Report on modern marine gravity data for selected areas of southern and eastern Baltic Sea

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Report prepared under the #S009 BalMarGrav project
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Contents

1 Introduction

The BalMarGrav project, co-financed under the Interreg Baltic Sea Region 2021-2027 Programme, aims to improve the insufficient mapping of the marine gravity field in the southern and eastern Baltic Sea regions. This task is very important due to the decision of the Baltic Sea Hydrographic Commission (BSHC) to implement a common height reference system called Baltic Sea Chart Datum 2000 (BSCD2000), which will be based on a geoid model determined by measurements of the Earth's gravity. The BalMarGrav project involves organisations from 8 countries of the Baltic Sea region (11 partner institutions) to jointly rework gravimetric measurements made in the 1960s–1980s in the southern and eastern parts of the Baltic Sea. These campaigns were mainly carried out with the support of the Soviet Union's research infrastructure. During the period of independence from the Soviet Union and the political transition, much of this data was forgotten or underutilised.

During the BalMarGrav project, four gravimetric campaigns were planned and carried out for verification and calibration of the historical gravity data. The surveys were conducted at the selected regions of coastal zones of Poland, Denmark, Lithuania and Latvia. This report contains the information about the surveys and data processing. The re-processed data will be available at the Nordic Geodetic Commission database under the BalMarGrav license.

2 Marine gravity survey

Two marine gravimetric campaigns were carried out for validation of the historical gravimetric measurements: marine gravity survey in Latvian waters, from April 18 to June 15, 2023 and marine gravity survey in Polish, Danish and Lithuanian waters, from July 4 to July 17, 2023.

2.1 Latvia

In the period from April 18 to June 15, 2023, a marine gravity campaign was conducted outside the Latvian coast. This campaign was performed within the BalMarGrav project by Lantmäteriet and the Latvian Geospatial Information Agency (LGIA) with support from the Riga Technical University. The measurements were made possible thanks to the Latvian Naval Forces, who hosted the Swedish marine gravimeter ZLS D13 on its P-09 "Rezekne" patrol vessel (Fig. 1).

Lantmäteriet's marine gravimeter ZLS D13 was installed by Örjan Josefsson and Tobias Nilsson. The gravimeter was installed in a small storage room located relatively close to the center of the ship. After the installation, a small test trip of about 45 minutes was made to confirm that everything worked fine. The LGIA employees who were going with the ship during the measurements received basic instructions on how to handle and operate the gravimeter.

The campaign started on April 19 and ended on June 15, 2023. An employee from LGIA was going with the ship all the time to check that the gravimeter worked properly. There were two longer breaks in the measurements – May 12-18 and May 26-31 when the ship stayed in harbour. Furthermore, the ship made shorter harbour stops every 1-4 days, either in Riga or in Liepaja, to get harbour ties needed for calibrating the drift of the gravimeter. In general, the weather was nice during the campaign, although there were few days with stronger winds and larger waves. The gravimeter worked fine during most of the campaign. The only major problem was that the gravimeter computer crashed on June 6. With remote assistance from Örjan Josefsson, the problem was resolved on June 7. After the end of the campaign, on Jun 16, 2023, the gravimeter was dismounted by Per-Anders Olsson and Thomas Eiderman from Lantmäteriet and brought back to Sweden.

BalMarGrav's partner, Riga Technical University, participated directly in the selection of

Figure 1: Latvian Naval Forces Patrol boat deck vessel P-09 "Rezekne" (left) and the Swedish ZLS D13 marine gravimeter (right)

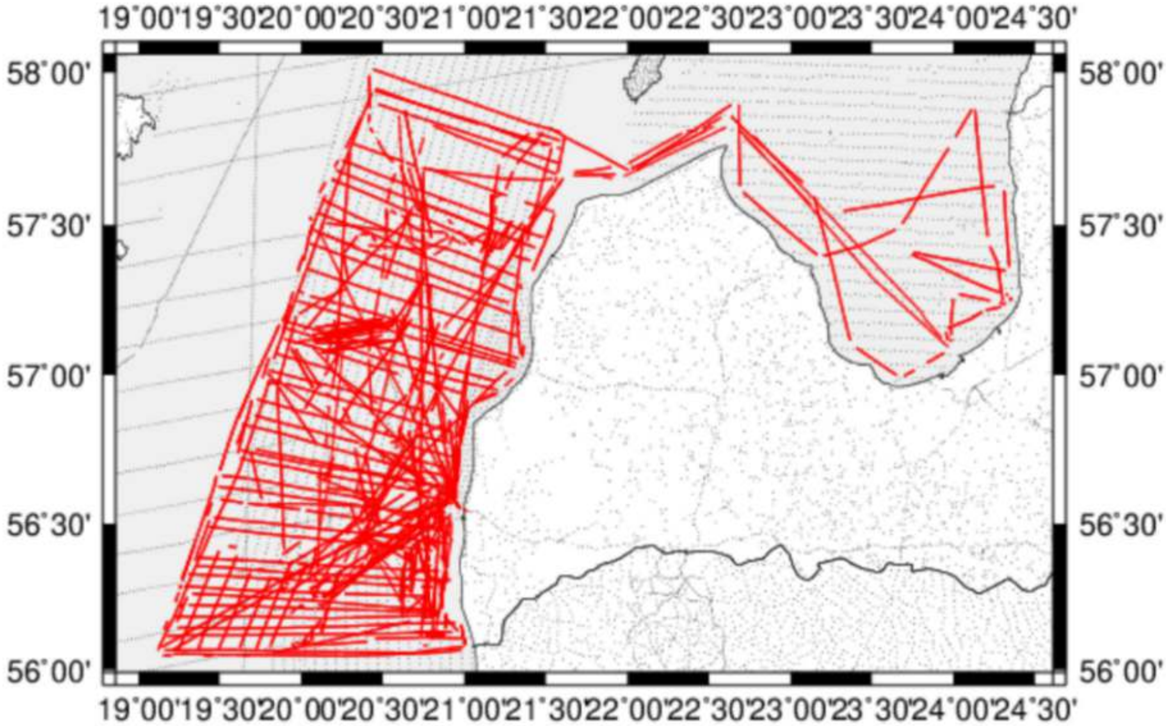

Figure 2: Selected marine gravity profiles measured during the Latvian campaign

the ships, installation of the marine gravimeter, preparation of measurements, removal of the gravimeter from the ship, as well as support measurements.

During the campaign, harbour visits was regularly made to the harbours in Riga and Liepaja in order to calibrate the drift of the gravimeter. In total, the ship was docked at six different locations during the harbour visits, three in each harbour. Thus, the gravity values of these six points needed to be measured.

This was done by first doing absolute gravity measurements at points close to the harbours, this was done on August 1-3, 2023, by colleagues from the Institute of Geodesy and Cartography in Poland, using the A10-020 absolute gravimeter (see section 3.1). Then the gravity at the harbour points were determined by doing relative gravity measurements between the absolute gravity points and the harbour points. The measurements in Liepaja were performed on May 22 and June 20-22 and the measurement in Riga were performed on June 26, all measurement were done by LGIA using two Scintrex instruments simultaneous CG-5-0333 and CG-6-0449.

The data collected in the campaign was analyzed with an in-house software developed at Lantmäteriet. The data was carefully investigated to remove bad measurements, e.g., around turns, when the ship changing speed, or during bad weather. Fig. 2 shows the selected marine profiles along which the gravity measurements were taken. The results were compared to the gridded data used for the NKG 2015 geoid model (Fig. 3). There are some small parts between the flight lines in the western part of the area where the new observations differ from the grid. Also it was noted a few areas where our measurements consistently deviate from the NKG database, indicating problems with the old data. The

