Improving the geoid model for future GNSS-based navigation in the Baltic Sea

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Key words: Baltic Sea, Gravity, Geoid Model, Navigation, FAMOS, Chart Datum

SUMMARY

The countries around the Baltic Sea are working towards the introduction of a common height reference for the whole Baltic Sea, the Baltic Sea Chart Datum 2000. The datum is based on the European Vertical Reference System (EVRS) at postglacial land uplift epoch 2000.0. An accurate geoid model is needed for the region to make full use of the new common unified vertical datum in modern GNSS-based navigation. Improving the geoid model for the Baltic Sea is one of the goals of Activity 2 within the project 'Finalising the Baltic Motorways of the Sea' (FAMOS). The FAMOS project is co-financed by the European Commission within the framework of the Connecting Europe Facility (CEF) funding program. In FAMOS activity 2, shipborne gravity measurements are carried out in various parts of the Baltic Sea in order to check existing marine and airborne gravity data, collect new data and calculate a new accurate geoid model covering the whole Baltic Sea by 2020.

One of the gravity campaigns was a dedicated gravity survey carried out in the Bothian Sea on board of the survey vessel Airisto in the autumn of 2015. Continuous gravity measurements were performed with the Chekan-AM sea gravimeter of GFZ German Research Centre for Geosciences Potsdam. Drifts in the gravity time series were estimated using crossover points and harbor reference values. The final gravity data was reduced to geoid level and compared with existing data. The results confirmed that the old Håkon Mossby shipborne data of 1996 has a positive offset with respect to surrounding observations, although its size varies over the area. Also newer ice measurements from the nineties show a similar positive offset. More discussion is needed to decide how to treat this offset in future geoid calculations. The effect of the new data on the geoid model is visible in the whole area of the Bothnian Sea. The differences are up to 5 cm, with the largest effect in the areas that overlap with the Håkon Mossby ship data.

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1. INTRODUCTION

Nautical charts in the Baltic Sea refer to national or local datums that are derived from tide gauges. To allow for seamless transitions between areas, a common height reference for the whole Baltic Sea is desired. The Baltic Sea Hydrographic Commission (BSHC) has decided to introduce the common Baltic Sea Chart Datum 2000. The datum is based on the European Vertical Reference System (EVRS) at postglacial land uplift epoch 2000.0. Thus, the zero level is an equipotential surface. The countries around the Baltic Sea will gradually introduce the new datum in their nautical charts.

To enable the full use of the new chart datum in future GNSS-based navigation, a high quality geoid model is needed for the Baltic Sea. The Nordic Geodetic Commission has in the past years been working on an improved Nordic geoid model, resulting in the NKG2015 geoid model (Ågren et al., 2016). Improvements to the geoid model were made by harmonizing coordinate and height references, unifying the treatment of tides and the transformation of all observations to the common epoch 2000.0. The focus was mainly on land. Now that the Nordic geoid model has been improved on land, the focus is shifting to the Baltic Sea.

The Baltic Sea is rather well covered by gravity data as can be seen in figure 1. However, the data is not as homogeneous as on land, existing of many different datasets with varying origin: Sea bottom, shipborne and airborne measurements as well as measurements made on ice. Uncertainties are large and offsets may exist between the data sets. To improve the geoid model for the Baltic Sea, the existing marine gravity data must be checked and new data collected. Activity 2 in the FAMOS-project, 'Finalising the Baltic Motorways of the Sea' addresses this issue (FAMOS consortium, 2014-2017). The FAMOS project is co-financed by the European Commission within the framework of the Connecting Europe Facility (CEF) funding program. The project involves 15 organizations from 7

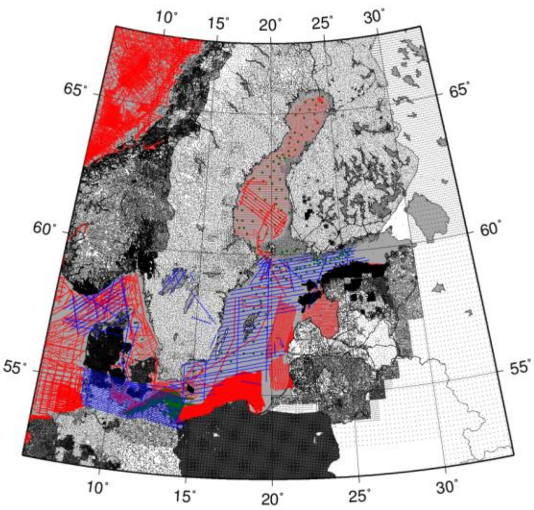

Figure 1. The NKG gravity database in the Baltic Sea Area in May 2015. Black dots are land (surface) data, red dots are either shipborne or ice measurements, blue dots are airborne and dark green sea bottom measurements.

