ISSN 2029-6991 / eISSN 2029-7009

VILNIUS TECH
Vilnius Gediminas Technical University

GEODESY and CARTOGRAPHY

2025
Volume 51
Issue 2
Pages 81–87
https://doi.org/10.3846/gac.2025.23991

UDC 528.27

HARMONIZATION OF MARINE GRAVITY DATA IN EASTERN BALTIC

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Article History:
- received 21 July 2024
- accepted 28 May 2025

Abstract. Marine gravity datasets covering areas of state scale typically are made up of data that has been surveyed over multiple campaigns. These campaigns often take place many years apart, are of varying resolution and accuracy. This is due to ship-borne campaigns being much more expensive and time consuming than the ones on land; because of this, there is added value in validating and possibly correcting older data sets.

Over the course of recent BalMarGrav marine gravity project, dense, high quality gravity data was obtained covering most of the Latvian exclusive economic zone. The new data have been compared to campaigns, both as means of new data validation, and to check for possible biases among older data sets. Purpose of this research is to further the effort, to provide wider coverage of old marine gravity points, to test automated gravity point digitization, and to perform inter-campaign comparisons, using new, filtered and more precise data.

Data recovered during this research covers the previous data gaps between sets used in previous research. Using a more complete data coverage can improve new campaign data set validation and provide insights on inter-campaign biases within older data. Recovered data cover shallow coastal areas, where gravity mapping was not done over BalMarGrav project. Thus, by applying correctional values geoid errors can be minimized in the problematic transition zone between terrestrial and marine data.

Survey reports containing 20th century marine gravity point data were digitized, using optical character recognition. Gravity point values were transferred to sea surface and transformed to modern reference frames. Both modern and historic marine gravity data were filtered for gross errors and bias tracks. Data set robustness was checked, using leave-one-out cross validation. After processing, a comparison was made between old and new data.

Results present re-processed and filtered marine gravity datasets, and their comparison statistics. Comparison statistics before and after filtering reveal the increased accuracy and precision of filtered data. Mean comparison values reveal inter-campaign biases and provide correction values, which can increase data accuracy for use as input in future research and surface modelling.

Keywords: gravity, heights, data harmonization, navigation, cross-validation, quasigeoid.

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Notations

Variables and functions

g_{obs} – observed gravity;

$\frac{\Delta g}{\Delta z}$ – vertical gravity gradient;

H – normal height;

ζ – height anomaly.

Abbreviations

CV – Crossvalidation;
LOO-CV – Leave-One-Out Crossvalidation;
OCR – Optical Character Recognition;
NKG – Nordic Geodetic Commission.

1. Introduction

Pointwise gravity values, when transferred to sea level, serve as the main input data for transformation models, used in modern positioning infrastructure. To reduce the need for logistically difficult, high-cost new data acquisition, older data sets can be brought up to date, using new data acquired in controlled conditions (Ellmann et al., 2011). Updated historical data can be used to improve national (Huang & Véronneau, 2013; Türk et al., 2011) and regional (Featherstone et al., 2018) geoid modelling. Baltic sea gravity data quality, due to the intensive use of waterways, is of particular interest for development of region's economy.

Study area covers part of Baltic sea belonging to Exclusive Economic Zones of Latvia and Lithuania, to the west of Irbe strait and Curonian lagoon. Historical development of the gravity data coverage in study area has been extensively covered in the review of historical datasets of Interreg Europe's *Homogenized Marine Gravity Maps of Souther and Eastern Baltic Sea for Modern 3D Applications in Marine Geodesy, Geology and Navigation* (BalMarGrav) project (Wilde-Piórko et al., 2023a).

