The Difference between the N60 and BK77 Height Systems

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Abstract: *This paper investigates the difference between the Finnish height datum N60 and the 1977 Baltic height system (BK77). The method used is comparison of the gravimetric and geometric geoid heights. It is important to determine the difference since there is still no precise levelling connection between the two countries. Finding the correct epoch for BK77 is a little problematic; some investigations made are described in this paper. All the new gravimetric data digitised over the last few years were used in the gravimetric geoid calculation, along with 110,000 points from north Estonia (measured by the Geological Survey of Estonia) and data from the area embracing Lake Peipsi and the adjoining parts of Russia. Also aerogravimetric measurements above the Gulf of Finland were used. The gravimetric geoid calculation method employed was remove-restore with FFT. The new gravimetric data contributed to getting a gravimetric geoid surface that was more precise. About 27 GPS-levelling points from Estonia and Finland were used for determining the difference between the height systems. The GPS points were taken from the first order net with precise orthometric, or normal, heights. Normal/orthometric heights were corrected for land uplift. A very small tilt could be observed between the gravimetric and the geometric geoid. The results showed that the difference between the geoids is similar in both Finland and Estonia, which means that the difference between the height systems is small, about 3 cm.*

Keywords: *height datum, geoid heights, height system difference*

1 Introduction

The connection between the Finnish and Estonian height networks attracts attention from several aspects. For quite some time already, there has been interest in connecting the so-called Baltic Ring. As the mainland connection through Russia has not yet been completed (published), the marine connection has provided a possibility for determining the difference between the zeros of the height datums of the two countries. The subject has been addressed by Jaakko Mäkinen and others (Mäkinen *et al.* 2002). In this article, the connection between the datums has been determined using the gravimetric geoid and GPS-levelling points only. The gravimetric geoid is calculated from gravity anomalies, the geometric one is based on GPS measurements and levelling. In the gravimetric geoid calculations we have additionally used gravimetric data from the Geological Survey of Estonia and 110,000 gravimetric points from north Estonia and Hiiumaa Island, among others. Geoid precision, in its turn, affects the precision of the levelling networks connection.

Calculation method

In this article we tried to determine the difference between the height systems based on differences between the gravimetric and the geometric geoids. The geometric geoid heights were calculated from the difference between measured geodetic heights and levelled normal, or orthometric, heights. We can derive the difference between the zeros of the height systems from the comparison of the geometric and the gravimetric geoids. If there is no tilt between the two geoid heights, the differences are the same in Estonia and in Finland and, assumedly, there are no differences between the height systems. The levelled heights were recalculated to epoch 1997, which is also the epoch for the GPS measurements. Consequently, the precision of the results depended primarily on the precision of the gravimetric geoid and the corrections made to the orthometric and normal heights.

2 Description of the height systems

So far the 1977 Baltic height system, with its height catalogues dating from 1975-1977 (the Estonian Land Board archives), has continued to be in use as the official system in Estonia. The catalogues were in force in the period of the Soviet Union, and still are in the Republic of Estonia, since no new system has been taken into use. The general rule in the previous period was that the old law applied until a new one was introduced. The Minister of The Environment's draft regulation "The Establishment of the Geodetic System of the Republic of Estonia" (to be adopted in 2004) confirms the data given in Table 1, stating that the epoch cannot be identified and noting that the 1977 Baltic height system has been implemented on Estonian territory by the Soviet Union's levelling network benchmarks and their normal heights.

Table 1 presents the main data about the height systems N60 and BK77.

Table 1. *Basic Data about the Height Systems (Mäkinen et al. 2002)*

System	N60	BK77
Reference Tide Gauge	Helsinki	Kronstadt
Mean sea level year	1944	1833
System epoch	1960	1970*
Heights	Orthometric	Normal
Tidal system	Mean	Mean