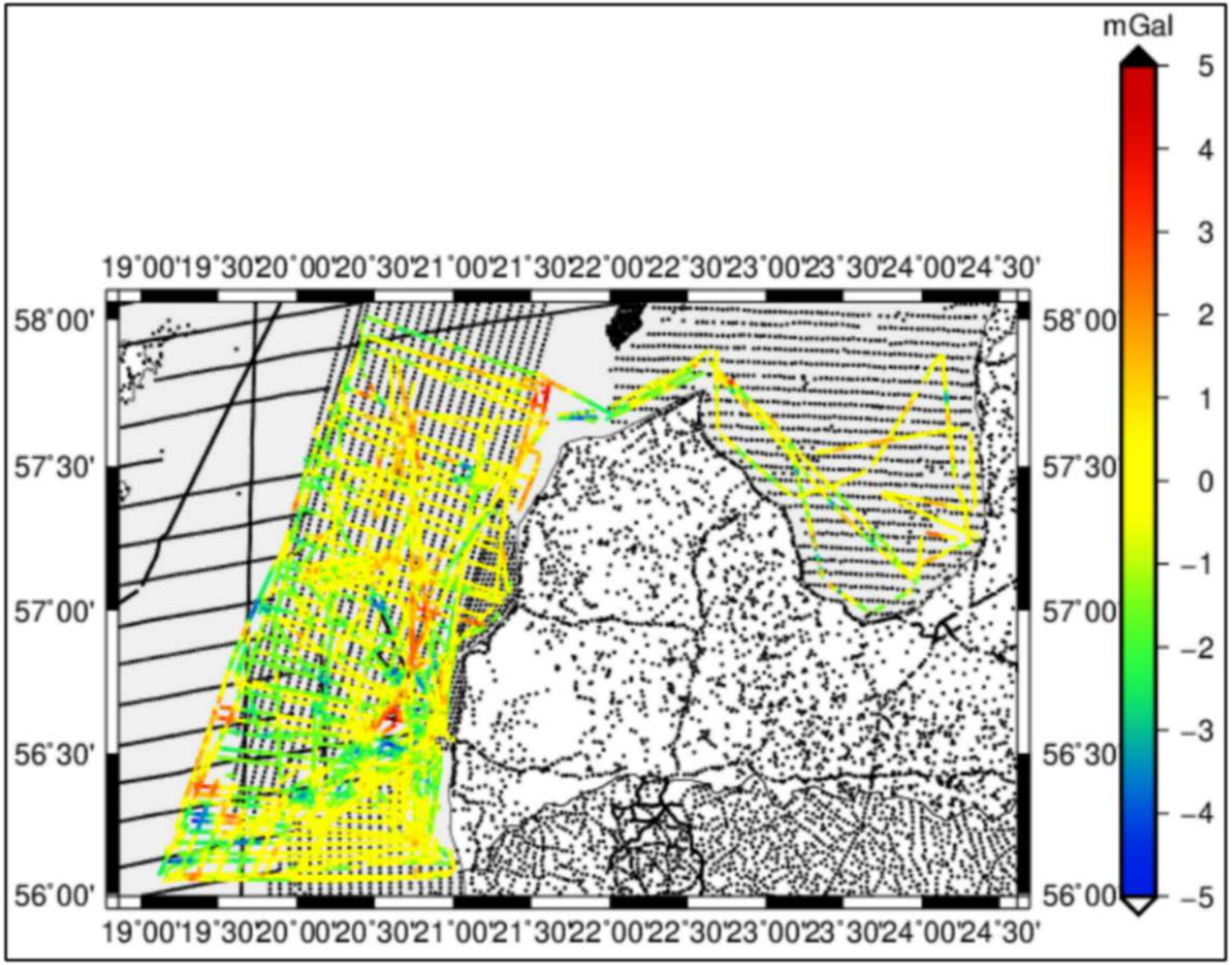

Figure 3: Results of Latvian marine gravity survey compared to the NKG 2015 grid: NIG - Latvia measurements. Black dots represents already existing data points in the NKG gravity database

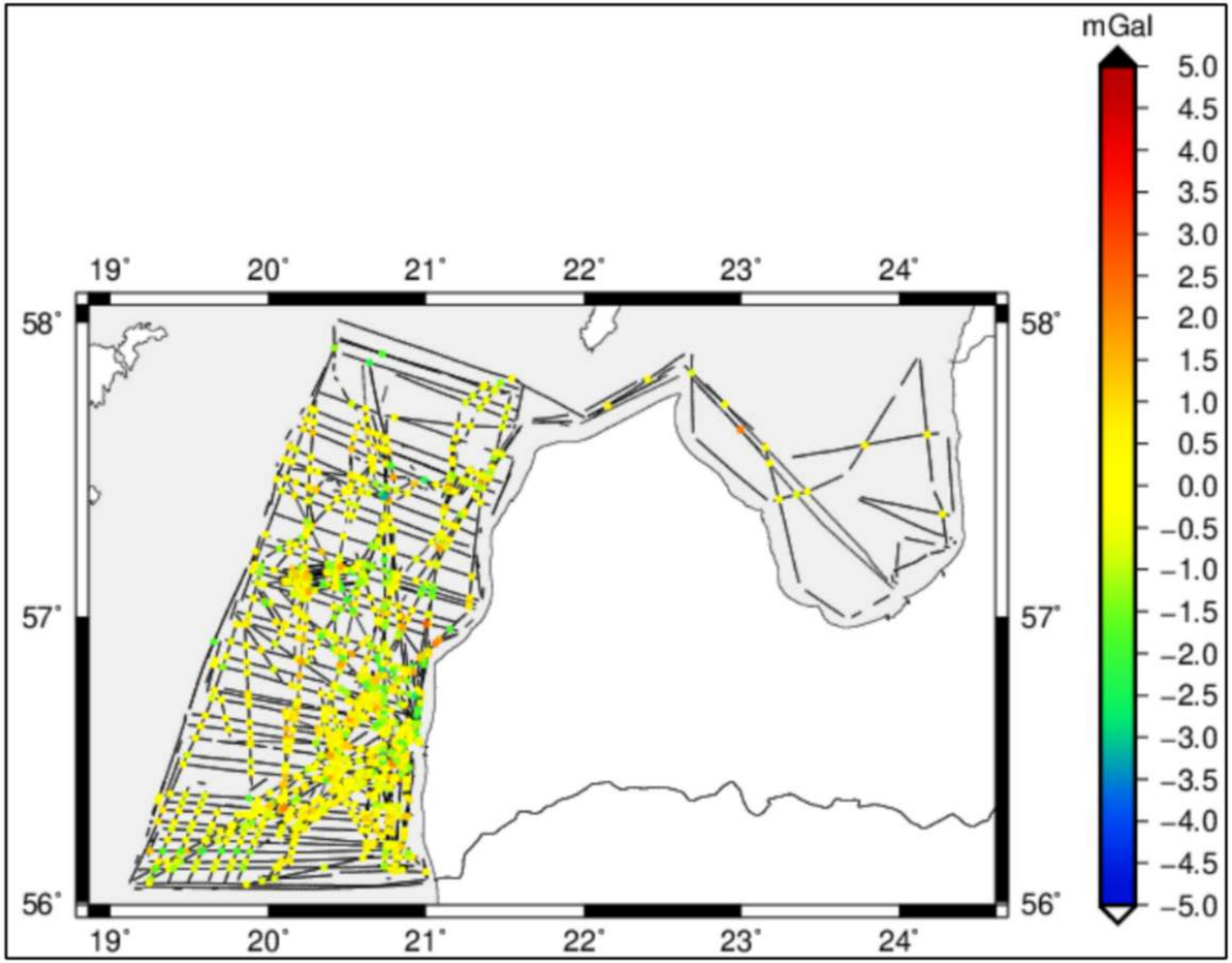

Figure 4: Internal crossover of the marine gravity data measured during the Latvian campaign

new data will help to improve the gravity map and in the end the geoid. Figure 4 shows the internal crossovers, i.e., comparison of the gravity values at points crossed by the ship several times during the campaign. The results look fine, the RMS (Root-Mean-Square) and the standard deviation for all crossover for selected lines are less than 0.9 mGal.

More details about the Latvian marine gravity campaign can be found in Appendix 1.

2.2 Poland-Denmark-Lithuania

The main campaign in the Polish, Dannish and Lithuanian waters was preceded by a preliminary campaign conducted on April 27 and 28, 2023. This small initial campaign was aimed at checking the correct operation of additional GNSS systems, which were intended to be used in the main part of gravimetric measurements. Figure 5 shows the equipment additionally installed on the ship and the assembly during work on the ship.

During the initial campaign, measurement profile plans were agreed upon with the ship's Captain in accordance with the needs of gravimetric measurements. The work performed as part of the marine gravimetric measurement campaign can be divided into three stages. We treat preparatory work, including the installation of a gravimeter, GNSS receivers and possibly accelerometers, as the first stage. Additionally, this work includes determining the offset of measuring devices located on the ship. The second stage is to prepare

