from PREM (Jentzsch, 1997) were used and in column 9 load Love numbers from Gutenberg-Bullen earth model (Farrell, 1972) were used for comparison. The second column is the effect due to the direct attraction (Eq. 3) and the third is the direct attraction when the station is located on the sphere (at sea level) corresponding to the first term in Eq. (2). The fourth and fifth columns correspond to the  $h$ - and  $k$ -term term, respectively.

The Visby station, which is located on the Gotland Island in the Baltic Sea, shows the largest effects for all components of the total effect but for the direct attraction because of

the height (the second minus the third column). Here Smögen, Kramfors, Onsala and Ratan, which all are located closer to and/or at higher elevation have bigger numbers. In (Virtanen and Mäkinen, 2003) the effect at Metsähovi, from one meter water in the Baltic Sea, is calculated with the program package NLOADF (Agnew, 1997) and the Gutenberg-Bullen earth model. The result, 3.08  $\mu\text{gal}$ , can be compared with the corresponding result from Table 2, 3.41  $\mu\text{gal}$ . The lower value from (Virtanen and Mäkinen, 2003) may partly be due to the fact that they do not include any water west of the 13° meridian (c.f. Figure 1).

**Table 2.** Calculated effect is from a load corresponding to one meter of water all over the Baltic Sea and its transition to the North Sea (blue in Figure 1). Figures in  $\mu\text{gal}$  and based on PREM if nothing else is indicated.

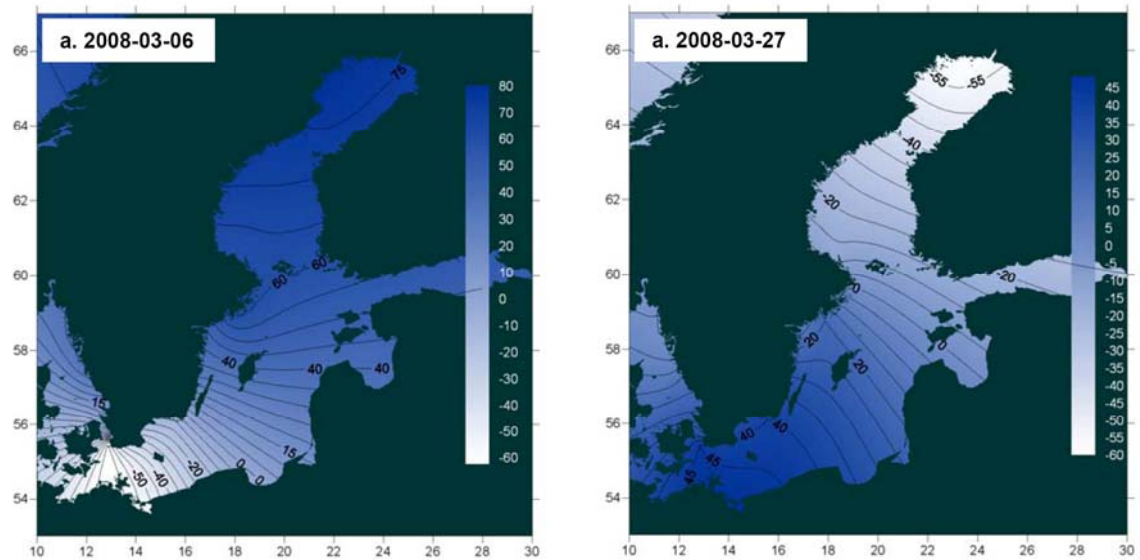
Station	Direct attraction ( $g_N$ )	Direct attraction ( $H = 0$ )	Effect due to vertical displacement ( $g_u$ )	Effect due to mass redistribution ( $g_v$ )	Loading effect ( $g_u + g_v$ )	Vertical displacement [mm]	Total effect ( $g_N + g_u + g_v$ )	Total effect (GB earth model)
Smögen	<b>7.5938</b>	0.7138	4.2460	-1.0536	3.1924	13.76	<b>10.7862</b>	<b>10.8622</b>
Kramfors	1.6404	0.6349	3.3203	-0.8484	2.4719	10.76	4.1123	4.1818
Onsala	1.0330	0.7514	4.4121	-1.1095	3.3026	14.30	4.3355	4.4255
Ratan	0.8980	0.6322	3.5471	-0.9037	2.6435	11.49	3.5414	3.6428
Visby	1.2012	<b>0.9791</b>	<b>5.9706</b>	<b>-1.5588</b>	<b>4.4118</b>	<b>19.35</b>	5.6130	5.7707
Skellefteå	0.7233	0.5346	2.7565	-0.7041	2.0524	8.93	2.7757	2.8473
Mårtsbo	0.7729	0.7245	3.7022	-0.9444	2.7578	12.00	3.5307	3.6087
Östersund	0.4343	0.4203	1.4500	-0.3437	1.1063	4.70	1.5406	1.5500
Metsähovi	0.7253	0.6880	3.5099	-0.9031	2.6068	11.37	3.3321	3.4102
Kiruna	0.2670	0.2628	0.7127	-0.1666	0.5462	2.31	0.8132	0.8160
Arjeplog	0.3329	0.3248	1.0042	-0.2381	0.7661	3.25	1.0991	1.1057
Lycksele	0.4585	0.4422	1.7562	-0.4415	1.3146	5.69	1.7731	1.7992
Gävle	0.7312	0.7113	3.6028	-0.9172	2.6856	11.67	3.4168	3.4903

A load corresponding to one meter of water all over the Baltic Sea is quite unrealistic (but half a meter is not). In Table 3 the effect from three more realistic sea level situations is presented. The second and third columns are calculated from a sea surface interpolated from Swedish tide gauge data (Figure 1) for two different days in March 2008. In the first case (2008-03-06) the wind is coming from south-west causing a sea surface tilt from north to south and in the second case (2008-03-27) the situation is the opposite (Figure 6). Because of lack of tide gauge data from other countries only Swedish tide gauges are used in these first calculations. Nevertheless this case clearly demonstrates a typical behaviour of the Baltic Sea, and the results indicate the magnitude of the effect in a realistic case.

**Table 3.** Total effect on gravity from two realistic sea level situations for the Baltic Sea (Figure 6). The last column in shows the effect on gravity caused by the secular apparent water decrease due to the post glacial rebound (Figure 1). Figures in  $\mu\text{gal}$  and based on PREM if nothing else indicated.

Station	2008-03-06	2008-03-27	$\dot{g}$ [ $\mu\text{gal/year}$ ]
Smögen	3.3374	0.2696	-0.0377
Kramfors	2.5170	-0.7547	-0.0346
Onsala	0.8550	0.5662	-0.0104
Ratan	2.2671	-1.0270	-0.0309
Visby	1.9536	0.9285	-0.0164
Skellefteå	1.7901	-0.8920	-0.0243
Mårtsbo	1.7442	-0.1525	-0.0209
Östersund	0.7384	-0.1342	-0.0110
Metsähovi	1.6140	-0.2712	-0.0147
Kiruna	0.3993	-0.1140	-0.0058
Arjeplog	0.5607	-0.1704	-0.0086
Lycksele	0.9884	-0.3394	-0.0138
Gävle	1.6861	-0.1536	-0.0204

The last column in table 3 shows the effect on gravity caused by the secular apparent water decrease due to the post glacial rebound (Figure 1). In GIA modelling the quantity  $\dot{g}/\dot{h}$  contains information about the viscoelastic properties of the upper mantle (Ekman and Mäkinen, 1996).



**Figure 6.** Interpolated sea surface topography from Swedish tide gauge data 2008-03-06 (a) and 2008-03-27 (b).

## 5. Conclusions

The effects from the Baltic Sea on gravity have been numerically investigated for twelve Swedish and one Finnish absolute gravity stations. The method used is the one described by Farrell (1972) complemented with the effect from the direct attraction of water masses close to the station. For stations that have a ratio of coast distance to height less than 100 and where the direct attraction is an important contribution to the total effect, the resolution of the grid and the coastline is of greatest importance.

The total effect have been calculated for one theoretical case with a homogenous one meter sea level rise and for two more realistic cases based on tide gauge observations from Swedish tide gauges. These tests show that the non tidal effect on gravity from the

Baltic Sea is significant for AG-measurements in the Nordic Absolute Gravity Project and should be corrected for.

Most of the AG-stations in the Nordic Absolute Gravity Project are collocated with permanent GPS and each station will, in the long run, contribute with an estimation of  $\dot{g}/\dot{h}$ . This number is  $\sim 0.20 \mu\text{gal mm}^{-1} \pm$  a few hundreds of  $\mu\text{gal mm}^{-1}$  and is interesting for GIA modelling purposes. For a station like Smögen, with  $\dot{g} \approx 0.04 \mu\text{gal yr}^{-1}$  and  $\dot{h} \approx 4 \text{ mm yr}^{-1}$ , the contribution to this number from the secular water decrease is  $\sim 0.01 \mu\text{gal mm}^{-1}$  which is significant for the unknown part of  $\dot{g}/\dot{h}$ . Considering loads at short distance angles and stations with significant slant angles to these loads will continue to engage us in improvement of the computation schemes. The situation also calls for an extension of the load Love number sets to much higher harmonic degree.

### Acknowledgements

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# Effects on gravity from non tidal sea level variations in the Baltic Sea

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## Abstract

The main purpose of this paper is to investigate numerically the effects of non tidal sea level variations in the Baltic Sea on gravity with special emphasis on the Swedish stations in the Nordic Absolute Gravity Project.