**In Tamm 1995. The epoch is valid for Estonia if a small tilt correction is used.*

Aado Tamm (Estonian Agricultural University) has concluded from a comparison of different levelling data that the heights of BK77 can be converted to epoch 1970 using a small tilt correction (Tamm 1995; actually concerning the 1984 catalogue; however, it also applies to the 1977 catalogues, as the heights in these catalogues are the same in spite of newer height differences). This means that the 1977 catalogue values are tilted compared to epoch 1970. A. Tamm's investigation is mainly based on a comparison of the adjusted catalogue values and the raw data from the I order levelling line Narva-Tallinn-Ikla-Riga (levelled in 1970). The tilt correction is 2 cm per 100 km almost exactly in the east-west direction (the real bearing being about 110°). The tilt correction shall be applied to the catalogue values based on the Põltsamaa benchmark, being negative (Table 3) for points to the west of Põltsamaa. After applying the tilt correction, we get BK77 values for epoch 1970. It seems that the abovementioned tilt correction may not be precisely valid for the islands of Hiiumaa and Saaremaa (Tamm 1995 and 1992). Nevertheless, we used the same correction for all Estonia in this paper.

The GPS-levelling points selected

The positions of the points selected are given in Figure 3. Eighteen points from Estonia and ten from Finland were used. The Estonian points were selected mainly from areas covered by dense gravity data (Figure 1). GPS-measurements of the Estonian points were performed in 1997. They belong to the I and II order GPS net, which is called the fundamental geodetic network. Their height precisions are declared to be identical, 1 cm (Rüdja 2002a). ITRF96 coordinates from epoch 1997.56 were transformed to the ETRS89 system (Rüdja 2002b).

GPS measurements of the Finnish points have been performed in 1996-1997. Ultimately, the coordinates were transformed to the ETRF89 system, epoch 1997.0 (Ollikainen *et al.* 2000). Table 2 presents the types of the Finnish points.

Table 2. *Types of the Finnish GPS points*

ID	Type
Metsähovi	Permanent GPS station
Tuorla	Permanent GPS station
Virolahti	Permanent GPS station
Degerby	Tide gauge
Helsinki	Tide gauge
Hanko	Tide gauge
Härkäpää	Triangulation point
Kymi	Triangulation point
Karhunoja	Triangulation point

The GPS coordinates from both countries are therefore given in the ETRS89 system. Consequently, we provided no separate correction for converting the GPS-measurements into the same system. Furthermore, we did not apply any correction to normal and orthometric heights, since it is insignificant here. The orthometric and geodetic heights of the Finnish points were taken from Ollikainen *et al.* (2000). The normal heights of the Estonian points were levelled in 1998 using I order levelling (Torim *et al.* 1998). The values of the fixed benchmarks were taken from the 1975-1977 catalogues (the Estonian Land Board archives). The geodetic heights were taken from the adjustment report of the GPS campaign (Rüdja and Lainevool 1998).

3 Conversion of the GPS-levelling points into the same epoch

For the Finnish and Estonian levelled heights to be usable they first needed to be converted into the same epoch. For Estonian points, a tilt correction was first applied to normal heights to convert the catalogue values to epoch 1970. The correction depended on the distance from the fundamental benchmark at Põltsamaa; it was calculated using the distance along the *y* (east-west) axis. The correction value was 2 cm per 100 km. Põltsamaa is situated in the middle of Estonia, where the relative land uplift is zero.

The main problem in the process was the calculation of the land uplift correction. In Estonia, it amounts to 2.5 mm per year relative to the mean sea level and in the region of Finland under study to 2-5 mm per year. If the measurements are performed in different epochs then the geometric geoid heights are directly dependent on the land uplift correction. As the land uplift correction differs from point to point, the points are subject to different corrections. Ekman’s model to calculate the land uplift correction map relative to the mean sea level (U_1) was employed. Then the heights were improved by the sea level eustatic uplift correction and the geoid rise correction. Accordingly, the land uplift relative to the

Earth's centre of mass, U_2, was expressed as follows:

$$U_2 = 1.06U_1 + U_e, \tag{1}$$

where U_e is the eustatic rise in the mean sea level (1.2 mm/yr) and 1.06 is the geoid rise correction (Ekman and Mäkinen 1998). The values for U_1 were taken from Ekman's model (Ekman 1996), calculated by Jaakko Mäkinen from the digital version (values for points 6481, 6477, 6454 were determined manually from the map).