Baltic Sea countries under the project management of the Swedish Maritime Administration (SMA). In FAMOS activity 2, shipborne gravity measurements are carried out in various parts of the Baltic Sea in order to check existing marine and airborne gravity data, collect new data and calculate a new accurate geoid model covering the whole Baltic Sea by 2020.

In 2015 and 2016 several gravity campaigns have been carried out in different parts of the Baltic Sea in the framework of the FAMOS project. One of the gravity campaigns was a dedicated gravity survey carried out in the Bothian Sea on board of the survey vessel Airisto in the autumn of 2015. In this paper we describe the Airisto 2015 gravity campaign and its outcome.

Section 2 gives an overview of the old data available in the Gulf of Bothnia. The details of the Airisto 2015 campaign are given in section 3. Section 4 describes the gravity data processing and section 5 the reduction of the data to zero heights. The new marine data is compared with old data in the area in section 6 and the effect the new data has on the geoid model in that area is shown in section 7. Conclusions are given in section 8.

2. OLD DATA EXISTING IN THE GULF OF BOTHNIA

Data in the Gulf of Bothnia consists of ice measurements made by the FGI in cooperation with Lantmäteriet and the Swedish Geological Survey (SGU) from 1978 to 1996 and shipborne

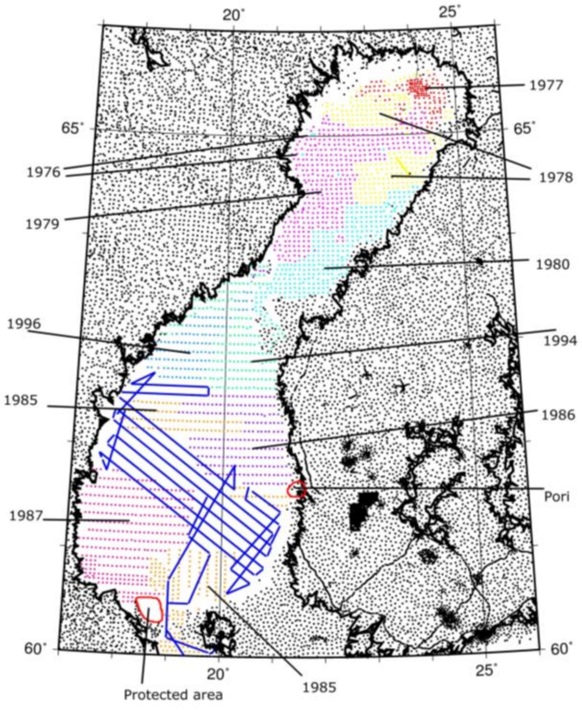

Figure 2. Existing data in the Gulf of Bothnia. Black dots are measurements on land, colored dots are measurements on ice in different years and the blue lines are shipborne measurements.

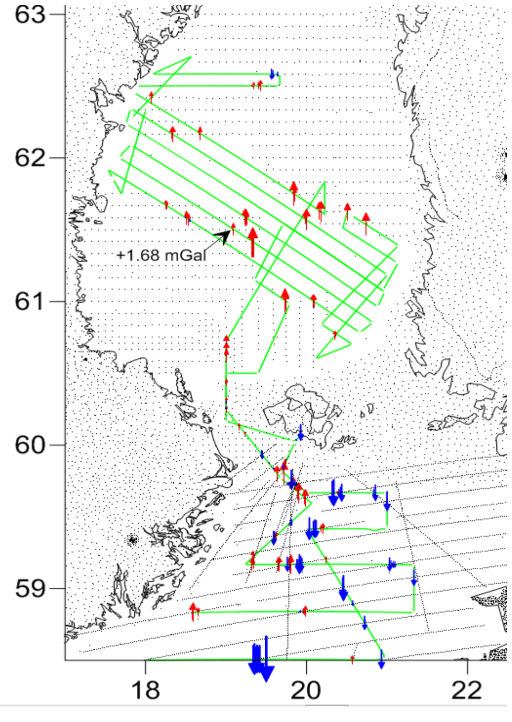

Figure 3. Differences between Håkon Mossby marine data and other data at distances less than 1 km.