To calculate the ocean loading effect on gravity the method described by Farrell (1972) is widely used. This method is based on convolution of a Green's function for gravity with the ocean load, but does not include the direct attraction depending on the height of the observation point. It is described how this effect is included in the Green's functions and how numerical integration is performed over a dense grid bounded by a very high resolution coastline. The importance of this high resolution is shown. The major part of the direct attraction for stations close to the coast comes from relatively small water masses close to the station. The total effect from the Baltic Sea, crustal loading and direct attraction, is calculated for twelve Swedish and one Finnish absolute gravity stations. The distance from the coast for these stations varies from 10 m to 150 km. It is shown that the total non tidal gravity effect is significant, easily reaching values of 2-3  $\mu\text{gal}$  for stations with high elevation close to the coast.

In modelling the Glacial Isostatic Adjustment (GIA), the relation between the change of gravity and the absolute land uplift ( $\dot{g}/\dot{h}$ ) contains information about the viscoelastic properties of the upper mantle. The Baltic Sea is located in the Fennoscandian postglacial land-uplift area and experience therefore a long term sea level decrease. It is also shown that the magnitude of this long term effect is not negligible for determination of the unknown part of  $\dot{g}/\dot{h}$ .

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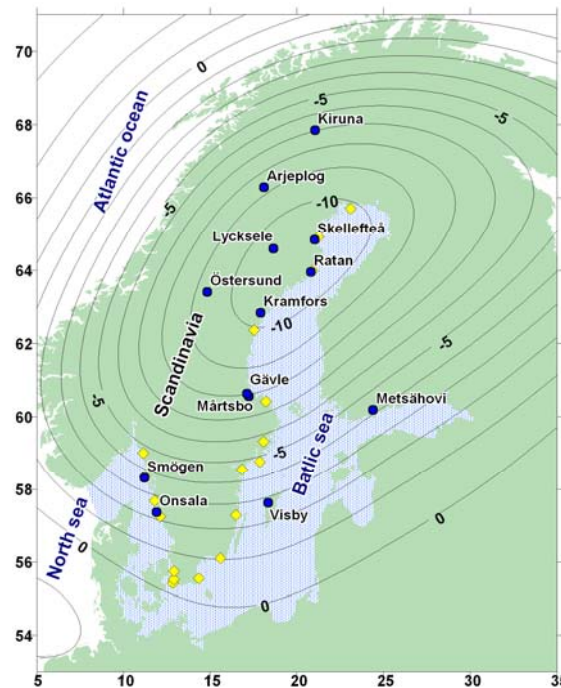
**Keywords:** Green's function for gravity, non tidal ocean loading, Baltic Sea, Newtonian effect at height

## 1. Introduction

The Baltic Sea is unique in many respects. This 377 000 km<sup>2</sup> basin is connected to the North Sea in the Atlantic Ocean only via narrow straits between the Danish islands (Figure 1). This special condition makes the ocean tides small, less than 10 cm, but the non tidal sea level variations relatively large. Different wind conditions are the main cause of the large non tidal sea level variations in the Baltic Sea. Short term effects, e.g. over 24 hours, caused by strong south-west or north-east winds redistribute the water



masses within the Baltic Sea, tilting the sea surface, causing sea level variations in the range  $\pm 1$  meter. Longer term effects, e.g. on a scale of 2-4 weeks, caused by strong south-west winds over the North Sea in the Atlantic Ocean tend to transport water masses through the Danish straits, successively increasing the amount of water in the Baltic Sea. This effect may cause local sea level excursions in the Baltic Sea of up to 0.5 m (Samuelsson and Stigebrandt, 1996). Further, the Baltic Sea is located on the Fennoscandian Shield and therefore experiences a secular, apparent water decrease of magnitude 0-10 mm/yr, caused by the postglacial rebound.



**Figure 1.** Fennoscandia with isolines representing the postglacial absolute land uplift in mm/year (Milne *et al.*, 2004), Swedish tide gauges (yellow squares) and Swedish absolute gravity stations (blue circles). Metsähovi is a Finnish absolute and superconducting gravity station.

Since 2003, annual absolute gravity measurements have been performed in Fennoscandia at more than 40 stations (Gitlein *et al.*, 2007) with the final purpose of computing the best possible Glacial Isostatic Adjustment (GIA) model. Nearly all absolute gravity stations are co-located with permanent GPS stations. Absolute gravimetry combined with geometrical methods makes it possible to separate vertical surface deformations and subsurface mass movements. The absolute gravity observations are corrected for tidal- and atmospheric effects according to the standard procedure for FG5 absolute gravimeters, i.e. with the “g”-software from Micro-g LaCoste Inc.. “g” includes the software ETGTAB and global ocean tide models, the atmospheric pressure corrections are handled with a barometric admittance factor. So far no corrections have been made for effects from hydrology or from non tidal sea level variations.

Non-tidal ocean loading effects on ground gravity measurements have been studied for example by Zerbini *et al.* (2004), Fratepietro *et al.* (2006) and Boy and Lyard (2008). In Virtanen and Mäkinen (2003) and Virtanen (2004) extensive investigations of the effect from the Baltic Sea on Metsähovi station in Finland have been carried out. The main purpose of this paper is to investigate numerically the effects of non tidal sea level variations in the Baltic Sea on twelve Swedish absolute gravity stations to get an idea of the order of magnitude of these effects. The Metsähovi station is also included for



comparison with the results from Virtanen and Mäkinen (2003). We extend our concerns to the secular change of water mass in the Baltic Sea as an effect of the land uplift, since this effect may bias the inference of earth structure in particular at those stations that have large vertical motion and happen to be located near the coast.

In Bos and Baker (2005) the error sources of ocean loading computations are assessed. Some of these error sources are critical for stations close to the coast. Since several stations in this investigation are located very close to the sea (10-1500 meters), it is clarified how these error sources (such as the direct attraction of water masses close to the station, the resolution of the loading grid and the coastline) have been handled.

## 2. Theoretical approach

The theoretical approach is based on the assumption of a spherically symmetric, elastic earth. The loading effect on gravity,  $\Delta g$ , is computed by convolution of a Green's function for gravity (Farrell, 1972) with the surface load

$$\Delta g = \iint_{\text{seasurface}} \Delta g_G(\theta) S(\bar{\theta}) \rho dA \quad (1)$$

where  $\Delta g_G$  is Green's function (Section 2.1),  $S(\bar{\theta})$  is the sea level deviation from MSL as a function of the spherical distance vector from the point of observation.  $\rho$  is the density of sea water. This approach is valid on the sphere, i.e. the load and the observation point are both located on the sphere. Since the gravity stations are all located on land with a certain height  $H$  above sea level there is an additional effect in terms of direct attraction from the water masses below the point of observation (Section 2.2).

### 2.1. Green's function for gravity

The Green's function is equal to the effect on gravity from a unit point load at spherical distance  $\theta$  from the point of observation (Farrell, 1972)

$$\Delta g_G(\theta) = \frac{G}{R^2} \sum_{n=0}^{\infty} [n + 2h'_n - (n+1)k'_n] P_n(\cos \theta) \quad (2)$$

where  $G$  is the gravitational constant,  $R$  is the radius of the spherical earth and  $h'$  and  $k'$  are load Love numbers for the PREM reference earth model (Dziewonski and Anderson, 1981). For comparison also load Love numbers from Gutenberg-Bullen earth model have been used (Farrell, 1972).

The first term in Eq. (2) represents the direct attraction from water masses, the second term represents the effect due to of the vertical displacement trough the gravity gradient and the third term the disturbance of the gravity field caused by redistribution of masses within the solid Earth.

### 2.2. Newtonian effect at height

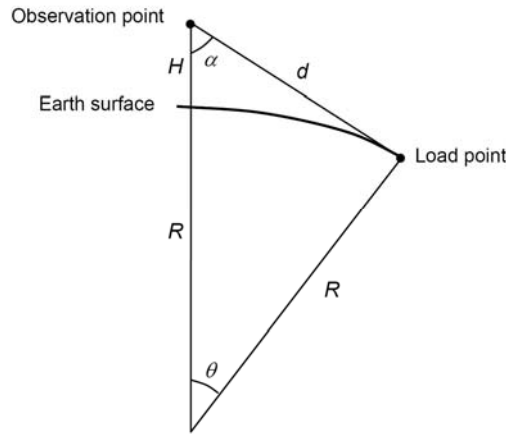
The Green's function for gravity in Eq. (2) assumes that the point of observation, as well as the loading point, is located on the earth surface approximated by a sphere. This is not the case for the Nordic absolute gravity stations that are located at some height  $H$  above sea level. This yields a total direct attraction from the water masses located below the point of observation of

$$\Delta g_{\text{Newton}}(H, \theta) = \frac{Gm}{R^2} t^2 \frac{1 - t \cos \theta}{(1 - 2t \cos \theta + t^2)^{3/2}} \quad (3)$$

where  $m$  is the mass of the loading point and  $t = R/(R+H)$  (Figure 2). Eqs. (3) include the whole effect from the direct attraction, that is the part that comes from the height of the station as well as the first term in Eq. (2). By substituting the first term of Eq. (2) by Eq. (3) the total effect on gravity from a unit mass point load on spherical distance  $\theta$  from the point of observation becomes

$$\Delta g_m(H, \bar{\theta}) = \frac{G}{R^2} \left[ t^2 \frac{1 - t \cos \theta}{(1 - 2t \cos \theta + t^2)^{3/2}} + \sum_{n=0}^{\infty} [2h'_n - (n+1)k'_n t^n] P_n(\cos \theta) \right] \quad (4)$$

where we have included the height dependence of the secondary gravity effect mediated by  $k'_n$ .



**Figure 2.** Geometry for the Newtonian effect at height

### 3. Practical approach

To evaluate Eq. (1) in practise, the midpoint method of numerical integration is used. With  $\Delta g_m(H, \bar{\theta})$  Eq. (1) becomes

$$\Delta g = \sum_{\text{sea\_surface\_grid}} \Delta g_m(H, \bar{\theta}_i) S_i A_i \rho \quad (5)$$

where  $S_i$  is the sea surface height (above normal) at discrete points forming a grid and  $A_i$  is the area of the  $i$ :th grid cell. The infinite summations in Eqs. (4) and (5) are impractical. Below we discuss how this limitation is handled and how it affects the result.

