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HARMONISATION OF MARINE GRAVITY DATA IN THE EASTERN BALTIC

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Abstract. Marine gravity datasets covering areas of state scale typically consist of data surveyed over multiple campaigns. These campaigns often take place many years apart and are of varying resolution and accuracy. Ship-borne campaigns are 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. Throughout the recent BalMarGrav marine gravity project, dense, high-quality gravity data covered most of the Latvian exclusive economic zone. The new data have been compared to campaigns, both as a means of new data validation and to check for possible biases among older data sets. This research aims to further the effort, provide more exhaustive coverage of old marine gravity points, test automated gravity point digitisation, and 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. The recovered data cover shallow coastal areas, where gravity mapping was not done over the BalMarGrav project. Thus, by applying correctional values, geoid errors can be minimised in the problematic transition zone between terrestrial and marine data. Survey reports containing 20th-century marine gravity point data were digitised using optical character recognition. Gravity point values were transferred to the sea surface and transformed to modern reference frames. 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 data's increased accuracy and precision. 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: cross-validation, geoid, gravity, heights, navigation.

1. Introduction

When transferred to sea level, pointwise gravity values are the primary input data for transformation models, used in modern positioning infrastructure (Sanso & Sideris, 2013). Older data sets can be brought up to date to reduce the need for logistically challenging, high-cost new data acquisition, using new data acquired in controlled conditions (Ellmann et al., 2011). Updated historical data can improve modelling results of national (Huang et al., 2010; Turk et al., 2011) and regional (Featherstone et al., 2018) geoids. Due to the intensive use of waterways, the quality of the Baltic Sea gravity data is crucial for developing the region's economy.

The study area covers part of the Baltic Sea belonging to Latvia and Lithuania's Exclusive Economic Zones, west of the Irbe Strait and Curonian Lagoon. The review of historical datasets of Interreg Europe's Homogenised Marine Gravity Maps of Southern and Eastern Baltic Sea for Modern 3D Applications in Marine Geodesy, Geology and Navigation (BalMarGrav) project has extensively covered the historical development of the gravity data coverage in the study area (Wilde-Piorko et al., 2023a).

Much of the Eastern Baltic marine area has been surveyed in the timespan of 1966-1977 (Aleksashin et al., 1968; Degtyar et al., 1969, 1970, 1972; Degtyar & Dorogan, 1971; Karpickis et al., 1973; Kovrigin et al., 1974; Lokshin et al., 1975, 1976; Schipev & Mamoshin,

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1977; Haritonov, 1979). Aside from changes in the instruments used, the methodology seems to be the same across 20th-century campaigns. Pointwise gravity observations were made on the sea floor, using various soviet era gravimeter models. Post-adjustment value accuracy estimates in the original documents vary 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 10s of meters. Temporary reference points were established on the seabed, which were tied to points on piers, and closed runs were performed with validation stations between separate ship runs.-

Data from campaigns of 1968/1969 has been available on the regional Nordic Geodetic commission database, in multiple copies (both years' campaign results as #372, and part of the 1968 results as #338). In 1977, a much larger area was surveyed, covering the Latvian and Estonian marine areas between 56.2 ° and 58.7 ° latitude (Figure 1). The last seabed marine survey of the 20th century within the study area was carried out in 1991 (source #345), covering a 30 km wide area along the coastline between 56.5 ° and 57.5 ° latitude with a 2.5 km data step (Spetzgeofizika, 1992). Data partially overlaps with source #615(1977). These datasets so far have been used as input for various national and regional height transformation surfaces (Ågren et al., 2016; Ellmann & Oja, 2018). Data source #622(1976) was digitised during the BalMarGrav project.

The aerogravity campaign by Forsberg et al. (1999) can be considered the start of modern observations in the Eastern Baltic, and the data of this campaign partially cover the study area. Numerous marine gravity surveys in the Baltic Sea were made during the project *Finalising Surveys for the Baltic Motorways of the Sea (FAMOS)* (Forste et al., 2020). Two isolated routes cross the study area and dataset #615(1977) from the port town of Liepāja to the west. 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 the Gulf of Finland; Liebsch et al. (2023) implemented all available data into a regional solution for the BSCD2000 height transformation surface.