measurements made on board of M/V Håkon Mossby in 1996 (see figure 2 and Kääriäinen and Mäkinen, 1997). The ice measurements have been observed with Lacoste & Romberg gravimeters and should be of comparatively high quality, but they have been measured in many years under many different circumstances and ice conditions. The horizontal and vertical positions are also somewhat uncertain. Most of these points were determined before the advent of GPS. Up to 1987 the Decca navigation system was used for horizontal positioning. Its accuracy deteriorated to the end of the period (Kääriäinen and Mäkinen, 1997).

The Håkon Mossby ship data overlaps in some areas with the ice data. When comparing data less than 1 km apart, there appears to be a clear systematic difference in the Gulf of Bothnia, with the Håkon Mossby observations higher than the ice data (see figure 3). However, south of the Åland islands this pattern cannot be seen.

3. 2015 AIRISTO GRAVITY CAMPAIGN

In the autumn of 2015 a dedicated gravity campaign took place on board of the survey vessel Airisto of Meritaito Oy. Considering the old data as described in section 2, the 2015 Airisto gravity campaign was planned so that it would connect most of the different datasets shown in figure 2 in the whole Gulf of Bothnia. However due to bad weather in the first part of the campaign, the measurements were restricted to the Sea of Bothnia between the Åland Islands and the city of Umeå. The campaign took place between September 25 and October 11, 2015. The tracks and measured gravity anomalies are shown in figure 4.

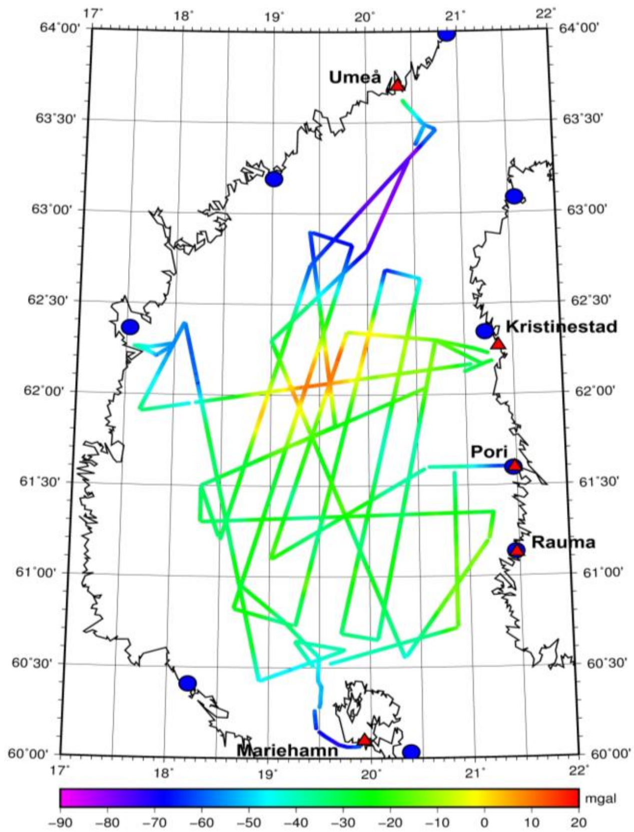

Figure 4. Tracks of the 2015 Airisto gravity campaign with measured gravity anomalies. Red triangles mark harbours where ties were measured to the first order gravity networks. Blue dots are tide gauges.

The continuous gravity measurements were performed with the Chekan-AM sea gravimeter of GFZ German Research Centre for Geosciences Potsdam. The Chekan gravimeter consists of a gravity sensor based on a double quartz elastic system with linear CCD optic-electronic converter and a gyro stabilizer. Measurements are taken at 10 Hz sample rate and the statistical accuracy is 1 mGal. In addition to the gravity observations, the vessel's GNSS observations were also stored during the whole campaign.