#### 3.1. Green's function for small $\theta$

We have decided to use precomputed load Love numbers for the PREM (Jentzsch, 1997) and Gutenberg-Bullen (Farrell, 1972) earth models respectively. They are given as a sparse set with respect to degree up to a maximum degree 10,000. Values for infinite degree have been derived by Farrell (1972) from the limiting case of a point load on a homogeneous half-space. In order to carry out the infinite sum of Eq. (4) the numbers were interpolated. The sums including the high-degree tail can be expressed analytically utilizing that

$$h_n \rightarrow h_\infty, nk_n \rightarrow k_\infty \quad (6)$$

In the Kummer transform employed by Farrell (1972) the sums

$$\sum_{n=0}^{\infty} (h_n - h_{\infty}) P_n(\cos \theta) \text{ and } \sum_{n=1}^{\infty} \frac{nk_n - k_{\infty}}{n} P_n(\cos \theta) \quad (7)$$

are truncated at  $n=10,000$ . If one, unlike Farrell, distinguishes between the Love numbers at  $N$  and their infinite limit, a Gibbs's like phenomenon shows up for small  $\theta$ . We have verified empirically that the truncation error does not yield significant errors for the stations treated in this paper.

### 3.2. Loading grid

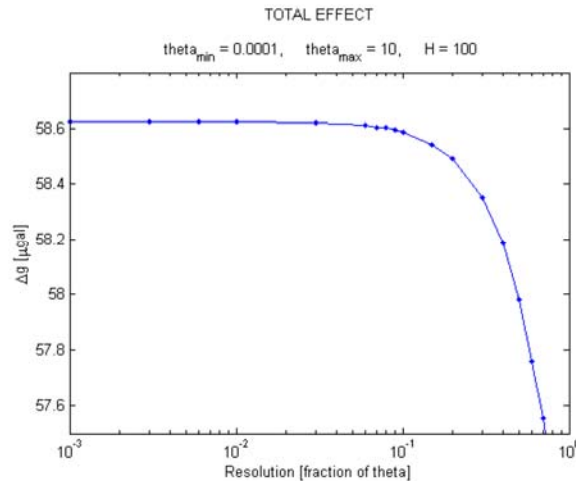
The surface load in Eq. (5) is represented by discrete values,  $S_i$ , in a grid. One important question is how dense the grid cells need to be to make the numerical integration sufficiently accurate. The resolution of the grid should be high enough to:

- avoid errors in the numerical integration
- represent the coastline accurate enough and
- represent variations in the load (sea level) accurately enough

We have found that these requirements are fulfilled by a grid with cell sizes that depends on the distance from the observation point  $\theta$ , as  $0.01 \cdot \theta$  in radial direction and  $0.02 \cdot \theta$  in azimuth. Below the choice of these numbers is discussed in more detail.

The distance from the observation point to the midpoint of the grid cell is crucial. If the resolution of the grid is too low, the resulting gravitational effect will be too low.

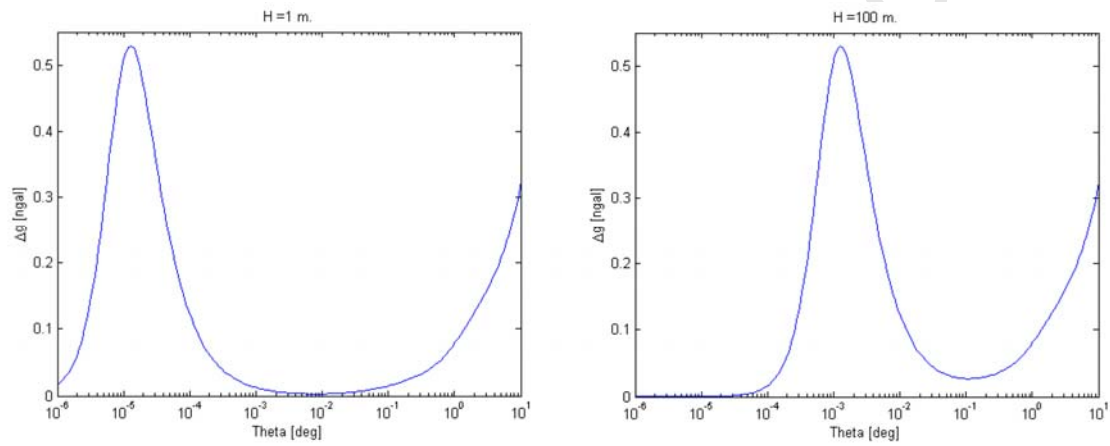
Figure 3 shows how the total effect (Eq. 4) from a load corresponding to one meter of water, distributed over a ring with inner radius  $0.0001^\circ$  and outer radius  $10^\circ$ , is affected by the radial resolution of the grid. This graph shows that a radial resolution higher than  $0.01 \cdot \theta$  does not improve the results on the  $0.01 \mu\text{gal}$  level. If the resolution is lower than  $\sim 0.08 \cdot \theta$ , the error introduced in the numerical integration will increase quickly.



**Figure 3.** The effect on gravity, from a load corresponding to one meter of water distributed over a ring reaching from  $0.0001$  to  $10$  degrees from the observation point, as a function of the grid resolution

Another important issue concerning grid resolution is the ability to represent the coastline in an appropriate way. For a station like Smögen (c.f. Section 4 below) situated 10 meters from the coast and 6 meters above MSL, about 70% of the total effect comes from water masses within a radius of 100 meters from the station. This indicates that a high resolution coastline is crucial. We have used a coastline provided by Lantmäteriet (the Swedish mapping, cadastre and registry authority) with an average accuracy of about one

meter. The method chosen for the numerical integration is the midpoint rule. On average the number of midpoints located on land (and thereby not included in the grid) but with some parts of its cell on the sea side of the coastline should be about the same as the number of cells with its midpoint in the sea but with some parts of its cell in land. Therefore the amount of water should in average be close to correct. Of course, there might happen to be some overweight of cells wrongly defined as “only water” or “only land” and the size of the cells and the amount of load they represent is important. Figure 4 shows how big part of the total effect one cell at a certain distance from the observation point represents. This is never more than 0.5 ngal (normally much smaller), indicating that you need an overweight of more than 200 cells either on land or in the sea to achieve an error of 0.1  $\mu\text{gal}$ . Figure 4 also indicates that a grid cell size that depends linearly on the distance from the observation point is reasonable, since the effect from a single grid cell close to the observation point is in the same range as one grid cell far from the observation point.



**Figure 4.** Contribution to  $\Delta g$  from one grid cell at distance  $\theta$  and with sides  $0.01\theta \times 0.02\theta$ .

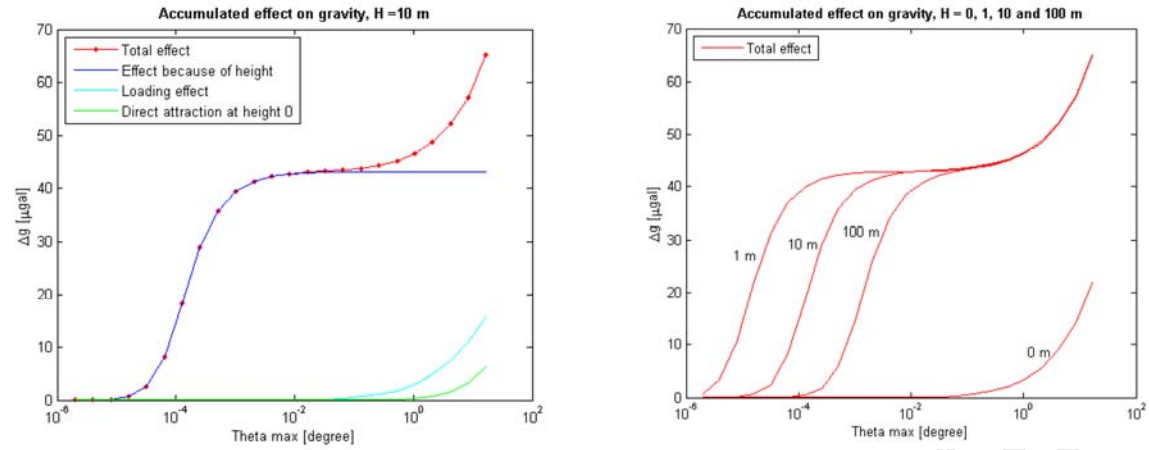
Finally it is important that the grid is dense enough to be able to describe the modelled sea level variations. With grid cell size  $0.01 \cdot \theta \times 0.02 \cdot \theta$  the sea level in the cells furthest away in the area of investigation (Figure 1) will be averaged over an area of about  $13 \times 26$  km which is sufficient considering the relative long wave nature of the modelling of sea level variations.

### 3.3. The dependence on height $H$

Figure 5 shows the accumulated effect on gravity for a theoretical case with a station surrounded by water from  $10^{-6}$  degrees ( $\theta_{\min}$ ) to  $\theta_{\max}$ . The load corresponds to one meter of water ( $\rho_{\text{water}} = 1030 \text{ kg/m}^3$ ) applied at MSL. The graphs show the accumulated effect on gravity for different station heights. The effect of the direct attraction from the water close to the station reaches  $\sim 43 \mu\text{gal}$ . The size of the area of influence depends on the station height. The major part of this effect is generated when

$$0.1H < \theta R < 10H$$

where  $H$  is the physical height of the station above MSL. By extending the upper limit to  $100H$  almost the whole effect is included. Within this area the resolution of the grid and the coastline is crucial (see Section 3.2 above).