Table 3 gives the point heights and the land uplift corrections for the levelled heights. Normal and orthometric heights were converted into epoch 1997 applying the correction U_2 from (1). Accordingly, we adjusted the levelled heights by a 27-year land uplift correction for Estonia and a 37-year correction for Finland, resulting in corrected heights H_c

$$H_c = H_{epoch} + U_2 \tag{2}$$

It is assumed that the geodetic heights of the Estonian and Finnish points belong to the same system and epoch. The numerical values for the corrections are given in Table 3.

4 Gravimetric geoid

The gravimetric geoid was calculated by the remove-restore method using the global model EGM96 and local gravimetric data taken from between 57˚ – 63˚ N. and 19˚ – 29˚ E., which served as the calculation (integration) area. In total, about 150,000 points were included in the calculation, including 110,000 points (measured by the Estonian Geological Survey) from north Estonia (Figure 1). Consequently, gravimetric data from north Estonia, Lake Peipsi-Pihkva and some parts of Russia were added (Figure 1) compared to the NKG2002 geoid gravimetric database. The high-density data from north Estonia considerably improved the geoid quality in the region. The software package Gravsoft (Tscherning *et al.* 1992) was used, and the same principle as in the NKG2002 geoid calculation was mainly applied. Due to the relatively small heights in the calculation area, we did not use any digital terrain data to take account of the effect of topography on the geoid heights.

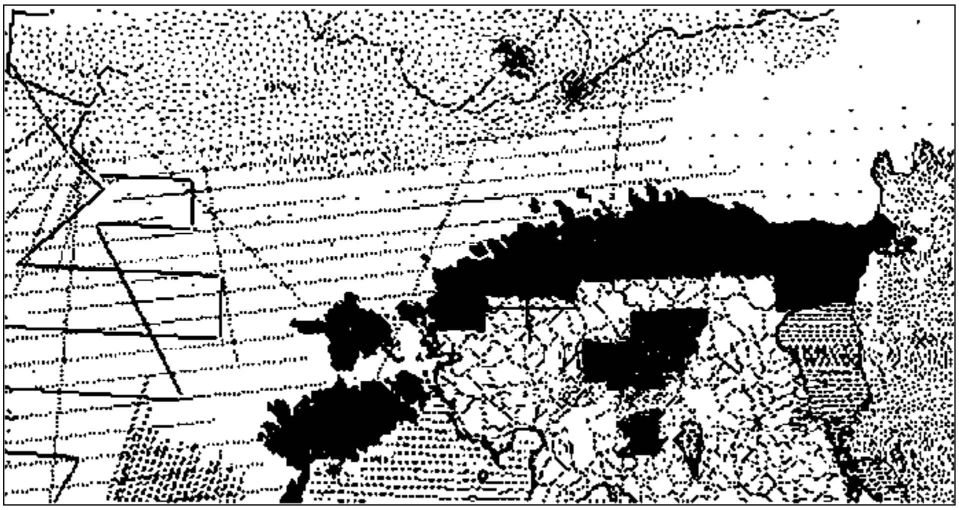

Figure 1. *Gravimetric data coverage close to Gulf of Finland*

The gravimetric geoid is simpler to use for determining the difference between height systems if there is no tilt between the geometric and the gravimetric geoid. The tilt is often there due to long wave errors of global models and other circumstances. In our case, the tilt was nearly nonexistent thanks to the high density and quality of the local gravimetric data (Figures 1 and 3). Expanding the area included in the gravimetric geoid calculation did not cause any change in the tilt between the two geoids in the test area. A problem was the lack of gravimetric data from the eastern part of the Gulf of Finland, which had an influence most of all on point Virolahti in Finland. It is noteworthy that the rapid increase in geoid heights from east to west was limited to the Gulf of Finland (Figure 2).