The campaign started from the harbor of

Pori, where the location of the gravimeter in the vessel's coordinate frame was determined and a connection was measured to the first order gravity network on land. During the campaign the Airisto made stops in the harbors of Mariehamn, Rauma, Kristinestad and Umeå. In all harbors a connection was established to the national gravity network.

4. GRAVITY DATA PROCESSING

At first the measurement trajectories were computed using the onboard GNSS data. In the second step the gravity data recorded with the Chekan gravimeter were taken along the GNSS trajectories and filtered using a 200 sec low pass filter to reduce the high-frequency noise. The GNSS data were only taken for trajectory estimation and not to compute and subtract the kinematic vertical accelerations because this is usually not necessary for shipborne gravimetry.

In the last step of the gravity data processing the drift behavior of the gravimeter was estimated using crossover points and the mentioned harbor references. Under normal conditions the Chekan gravimeter has a drift rate of approximately +2 mGal/day which is in accordance with the specification of the manufacturer. But, during the drift analysis of this campaign it became obvious that the gravity meter temporarily featured an abnormal negative and partially non-linear drift behavior. This drift behavior changed with time and was obviously induced by storm events during the ride. Fortunately, the recorded crossover points and the harbor references allowed for a closed drift estimation.

The crossover points as included for the drift estimation are given in figure 5. The various colors indicate different drift behavior. While for the green tracks a linear negative drift has been estimated, for the black and blue parts non-linear negative drifts were obtained, whereas the red tracks show a continuous normal drift of about +1.6 mGal/day.

Table 1 gives the statistics for the crossover points after the drift estimation and shows a comparison between the tracks with normal drift and all tracks together. The achieved RMS values of approx. 0.5 mGal for the tracks with normal drift as well as for all tracks meet the accuracy requirement of the FAMOS project and show a satisfactory gravity data processing for this campaign.

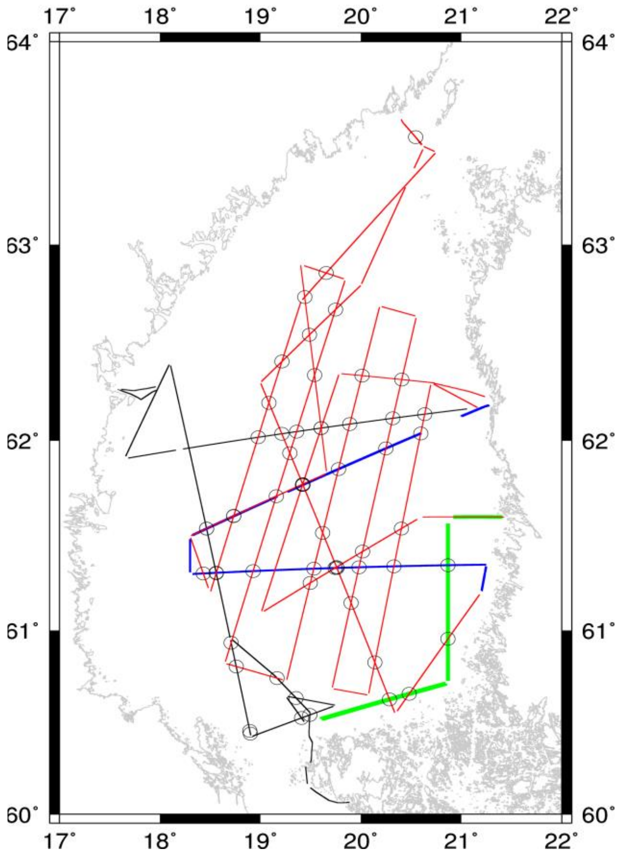

Figure 5. Location of the crossover points used for the drift estimation of the Chekan gravimeter. The various colors for the tracks (green, black, blue and red) indicate different drift behaviours.

Table 1. Gravity difference statistics for the crossover points (see figure 5), all numbers in mGal.