**Figure 5.** The accumulated effect on gravity for a station at height  $H$  above sea level, surrounded by water from  $\theta_{\min} = 10^{-6}$  degrees to  $\theta_{\max}$ . The load corresponds to meter of water applied at MSL. To the left the total effect is separated in the direct attraction because of height, the direct attraction at height 0 and the loading effect. To the right is the total effect for four different station heights shown.

#### 4. Results

For twelve Swedish and one Finnish absolute gravity (AG) station (see Figure 1 and Table 1), the effects from the Baltic Sea and its transition to the North Sea (the blue area in Figure 1) have been calculated.

**Table 1.** Coordinates used (in most cases rough estimations (crucial for Smögen)).

Station	Latitude	Longitude	Height (RH2000)	Distance from coast [m]
Smögen	58.35354	11.21798	6	10
Kramfors	62.8755	17.9277	120	1 120
Onsala	57.3953	11.9255	6	170
Ratan	63.991	20.823	53	2 200
Visby	57.6539	18.3673	46	2 770
Skellefteå	64.8792	21.0483	55	1 360
Mårtsbo	60.5951	17.2585	44	7 380
Östersund	63.4428	14.8581	453	150 000
Metsähovi	60.2172	24.3958	56	16 400
Kiruna	67.8776	21.0602	466	154 000
Arjeplog	66.3180	18.1249	450	156 000
Lycksele	64.6276	18.6666	245	113 400
Gävle	60.6665	17.1314	14	2 720

For comparison, the effect from one meter of water all over the area is calculated and the results are presented in table 2. In column 2-8 load Love numbers from PREM (Jentzsch, 1997) were used and in column 9 load Love numbers from Gutenberg-Bullen earth model (Farrell, 1972) were used for comparison. The second column is the effect due to the direct attraction (Eq. 3) and the third is the direct attraction when the station is located on the sphere (at sea level) corresponding to the first term in Eq. (2). The fourth and fifth columns correspond to the  $h$ - and  $k$ -term term, respectively.

The Visby station, which is located on the Gotland Island in the Baltic Sea, shows the largest effects for all components of the total effect but for the direct attraction because of

the height (the second minus the third column). Here Smögen, Kramfors, Onsala and Ratan, which all are located closer to and/or at higher elevation have bigger numbers. In (Virtanen and Mäkinen, 2003) the effect at Metsähovi, from one meter water in the Baltic Sea, is calculated with the program package NLOADF (Agnew, 1997) and the Gutenberg-Bullen earth model. The result, 3.08  $\mu\text{gal}$ , can be compared with the corresponding result from Table 2, 3.41  $\mu\text{gal}$ . The lower value from (Virtanen and Mäkinen, 2003) may partly be due to the fact that they do not include any water west of the 13° meridian (c.f. Figure 1).

**Table 2.** Calculated effect is from a load corresponding to one meter of water all over the Baltic Sea and its transition to the North Sea (blue in Figure 1). Figures in  $\mu\text{gal}$  and based on PREM if nothing else is indicated.

Station	Direct attraction ( $g_N$ )	Direct attraction ( $H = 0$ )	Effect due to vertical displacement ( $g_u$ )	Effect due to mass redistribution ( $g_v$ )	Loading effect ( $g_u + g_v$ )	Vertical displacement [mm]	Total effect ( $g_N + g_u + g_v$ )	Total effect (GB earth model)
Smögen	<b>7.5938</b>	0.7138	4.2460	-1.0536	3.1924	13.76	<b>10.7862</b>	<b>10.8622</b>
Kramfors	1.6404	0.6349	3.3203	-0.8484	2.4719	10.76	4.1123	4.1818
Onsala	1.0330	0.7514	4.4121	-1.1095	3.3026	14.30	4.3355	4.4255
Ratan	0.8980	0.6322	3.5471	-0.9037	2.6435	11.49	3.5414	3.6428
Visby	1.2012	<b>0.9791</b>	<b>5.9706</b>	<b>-1.5588</b>	<b>4.4118</b>	<b>19.35</b>	5.6130	5.7707
Skellefteå	0.7233	0.5346	2.7565	-0.7041	2.0524	8.93	2.7757	2.8473
Mårtsbo	0.7729	0.7245	3.7022	-0.9444	2.7578	12.00	3.5307	3.6087
Östersund	0.4343	0.4203	1.4500	-0.3437	1.1063	4.70	1.5406	1.5500
Metsähovi	0.7253	0.6880	3.5099	-0.9031	2.6068	11.37	3.3321	3.4102
Kiruna	0.2670	0.2628	0.7127	-0.1666	0.5462	2.31	0.8132	0.8160
Arjeplog	0.3329	0.3248	1.0042	-0.2381	0.7661	3.25	1.0991	1.1057
Lycksele	0.4585	0.4422	1.7562	-0.4415	1.3146	5.69	1.7731	1.7992
Gävle	0.7312	0.7113	3.6028	-0.9172	2.6856	11.67	3.4168	3.4903

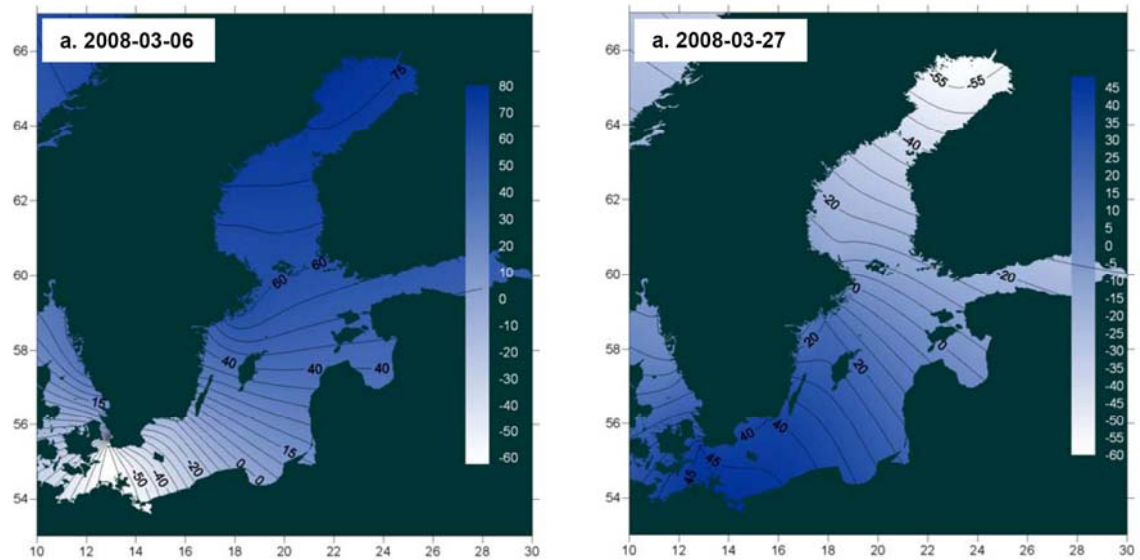
A load corresponding to one meter of water all over the Baltic Sea is quite unrealistic (but half a meter is not). In Table 3 the effect from three more realistic sea level situations is presented. The second and third columns are calculated from a sea surface interpolated from Swedish tide gauge data (Figure 1) for two different days in March 2008. In the first case (2008-03-06) the wind is coming from south-west causing a sea surface tilt from north to south and in the second case (2008-03-27) the situation is the opposite (Figure 6). Because of lack of tide gauge data from other countries only Swedish tide gauges are used in these first calculations. Nevertheless this case clearly demonstrates a typical behaviour of the Baltic Sea, and the results indicate the magnitude of the effect in a realistic case.

**Table 3.** Total effect on gravity from two realistic sea level situations for the Baltic Sea (Figure 6). The last column in shows the effect on gravity caused by the secular apparent water decrease due to the post glacial rebound (Figure 1). Figures in  $\mu\text{gal}$  and based on PREM if nothing else indicated.



Station	2008-03-06	2008-03-27	$\dot{g}$ [ $\mu\text{gal/year}$ ]
Smögen	3.3374	0.2696	-0.0377
Kramfors	2.5170	-0.7547	-0.0346
Onsala	0.8550	0.5662	-0.0104
Ratan	2.2671	-1.0270	-0.0309
Visby	1.9536	0.9285	-0.0164
Skellefteå	1.7901	-0.8920	-0.0243
Mårtsbo	1.7442	-0.1525	-0.0209
Östersund	0.7384	-0.1342	-0.0110
Metsähovi	1.6140	-0.2712	-0.0147
Kiruna	0.3993	-0.1140	-0.0058
Arjeplog	0.5607	-0.1704	-0.0086
Lycksele	0.9884	-0.3394	-0.0138
Gävle	1.6861	-0.1536	-0.0204

The last column in table 3 shows the effect on gravity caused by the secular apparent water decrease due to the post glacial rebound (Figure 1). In GIA modelling the quantity  $\dot{g} / \dot{h}$  contains information about the viscoelastic properties of the upper mantle (Ekman and Mäkinen, 1996).



**Figure 6.** Interpolated sea surface topography from Swedish tide gauge data 2008-03-06 (a) and 2008-03-27 (b).

## 5. Conclusions

The effects from the Baltic Sea on gravity have been numerically investigated for twelve Swedish and one Finnish absolute gravity stations. The method used is the one described by Farrell (1972) complemented with the effect from the direct attraction of water masses close to the station. For stations that have a ratio of coast distance to height less than 100 and where the direct attraction is an important contribution to the total effect, the resolution of the grid and the coastline is of greatest importance.

The total effect have been calculated for one theoretical case with a homogenous one meter sea level rise and for two more realistic cases based on tide gauge observations from Swedish tide gauges. These tests show that the non tidal effect on gravity from the



Baltic Sea is significant for AG-measurements in the Nordic Absolute Gravity Project and should be corrected for.