Much of the Eastern Baltic marine territory has been surveyed in the timespan between years 1966 and 1977 (Aleksashin et al., 1968; Degtyar et al., 1969, 1970, 1972; Degtyar & Dorogan, 1971; Karpitsky et al., 1973; Kovrigin et al., 1974; Lokshin et al., 1975, 1976; Mamoshin & Schipachov, 1977; Haritonov, 1979). Across these 20th century campaigns, asides from changes in instruments, methodology stayed the same. Pointwise gravity observations were made on the sea floor, using various soviet era gravimeter models. Original reports estimate the post-adjustment value accuracy from 0.3 mGal (Kovrigin et al., 1974) to 0.5 mGal (Aleksashin et al., 1968). Radio triangulation was used for positioning with estimated precision within couple of 10s of meters. Temporary reference points were established on seabed, which were tied to points on piers, closed runs were performed with validation stations between separate ship runs and adjacent data from previous campaigns.

Data from years 1968/1969/1970 has so far been available on the regional Nordic Geodetic Commission Gravity Data Base, in multiple copies (all three years as data source #372, and part of 1968 results as #338). In 1977 a much larger area, covering Latvian and Estonian marine areas between 56.2° and 58.7° latitude, was surveyed (source #615). The last seabed marine survey of 20th century within study area was carried out in 1991 (source #345), covering 30 km wide area along the coastline between 56.5° and 57.5° latitude with 2.5 km data step (Spetzgeofizika, 1992). Data partially overlaps with campaign of 1977 (#615). These datasets so far have been used as input of various national and regional height transformation surfaces (Ågren et al., 2016; Ellmann & Oja, 2018). Data of campaign 1976 (source #622) was first digitized during the BalMarGrav project.

Aerogravity campaign reported by Forsberg et al. (2001) can be considered as the start of modern gravity observations in Eastern Baltic; data of this campaign partially covers the study area. Adjacent to study area, numerous marine gravity surveys were made as part of the project *Finalising Surveys for the Baltic Motorways of the Sea (FAMOS)*, see Förste et al. (2020) for a comprehensive overview. Two isolated routes cross study area and dataset of 1977 west of port town of Liepāja. Research based on data acquired during the project, focusing on geoid height determination and height anomaly modelling was performed by Varbla et al. (2017) in Estonian marine territory, Saari et al. (2021) within Gulf of Finland; Liebsch et al. (2023) implemented all at-the-moment available data as input for BSCD2000 height transformation surface.

In 2023, extensive surveys of study area were made as a part of the wider BalMarGrav initiative (Wilde-Piórko, 2023b). For the survey of Latvian marine area, including study area, 6 weeks of continuos gravity obervations, were made over six weeks, totalling around 8000 nautical miles of ship track data (source #621). The mapping authority of Sweden Lantmäteriet provided the ZLS marine gravimeter, instructions for operating in field, and performed the processing of acquired data. Standard deviation of post-processing internal track crossover value is reported as 0.9 mGal. For a more detailed descriptions, see BalMarGrav modern campaign report (Wilde-Piórko et al., 2023b). Since 2021, annual surveys have been made in the Lithuanian territorial waters (Popovas et al., 2024). In this research, only modern data from source #621 is used for analysis.

Over the course of BalMarGrav project, historical datasets were checked for bias against modern survey values (Schwabe, 2024; Wilde-Piórko et al., 2023b); when compared to modern source #621, mean value of comparisons was found below 0.5 mGal for most; –0.77 mGal value was found for source #372. Updated historical datasets were used to create a grid of Bouguer and Free air anomaly surfaces (Varbla, 2024; Wilde-Piórko et al., 2023b).

Comparison statistics hint at varying, sub-mGal bias between older data sources, which can be seen the most when looking at source #338 and #372, supposedly digitized from the same observation report. Dataset #622 has been added to the Nordic Geodetic commission's gravity database, however, procedures of digitization and transformations applied are unavailable. Digitizing the aforementioned datasets within a single effort, could possibly reduce inter-campaign bias, leading to laterally smoother modelling outputs. Additional filtering of the modern data source #621 could remove biased ship track influence on dataset statistics; this could be observed as improvement of data comparison results.