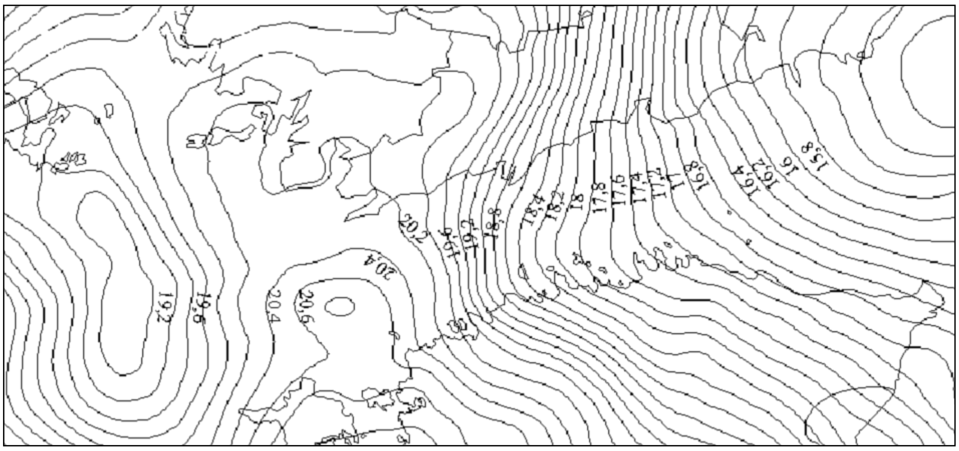

Figure 2. *Gravimetric geoid heights (m)*

5 Calculation of geoid differences between Finland and Estonia

5.1 GPS levelling points

The number of suitable points in Estonia and Finland was very limited and insufficient, particularly in south Finland. While there are high-precision GPS points available, not all of them are provided with precise levelled heights. We did not choose points from further north, since the gravimetric geoid may get distorted in the peripheral regions of the calculations. The Estonian points chosen are located fairly evenly across the northern part of Estonia. These are selected mainly from areas covered by the dense network of gravimetric data measured by the Geological Survey of Estonia, thus expecting to get more precise geoid heights from the region. The Finnish point at Virolahti, situated in the eastern part of the Gulf of Finland, however, run quite counter to the expectation. In this regard, it has to be taken into account that no gravimetric data are available from this region of the Gulf of Finland (Figure 1). The aerogravimetric measurements in 1999 failed to reach that region due to political reasons. This, in turn, led to an error in the gravimetric geoid, which apparently was reflected in the results herein. Virolahti was therefore ignored in the mean difference calculation. A total of 18 points from Estonia and 9 from Finland were included. In the east-west direction, both countries were almost entirely covered with the points. In the north-south direction, the points covered Finland for 130 km and Estonia for 80 km.

The geoid differences in north Estonia were very homogeneous. The mean difference was -60.8 cm (Table 3, geometric minus gravimetric geoid height). The minimal difference was -58.7 cm on Point 6386. Greater differences appeared on points 6494 and 6267 (-65 cm on both). Points 6494 and 6267 revealed a greater difference even when viewing Estonia as a whole (Jürgenson 2003). The median was -60.3. The Hiiumaa normal heights may contain a slight error since they were transferred from the mainland by means of hydrostatic levelling. Furthermore, that region may not belong to precisely the same epoch as the mainland area, as mentioned above.

In Finland, the mean difference was -63.6 cm. It also appeared that two westerly points in Finland, Hanko and Degerby, had a greater difference, -69.1 cm and -70.4 cm, respectively. The difference was the smallest on the point of Hevosoja (-59.8 cm). The value of median was -62.7 cm.

Geoid differences between two countries were most homogeneous when viewing the environs of Helsinki and Tallinn. Nevertheless, it appeared that there was no systematic tilt between the geoids from east to west (Figure 3).