Included tracks (numbers of crossover points)	Min	Max	Mean	RMS
Tracks with normal drift only, red (24)	-0.578	1.079	0.067	0.450
All tracks (62)	-1.652	1.079	0.006	0.551

5. REDUCTION OF DATA TO GEOID LEVEL

In the databases of the FGI and the NKG, the marine gravity observations are given at zero height, in other words at geoid level. The Airisto gravity results were at the height of the gravimeter sensor. To be fully comparable to the old data, the new data had to be reduced, first from the gravity sensor to the sea level and then from the sea level to geoid level. Figure 6 shows the heights involved in the process. The reductions were performed on the gravity anomaly $\Delta g = g - \gamma_0$, where γ_0 is the normal gravity.

First, the gravity values were reduced from the sensor to the sea surface using the free-air correction over distance dh_6 (see figure 6):

$$\Delta g_{\text{sea level}} = \Delta g_{\text{sensor}} + 0.3084 dh_6$$

dh_6 is the sum of the distances dh_3, dh_4 and dh_5, where dh_4 and dh_5 are constant. dh_3 changes in time and could be determined from information gathered on the vessel during the campaign. The resulting corrections to the gravity values were between 0.16 mGal and 0.25 mGal.

In the next step the gravity values were transferred from the sea surface to zero height at the geoid surface using time series from the tide gauges surrounding the area (see figure 4). The tide gauge data is hourly data related to the national height systems, RH 2000 in Sweden and N2000 in Finland. These systems can be considered to refer to the same zero level. The sea level at the observation epochs was calculated by linear interpolation of the hourly tide gauge values. Then, the sea level at the observation locations was determined by inverse distance weighting interpolation:

$$H_i(t_i) = \frac{\sum_{n=1}^{9} \frac{1}{d_n} H_n(t_i)}{\sum_{n=1}^{9} \frac{1}{d_n}},$$

where $H_i(t_i)$ is the sea level at the gravity observation location i and epoch t_i. $H_n(t_i)$ is the sea level at tide gauge n and epoch t_i, and d_n the distance between the vessel and the tide gauge n at epoch t_i.

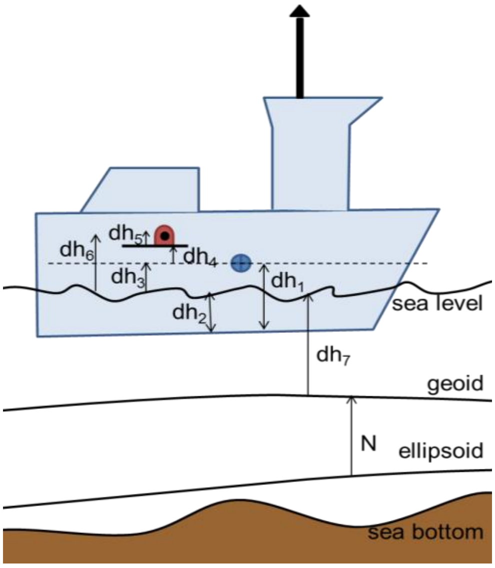

Figure 6. Heights needed for the reduction of gravity values from sensor height to geoid level.

After the sea level, dh_8, at the gravity observation epochs and locations was obtained, the gravity value was reduced to the zero level by removing the water between the sea surface and the geoid and then bringing the gravity value down to geoid level using the free air reduction:

$$\begin{aligned}\Delta g_{geoid} &= \Delta g_{sea\ level} - 2\pi G\rho_{water} dh_8 + 0.3084 dh_8 \\ &= \Delta g_{sea\ level} - 0.0419 dh_8 + 0.3084 dh_8 \\ &= \Delta g_{sea\ level} - 0.2665 dh_8\end{aligned}$$

In the above, G is the gravitational constant and ρ_{water} is the desity of water. The resulting corrections to the gravity values are very small, between -0.05 mGal and 0.04 mGal.

6. COMPARISON WITH OLD GRAVITY DATA

The new gravity data can now be compared with the old data available in the area. Figure 7 shows that at a first glance the data seems to fit well to the old shipborne and ice data. However, figure 8 shows that there are differences. It seems that the new data is lower than the Håkon Mossby ship data in most of the area, but is at the same level as the ice data surrounding the Håkon Mossby data. This would confirm the earlier findings that the Håkon Mossby data might have a positive offset with respect to the surrounding observations.