2. Methods

Elimination of errors within marine gravity data was done in two steps; first, manually; afterwards, for a quantitative approach, cross validation can be used for the same goals (Märdla et al., 2017). Usually, in cross validation when using the same data set for training and testing, overfitting is a valid cause for concern. On the other end of the spectrum, lot of attention is usually paid to the training of the model (Arlot & Celisse, 2010). Taking in mind that within research the main purpose of CV was to automatize gross error and bias run identification, author chose to ignore these issues and employ a simplified interpolation model. Leave-one-out cross-validation was implemented, using the *LeaveOneOut* module from Python library *scikit-learn* and 2nd order polynomial for the training dataset. CV was performed before and after modern data filtering, to evaluate the improvements from manual and automatic error elimination, as well as during the historical data digitization, to check for possible input errors. For results residual values at test points here used to calculate base statistics. Residuals exceeding 3σ values were flagged as biased data. Some false positives were flagged in areas identified as local anomalies, using 2023 datasets, as well as around edges of campaign area.

Historical report digitization was achieved, using optical character recognition engine *Tesseract*. Extracted data values were transformed to normal anomalies, using Chebychev's approximation of Somigliana formula, with GRS80 parameters up to 4th parameter. Gravity anomalies were continuated to sea level, after Wilde-Piórko et al. (2023a),

$$g_{h=0} = g_{obs} + \left(\frac{\Delta g}{\mathrm{X}z} - 4\pi G\rho\right)\times H, \tag{1}$$

where $\frac{\Delta g}{\Delta z} = 0.308\ \mathrm{mGal/m}$ and seawater density is assumed $\rho = 1.010\ \mathrm{t/m^3}$. Point values were transformed to modern reference frame, using constant correction –14.0 mGal. Values of campaign 1976 were already given in IGSN71 reference frame. For the campaign of 1969/1970, where point coordinates were given only in Coordinate System of 1942, transformation was performed to LKS-92 geodetic coordinates.

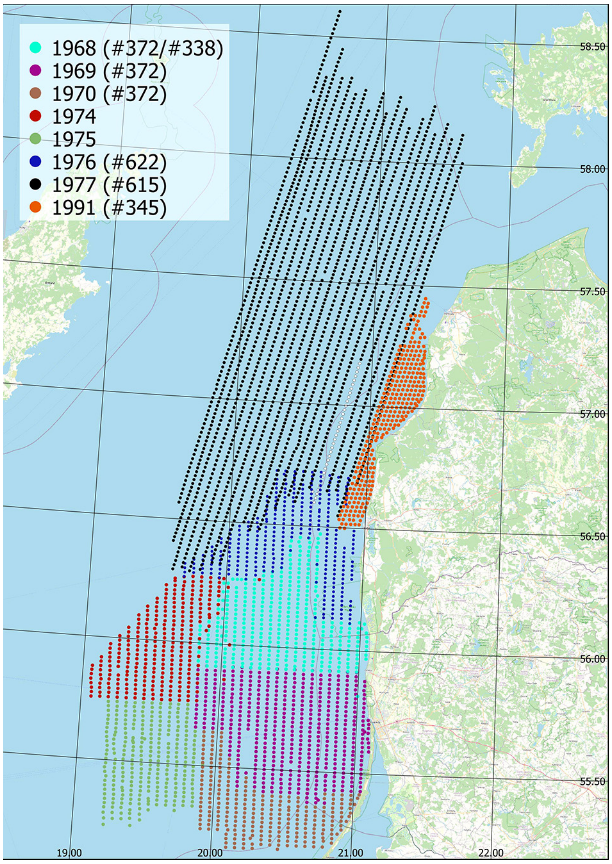
New and historical gravity data comparisons were made, using methods laid out during BalMarGrav project (Schwabe, 2024; Varbla, 2024). Historical gravity datasets were gridded to surfaces, using Least Squares Collocation available on *GRAVSOFT* library's module *GEOGRID,* using up to 100 nearest points and Correlation length value $\chi_{1/2} = 15\ \mathrm{km}$. Free air anomaly values were used for comparison (contrary to Bouguer anomalies used in BalMarGrav project). 2023 data values were then compared to sampled values from historical free air anomaly surface. Differences between gridded historical data surfaces and observed modern point values were used in calculating base statistics for each aera of historical campaign data set used in the comparison. To evaluate cross-validation effect on data set accuracy, comparisons were performed with both unfiltered and filtered 2023 (#621) data. Project FAMOS data within study area was not used in comparisons.