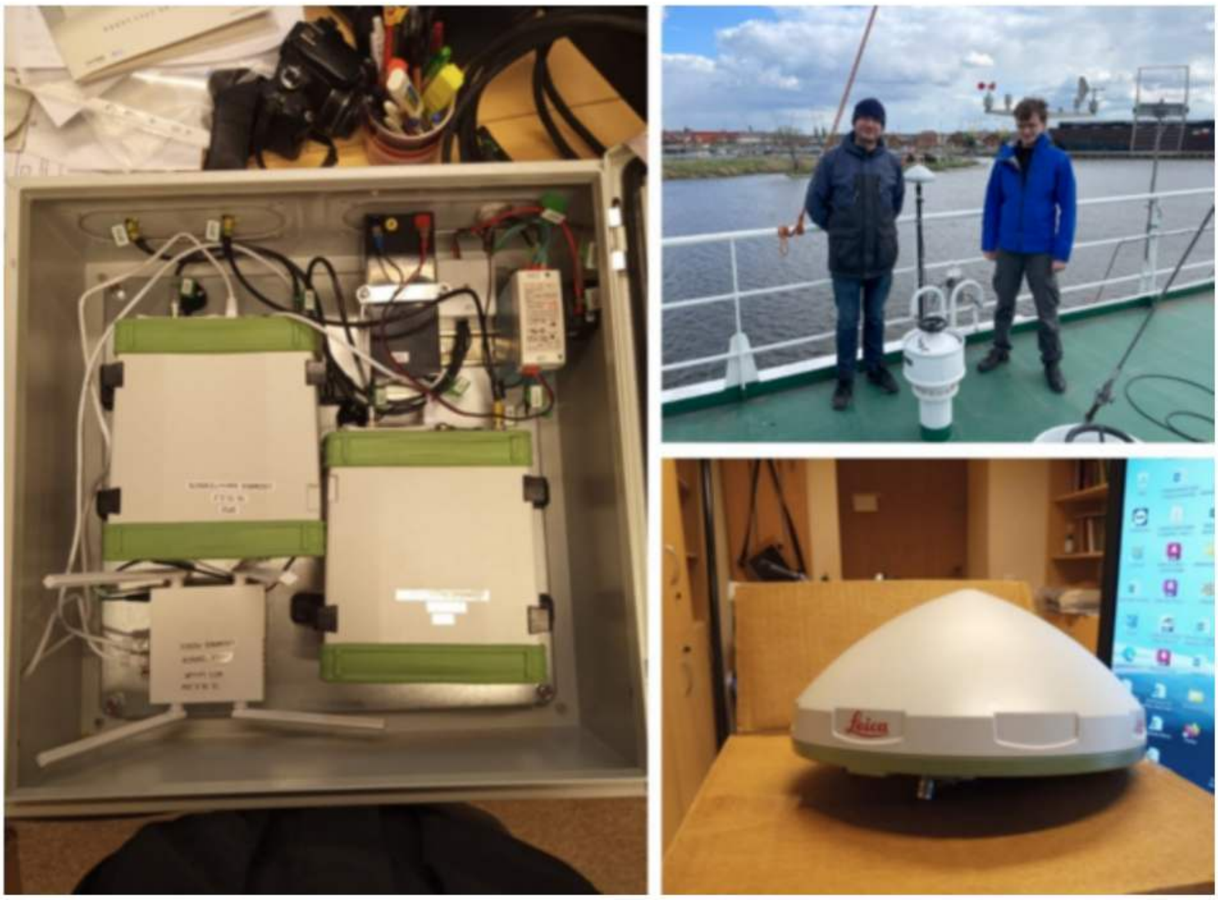

Figure 5: GNSS devices prepared for installation and the measurement team after installing the devices on the ship

Figure 6: MGS-6 installed in the ship's cabin and combined teams of the Maritime University of Technology in Szczecin and the Gdańsk University of Technology

measurement plans in maritime areas and record signals from the gravimeter of GNSS receivers and accelerometers. The last stage is the post-processing of raw signals into a useful signals. The accuracy of the work performed at all stages contributes to the final result.

The main campaign of marine gravimetric measurements started on June 4 2023, and ended on June 17, 2023. The maritime measurement campaign was carried out on a "dedicated" research vessel "Nawigator XXI", owned by the Maritime University of Technology in Szczecin. Employees of the Gdańsk University of Technology brought the MGS-6 Marine Gravimetric System to Szczecin and installed it in the ship's cabin (Fig. 6).

Thanks to additional data obtained from GNSS and accelerometers, corrections for vertical accelerations caused by the ship's motion and the dynamic effect resulting from cross-coupling between the horizontal and vertical acceleration components were taken into account, including these last two corrections led to gravimetric data with an uncertainty of less than 1 mGal. Our analyses suggest that gravity campaigns conducted at sea are highly dependent on GNSS data. Errors resulting from poorly prepared GNSS measurements in the sea cause errors to accumulate during the post-processing of gravimetric data. Satellite data can be used to complement dedicated marine gravimetric campaigns and help improve the accuracy of gravimeter-recorded data.

The campaign was five times bounded in harbours to the land values (see sections 3.1 and 3.2). The preparation of the land reference point was accomplished by the teams from the country to which the harbour belongs. The final results of binding are visible in Figure 7.

The drift observed during the campaign was linear and low in value. Thus, the two-point continuous drift method was used to remove it instead of calculating the piecewise linear drift between each harbour. The data was filtered using a combined filtration method employing both Exact-Blackman FIR filter with 180 s window and Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) smoothing. In the effect of procedures applied, the free-air anomaly was calculated, which was shown on the Figure 8.

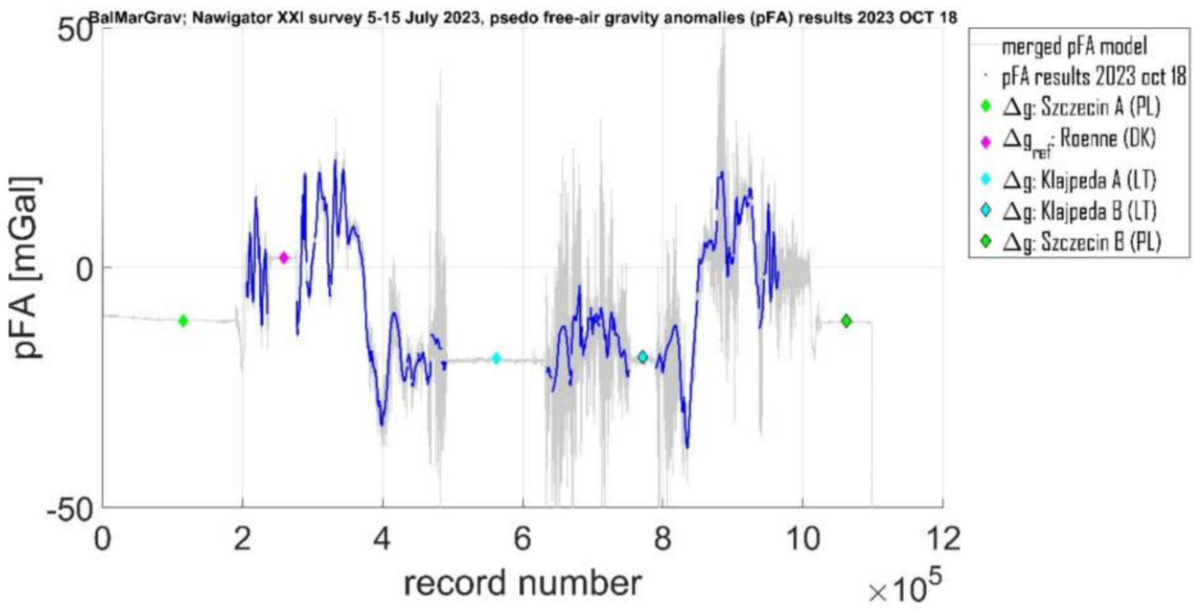

Figure 7: The comparison of fitting of pseudo-Free-air data collected during measurements to the land gravity values on the piers in harbours

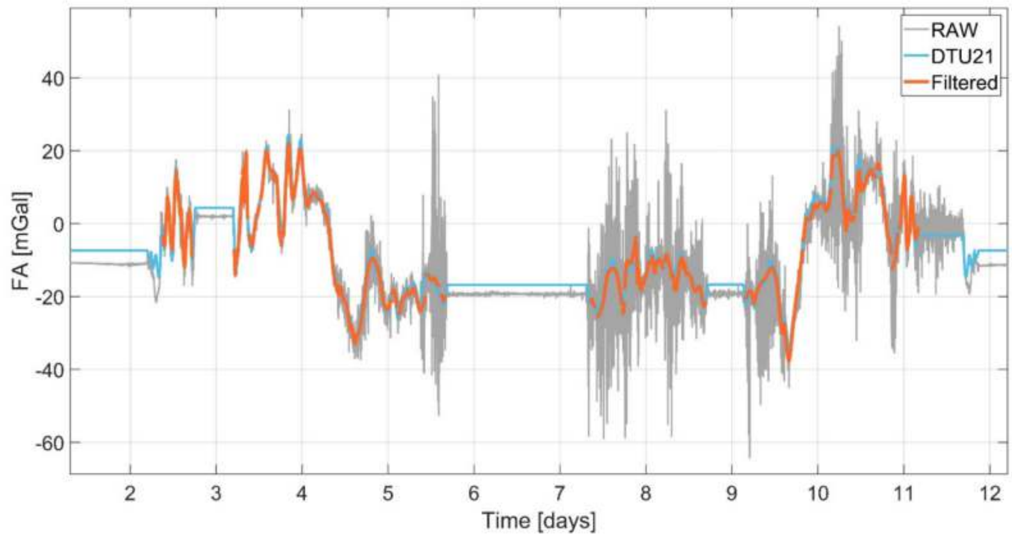

Figure 8: The comparison of pseudo-Free-air data, DTU 21 athymetric model and Raw gravimetric data

The spatial distribution of data marine gravity data after all filtration was applied is shown in Figure 9. We have a total of 30 internal crossing between lines, so the cross-difference statistics was calculated to check the internal consistency of measurements. The following statical parameters were found for cross differences:

- Mean: 0.18 mGal
- Standard deviation: 0.69 mGal
- Root mean square: 0.71 mGal

- Minimal: -1.01 mGal
- Maximal: 1.82 mGal

These statistics suggest that data internal consistency is good since the crossover standard deviation is significantly lower than 1 mGal. The 0.18 mGal mean suggests some bias in the data. However, it is not significant and will be most likely even reduced in the next processing, when more data will be collected in this region.