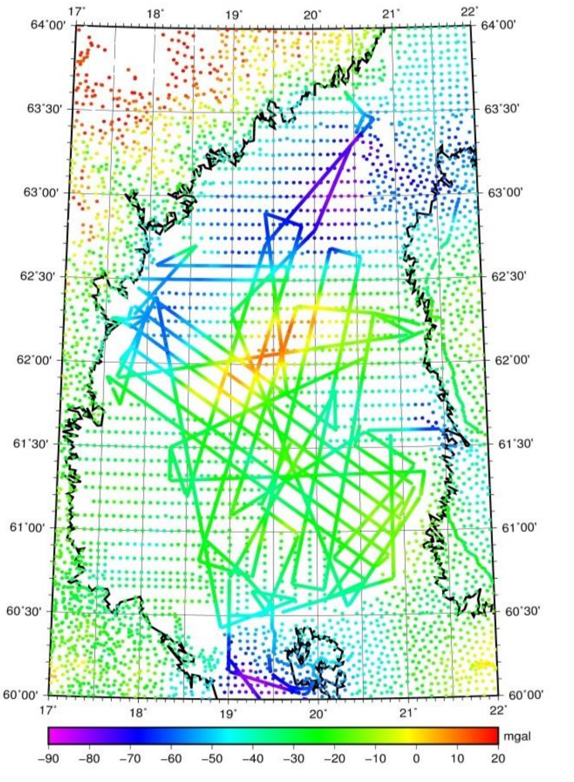

Figure 7. Free air anomalies of the old and new gravity data in the Bothnian Sea

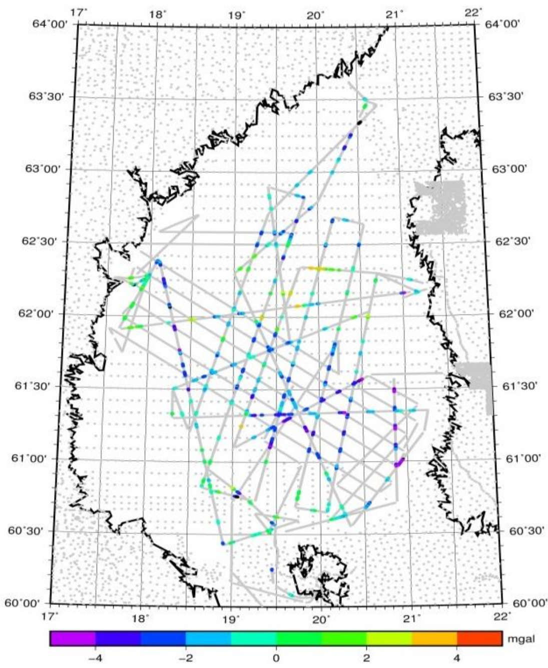

Figure 8. Differences between the new data and values interpolated from the old data when an observation of the old data was at a distance of less than 1 km. The values are positive when new values are larger than old values. The interpolation is made on the free air anomalies using inverse distance interpolation with power 1.

Table 2. Statistics of the comparisons between the new data and values from the old data for the whole old data set, ice data sets of different years and the Håkon Mossby shipborne data of 1996 (Old ship) in mGals. n is the number of observations with a distance of less than 1 km between the old and new data.

	All old	ice1980	ice1985	ice1986	ice1987	ice1994	ice1996	Old ship
n	146423	736	11389	12542	7138	4535	1340	73963
min	-15.30	-0.10	-4.03	-5.25	-5.11	-5.20	-8.39	-15.36
max	10.31	2.44	4.11	5.90	2.82	0.00	0.00	5.11
av	**1.42**	**1.11**	**0.02**	**0.14**	**-0.73**	**-2.02**	**-2.25**	**-1.79**
stdev	5.09	0.47	1.37	2.42	1.20	0.99	2.00	1.57
rms	5.28	1.21	1.37	2.43	1.40	2.25	3.01	2.38

Table 2 shows the comparison of the new data with the old data sets of different years. The new data on average 1.8 mGal below the Håkon Mossby ship data, but the standard deviation is rather large, 1.6 mGal. The old ice data of 1980, 1985, 1986 and 1987 (figure 2) fit well to the new data, but variations around the mean are quite large for the data of 1985 and 1986. The later ice data of 1994 and 1996 also show an offset with the new ship data with differences of -2.0 mGal and -2.3 mGal respectively.

More discussion is needed to decide how to deal with these differences in the geoid calculations.