Historical datasets overlapping each other were compared to each other in the same manner. For datasets with observation points repeated between campaigns (years 1968, 1969, 1970, 1974, 1975, 1976) point values were compared directly.

3. Historical gravity data modernization

Motivating the research, reports of gravity surveys, providing continuous cover over Baltic sea southeast of 57.5°N/19.5°E, were discovered in the State geology fund of Latvia. One such campaign of 1974 falls within study area, to the west of data source #338(1969). Each report's catalogue includes point coordinates (arcsec^{-1} accuracy) in geodetic or 1942 coordinate system, sea depth (m^{-1} accuracy) and observed gravity (mGal^{-2} accuracy) values. In the reports, post processing MSE of gravity points is estimated to be 0.3 mGal (0.1 mGal in the case of #345/1991). Due to necessary transformations and instrument limitations, it is widely accepted that 20$^{\text{th}}$ century data precision should can be expected to be around 1 mGal (Wilde-Piórko et al., 2023a). Alongside the previously unpublished campaigns, data from adjacent areas, namely sources #338(1969), #372(1969), #622(1976) were re-digitized as well; all data were subjected to the same transformations. Campaigns of 1968, 1969, 1974 and 1976 have points with shared repeated measurement points over multiple campaigns. For the entire soviet data coverage in study area see Figure 1.

OCR recognition success rate varies depending on typewritten source quality. Results can be increased substantially by providing high quality, orthometric document scans. Typewritten data proved to contain a large amount of human input error, so alternative verification was proven to be necessary.



Note: 20th century marine gravity datasets denoted by campaign year. Campaign field reports referenced for each campaign are dated to the following year. Historical data points eliminated through cross validation in white.

Figure 1. Study area

4. Modern gravity data filtering

During BalMarGrav marine gravity campaign, over the span of six weeks in May/June 2023, 10 separate survey runs were made (marked by reference measurements at one out of five reference points, located on two different piers in Liepaja and one pier in Riga). Each run is composed of between 10 and 30 separate tracks – longer, straight sections traversed at constant speed, during which main data acquisition happens. In case of extreme weather, technical issues or rescue operations, track traverses were interrupted by short detours; ship was intermittently set to drift for extended period of time.

Manual inspection of post processing data suggested inter-track bias within data set. Also, high frequency undulations of measures values were seen at separate tracks, which seem to represent instrument errors. Track crossover analyses performed during BalMarGrav project seemed to indicate areas of high frequency of inter-track bias; because of this, it was decided that additional filtering of the dataset should be done.

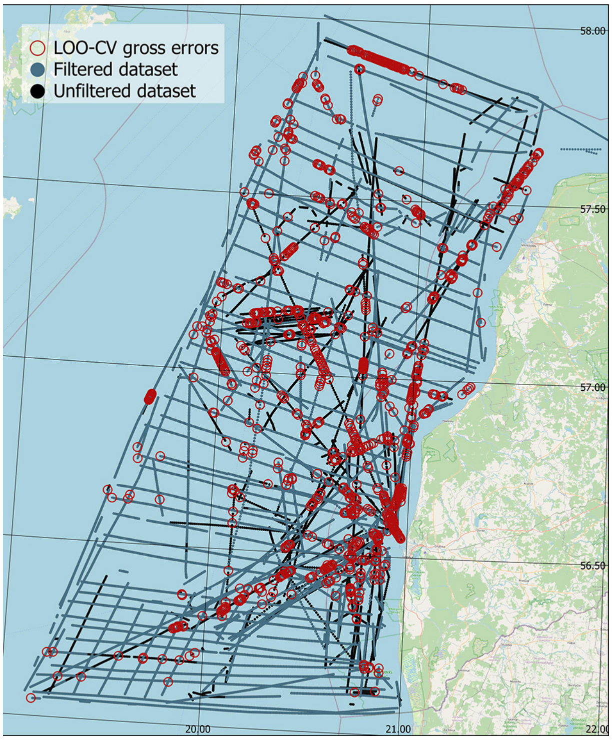
Table 1 shows the percentage of data eliminated during filtering, per dataset. As a means to flag errors, cross validation seems to work the best on track crossovers, indicating discontinuities; Figure 2 shows flagged points associate strongly with diagonal "transit" routes, which were high speed transfers between piers and survey site. Historical datasets seem to be much less useful for such methods, hence only a few gross errors were identified. CV was mostly used here to flag input errors.