Most of the AG-stations in the Nordic Absolute Gravity Project are collocated with permanent GPS and each station will, in the long run, contribute with an estimation of  $\dot{g}/\dot{h}$ . This number is  $\sim 0.20 \mu\text{gal mm}^{-1} \pm$  a few hundreds of  $\mu\text{gal mm}^{-1}$  and is interesting for GIA modelling purposes. For a station like Smögen, with  $\dot{g} \approx 0.04 \mu\text{gal yr}^{-1}$  and  $\dot{h} \approx 4 \text{ mm yr}^{-1}$ , the contribution to this number from the secular water decrease is  $\sim 0.01 \mu\text{gal mm}^{-1}$  which is significant for the unknown part of  $\dot{g}/\dot{h}$ . Considering loads at short distance angles and stations with significant slant angles to these loads will continue to engage us in improvement of the computation schemes. The situation also calls for an extension of the load Love number sets to much higher harmonic degree.

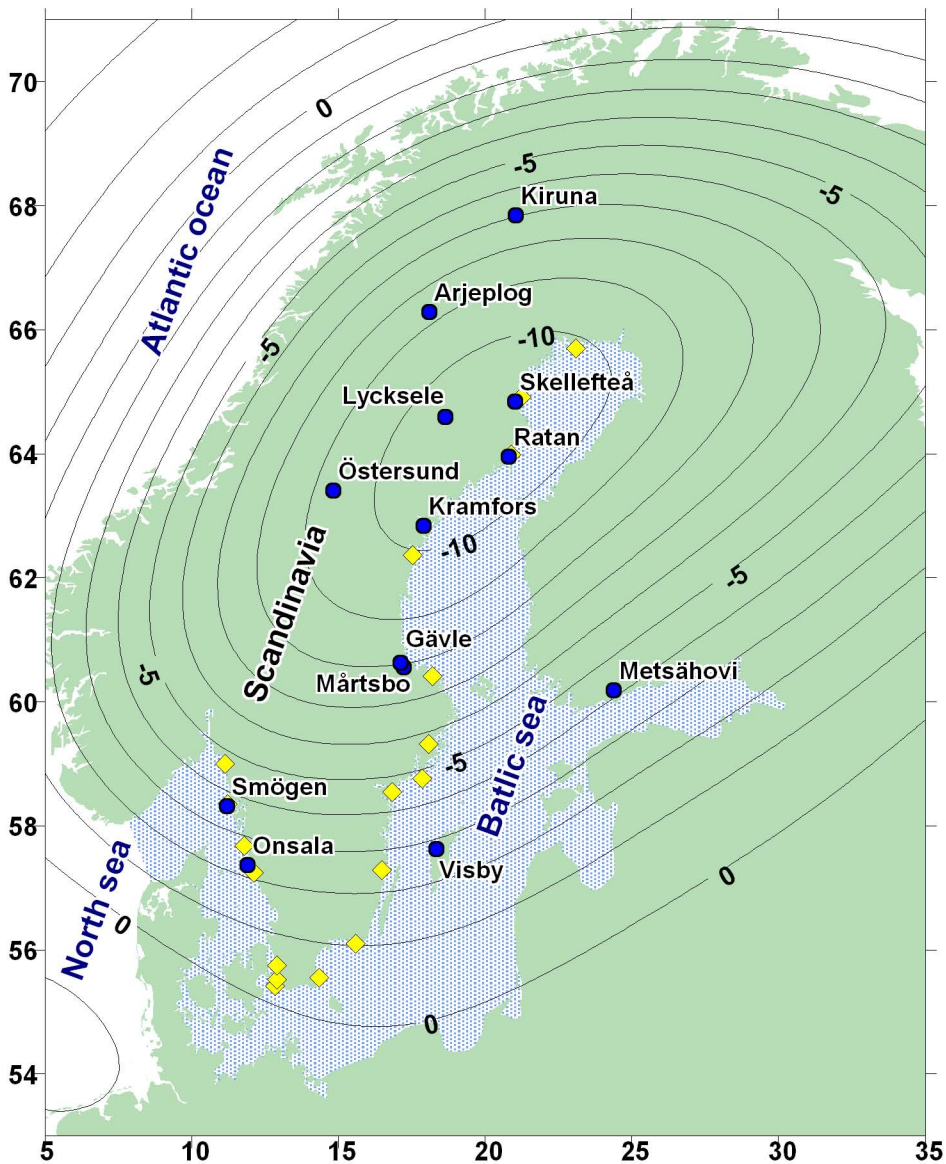
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Observation point