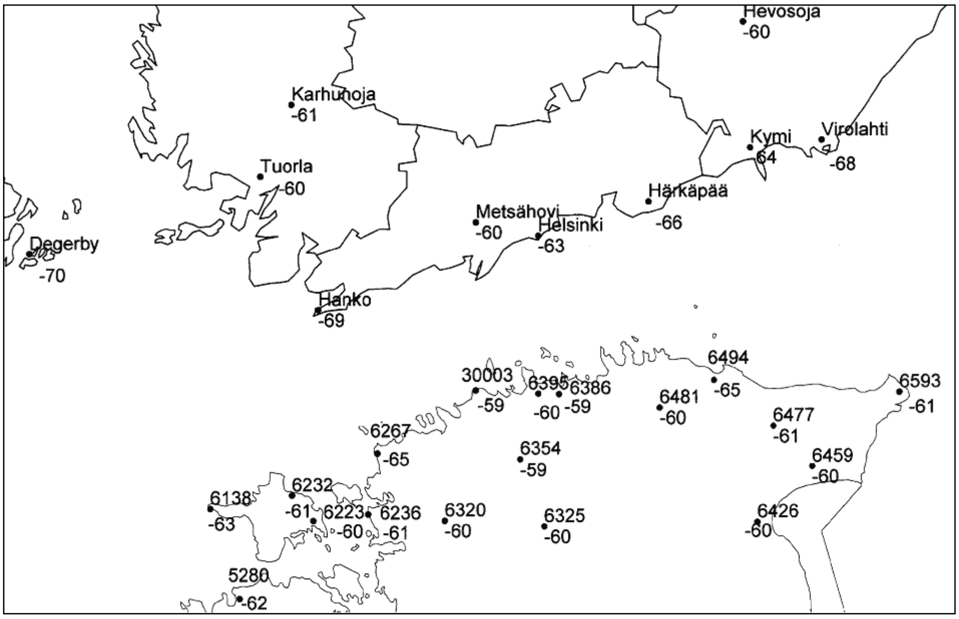

Figure 3. *Differences ΔN between gravimetric and geometric geoids (cm, geometric minus gravimetric)*

Figures 4 and 5 depict the dependence of Δ*N* on the east longitude. No statistically reliable tilt could be observed either in Estonia or in Finland. In Finland, also the less reliable point Virolahti (longitude 27.5˚, not presented here) produces the same result (-68 cm) as the westerly points Degerby and Hanko.

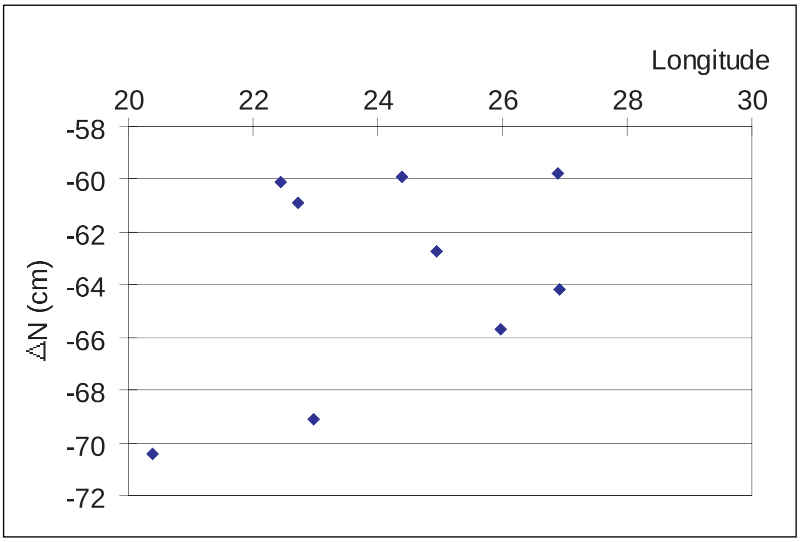

***Figure 4**.* ΔN *from west to east in Finland*

Table 3. *GPS-levelling points, land uplift rates, corrections and geoid differences*