Table 1. Data count before and after cleanup

Year	n, original	n, post-CV	% data eliminated
2023	21821	15171	30.47
1977	2030	1996	1.67

5. Modern and historical data comparison

After data filtering and uniform digitization, comparisons were made between historical data and 2023 campaign results. To evaluate the impact of data filtering, additional comparisons were performed, using unfiltered data of 2023. Additional comparisons were made between overlapping historical datasets. The base statistics of comparisons are given on Table 2.



Note: Observation points flagged as CV errors in red. Eliminated biased tracks in black.

Figure 2. 2023 marine campaign data before and after data filtering

When comparing campaign of 1969 to adjacent data, we see the same bias, which was first identified between

Table 2. Statistics of dataset comparisons between modern and historical datasets, and between overlapping historical datasets. Mean value increase with filtered data imply more accurate comparison

Modern and historical dataset comparisons						
Source	n	Mean	Median	SD	Min	Max
621_unfiltered-1968	1966	–0.03	0.03	0.56	–1.92	2.98
621_filtered-1968	1743	–0.02	0.02	0.54	–1.68	1.86
621_unfiltered-1974	680	0.05	0.17	0.70	–1.90	1.74
621_filtered-1974	642	0.15	0.28	0.64	–2.01	1.74
621_unfiltered-1976	3573	0.13	0.14	0.71	–4.95	3.67
621_filtered-1976	2353	0.21	0.2	0.55	–1.70	2.45
621_unfiltered-1977	10959	–0.38	–0.39	1.04	–10.9	4.22
621_filtered-1977	7319	–0.50	–0.51	0.97	–4.29	4.22
621_unfiltered-1991	1143	–0.07	–0.1	0.95	–2.97	4.12
621_filtered-1991	495	–0.08	–0.14	0.80	–2.97	3.87
Historical campaign inter-comparisons						
1968–1969	19	0.89	0.89	0.34	0.35	1.57
1970–1969	23	0.89	0.89	0.43	–0.44	1.79
1977–1976	81	0.99	0.98	1.07	–1.27	6.22
1977–1991	36	1.59	1.56	1.09	–0.63	3.51
1991–1977	42	–1.67	–1.65	1.12	–1.05	3.57
1968–1974	11	0.02	0.02	0.42	–0.68	0.68

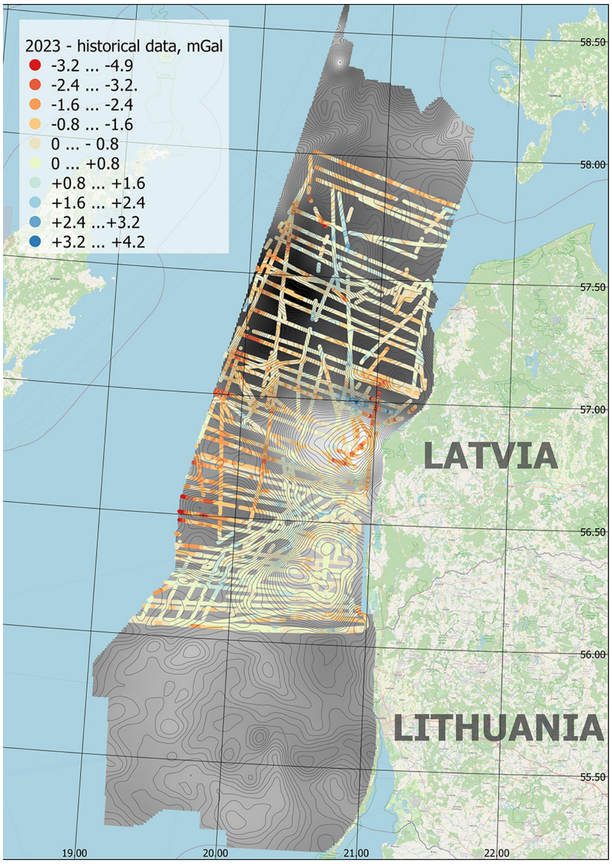
sources #338 and #372 in BalMarGrav project between –0.77 and –0.88 mGal. Again, when comparing the adjacent datasets (1968, 1976) to modern data, both filtered and unfiltered data provide good agreement.