Earth surface

Load point

$H$

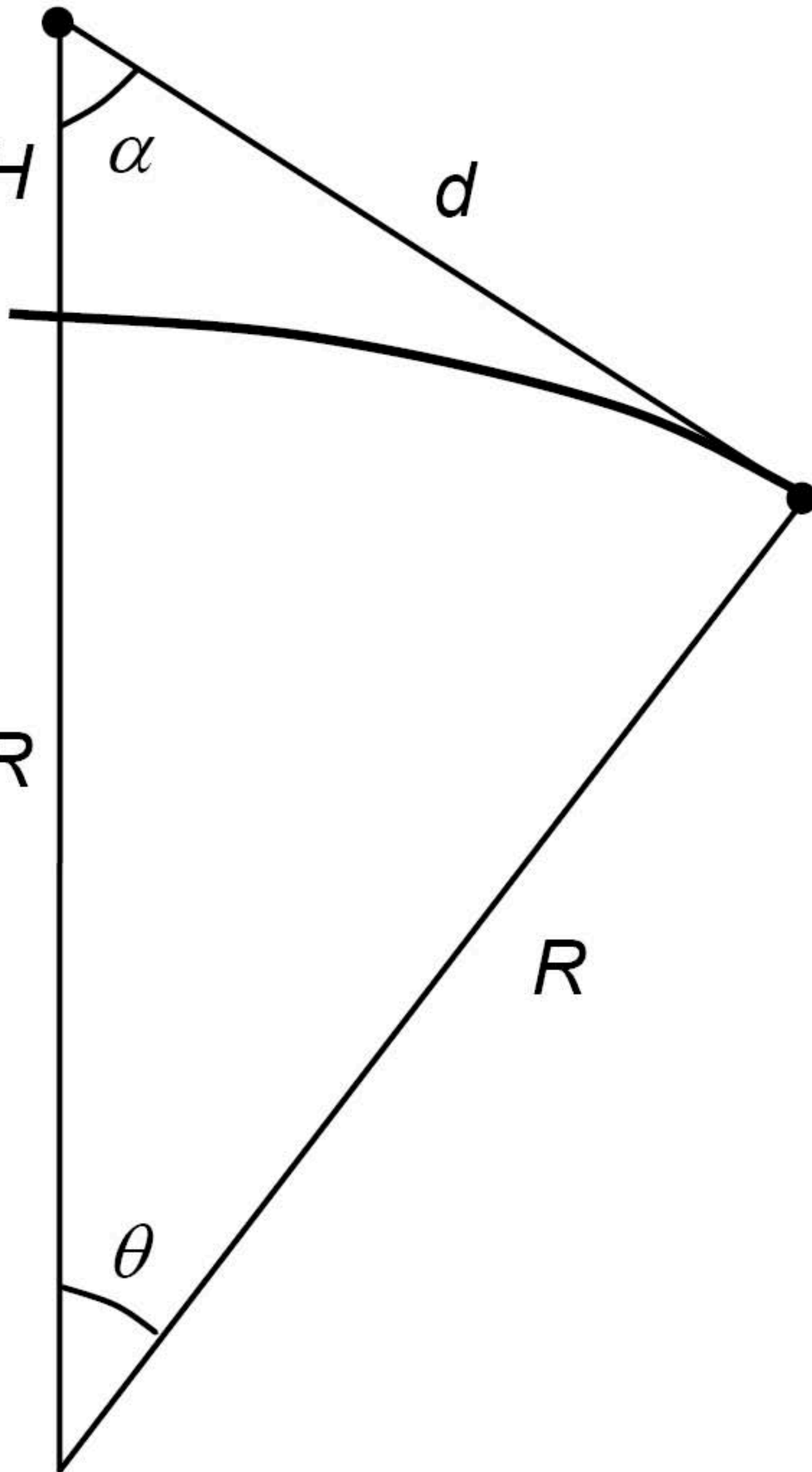
$\alpha$

$d$

$R$

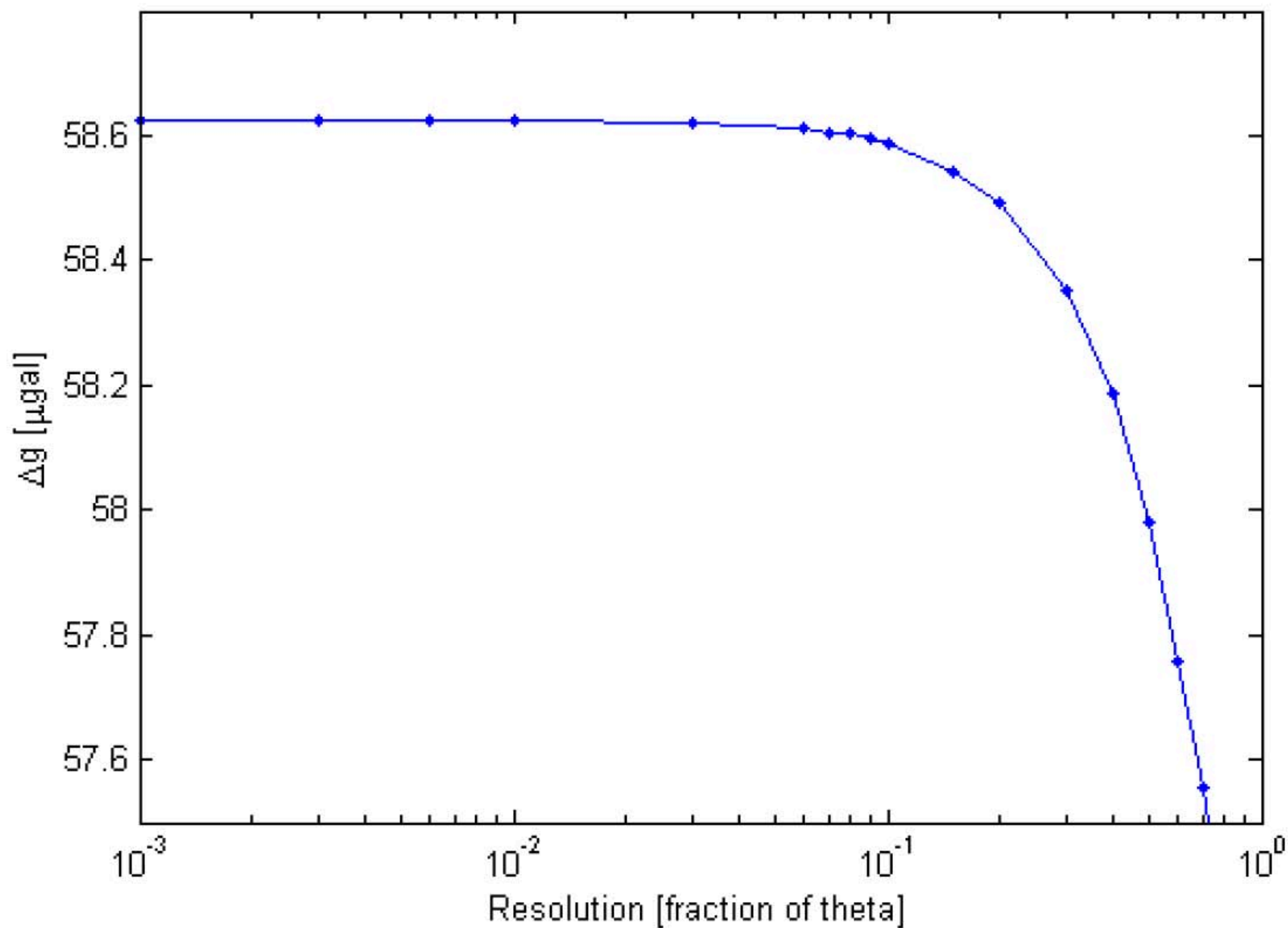
$R$

$\theta$

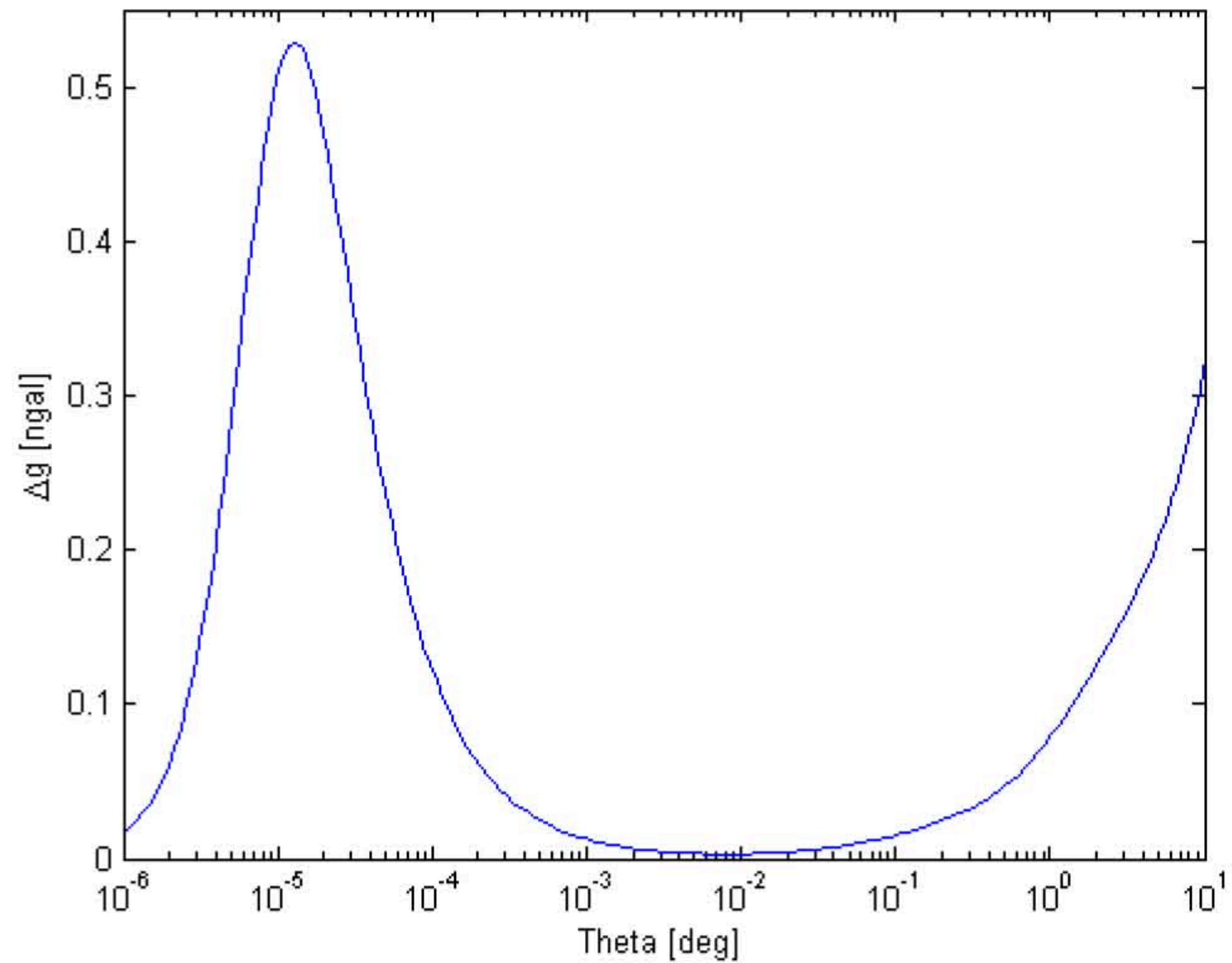


# TOTAL EFFECT

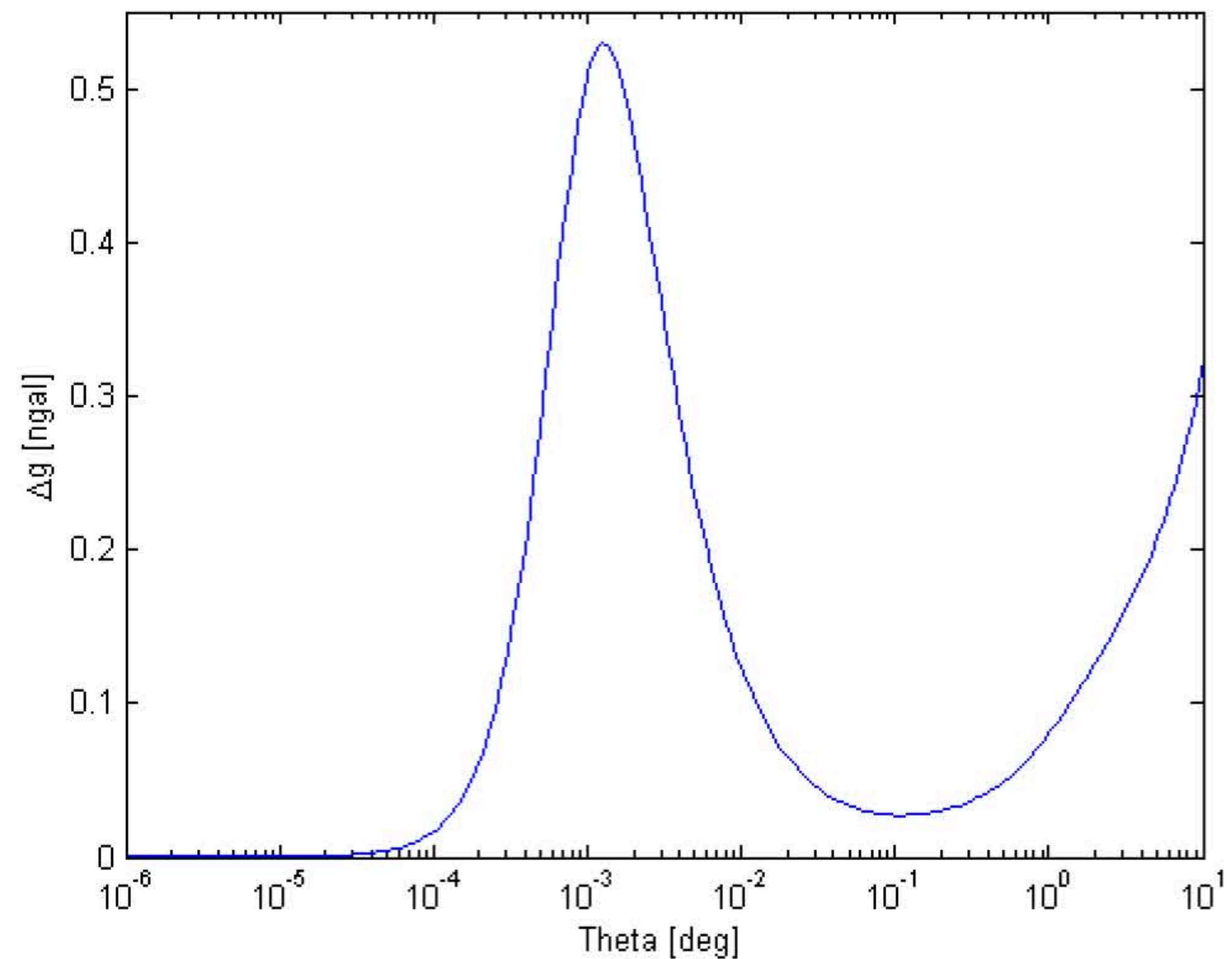
$\theta_{\min} = 0.0001$ ,  $\theta_{\max} = 10$ ,  $H = 100$



H=1 m.