Point ID	B°	L°	h	H N60	Distance from Põltsamaa, km	Tilt correction to ep.1970	U_1	U_2	Total U_2 1960 - 1997, m	Hc epoch 1997, m	Geometric geoid m	Gravimetric geoid m	Geoid difference ΔN cm
Finland			m	m			mm/y	mm/y					
Metsähovi	60.217470	24.395315	94.568	75.655			2.8	4.3	0.158	75.813	18.755	19.354	-59.9
Tuorla	60.415847	22.443419	60.552	40.825			4.2	5.7	0.210	41.035	19.517	20.118	-60.1
Degerby	60.031347	20.384467	21.642	2.687			4.5	6.0	0.223	2.910	18.732	19.436	-70.4
Helsinki	60.153676	24.956732	24.157	6.346			2.5	3.9	0.146	6.492	17.665	18.292	-62.7
Hanko	59.822677	22.976510	24.842	5.031			3.1	4.5	0.168	5.199	19.643	20.334	-69.1
Härkäpää	60.295832	25.958795	51.343	35.10			2.2	3.6	0.134	35.234	16.109	16.766	-65.7
Kymi	60.521074	26.907157	71.214	55.95			2.1	3.5	0.130	56.080	15.134	15.776	-64.2
Karhunoja	60.742366	22.712534	122.321	103.02			4.5	6.0	0.223	103.243	19.078	19.687	-60.9
Hevosoja	61.085464	26.894780	152.200	136.25			2.6	4.0	0.148	136.398	15.802	16.4001	-59.8
												Mean	-63.6
Virolahti*	60.538799	27.554991	36.922	22.028			1.9	3.3	0.121	22.149	14.773	15.452	-67.9
Estonia				H BK77		m			1970 - 1997				
6494	59.485741	26.495165	66.201	49.364	27	0.005	1.3	2.7	0.072	49.441	16.760	17.405	-64.5
6267	59.181774	23.514431	24.529	4.585	-142	-0.028	2.3	3.7	0.101	4.658	19.871	20.521	-65.0
6386	59.442794	25.117712	56.119	38.337	-51	-0.010	2.0	3.4	0.091	38.418	17.701	18.288	-58.7
6395	59.446430	24.933961	53.942	36.000	-62	-0.012	2.1	3.5	0.093	36.081	17.861	18.456	-59.5
6138	58.920518	22.065272	25.742	5.925	-226	-0.045	2.4	3.8	0.102	5.982	19.760	20.391	-63.1
6232	58.989332	22.770057	29.567	9.251	-185	-0.037	2.3	3.7	0.100	9.314	20.253	20.859	-60.6
6236	58.908530	23.436924	26.452	6.039	-147	-0.029	2.1	3.5	0.093	6.103	20.349	20.959	-61.0
6223	58.876898	22.959019	33.074	12.687	-175	-0.035	2.1	3.5	0.095	12.747	20.327	20.927	-60.0
6593	59.388594	28.121655	43.361	27.167	119	0.024	0.3	1.6	0.044	27.235	16.126	16.737	-61.1
30003	59.463900	24.382200	61.770	43.316	-93	-0.019	2.3	3.7	0.100	43.397	18.373	18.959	-58.6
6481	59.370846	26.001956	106.74	89.301	-1	0.000	1.4	2.8	0.076	89.376	17.364	17.964	-60.0
6354	59.153832	24.766374	79.048	59.824	-71	-0.014	2.0	3.4	0.092	59.902	19.146	19.736	-58.9
6477	59.269041	26.998873	69.548	52.552	56	0.011	0.5	1.8	0.049	52.612	16.936	17.548	-61.2
6320	58.880383	24.088595	44.509	24.332	-109	-0.022	2.0	3.4	0.092	24.402	20.107	20.703	-59.6
6325	58.850786	24.969154	91.581	72.007	-59	-0.012	1.4	2.8	0.076	72.071	19.510	20.106	-59.6
6459	59.079858	27.316833	74.983	57.794	75	0.015	0.4	1.7	0.046	57.855	17.128	17.732	-60.4
5280	58.521097	22.335184	26.807	6.423	-212	-0.042	1.9	3.3	0.089	6.470	20.337	20.958	-62.1
6426	58.840800	26.820619	75.183	57.168	48	0.010	0.5	1.8	0.049	57.226	17.957	18.560	-60.3
												Mean	-60.8

* Virolahti was not included in the mean value calculations due to a lack of gravimetric data from that region.