LOO-CV based filtering has improved data performance, where all 20th century data sources now show better agreement with campaign of 2023. Filtering the data has resulted in reducing the range and standard deviation of difference values. Lower range of differences when comparing historical data to unfiltered dataset could indicate the positive impact of repeated, unified digitalization effort. A possible explanation for the increased mean and median values would be that in unfiltered data, noisy, normally distributed data overshadow the actual biases between modern observations and historic data. Since over the course of this research data has been independently digitized and transformed, we can conclude that the bias of dataset #372 is most probably due to error within observed values themselves. To the problem that bias is present in the entire source #372, not just southern part (surveyed in 1969), we can hypothesize that at some point after digitization of both 1968–1970 data, 1968 and 1970 data must have been recalculated, using correction values from biased 1969 dataset, creating the biased data source #338. Since at the time data source was isolated and there hadn't been appropriate validation data available until BalMarGrav, error has been propagated into further work. Such findings especially underline the value and opportunities projects like BalMarGrav provide to scientific community. With new data surveys becoming available due to campaigns in Lithuanian marine area, further comparisons would help with validating digitized data of campaigns of 1975/1974.

6. New data influence on height conversion

Regional quasigeoid solutions are available in the study area, such as NKG2015 quasigeoid (Ågren et al., 2016) and BSCD2000 height conversion surface (Liebsch et al., 2023). These model inputs are based on the soviet era data reviewed in this paper, and available from the NKG Gravity Data Base. In order to test the improvements new data can provide in height conversion, a new model was made for the study area, tied to EVRS realization in Latvia LAS-2000,5, which in this paper will be referred to as *Model'25*. Within study area, 2023 gravity data and historical data digitized within this research is used for gravity input. A correction value of –0.89 mGal has been applied to data of 1969. 1977 data is omitted from input, with the exception in Estonian marine area. Model was gridded, using Least Squares Collocation and correlation length of 22 km. GO_CONS_GCF_DIR_R6 model at maximum order 240 was used for global geopotential anomaly field reduction (Bruinsma et al., 2014).

Model'25 was compared to NKG2015 and BSCD2000 quasigeoid grids (Figure 4). Statistics on differences between models within study area are given in Table 3.



Note: Differences between free air anomaly values of 2023 campaign pointwise data and gridded 20th century data are given in colour. Free air anomaly grid of study area in background.

Figure 3. Dataset comparison results

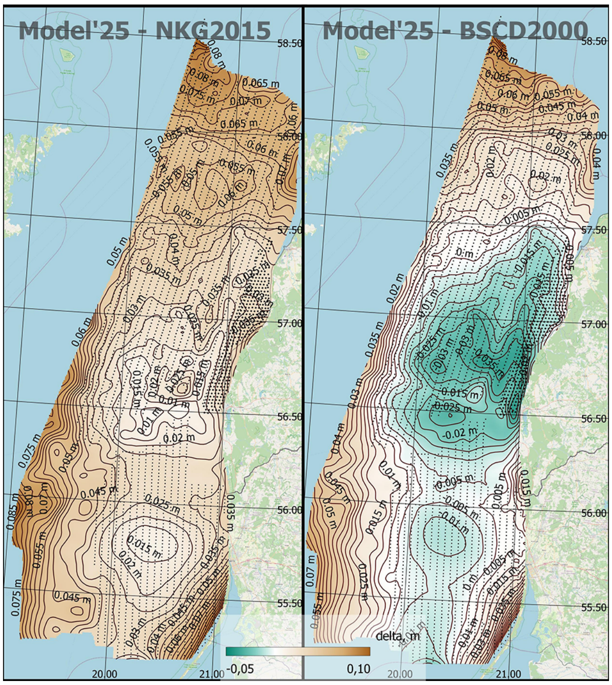
Table 3. Statistics of height anomaly differences in study area, in meters