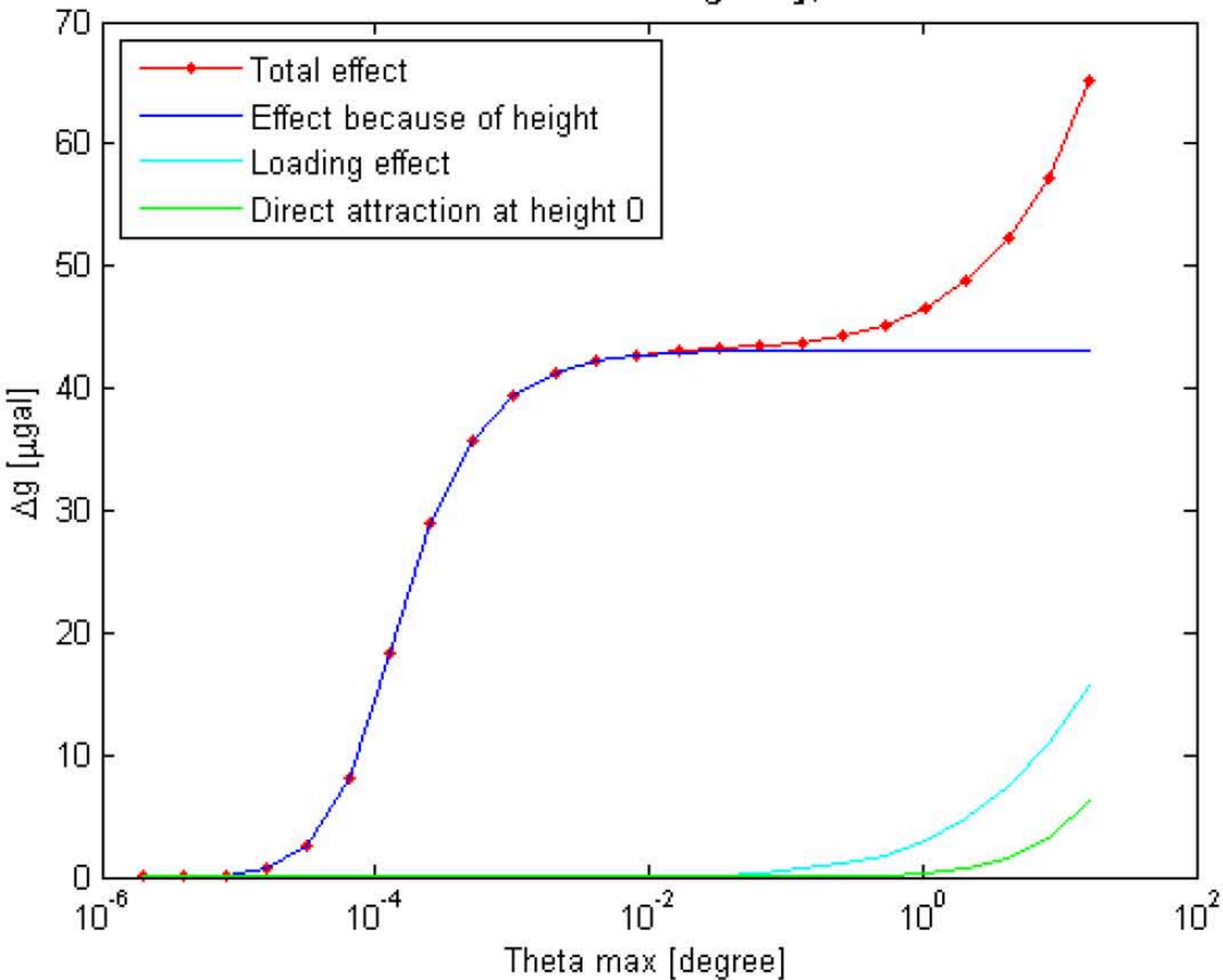


H=100 m.