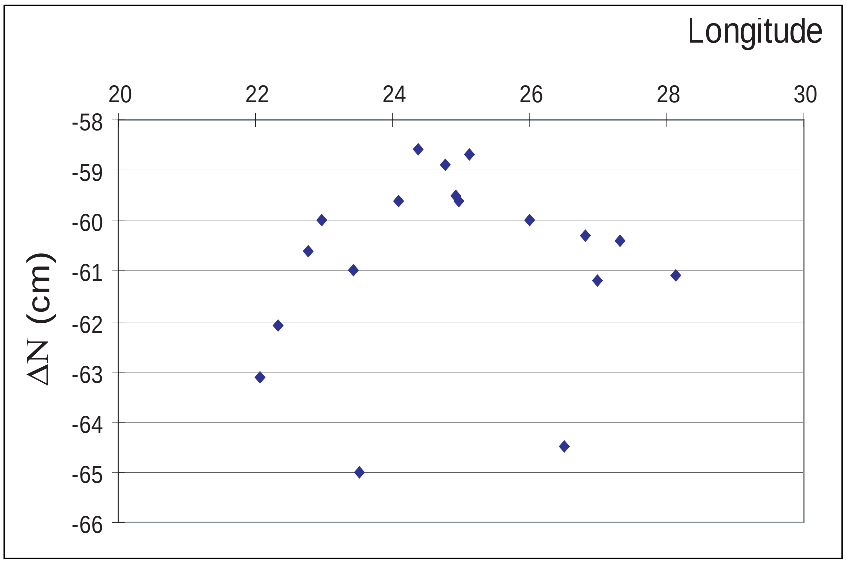

Figure 5. ΔN *from west to east in Estonia*

Figures 6, 7 and 8 present the residuals of geoid differences when only the mean was removed. The residuals were calculated separately in Estonia and Finland using the mean values -60.8 and -63.6 cm, respectively. It can be seen that the residuals are very small, particularly those in Estonia.

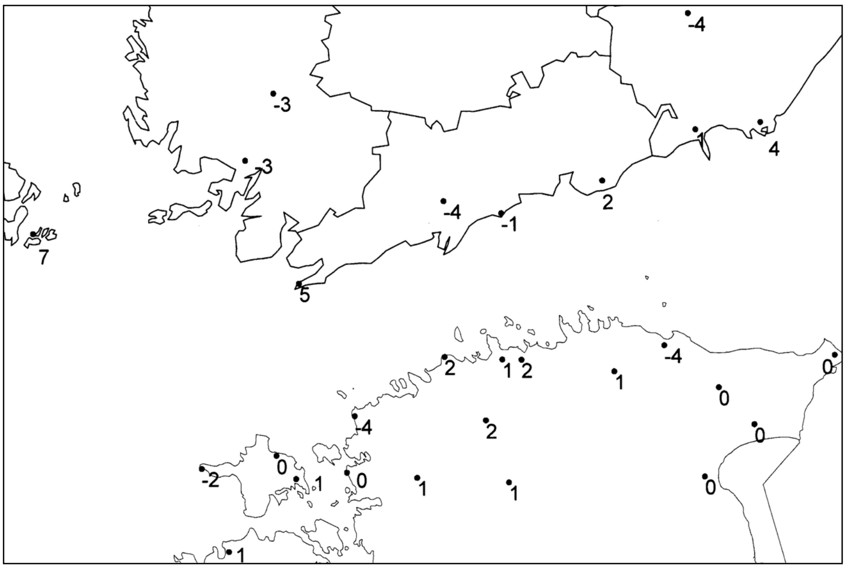

Figure 6. *Residuals (cm) of geoid differences. The mean is removed separately in Estonia and Finland using the mean values of* ΔN *from Table 3.*