7. EFFECT OF THE NEW GRAVITY DATA ON THE GEOID MODEL

Figure 9 shows the effect of the new data on the geoid model for the Bothnian Sea. First, a geoid was calculated with the old data, as used for the NKG2015 geoid model. Then, the new data was combined with the old data and a new geoid model was calculated. Figure 8 shows that the geoid model changes in almost the whole Bothnian Sea as a result of the new data, with the biggest change in the area where the new data overlaps with the Håkon Mossby data. The differences are between +1 cm and -5 cm.

The small positive signal (red) south-west in figure 9 is an interpolation effect. The area is the Gräsö Östra Skärgård nature reserve, where there is a gap in the gravity observations (see figure 2).

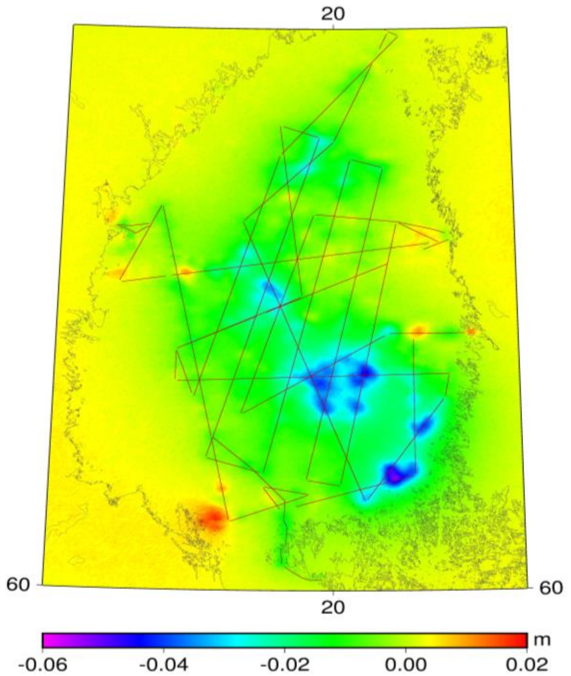

Figure 9. Differences between the geoid model created with the old data and the model calculated with the old and new data together.

8. CONCLUSIONS

In the framework of activity 2 of the FAMOS project ‘Finalising the Baltic Motorways of the Sea’ a dedicated gravity campaign was carried out in the Bothnian Sea in the autumn of 2015. For comparison with the old data and geoid calculation, the new gravity data was reduced to geoid level (zero height in the national height system) using surrounding tide gauge time series.

The new data was compared with old datasets that were used in the NKG2015 geoid model computations. The results confirmed that the old Håkon Mossby shipborne data of 1996 has a positive offset, although its size varies over the area. Also newer ice measurements from the nineties show a similar positive offset. More discussion is needed to decide how to treat this offset in future geoid calculations.

When ignoring the offsets and using the new data together with the old data in geoid calculation, the effect of the new data on the geoid model is visible in the whole area of the Bothnian Sea. The differences are up to 5 cm, with the largest effect in the areas that overlap with the Håkon Mossby ship data.

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BIOGRAPHICAL NOTES

Mirjam Bilker-Koivula is a senior scientist at the FGI where she leads the gravity research group. She has 20 years of experience in geodesy, especially in gravimetry and geoid modelling.

Jyrki Mononen is an expert at the Finnish Transport Agency, Information department, Hydrographic Survey Data Management -unit. He has been working within the field of hydrography since 2006.

Timo Saari is a PhD student at the FGI working on geoid calculation and the determination of future height systems.

Christoph Förste is a senior scientist at GFZ Potsdam and head of the FAMOS team there. He has more than 25 years of experience in geodesy, especially in global gravity field determination and in satellite and terrestrial data.

Franz Barthelmes is a senior scientist at GFZ Potsdam and has many years of experience in geodesy, especially in global and regional gravity field modelling.

Biao Lu is a PhD student at GFZ Potsdam working on airborne and shipborne gravimetry data processing.

Jonas Ågren is a senior geodesist at the Geodetic Infrastructure Department of Lantmäteriet with more than 20 years of experience in geoid calculation, gravimetry, land uplift modelling and height systems. He is the chair of the NKG Working Group of Geoid and Height Systems and the leader of activity 2 in the FAMOS project.

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