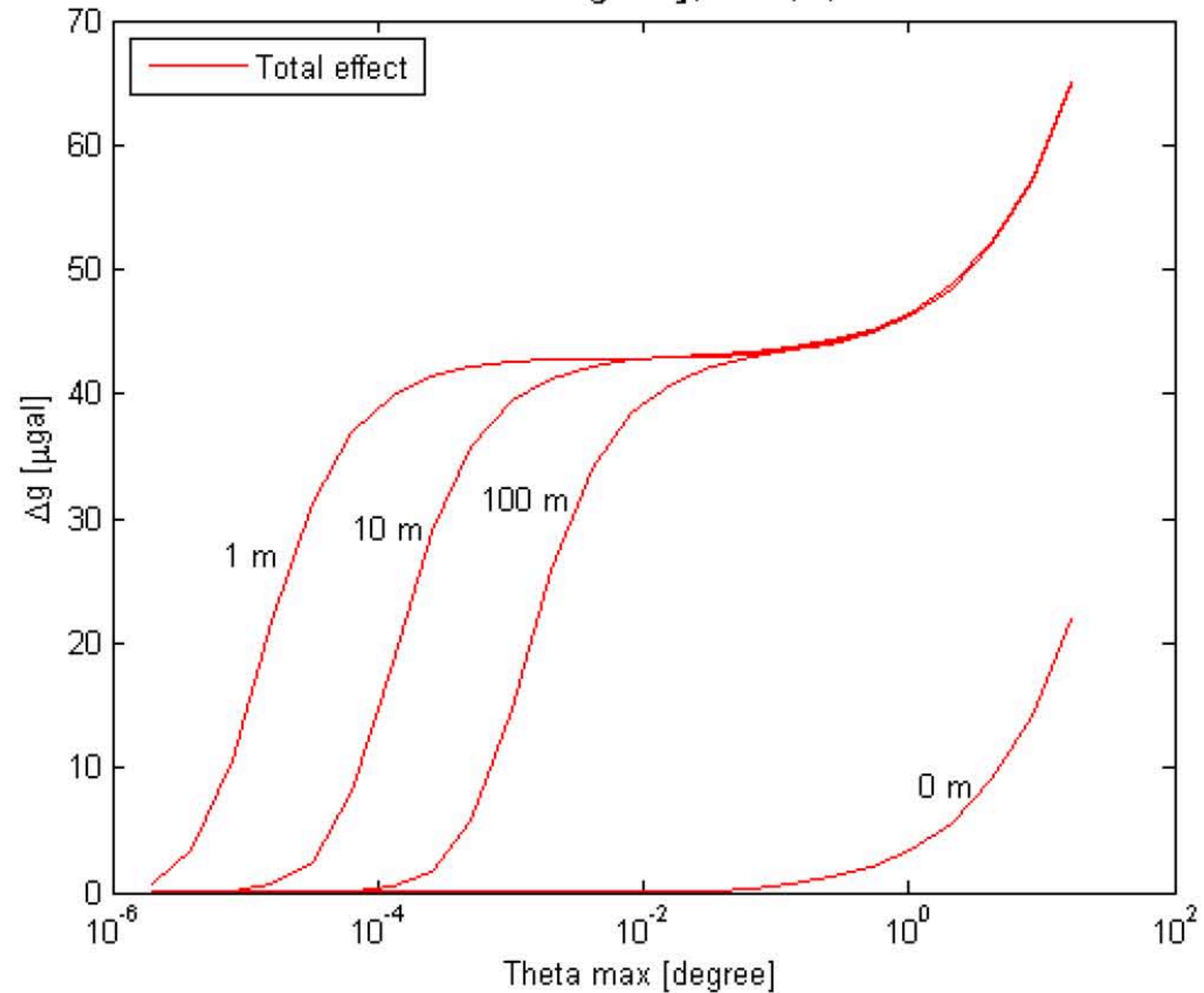




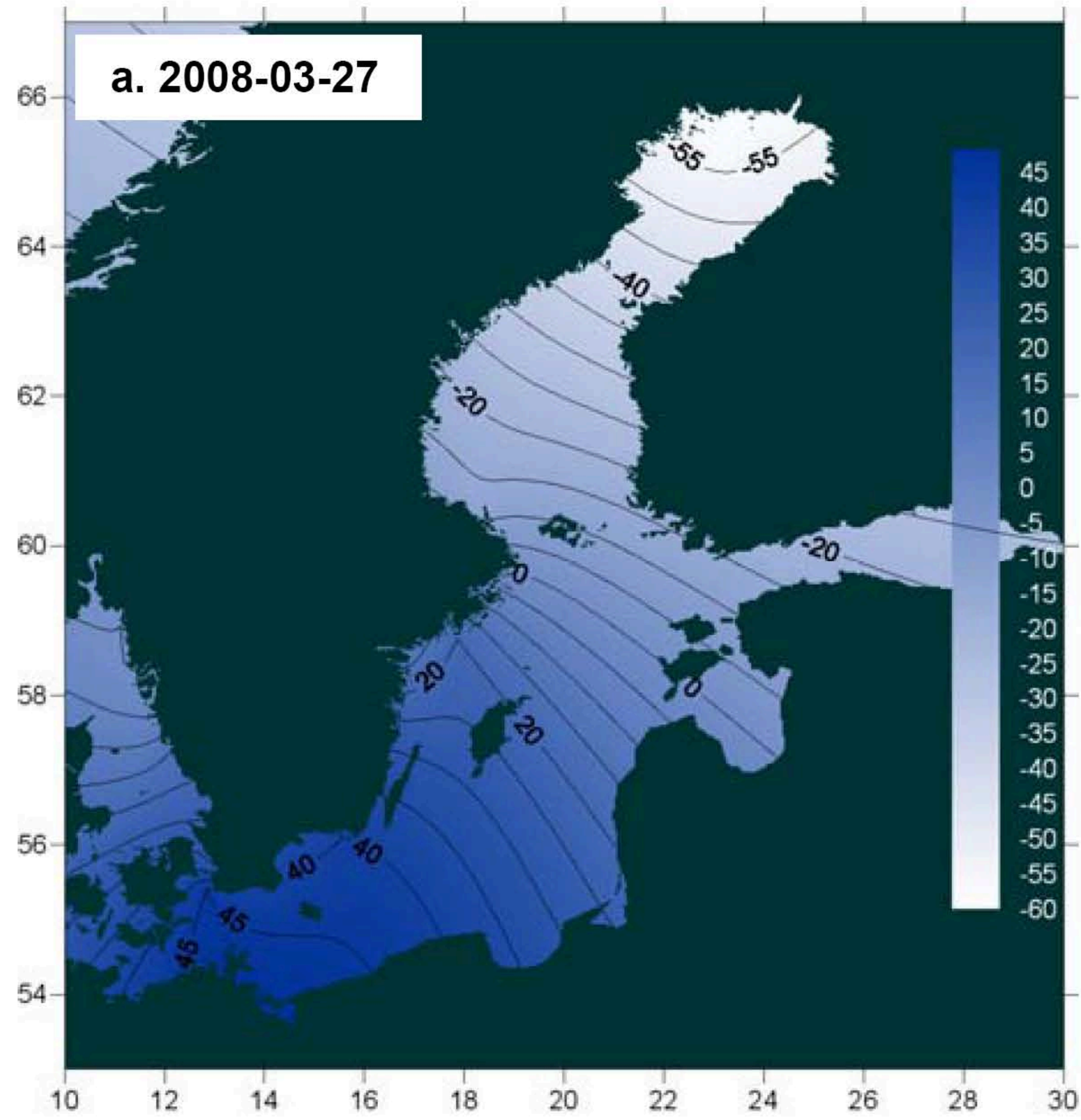
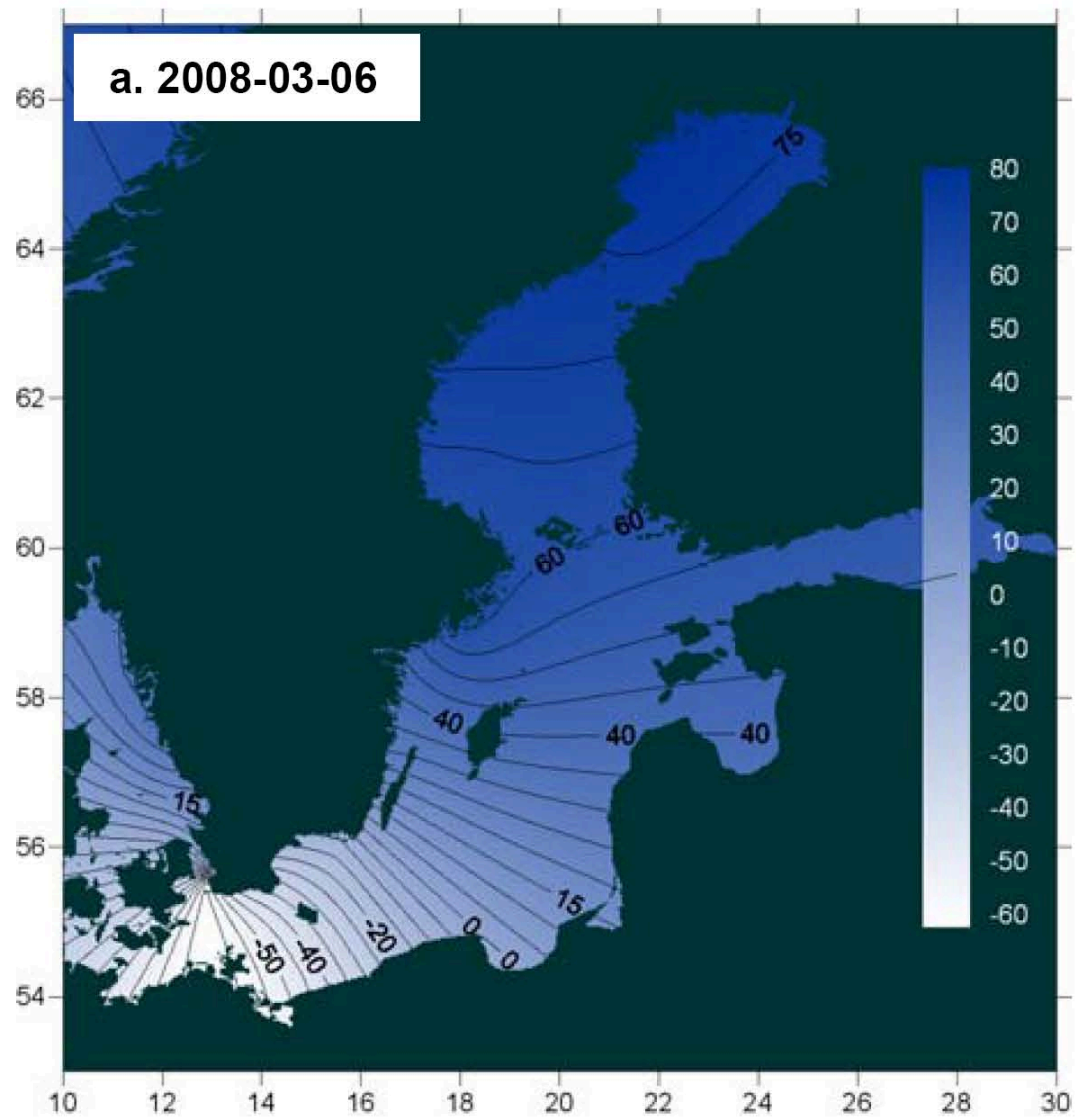
Accumulated effect on gravity, H = 10 m



Accumulated effect on gravity, H = 0, 1, 10 and 100 m









Station	Latitude	Longitude	Height (RH2000)	Distance from coast [m]
Smögen	58.35354	11.21798	6	10
Kramfors	62.8755	17.9277	120	1 120
Onsala	57.3953	11.9255	6	170
Ratan	63.991	20.823	53	2 200
Visby	57.6539	18.3673	46	2 770
Skellefteå	64.8792	21.0483	55	1 360
Mårtsbo	60.5951	17.2585	44	7 380
Östersund	63.4428	14.8581	453	150 000
Metsähovi	60.2172	24.3958	56	16 400
Kiruna	67.8776	21.0602	466	154 000
Arjeplog	66.3180	18.1249	450	156 000
Lycksele	64.6276	18.6666	245	113 400
Gävle	60.6665	17.1314	14	2 720



Station	Direct attraction (g <sub>N</sub> )	Direct attraction (H = 0)	Effect due to vertical displacement (g <sub>u</sub> )	Effect due to mass redistribution (g <sub>v</sub> )	Loading effect (g <sub>u</sub> +g <sub>v</sub> )	Vertical displacement [mm]	Total effect (g <sub>N</sub> +g <sub>u</sub> +g <sub>v</sub> )	Total effect (GB earth model)
Smögen	<b>7.5938</b>	0.7138	4.2460	-1.0536	3.1924	13.76	<b>10.7862</b>	<b>10.8622</b>
Kramfors	1.6404	0.6349	3.3203	-0.8484	2.4719	10.76	4.1123	4.1818
Onsala	1.0330	0.7514	4.4121	-1.1095	3.3026	14.30	4.3355	4.4255
Ratan	0.8980	0.6322	3.5471	-0.9037	2.6435	11.49	3.5414	3.6428
Visby	1.2012	<b>0.9791</b>	<b>5.9706</b>	<b>-1.5588</b>	<b>4.4118</b>	<b>19.35</b>	5.6130	5.7707
Skellefteå	0.7233	0.5346	2.7565	-0.7041	2.0524	8.93	2.7757	2.8473
Mårtsbo	0.7729	0.7245	3.7022	-0.9444	2.7578	12.00	3.5307	3.6087
Östersund	0.4343	0.4203	1.4500	-0.3437	1.1063	4.70	1.5406	1.5500
Metsähovi	0.7253	0.6880	3.5099	-0.9031	2.6068	11.37	3.3321	3.4102
Kiruna	0.2670	0.2628	0.7127	-0.1666	0.5462	2.31	0.8132	0.8160
Arjeplog	0.3329	0.3248	1.0042	-0.2381	0.7661	3.25	1.0991	1.1057
Lycksele	0.4585	0.4422	1.7562	-0.4415	1.3146	5.69	1.7731	1.7992
Gävle	0.7312	0.7113	3.6028	-0.9172	2.6856	11.67	3.4168	3.4903



Station	2008-03-06	2008-03-27	$\dot{g}$ [μgal/year]
Smögen	3.3374	0.2696	-0.0377
Kramfors	2.5170	-0.7547	-0.0346
Onsala	0.8550	0.5662	-0.0104
Ratan	2.2671	-1.0270	-0.0309
Visby	1.9536	0.9285	-0.0164
Skellefteå	1.7901	-0.8920	-0.0243
Mårtsbo	1.7442	-0.1525	-0.0209
Östersund	0.7384	-0.1342	-0.0110
Metsähovi	1.6140	-0.2712	-0.0147
Kiruna	0.3993	-0.1140	-0.0058
Arjeplog	0.5607	-0.1704	-0.0086
Lycksele	0.9884	-0.3394	-0.0138
Gävle	1.6861	-0.1536	-0.0204