Model name	Mean	Stdev	Min	Max
Model25-NKG2015	0.040	0.018	0.005	0.103
Model25-B0SCD2000	0.007	0.025	–0.031	0.105

Additionaly, difference values were sampled at input point locations in areas, which so far have been void of data (campaigns 1974, 1975, 1976). For differences between *Model'25* and *BSCD2000*, mean values in the area of campaign of 1974 are +0.025 (σ 0.017) m, in the area of 1975 +0.029 (σ 0.018) m, and in the area of 1976 +0.018 (σ 0.009) m.

NKG2015 quasigeoid model has been adjusted to fit regional normal height systems, using a constant offset value of –0.4874 m (Saari et al., 2021); hence the local mean value offset of 0.04 m. Overall, disagreement with regional models tends to increase towards periphery of the study area, possibly due to differences between input data used outside study area.

For data area of campaign of 2023, differences between ζ grids follow the same trend observed with free air anomalies possibly revealing error propagation from



Note: Differences between quasigeoid model Model'25 and two regional height conversion surfaces (NKG2015 and BSCD2000).

Figure 4. Results of height anomaly grid comparison

biased 1977 campaign data further in later steps of quasigeoid modeling (Figures 3, 4). Local variations coincide with erroneous data deleted from 1977 campaign, based on LOO-CV results, or with new, higher density data distribution. Difference values in areas of soviet data input (campaigns 1968–1976) vary between areas of annual campaigns. In both models are more uniform, trend changing between different campaign years. In the area of campaigns 1968, 1969, 1970, average difference value of –0.015 m, possibly reflecting the influence of applied correction value.

Validation of modern and historical data, using geoid heights derived from GNSS measurements at sea, could better evaluate the influence updated gravity data has on marine geoid modelling. During the 2023 campaign, a single antenna was used for positioning, hence records and possible correction of ship dynamics is limited. There is a this can be made possible by further dedicated (Saari et al., 2021) or automated piggyback (Varbla et al., 2017) shipborne GNSS campaigns in the future.

7. Conclusions

Older and newfound field report digitization and modernization has provided opportunity to determine inter- and intra- dataset biases more precisely. Gross and biased data elimination has potentially improved accuracy of recently acquired datasets. Comparison of new and old data has provided correction values for older campaigns. All three pursuits have provided high quality pointwise gravity input data to be used in further research and government work.

Work has provided input data for height transformation surface modelling. This should also include precise geoid height determination. More attention to models employed in the cross-validation process could improve training results, thus making discrepancies in the anomaly surface easier to identify.

Judging from comparison results, author advises applying a correction value of +0.89 mGal to the campaign data of 1969. Comparison results from campaign data of 1977 suggest a bias against other campaigns, ranging between +0.64 and +1.60 mGal; differing values suggest a tilted correctional surface should be used. For better results, re-processing is advised.

Acknowledgements

Author wishes to acknowledge the work done so far on the topic of Baltic marine gravity data management by BalMarGrav project, which paved the way for this publication. I would like to extend gratitude personally to colleagues from Lantmateriet who's work on campaign planning and marine data processing made any further data analysis possible, as well as Monika Wilde-Piorko of Polish marine gravity institute, during discussions with whom the idea to rejuvenate archived gravity data was formulated. Revised data will be included in the updated NKG gravity database.

Disclosure statement

Author states no competing financial, professional, or personal interests from other parties.

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