In 2023, extensive surveys of the study area were made as a part of the broader BalMarGrav initiative (Wilde-Piorko, 2023c), among them a survey of Latvian marine area, during which continuous gravity observations were made over six weeks, totalling around 8000 nautical miles of ship track data (source #621). The standard deviation of the post-processing internal track crossover value is reported to be 0.9 mGal. For a more detailed description, see BalMarGrav's modern campaign report (ibid.). Since 2021, annual surveys have been made in the Lithuanian territorial waters (ibid., Popovas et al., 2024). For the scope of this research, only modern data from source #621 is used for analysis.

Throughout the BalMarGrav project, historical datasets were checked for bias against modern survey values (Wilde-Piorko, 2024); when compared to modern source #621, the 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 in gridding Bouguer and free-air anomaly surfaces (Wilde-Piorko, 2024).

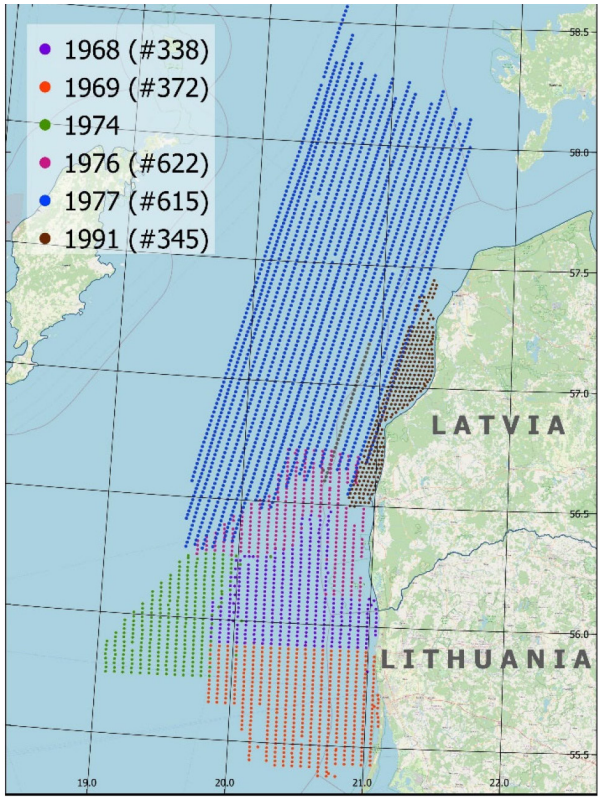


Figure 1. Study area. Campaigns denote 20th-century marine gravity datasets. Campaign field reports referenced for each campaign are dated to the following year. The campaign of 1974 has for the first time been described in this publication - historical data points eliminated through cross-validation in grey

Comparison statistics hint at varying, sub-mGal bias between older data sources, which can be seen most when looking at sources #338 and #372, supposedly digitised from the same observation report. Dataset #622 has been added to the NKG gravity database. However, the procedure of data digitisation and applied transformations is unknown. Modernising the aforementioned datasets together, as a single effort, could reduce inter-campaign bias, leading to laterally smooth modelling outputs. Additional filtering of the modern data source #621 could remove biased ship track influence on dataset

statistics; this could be observed as an improvement in data comparison results.

2. Methods

Eliminating errors within marine gravity data was done twice – first, manually, as is the norm for similar works (Liebsch et al., 2023). Alternatively, for a quantitative approach, cross-validation can be used for the same goals (Mardla et al., 2017). Usually, in cross-validation (CV), when using the same data set for training and testing, overfitting is a valid cause for concern. On the other end of the spectrum, much attention is usually paid to the training of the model (Arlot & Celise, 2010). Because CV's primary purpose was to automate gross error and bias run identification over this project's scope, we chose to ignore these issues and employ a simplified interpolation model. Leave-one-out cross-validation was implemented, using the *LeaveOneOut* module from the Python library *scikit-learn*. CV was performed before and after modern data filtering to evaluate the improvements from manual and automatic error elimination, and during the historical data digitisation to check for possible input errors. For results, residual values at test points are used to calculate base statistics. For bias detection, residuals exceeding 2.5 σ values were flagged as errors.