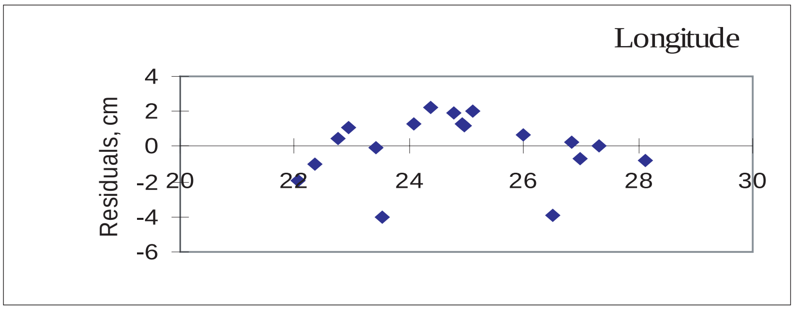

Figure 7. *Geoid difference (ΔN) residuals plot for the Estonian points*

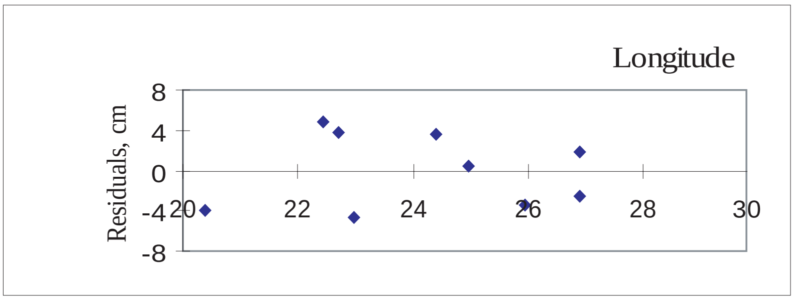

Figure 8. *Geoid difference (ΔN) residuals plot for the Finnish points*

5.2 Calculation of the height system differences

Two procedures were used to compare the geoid differences Δ*N* between Estonia and Finland. The first was simply comparing the means; the second was calculating the geoid differences using the covariance analysis with dummy variable. The dummy variable was the country while the other variable was dependence on the east longitude.

Calculation of the difference ΔN using the means:

The mean ΔN value for Finland was –63.64 cm and the standard error was 1.34 cm. The mean ΔN value for Estonia was –60.79 cm and the standard error was 0.43 cm. Judging from the geoid differences ΔN, the difference between the height systems was small or, more precisely,

$$\Delta N_{FIN} - \Delta N_{EST} = -63.64 - (-60.79) = -2.9 \text{ cm}$$

The standard error of the differences can be calculated from the standard errors of the means:

$$\sqrt{1.34^2 + 0.43^2} = 1.41 \text{ cm}$$

Calculation of the difference ΔN using the covariance analysis:

We can calculate the difference ΔN using covariance analysis. Then all the points are included in the same calculation. The dependent variable is "ΔN difference", the first predictor variable is "longitude" and the second predictor variable is a dummy variable "country" (Finland = 1; Estonia = 0). The magnitude of the dummy variable represents the height difference between the two countries. Naturally, we have to simultaneously assume that the slope in both countries is the same.

The difference of levels (dummy variable) in Finland and Estonia was -2.6 cm at the standard error ±1.1 cm. The probability (P-value) of the dummy variable was 0.027, which means that the significance level was 97% (the confidence level was over 95%).

Comparison of the results:
The height system differences were based on the following data:
-2.9 cm ±1.4 cm (calculated from the means) and
-2.6 cm ±1.1 cm (calculated using covariance analysis).

The recalculation of an N60 height into a BK77 height therefore requires the following formula:

$$H_{N60} \text{->} H_{BK77} = \Delta T + (1970\text{-}1960)\ U_2 \qquad (3)$$

where ΔT is the difference between the height systems and 1970-1960 is the difference between the epochs in years. The units are given in meters.

$$H_{BK77} = H_{N60} + \Delta T + (1970\text{-}1960)\ U_2 \qquad (4)$$

$$H_{BK77} = H_{N60} + (-0.03) + 10\ U_2 \qquad (5)$$

5.3 Comparison with other results

When evaluating in very simplified terms the difference between the height systems based on the sea surface topography, the difference should be 4 cm, which is equivalent to the sea surface topography (SST) difference between Kronstadt and Helsinki (Ekman and Mäkinen 1996). In Kronstadt, the sea surface is higher; hence the zero of BK77 is higher than that of N60. Furthermore, according to Aado Tamm's personal comment, the connection between Kronstadt and the mainland established in 1969 (Tamm 1992) was not very precise either (Aado Tamm participated in the measurements). Also, levelling into Estonia entailed further errors. Consequently, the SST difference -4 cm differs from the values -2.9 cm ±1.4 cm and -2.6 cm ±1.1 cm calculated herein. Taking account of standard errors, we can say that the results coincide at the 1 cm level.

6 Conclusions

It appears from the differences between the gravimetric and the geometric geoid that the difference between the two height systems is small, namely -2.9 cm ±1.4 cm when calculated from the means, or -2.6 cm ±1.1 cm when calculated using covariance analysis. It may be inferred that the N60 heights in Finland are higher than the BK77 heights in Estonia, i.e. they are referred to an equipotential surface that is lower by -2.9 cm ±1.4 cm. An analogous result is obtained from the sea surface topography.

The method employed herein cannot be used to establish the height system difference with a 1-cm precision due to errors in the geoid and in the heights. Naturally, the precision of the results is dependent on the precision of the land uplift corrections. When points with more precisely measured geoid height became available from the region, future investigation will be necessary.

Acknowledgements

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