The estimation of external consistency requires comparison with other data sources available for the region. The multi-stage comparison was conducted. First, the whole dataset was compared to the altimetric models. The newts used model is shown in Figure 8. The shape of the marine gravity data is strongly correlated with the model. Only minor, short wavelength differences are present. This is explainable by the fact that altimetry cannot capture small regional features of the gravity field. Thus, these differences do not have to be the noise. Secondly, the data was compared against other modern marine gravity campaigns which are available in the area. The DENEB 2018 and NAWIGATOR XXI 2019 were chosen since they have significant overlap with the current campaign, and datasets from that campaigns are mature and well-validated. The spatial distribution for this campaign is shown in Figure 10. The crossover statistics with those campaigns are also promising since the max difference does not exceed the for them is 1.5 mGal.

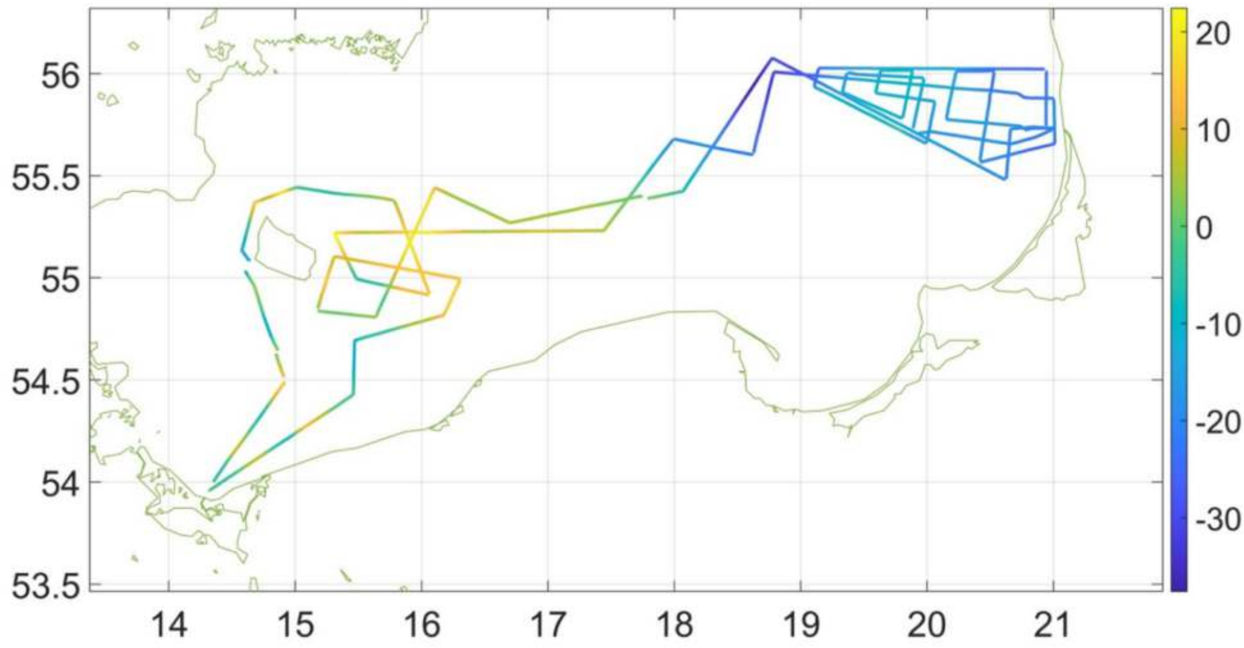

Figure 9: The spatial distribution of Free-air gravity anomalies calculated from the data collected during Nawigator XXI campaign in 2023

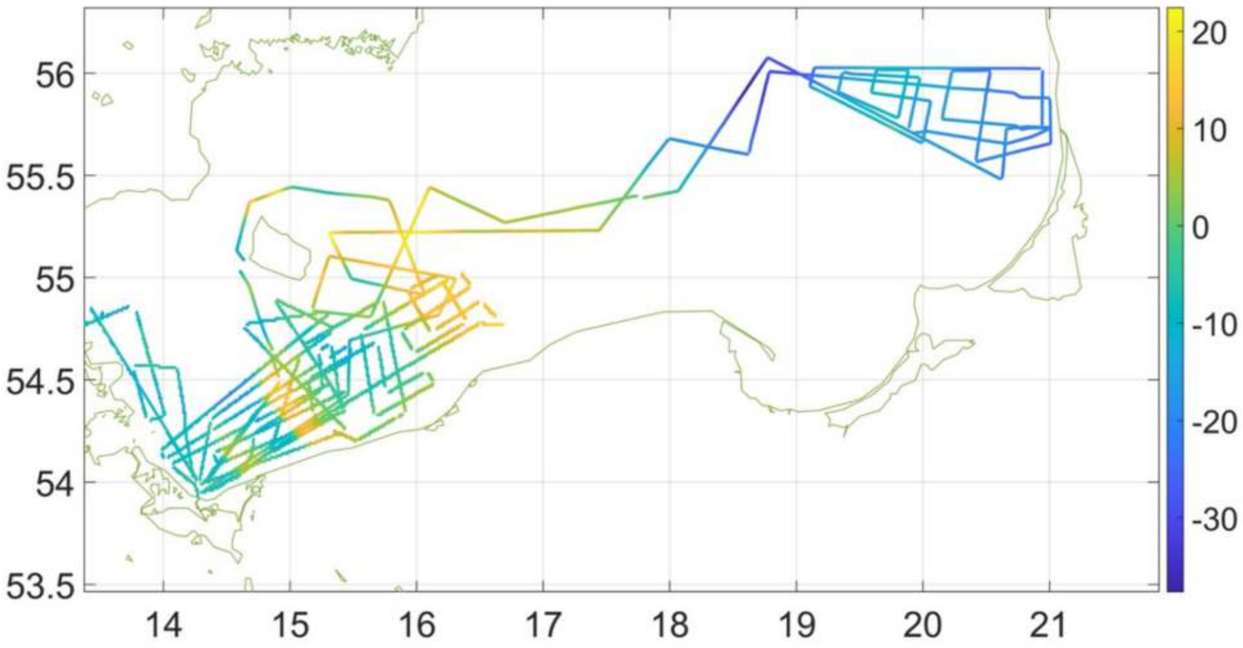

Figure 10: The spatial distribution of Free-air gravity anomalies calculated from the data collected during Navigator XXI campaign in 2023, Deneb in 2018 and Navigator XXI in 2019

3 Supporting terrestrial gravity survey

3.1 Poland-Lithuania-Latvia

The gravity surveys described in the report were conducted for the needs of the project with the main goal of providing reliable gravity reference values in the harbours, where marine gravimeters were used, both current and historic surveys. Two independent gravity campaigns were conducted by the team of the Institute of Geodesy and Cartography (Poland) – travel routes are presented in Fig. 11:

I. 2023.08.1-3 – Near the ports of Klaipeda (Lithuania), Liepaja and Riga (Latvia) – only absolute gravity measurements with additional vertical gravity gradient determinations with the use of A10-020 absolute gravimeter and LaCoste&Romberg G1012 and G1036 gravimeters (participants: P. Dykowski, M. Sękowski),

II. 2023.09.6-7 – Near the ports of Szczecin and Świnoujście – absolute gravity measurements, vertical gravity gradients as well as relative gravity surveys with the use of A10-020 absolute gravimeter and LaCoste&Romberg G1036 and G1084 gravimeters (participants: P. Dykowski, R. Michałowski).

The measurement methodology used was as follows:

- absolute gravity survey: two independent setups, 8 sets each with 120 drops performed every second (in total 1920 single drops per survey),
- vertical gravity gradient: using two gravimeters at the same time a schematic of ABABAB on a height difference 1 meter is performed. On each position at least two independent gravimeter readings are performed,

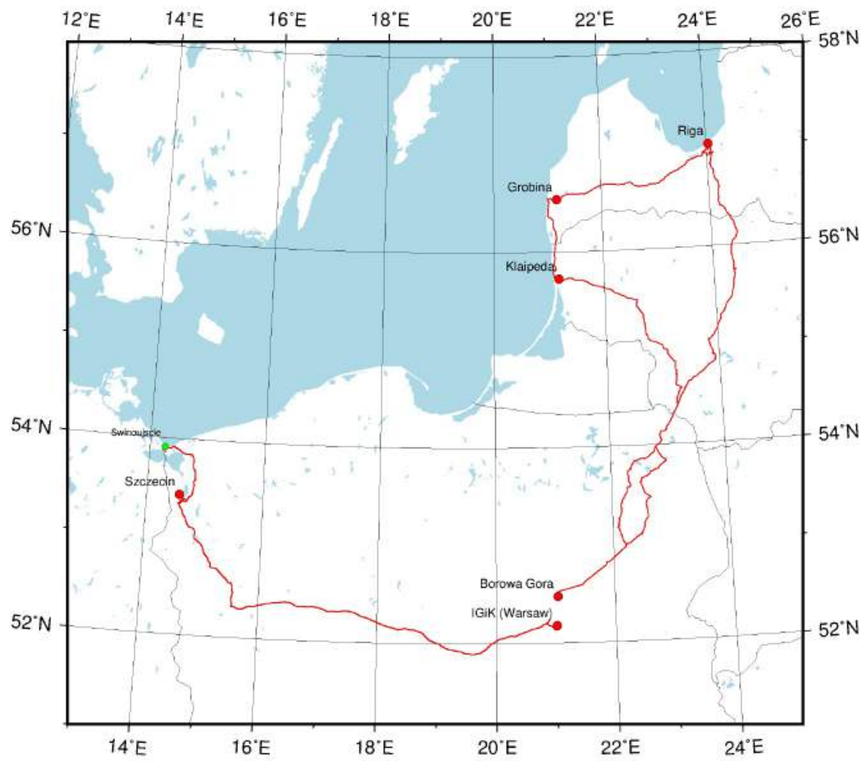

Figure 11: Travel routes and stations included in the 2023.08-09 gravity campaigns within the BalMarGrav project

- relative gravity survey: using two gravimeters at the same time a schematic of ABAB is performed. On each position at least three independent gravimeter readings are performed.

Figure 12: The absolute gravity stations: Grobina (GROB) (left) and Klaipeda (KLAI) (right)

Figure 13: The absolute gravity station Szczecin (SZCZ) (left) and the relative gravity station Świnoujście (PETR) (right)

Details about the location of absolute and relative gravity stations, as well as station location documentation are given in Appendix 2. And example of station locations are shown in Figures 12 and 13.

The results are given in accordance to the IGRS2020 Conventions related to the ITGRF gravity reference level. Provided gravity values are given in the conventional zero-tide system. Corrections include body tided (Tamura catalogue), ocean tidal loading (FES04), barometric correction with standard -0.3 μGal/hPa coefficient, polar motion correction (IERS bulletin B final values) as well as self-attraction and diffraction corrections. Also there are included the most up to date laser frequencies and rubidium oscillator frequencies as well as a verified barometer offset. An offset of -12 μGal was added to the final absolute gravity values to provide a link to the ITGRF gravity reference level. Absolute gravity measurements were reprocessed at the effective height and further reduced to the benchmark level using the true determined vertical gravity gradient. Errors are provided at k=1, 67% confidence level.

The results of the measurement are as follows:

I. Campaign I - absolute gravity surveys

  - Klaipeda (KLAI) – 2023.08.01
    Vertical gravity gradient: W_{zz} = -0.3040 $\pm$ 0.0059 mGal/m
    Absolute gravity value at benchmark level (0.0 cm): g_{0cm} = 981547.765 $\pm$ 0.009 mGal

- Grobina (GROB) – 2023.08.02
  Vertical gravity gradient: W_{zz} = -0.3137 ± 0.0087 mGal/m
  Absolute gravity value at benchmark level (0.0 cm): g_{0cm} = 981642.989 ± 0.009 mGal
- Riga (RIGA) – 2023.08.02
  Vertical gravity gradient: W_{zz} = -0.3036 ± 0.0039 mGal/m
  Absolute gravity value at benchmark level (0.0 cm): g_{0cm} = 981658.397 ± 0.007 mGal

II. Campaign II - absolute gravity surveys

- Szczecin (SZCZ) – 2023.09.06
  Vertical gravity gradient: Wzz = -0.3160 ± 0.0081 mGal/m
  Absolute gravity value at benchmark level (0.0 cm): g_{0cm} = 981357.018 ± 0.009 mGal

II. Campaign II - relative gravity surveys

- Szczecin (NAWI)
  g_{SZCZ} = 981357.018 ± 0.009 mGal
  $\Delta g_{SZCZ-NAWI}$ = 3.554 ± 0.012 mGal
  g_{NAWI} = 981360.572 ± 0.015 mGal

- Świnoujście (PETR)
  g_{DENE} = 981402.478 ± 0.009 mGal (IGiK, 2018 survey)
  $\Delta g_{DENE-PETR}$ = -0.237 ± 0.006 mGal
  g_{PETR} = 981402.242 ± 0.011 mGal

More details about the terrestrial marine gravity campaign can be found in Appendix 2.

3.2 Denmark

A one day relative gravity survey with two CG5s (CG5_GEK and CG5_GDK) has been done by Gabriel Strykowski and Nikolaj Hansen from the DTU Space, starting from the DTU Space in the morning on July 5, 2023, driving through southern Sweden to Ystad, taking a ferry boat to Rønne and back the same way in the afternoon. Relative survey was tied to the following AG stations: DTU abs, Tejn GNSS abs and Rønne Church.

Concerning the FG5/A10 g-values @ 0m the AG gravity survey with A10-19 had been carried out earlier this year, in 2023, where all AG stations in Bornholm (except Rønne Church) were remeasured. The last station was not measured because the AG meter broke down on the last day of AG survey. In parallel a relative campaign with 3 gravimeters was done to estimate the 2023 g-value additionally. Unfortunately, the results of A10-019 measurements indicate a systematic bias of -15 microGal or less (i.e. more negative) for all AG stations (also outside Bornholm) except for one where something else possibly happened. Some of these AG stations have a long history of stable measurements. This is relevant because the question is which absolute g-values to use in adjustment of relative gravity measurements. Finally, it was decided to discard the new measurements and use the existing pre-2023 reference values. They are shown in Table 1.

Table 1: The g values in mGal at the selected stations of the Danish gravimetric control network

Station	St #	g_{abs}@ 0m	Std. dev
DTU Space	1	981545.975	0.007
Tejn GNSS	3	981551.946	0.012
Rønne Church	4	981517.205	0.013

Table 2: The g values in mGal at the selected stations of the Danish gravimetric control network

Station	St #	g_{abs}@ 0m	Std. dev	g_{abs}@0m - g_{abs}@0m
DTU Space	1	981545.973	0.009	-0.002
Rønne Harbour	2	981517.036	0.009	-
Tejn GNSS	3	981551.946 - 0.003	0.012	-0.003
Rønne Church	4	981517.205 + 0.003	0.013	0.003

Two stations were fixed in the adjustment (in red below) at the above values, obtaining the g-value on the pier (st #2) presented in the Table 2. The adjusted value changed a bit for the reference stations, indicated as ±0.003 mGal (in red). The DTU Space was kept free in the adjustment and the estimated g-value fits nicely (within 2 microGals) the reference value. The deviations in mGal are indicated in green in the last column. This is kind of a sanity check.

Thus, the result is that the g-value for the point on the pier is: 981517.036 ± 0.009 mGal.

The coordinates of the point on the pier was measured by the RTK and they are estimated as:

ETRS89/UTM32N coordinates
N: 6120052.485 m
E: 863221.564 m
h: 36.05 m

These coordinates were transformed to the official DVR90 (orthometric-) heights, obtaining:

ETRS89+DVR90 coordinates
Lat (dd): 55.09379838
Lon (dd): 14.69465632
HDVR90: 1.5287 m

Subsequently, the free-air gravity anomaly for the point on the pier was computed as: $\Delta g_{ref} = 2.08$ mGal.

A sanity check by comparing this value with a point nearby from the gravity DB was made and it fits nicely. On July 5, 2023 at UTC 12:08 the difference in height between the pier and the water level was 1.60 m.

Acknowledgement

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BLUE ECONOMY BalMarGrav

2023-10-18

REPORT

Marine gravity measurements outside the Latvian coast, 2023

Contents

Gävle 2023
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Janis Kaminskis, Riga Technical University Latvia.

1 Introduction

In the period April 18 to June 15, 2023, a marine gravity campaign was conducted outside the Latvian coast. This campaign was performed within the BalMarGrav project by Lantmäteriet and the Latvian geospatial information agency (LGIA) with support from Riga Technical University. The main aim of the campaign was to collect new data which could be used within the BalMarGrav project to validate the historical marine data in the Latvian waters. In total, the campaign consisted of six weeks of measurements, during which the ship covered a total distance of about 15 000 km.

2 Preparations

The first task was to find a ship for the measurements. Initially, it was planned to use the hydrographic survey ship Kristians Dahls. However, a disadvantage with that ship would be that it would be a pure so-called piggy-back campaign, with very small possibilities to influence the route of the ship. The normal routes of a hydrographic survey (relatively short lines in a dense area) are not ideal for marine gravity measurements.

An alternative ship was found through the connections of LGIA to the Latvian Naval forces. They offered us to use one of their patrol boats: P-09 “Rezenke” (see Figure 2-1). With this ship we were able to highly influence the route. The ship still did its normal duty of monitoring Latvian waters during the campaign, which meant that occasionally they had to divert from the planned route to go off and do other tasks. Nevertheless, due to the long duration of the campaign, this meant that we were able to get an excellent coverage of the Latvian waters.

The installation of the gravimeter, Lantmäteriet’s marine gravimeter ZLS D13, was done in Riga on April 18, 2023, by Örjan Josefsson and Tobias Nilsson. The gravimeter was installed in a small storage room (see Figure 2-2) located relatively close to the center of the ship, which is the preferred placement of a marine gravimeter on a ship, however it was not possible to find a space that also was close to the sea level which is even more ideal. After the installation, a small test trip of about 45 minutes was made to confirm that everything worked fine. The LGIA employees who were going with the ship during the measurements received basic instructions on how to handle and operate the gravimeter.

Figure 2-1: The Latvian Naval Forces patrol boat P-09 "Rezekne", which was used in the campaign (source: https://www.flickr.com/photos/latvijas_armija/albums/72157642632471605/).

Figure 2-2: The ZLS D13 marine gravimeter installed on Rezekne.

3 The measurements

The campaign started on April 19 and ended on June 15, 2023. An employee from LGIA was going with the ship all the time to check that the gravimeter worked properly. A map of the planned route can be seen in Figure 3-1. The selected good parts are showed in Figure 3-2. There were two longer breaks in the measurements – May 12-18 and May 26-31 when the ship stayed in harbour – thus the campaign produced about six weeks of measurements. Furthermore, the ship made shorter harbour stops every 1-4 days, either in Riga or in Liepaja, to get harbour ties needed for calibrating the drift of the gravimeter.

In general, the weather was nice during the campaign, although there were a few days with stronger winds and larger waves. The gravimeter worked fine during most of the campaign. The only major problem was that the gravimeter computer crashed on June 6. With remote assistance from Örjan Josefsson, the computer and the gravimeter were restarted on June 7, and after that everything worked well until the end of the campaign.

After the end of the campaign, on Jun 16, 2023, the gravimeter was dismounted by Per-Anders Olsson and Thomas Eiderman from Lantmäteriet and brought back to Sweden.

LGIA personnel on board during the measurements:
Vents Zuševics, Toms Lūdumnieks, Elmārs Ozoliņš, Aigars Keiselis and Jānis Sakne.

BalMarGrav's partner, Riga Technical University, participated directly in the selection of the ships, installation of the marine gravimeter, preparation of measurements, removal of the gravimeter from the ship, as well as support measurements.

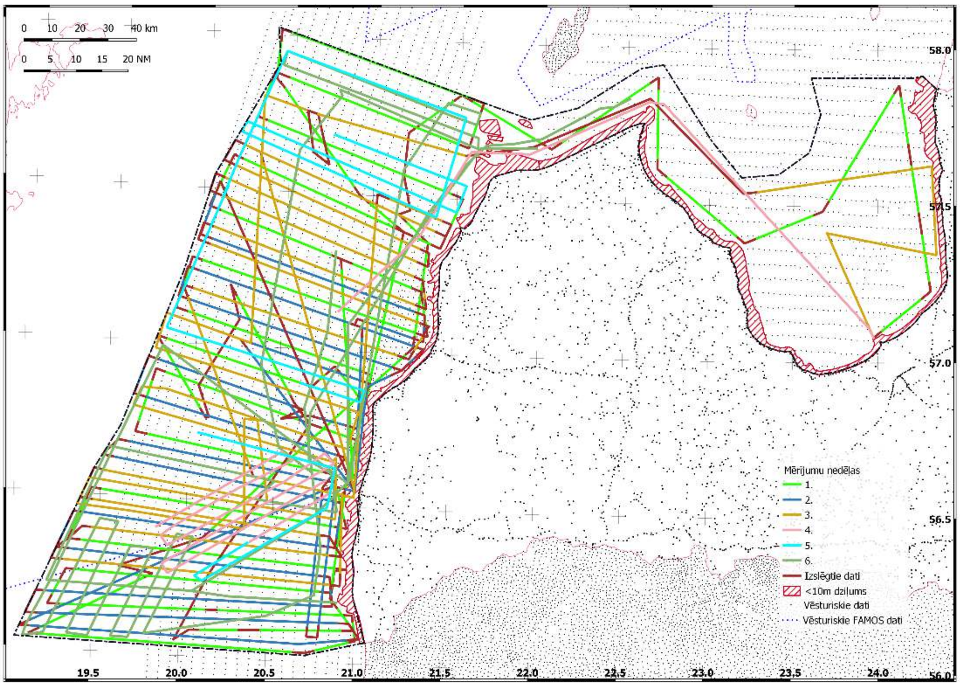

Figure 3-1: The planned routes covered by the ship during the campaign Different colors represent different weeks

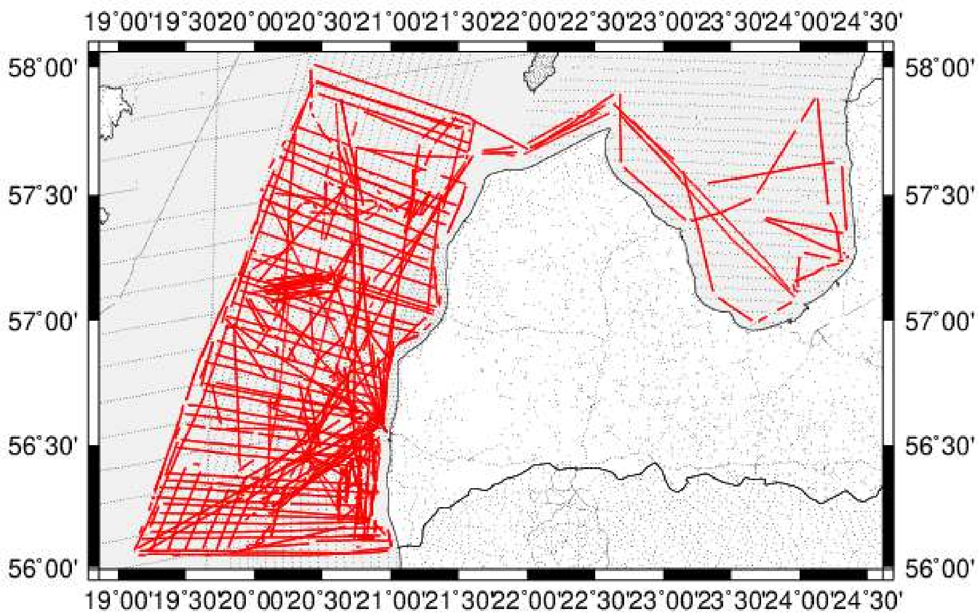

Figure 3-2: Selected parts with good gravity data.

4 Harbour ties

In order to calibrate the drift of the gravimeter, harbour visits need to be made every few days to a harbour point with known gravity. During the campaign, harbour visits was regularly made to the harbours in Riga and Liepaja. In total, the ship was docked at six different locations during the harbour visits, three in each harbour. Thus, the gravity values of these six points needed to be measured.

This was done by first doing absolute gravity measurements at points close to the harbours, this was done on August 1-3, 2023, by colleagues Institute of Geodesy and Cartography in Poland, using the A10-020 absolute gravimeter. Then the gravity at the harbour points were determined by doing relative gravity measurements between the absolute gravity points and the harbour points. The measurements in Liepaja were performed on May 22 and June 20-22 and the measurement in Riga were performed on June 26, all measurement were done by LGIA using two Scintrex instruments simultaneous CG-5-0333 and CG-6-0449.

5 Data analysis and Results

The data collected in the campaign was analyzed with an in-house software developed at Lantmäteriet. The data was carefully investigated to remove bad measurements, e.g., around turns, when the ship changing speed, or during bad weather.

The results were compared to the gridded data used for the NKG 2015 geoid model, see Figure 5-1. There are some small parts between the flight lines in the western part of the area where the new observations differ from the grid. That indicates some problem with the NKG 2015 grid between the flightlines. We can also note a few areas where our measurements consistently deviate from the NKG database, indicating problems with the old data. The new data will help to improve the gravity map and in the end the geoid.

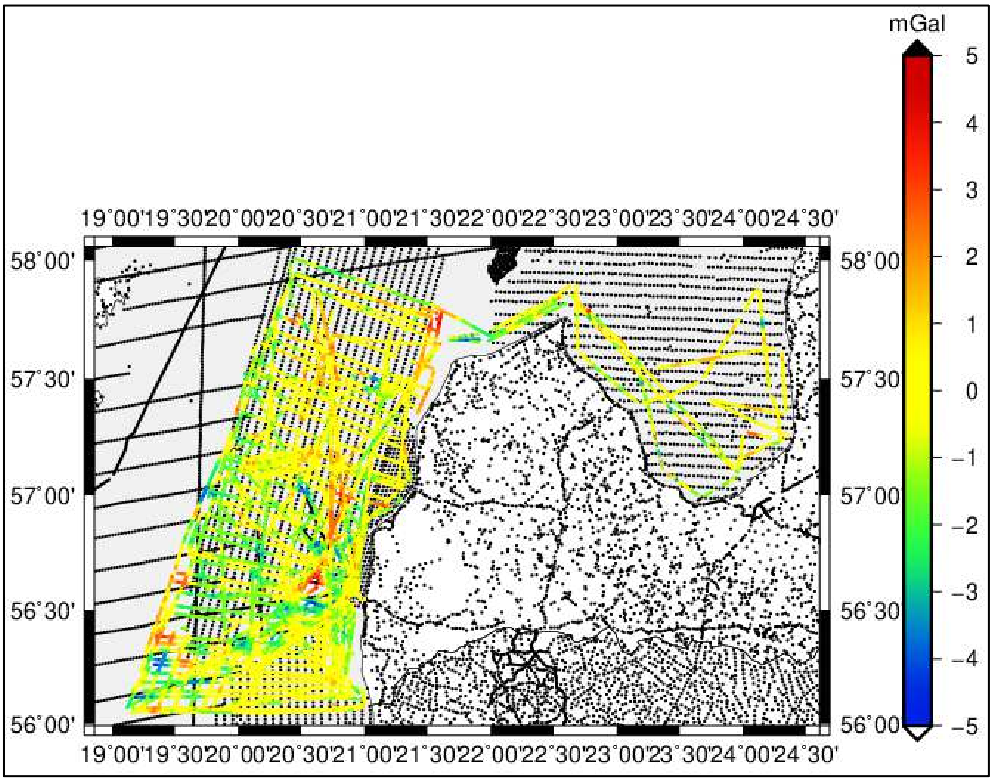

Figure 5-1: Results compared to NKG 2015 grid. NKG – Latvia measurements. Black dots represent already existing data points in the NKG gravity database.

Figure 5.2 shows the internal crossovers, i.e., comparison of the gravity values at points crossed by the ship several times during the campaign. The results look fine, the RMS (Root-Mean-Square) and the standard deviation for all crossover for selected lines are less than 0.9 mGal. Typically, we consider the results to be good if those values are less than 1 mGal.

Here are the statistics:

Nr of crossovers: 1506
Mean: -0.1298
Min: -4.2300
Max: 2.8600
StdDev: 0.8851
RMS: 0.8943

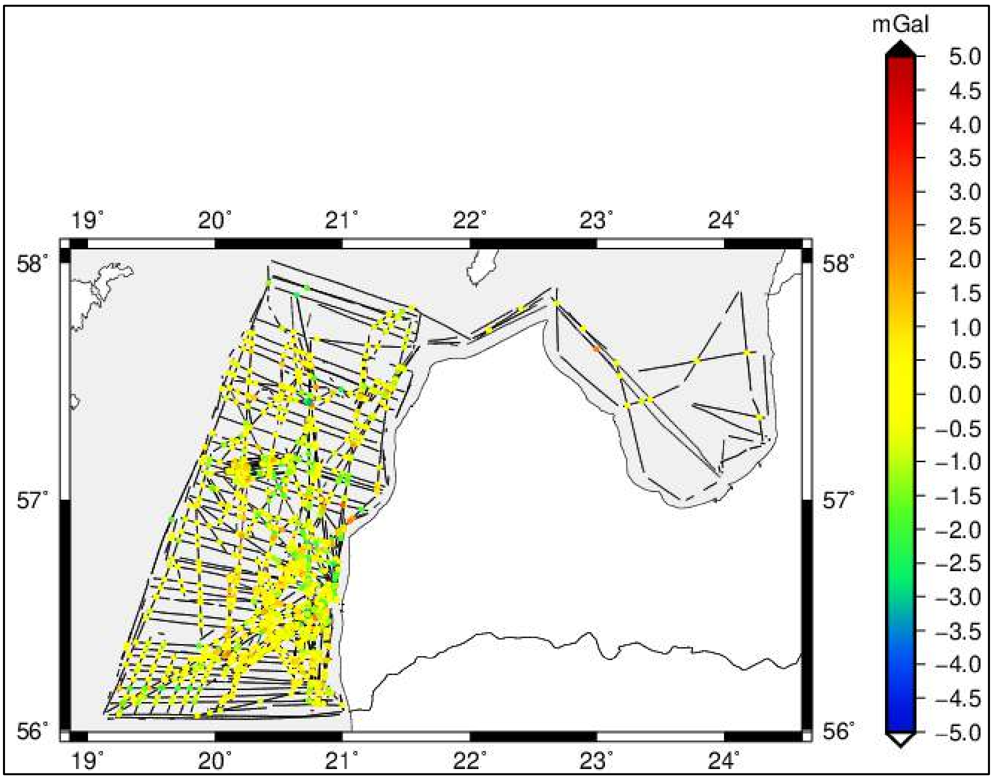

Figure 5-2: Internal Crossovers.

The results have been delivered to Gabriel Strykowski, DTU Space, in a standardized data format. He will include the data in the BalMarGrav part of the NKG database.

6 Acknowledgments

We are grateful to the Latvian Naval Forces and the crew of Rezekne for letting us use their ship for the measurements.

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Absolute and relative gravity measurements in the BalMarGrav project August-September 2023

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Warsaw, September 2023

Institution responsible for the survey

Institute of Geodesy and Cartography, Centre of Geodesy and Geodynamics

Survey team

PhD Przemysław Dykowski, PhD Marcin Sękowski, MSc Rafał Michałowski

Measurement methodology

- **Absolute gravity survey**

Two independent setups, 8 sets each with 120 drops performed every second (in total 1920 single drops per survey).

- **Vertical gravity gradient**

Using two gravimeters at the same time a schematic of ABABAB on a height difference ~1 meter is performed. On each position at least two independent gravimeter readings are performed.

- **Relative gravity survey**

Using two gravimeters at the same time a schematic of ABAB is performed. On each position at least three independent gravimeter readings are performed.

Gravity units used in the report

0.001 mGal = 1 μGal = $1 \cdot 10^{-8}$ m/s^2

Scope

The gravity surveys described in the report are related to the BalMarGrav project and were performed with a direct intent to provide reference gravity values for marine gravity measurements conducted in the project as well as historic marine gravity campaigns. Two independent gravity campaigns were conducted, travel routes are presented in Fig. 1.:

I. 2023.08.1-3 – Near the ports of Klaipeda (Lithuania), Liepaja and Riga (Latvia) – only absolute gravity measurements with additional vertical gravity gradient determinations with the use of A10-020 absolute gravimeter and LaCoste&Romberg G1012 and G1036 gravimeters (participants: P.Dykowski, M.Sękowski)

II. 2023.09.6-7 – Near the ports of Szczecin and Świnoujście – absolute gravity measurements, vertical gravity gradients as well as relative gravity surveys with the use of A10-020 absolute gravimeter and LaCoste&Romberg G1036 and G1084 gravimeters (participants: P.Dykowski, R.Michałowski)

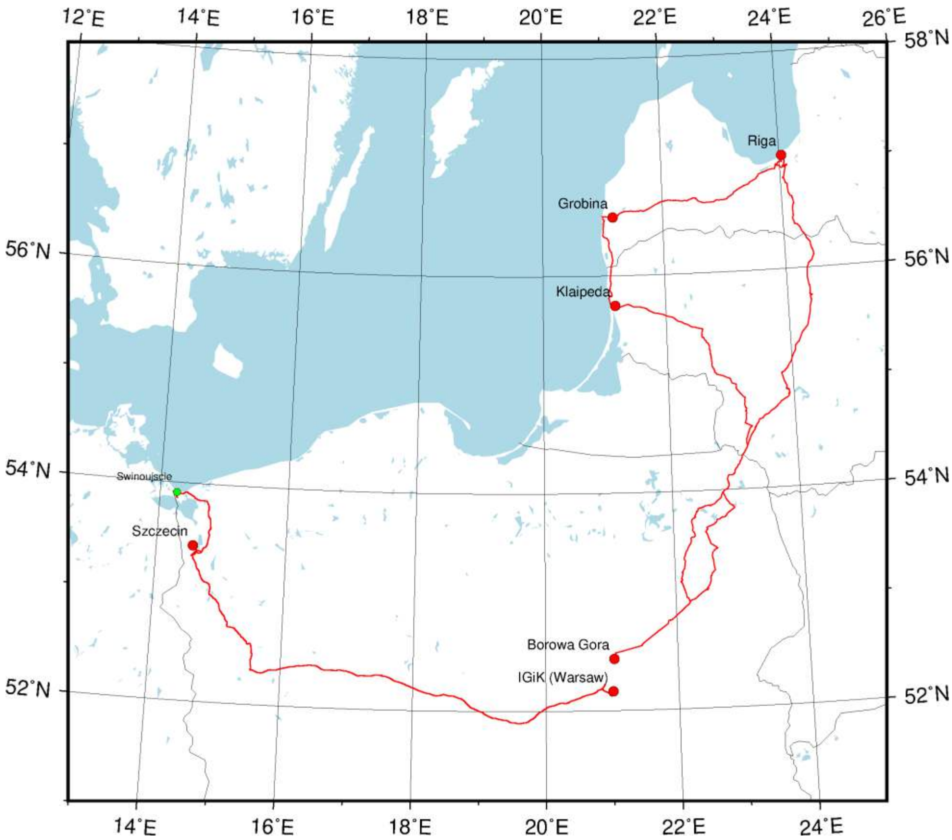


Fig.1. Travel routes and stations included in the 2023.08-09 gravity campaigns within BalMarGrav project

Information on stations and data used for the re-processing.

A group of location is enlisted and described below. For each location a photograph from the gravity survey is included in the appendix.

Absolute gravity stations:

- Klaipeda (KLAI)

  Latitude: 55.723444 °
  Longitude: 21.175222 °
  Height above sea level: 15.64 m

Location corresponds to the indoor absolute gravity station in Klaipeda in a military base. Coordinates and height are precisely determined.

- Grobina (GROB)

  Latitude: 56.536362 °
  Longitude: 21.168000 °
  Height above sea level: 23.5 m

Location corresponds to a field gravity station on the doorstep to a local school in Grobina, a city east of Liepaja. Coordinates and height are approximately determined within a few meters horizontally and 1 meter vertically.

- Riga (RIGA)

  Latitude: 57.041616 °
  Longitude: 24.038595 °

Height above sea level: 1.9 m

Location corresponds to a field gravity station under a steel shed in a military base in Riga. Coordinates and height are approximately determined within a few meters horizontally and 1 meter vertically.

- Szczecin (SZCZ)

  Latitude: 53.429430 °
  Longitude: 14.564945 °
  Height above sea level: 15.0 m

Location corresponds to a field gravity station on a concrete block (north of the 3 entry blocks) in the entrance to the "Rotunda Południowa" historical monument in Szczecin. Coordinates and height are approximately determined within a few meters horizontally and 1 meter vertically.

Relative gravity stations:

- Szczecin, pier value next to the Nawigator Vessel (NAWI)

  Latitude: 53.428720 °
  Longitude: 14.566492 °
  Height above sea level: 1.8 m

Location corresponds to the indicated by Gdańsk University of Technology pier position related to marine gravimeter position at the Nawigator XXI vessel of Maritime University of Szczecin. Coordinates and height are approximately determined within a few meters horizontally and 1 meter vertically. Relative gravity surveys to this location were conducted with respect to SZCZ absolute gravity station described above.

- Świnoujście, pier value related to the Petrobaltic marine gravity campaign 1978-1979 (PETR)

  Latitude: 53.907497 °
  Longitude: 14.260616 °
  Height above sea level: 2.0 m

Location corresponds to a pier location identified on a point description (included in the appendix) provided by the Polish Geological Institute – National Research Institute in relation to the Petrobaltic marine gravity measurement campaign conducted in 1979 in the Świnoujście pier of Władysław IV ("wybrzeże Władysława IV"). Coordinates and height are approximately determined within a few meters horizontally and 1 meter vertically. Relative gravity surveys to this location were conducted with respect to absolute gravity measurement conducted on the same pier by IGiK in 2018 within a contract with German BKG in relation to marine gravity survey by the Deneb vessel (code DENE). In the processing the absolute gravity value obtained in 2018 was corrected for the offset relation to ITGRF of -8.9 μGal.

SURVEY RESULTS

Reprocessing explanation:

The results are given in accordance to the IGRS2020 Conventions related to the ITGRF gravity reference level. Provided gravity values are given in the conventional zero-tide system. Corrections include body tided (Tamura catalogue), ocean tidal loading (FES04), barometric correction with standard -0.3 µGal/hPa coefficient, polar motion correction (IERS bulletin B final values) as well as self-attraction and diffraction corrections. Also there are included the most up to date laser frequencies and rubidium oscillator frequencies as well as a verified barometer offset. An offset of -12 µGal was added to the final absolute gravity values to provide a link to the ITGRF gravity reference level. Absolute gravity measurements were reprocessed at the effective height and further reduced to the benchmark level using the true determined vertical gravity gradient.

Errors are provided at k=1, 67% confidence level.

Campaign I.

Absolute gravity surveys

- **Klaipeda (KLAI) – 2023.08.01**

Vertical gravity gradient:

W_{zz} = -0.3040 ± 0.0059 mGal/m

Absolute gravity value at benchmark level (0.0 cm)

g_{0cm} = 981547.765 ± 0.009 mGal

- **Grobina (GROB) – 2023.08.02**

Vertical gravity gradient:

W_{zz} = -0.3137 ± 0.0087 mGal/m

Absolute gravity value at benchmark level (0.0 cm)

g_{0cm} = 981642.989 ± 0.009 mGal

- Riga (RIGA) – 2023.08.02

Vertical gravity gradient:

W_{zz} = -0.3036 ± 0.0039 mGal/m

Absolute gravity value at benchmark level (0.0 cm)

g_{0cm} = 981658.397 ± 0.007 mGal

Campaign II.

Absolute gravity surveys

- **Szczecin (SZCZ) – 2023.09.06**

Vertical gravity gradient:

W_{zz} = -0.3160 ± 0.0081 mGal/m

Absolute gravity value at benchmark level (0.0 cm)

g_{0cm} = 981357.018 ± 0.009 mGal

Relative gravity surveys

- **Szczecin (NAWI)**

g_{SZCZ} = 981357.018 ± 0.009 mGal

$\Delta g_{SZCZ-NAWI}$ = 3.554 ± 0.012 mGal

g_{NAWI} = 981360.572 ± 0.015 mGal

- **Świnoujście (PETR)**

g_{DENE} = 981402.478 ± 0.009 mGal (IGiK, 2018 survey)

$\Delta g_{DENE-PETR}$ = -0.237 ± 0.006 mGal

g_{PETR} = 981402.242 ± 0.011 mGal

All raw data files related to this report are in the possession of the Institute of Geodesy and Cartography.

Appendix. Station location documentation:

Klaipeda (KLAI)

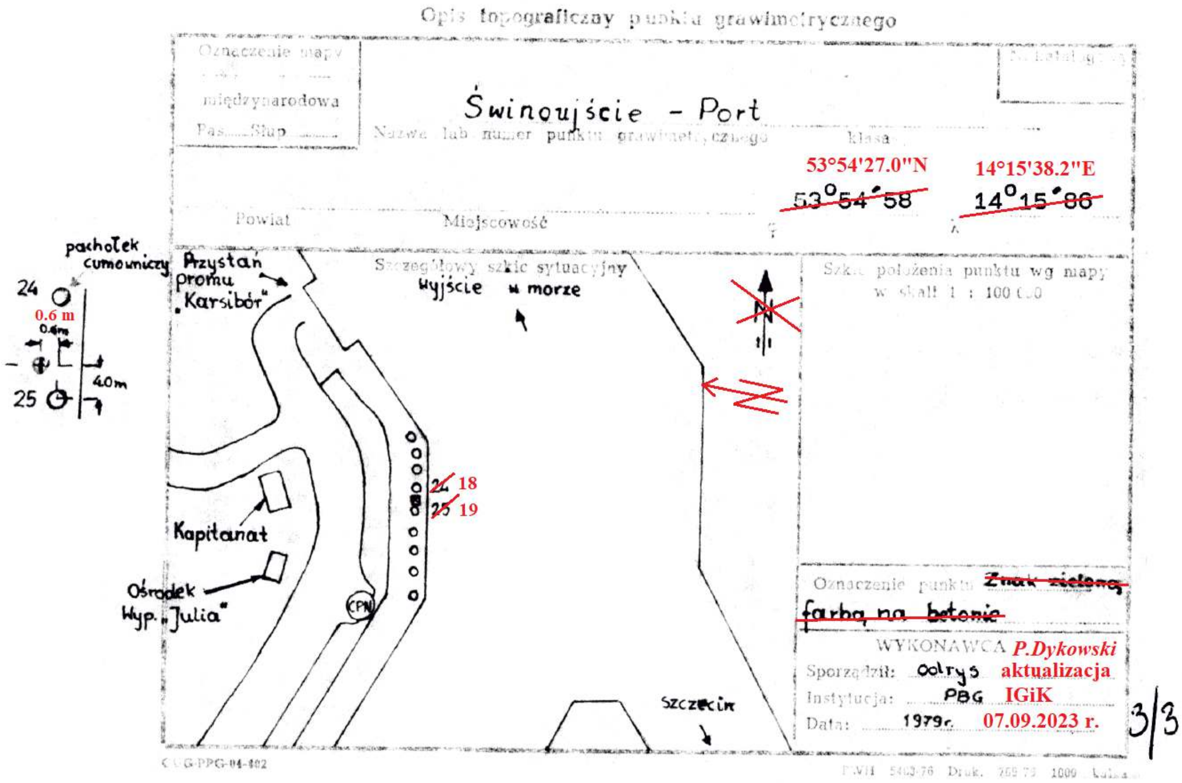
Grobina (GROB)

Riga (RIGA)

Szczecin (SZCZ)

Szczecin (NAWI)

Świnoujście (PETR)



Świnoujście (PETR) – opis topograficzny, aktualizacja 07.09.2023