Historical report digitisation was achieved using the optical character recognition (OCR) engine *Tesseract*. Extracted data values were transformed to normal anomalies, using Chebyshev's approximation of the Somigliana formula, with GRS80 parameters up to the fourth parameter. Gravity anomalies were continued to $H = 0$, after Wilde-Piorko et al. (2023a),

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

where $\frac{\Delta g}{\Delta z} = 0.308$ mGal/m and seawater density is assumed p = 1,010 t/m^3. Varying salinity levels, corresponding to different Poincaré-Prey reduction values, seem to have been used across gravity data holders (ibid.). Point values were transformed to a modern reference frame, using a constant correction of −14.0 mGal. Values of the campaign 1976 were already given in the IGSN71 reference frame. For the campaign of 1969/1970, where point coordinates were given only in the Coordinate System of 1942, transformation was performed to LKS-92 geodetic coordinates.

New and historical gravity data were compared using methods laid out by Wilde-Pirko et al. (2024) during BalMarGrav. Historical gravity datasets were gridded to surfaces using the GMT module *surface*. Modern data values were then compared to sampled values from said surfaces. Differences between gridded historical data surfaces and observed modern point values were used in calculating base statistics for each area of the historical campaign data set used in the comparison. Additionally, historical datasets were compared in the same manner in places where historical dataset points overlapped. For datasets with observation points from previous campaigns (1968 and 1969, 1976, 1974) repeated, point values were compared directly. To evaluate the cross-validation effect on dataset accuracy, comparisons were performed with both unfiltered and filtered #621 datasets.

3. Historical gravity data modernisation

Reports of gravity surveys, providing continuous cover over the 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 the 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 20th-century data precision should be expected to be around 1 mGal (Wilde-Piorko et al., 2023a). Alongside the previously unpublished campaigns, data from adjacent areas, namely sources #338(1969), #372(1969), #622(1976), were re-digitised 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.

The OCR recognition success rate varied between 30% and 90% of characters recognised per report page and correlated strongly with typewritten source quality. Results can be substantially increased by providing high-quality, orthometric document scans. Typewritten data proved susceptible to a large amount of human input error, so verification is still necessary, where leave-one-out cross-validation was used successfully.

4. Modern gravity data filtering

Throughout the six-week campaign, 10 runs were performed (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 comprises between 10 to 30 separate tracks – longer, straight sections made at constant speed, during which the main data acquisition happens. Due to climate and other

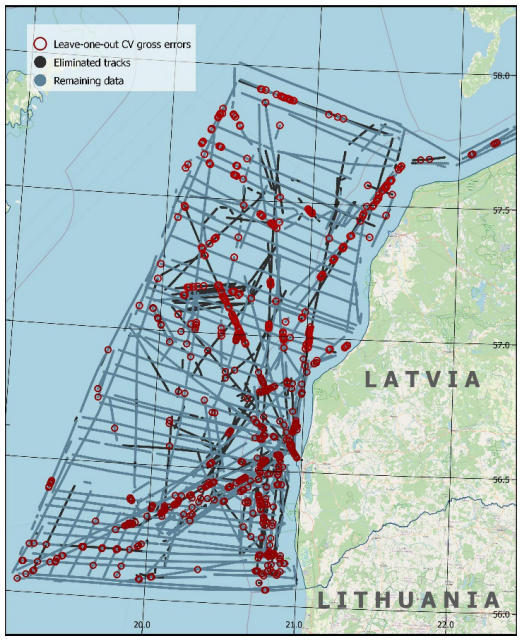


Figure 2. Year 2023 marine campaign data before and after data filtering. Observation points flagged as CV errors in red. Eliminated biased tracks, identified through cross-validation or visual inspection, in black.

circumstances, ships used to pause tracks to do short detours, or were sometimes set to drift for extended periods.

After looking at post-processing values manually, we noticed high biases on some tracks, usually present right after ship turns are made. