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GEOID PROFILES IN THE BALTIC SEA DETERMINED USING GPS AND SEA LEVEL SURFACE

Harli Jürgenson[1], Aive Liibusk[2], Artu Ellmann[3]

[1, 2] *Dept of Geomatics, Estonian University of Life Sciences,*
Kreutzwaldi 5, 51014 Tartu, Estonia
E-mail: [1] harli.jyrgenson@emu.ee
[3] *Faculty of Civil Engineering, Tallinn University of Technology,*
Ehitajate tee 5, 19086 Tallin, Estonia
E-mail: Artu.Ellman@ttu.ee

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Abstract. The idea was to compare the geoid of sea areas by an independent method, like GPS levelling, on the mainland. On the earth surface we can compare the gravimetric geoid with GPS levelling to get an accuracy estimation and tilt information. On the sea we can do it by the GPS methodology and eliminating the current water tilt corrections and the sea surface topography effect. A modern GPS device on board a ferry can store data every second and determine heights with an accuracy of a few centimetres (using the kinematic method with the post-processing of data obtained from several base stations close to the ferry line). As a result, it is possible to observe the current water level's relative profile in reference to the ellipsoid. Some areas close to Estonia, such as the eastern part of the Gulf of Finland, are not completely covered by gravity measurements. The Baltic Sea has been measured using airborne gravimetry with the accuracy of about 2 mGal. Therefore, the gravimetric geoid is not fully reliable for the region either. If we take into account the tilt of the water level at the moment of measurement, we can observe the relative change of the geoid using an independent methodology, which serves as a comparison to the gravimetric geoid solution. The main problem during the measurement campaign, of course, was how to eliminate a water tilt. Water placement in relation to level surface is a very complex issue; special studies of that were conducted as well.

Keywords: geoid precision, GPS survey, sea level.

1. Introduction

There are local geoid models derived by A. Ellmann (2004) and H. Jürgenson (2003) as well, but model NKG04 was chosen due to fact of bigger area covered. The gravimetric geoid NKG04 (Forsberg *et al.* 2004) was derived by KMS using all the gravimetric data available from the region. Unfortunately, the data set does not originate from one and the same time period, the coverage is not homogeneous, and the quality varies from region to region. We used GPS-measurements and ferries on regular lines to cover areas on the Baltic Sea (Fig. 1). One such an area lies about 30 km north of the island of Hiiumaa, where the geoid has a "lump": the separation of the geoid from the ellipsoid changes by 1 meter over a 70-km distance starting from Paldiski; further towards Sweden the original separation is restored. In addition, we analyzed all the Estonian and Swedish profiles, using GPS data from Swedish base stations as well.

We also performed the same kind of measurements on ferries running a regular line between Tallinn and St. Petersburg. Those measurements were of particular interest as there was no gravimetric data available for the eastern part of the Gulf of Finland (Jürgenson 2003).

As a third track, measurements were performed on liners running between Sillamäe and Kotka. The good coverage of GPS permanent base stations made the measurements easier. The main hurdle to negotiate during the campaign was how to eliminate a water tilt.

2. Method

A GPS receiver was placed on a ferry and measurements were performed using the kinematic technology (or real-time kinematics). The GPS receiver stores the position and the height every second. Post-processing was performed by several base stations located closest to the measured line. The GPS receiver was placed on the open deck of the ferry (Fig. 2) and was static during the measuring period. GPS receivers Trimble 5700 and 5800 were used. We only wanted to determine the relative change of sea level surface, to the disregard of the absolute height from sea level. In some instances, two GPS receivers were used simultaneously on a ferry (Sillamäe–Kotka ferry line). The aim was to determine more details about ferry movements.

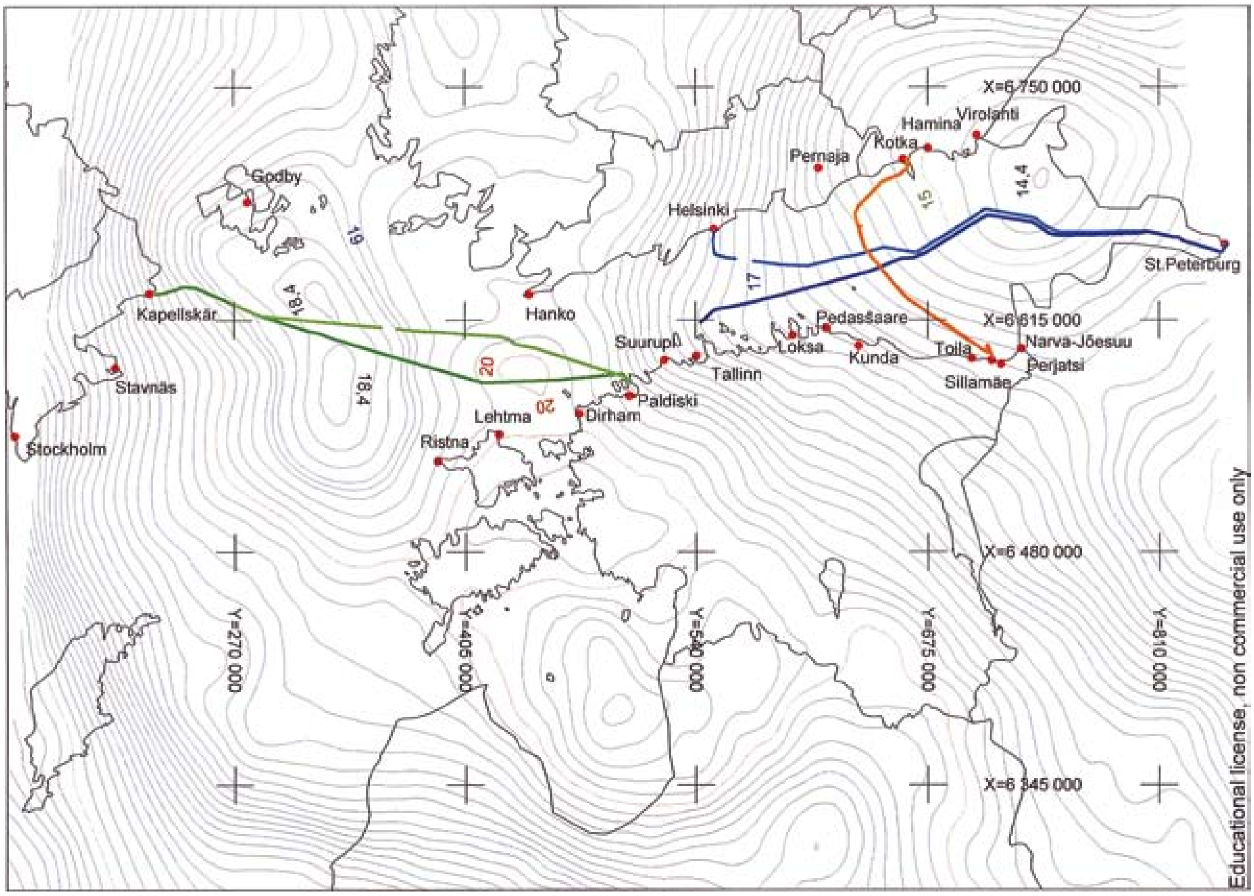

Fig. 1. Tracks measured using GPS on ferry. Background is Geoid Model NKG04; contour interval is 0.2 m (500.000 m corresponds to longitude 24°)

Fig. 2. GPS Trimble 5700 on board

During the measurements, the current water level heights were obtained from the closest tide gauges for water tilt estimation. After a comparison, the water tilt correction was added. The wave effect was eliminated using the trend line of real stored points. Usually, GPS data was stored every second, which was enough for a trend line. One second corresponds to a distance of about 8 m.

Estonian tide gauges provide water levels relative to the Baltic height system (BK77) and Finnish ones relative to the mean sea level. The mean sea level values from tide gauges were recalculated into the N60 height system to eliminate the land uplift effect. The formula presented by the Finnish Institute of Marine Research (http://www.fimr.fi) was used.

The Finnish N60 height system differs from the BK77 system by about 3 cm (Jürgenson, Kall 2004). Furthermore, Estonia's (northwest region's) height benchmarks have been affected by a relative land uplift of about 6 cm over 30 years. However, the Estonian tide gauges used in the campaign were mostly situated in a region with a similar extent of land uplift. Hence, all the water level heights (as well as the heights from Sweden) were computed to the Baltic height system BK77 before they were used (Ekman 1992).

The sea surface topography is small in the tested regions, about 4 cm between Tallinn and St. Petersburg and probably 10 cm between Paldiski and Stockholm (Ekman, Mäkinen 1996; Poutanen, Kakkuri 1999). As the measuring lines were mostly shorter, the topographic influence was considered insignificant and not taken into account here.

The accuracy of GPS measurements is a few cm depending on the actual atmospheric conditions, the number of satellites and the PDOP as well as the vector length (for example, 1 ppm makes 4 cm per 40 km). The number of satellites in particular was likely to pose problems due to the long distances from the base stations. Planning the timing of the measurements was difficult as we were dependent on the ferry schedules. Taking also into account the water tilt elimination problems, the determined level surface accuracy, according to our estimation, was 5–15 cm. Yet this method was for estimating the geoid; actual geoid changes are usually 10 times greater along the measuring profile. There was a special interest in areas for which gravimetric data were missing or had serious quality problems.

3. Test measurements

The first measurements took place on 29–30 June in 2004 between Paldiski and Kapellskär. The method was tested in areas of faster geoid changes. One of the areas lies about 30 km to the north of the island of Hiiumaa (North-West Estonia). The area is especially interesting because the geoid surface is placed a little higher compared to the surrounding area (Fig. 3). Continuous RTK measurements were performed on board ferries running the regular line between Paldiski, Estonia, and Kapellskär, Sweden. Two base stations were used for RTK (Dirhami and Tahkuna) in order to ensure that the baseline length does not exceed 35 km. A GSM connection was used to transmit RTK corrections. The westernmost part of the line was measured using the kinematic method with post-processing from the Hiiumaa base station. Ferry speed was 30 km/h, thus half the distance (70 km) was measured during less than 3 hours. The storing interval of the GPS measurements was 1 or 2 seconds. Trimble 5700 GPS devices were used. The RTK fixed solution was obtained during the measurements. Wind speed was mostly less than 6 km/h. The ferry's up-and-down movement was normally less than 20 cm (Fig. 4; the scale of the figure is a little distorted as only the east or north component was used).

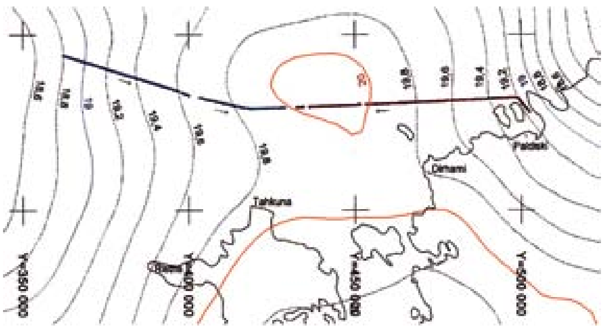

Fig. 3. GPS measurement on ferry to determine relative geoid change. Background is the gravimetric geoid KG04 with a contour line interval of 0.2 m

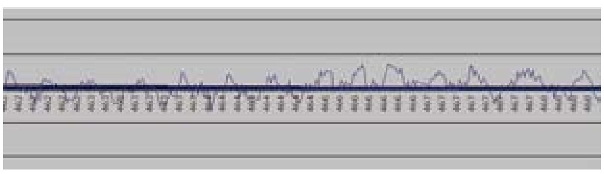

Fig. 4. Typical up and down movement of the ferry. The vertical axis shows lines with a 10-cm interval and the horizontal axis shows km-s; the storing interval was 1 second

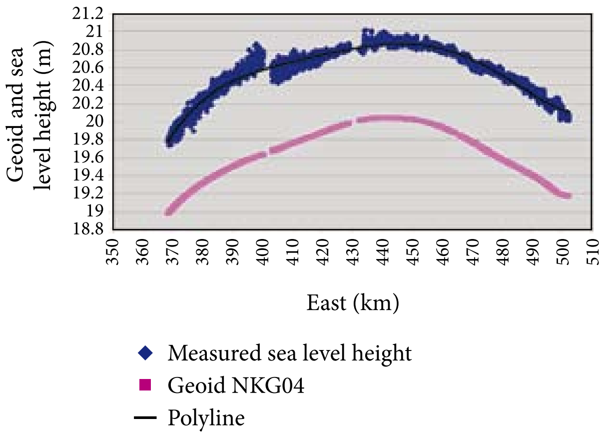

Fig. 5. Water level relative heights by kinematic GPS between 370 and 502 km along the East coordinate (500 km corresponds to longitude 24°)

The tide gauge data did not show any remarkable changes in water level during the measurements (less than 3 cm). However, that day's water level at the tide gauges of Ristna and Dirhami (Fig. 3) differed from the zero value by +3 and +17 cm respectively. This indicated that water was tilted by 14 cm between the tide gauges (over 80 km in the east-west direction). The Paldiski tide gauge provided a reading similar to that of Dirhami. Unfortunately, there were no more tide gauges available in the region. From the results, a smooth trend line was generated (Fig. 5) to eliminate local sea level change caused by wind effect.

The gravimetric geoid difference from Paldiski to the maximum point was 92 cm (Figs 3, 5), while the RTK GPS measurements showed a relative change of 77 cm (Fig. 5, the value was obtained from the trend line) along the same line.

If we take into account the tilt of the water level (about 8 cm per 50 km, Table 1), the results agree with about 8 cm accuracy: 92 – 8 = 84 cm, 84 – 77 = 7 cm. So, a comparison of the relative change of the gravimetric solution with that of the ferry GPS solution showed that

Table 1. Tide gauges at Ristna, Dirhami and Paldiski

Station	Time	Water level BK77 (cm)
29.06.2004		
Ristna	08.00	+4
Ristna	14.00	+1
Ristna	20.00	+3
Paldiski	08.00	+17
Paldiski	20.00	+12
Dirhami	08.00	+17
Dirhami	20.00	+14
30.06.2004		
Ristna	08.00	+3
Ristna	14.00	+5
Paldiski	08.00	+16
Paldiski	20.00	+26
Ristna	20.00	+5
Dirhami	08.00	+17
Dirhami	20.00	+23

the preliminary results fell within a 7-cm accuracy range for the eastern part of the test line.

The western part of the line (360–430 km in the east-west direction) was measured during the next night using kinematic measurement with post-processing and RTK data from the Tahkuna base station (Fig. 3). Similarly, the western part shows a clearly negative trend until East Coordinate 367 km, as does the gravimetric geoid (Fig. 5). In the western part, the water difference measured with GPS was 1,08 m. If we subtract the water tilt correction 8 cm, we get 1 m for the water profile difference. The tilt-corrected water (sea) level change agrees with the NKG04 within the range of 10 cm.

4. Repeated measurements between Paldiski and Kappelskär

To improve reliability, the measurements were repeated on 6–7 November 2004. The entire distance from Paldiski to Sweden (Fig. 1) was measured using kinematic GPS. Only the kinematic method with post-processing was used. A base station was established in the north of Hiiumaa (Lehtma, Fig. 1). Additionally, data from a second base station at Hanko was used for a higher reliability. Fig. 6 presents the same profile as Fig. 5. Unfortunately, at that time the western part of the distance was measured under a stronger wind. The water level was even more stable than the first time; the western part of the profile was about 10 cm lower; consequently, the water tilt was about 10 cm per 130 km (Table 2).

The results are about the same as those obtained in the first round of measurements. From Paldiski to the maximum of the gravimetric geoid the water level height increased by 84 cm and the tilt-corrected water level height changed by 94 cm (the correction applied + 4 cm for 60 km), yielding a difference of 10 cm (Table 2). As well, the western part fell within the range of 12 cm, in spite of the stronger wind.

On the return trip, the ferry followed a slightly different route (Fig. 1, northern line). Therefore the gravimetric geoid heights are slightly different. The results are presented in Fig. 7. Nevertheless, we can recognize a clearly similar profile for both the gravimetric geoid and

Table 2. Tide gauge data from some stations in Estonia and Sweden (6–7 November 2004)

Station	Time	Water level BK77 (cm)
	06.11.2004	
Ristna	08.00	−1
Ristna	14.00	−1
Ristna	20.00	+2
Lehtma	08.00	+7
Lehtma	14.00	0
Lehtma	21.00	+5
Dirhami	08.00	+7
Dirhami	20.00	+4
Paldiski	08.00	+12
Paldiski	20.00	+4
Stockholm	14.00	0
Stockholm	18.00	+3
Stockholm	20.00	+2
Stockholm	23.00	−1
Marviken	14.00	−5
Marviken	18.00	−3
Marviken	20.00	0
Marviken	23.00	−4
	07.11.2004	
Ristna	08.00	−1
Lehtma	01.00	0
Lehtma	07.00	+7
Dirhami	08.00	+5
Paldiski	08.00	+5
Stockholm	00.00	−5
Stockholm	01.00	−3
Stockholm	03.00	−8
Stockholm	05.00	−7
Stockholm	07.00	−7
Stockholm	08.00	−7
Marviken	00.00	−6
Marviken	01.00	−6
Marviken	03.00	−10
Marviken	05.00	−7
Marviken	07.00	−4
Marviken	08.00	−5

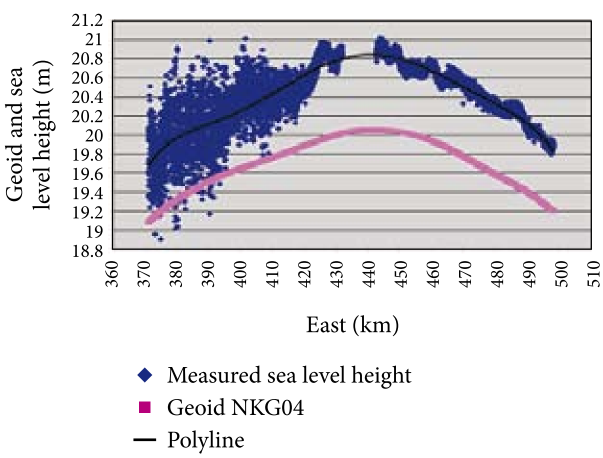

Fig. 6. Water level relative heights by kinematic GPS. The profile length is over 132 km, 6 Nov 2004 (500 km corresponds to longitude 24°)

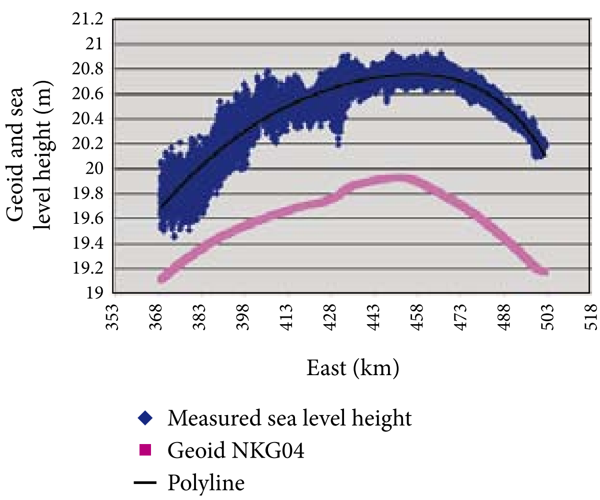

Fig. 7. The measured profile of the northern route, from Sweden to Estonia (Fig. 1), 7 Nov. 2006

the measured water level. As appears from the tide gauge data, the water level was virtually untilted (Table 2) during the measurements.

5. Profile in the middle of the Baltic Sea

Fig. 1 presents the measured lines between Paldiski and Kapellskär. The aim was to follow a geoid low situated south of Marinehamn. Again, a regular ferry liner was used. The results are presented in Figs 8, 9.

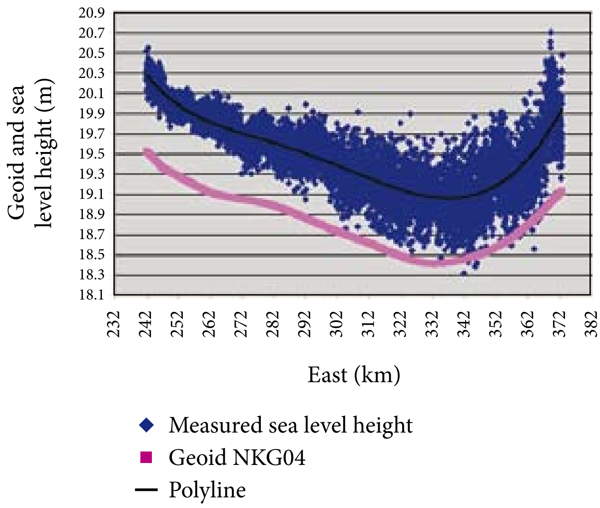

Fig. 8. Water level relative heights by kinematic GPS, 6 Nov 2004 (300 km corresponds to longitude ~20,5°)

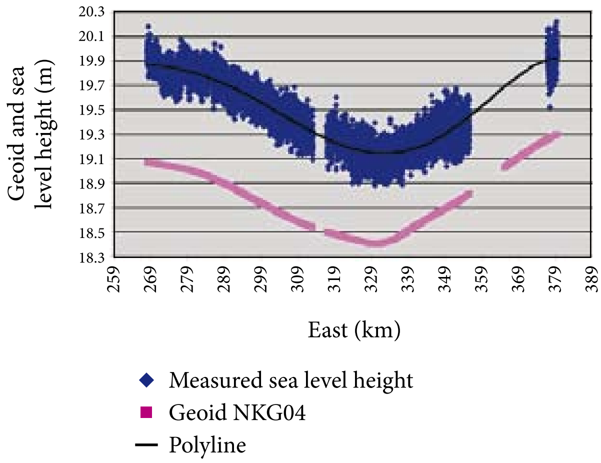

Fig. 9. Water level relative heights by kinematic GPS, 7 Nov 2004 (300 km corresponds to longitude ~20,5°)

Additionally, data from the base stations at Godby and Stavsnas was used for post-processing. The stations are a part of the RTK network in Finland and Sweden, respectively. As well, tide gauge data from Stockholm and Marviken was used (Table 2). All the tide gauge data were converted to the Baltic height system (Morozova 2005). As the water was almost untilted during the measurements (Table 2), we did not apply any water tilt correction. The changes in the geoid and the measured water profile coincide within the range of 10 cm (Figs 8, 9, southern and northern route, respectively (Morozova 2005).

6. Measurements between Tallinn, Estonia, and St. Petersburg, Russia, on 13–14 Dec 2004

Fig. 1 presents the measured lines between Tallinn–St. Petersburg-Helsinki. Regular ferry liners were used. The results are presented in Fig. 10.

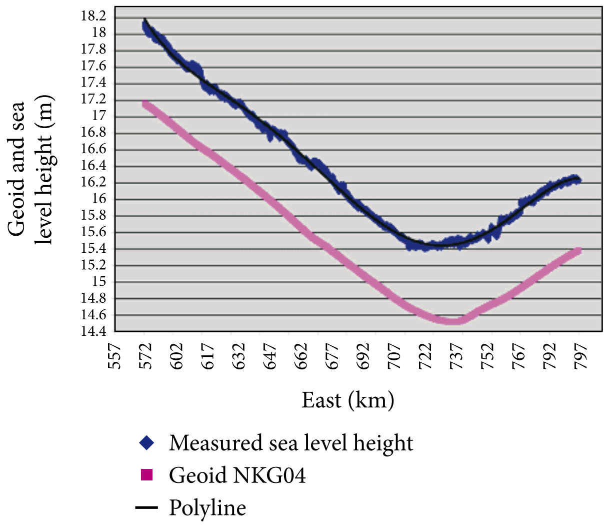

Fig. 10. Water level relative heights by kinematic GPS between Tallinn and St. Petersburg, 13 Dec 2004 (700 km corresponds to longitude ~27.5°)

Table 3. Tide gauge data from some Estonian and Russian stations (13 and 14 Dec. 2004)

Station	Time	Water level BK77 (cm)
	13.12.2004	
Loksa	20.00	+17
Kunda	20.00	+19
Toila	20.00	+22
Narva-Jõesuu	20.00	+21
St. Petersburg	20.00	+35
	14.12.2004	
Loksa	08.00	+21
Kunda	08.00	+21
Toila	08.00	+24
Narva-Jõesuu	08.00	+24
St. Petersburg	08.00	+44

Base stations at Pedassaare and Virolahti were used for post-processing. The Virolahti base station is a part of the Finnish RTK network.

Tide gauge data from Hamina, St. Petersburg, Toila, Kunda, Loksa and Narva-Jõesuu was used (Table 3). The tide gauge data was converted to the Baltic height system. The weather was fairly quiet during the campaign. Ferry up-and-down movements did not exceed 15 cm.

The water level difference between Narva-Jõesuu and St. Petersburg was 20 cm (24 and 44 cm respectively) (Table 3). This means that 700 km toward the east water was higher, which is also observable in Fig. 10.

The geoid and GPS determined water profiles coincide after water tilt correction (which was not applied in the figures).

7. Measurements between Estonia and Finland on 16 and 18 May 2006

The measurement track between Sillamäe and Kotka is presented in Fig. 1. Two GPS-receivers set up on board a ferry were used for the measurements (Trimble R8 and Trimble 5800). The receivers were placed on the right and left boards of the ferry. The use of two receivers simultaneously allowed a more precise comparison and estimation of the measurement results.

Data from the Pernaja GPS base station and from the base station situated at Toila were used in post-processing. The southern part of the route was post-processed using data from the Toila base station and the northern part using those from Pernaja (Fig. 1).

Tide gauge data were collected from Hamina and Helsinki in Finland and from Toila, Narva-Jõesuu and Kunda in Estonia. As the tide gauge data varied very little, by a maximum of 5 cm, during the measurements, no water tilt corrections were added to the GPS measurement results.

Fig. 11 presents the chart of the Kotka–Sillamäe track. To improve the readability of the chart, 17 m was subtracted from the heights measured with the Trimble 5800 receiver and 17.5 m from those measured with the R8 receiver.

As the bulk of the Sillamäe–Kotka ferry line runs almost parallel to geoid NKG04 contours (Fig. 1), the height change is not so drastic; nevertheless, it follows the same trend as in all the earlier measurements. The gap in the data in Fig. 11 is due to the kinematic data processing software ambiguity solutions yielding no solution in the middle of the Gulf of Finland.

The data (heights) from the two GPS receivers used on the ferry show identical sharp protrusions, which invite a conclusion that they have to do with sea surface peculiarities or external disturbances in these particular areas rather than with GPS measurement errors. The protrusions were observed in exactly the same places irrespective of whether the ferry was bound for Estonia or Finland. The sharp changes in height (10–40 cm) occurred over short distances (1–6 km).

As mentioned before, we can usually see a short-period (about 4 km) change in the water profile. Fig. 12 shows a temporary change of 10 cm over 4 km. It seems that such low data result from an unequal placement of sea water. Probably, the main factor for short-distance anomalies in water placement is the wind. It cannot be air pressure, since the changes occur over a very short distance (about 5 km).

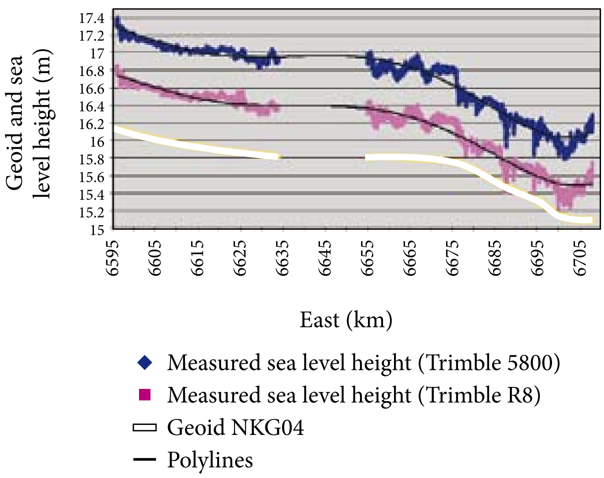

Fig. 11. Water level relative heights by kinematic GPS between Sillamäe and Kotka, 18 May 2006. (6655 km corresponds to latitude ~60°) (the scale is slightly distorted as only the north component is used)

8. Conclusion

Some water level profiles were measured on the sea using GPS kinematic method. The water tilt effect was eliminated inasmuch as possible using different tide gauge data. The GPS measurements yielded results with the accuracy of a few cm; the regional water tilt effect could not be completely removed. However, the results showed the measured profiles to be similar to those of Geoid Model NKG04 within the bounds of 7–15 cm. Consequently, we did not discover any big or remarkable differences between the measured sea level surface and the NKG04, even in areas for which gravity data were of low quality or missing altogether.

9. Acknowledgment

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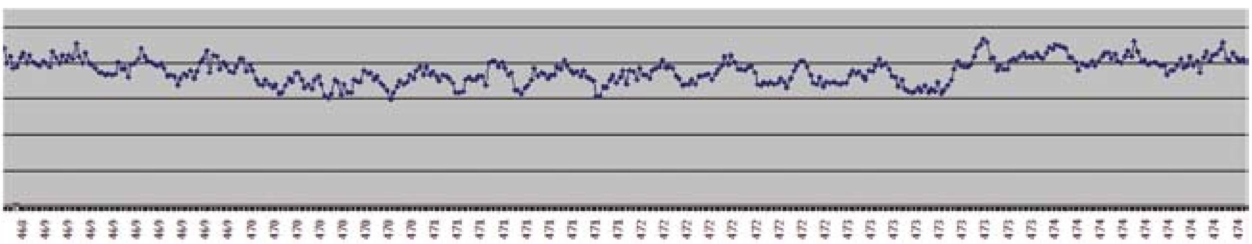

Fig. 12. A depression in the water profile, length about 4 km (the example is from a Swedish profile)

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Harli JÜRGENSON, Assoc. Prof. Estonian University of Life Sciences, Dept of Geomatics, Ph +3727313119, Fax +372 313 154.

PhD degree since 2003 from Estonian University of Life Sciences in Tartu. Ass. Prof. since 2003. Over 15 presentations in international conferences and seminars, author of over 20 publications in referred Conference Proceedings, technical reports, magazine articles. Research interests: gravity field and geoid modelling, height data.

Aive LIIBUSK, PhD student, Estonian University of Life Sciences, Dept of Geomatics, E-mail: liibusk@emu.ee

Research interests: geoid, GPS, height datums.

Artu ELLMANN, Assoc. Prof. Tallinn University of Technology, Dept of Transportation, Geodesy Chair. Ph. +372 6202 603, Fax +372 6202 601.

He holds (since 2004) a PhD degree from the Royal Institute of Technology (KTH) in Stockholm. Over 30 presentations at international conferences, author/co-author of over 60 publications in referred Journals and Conference Proceedings, technical reports, magazine articles. Research interests: physical geodesy, gravity field and geoid modelling in particular, national geodetic networks.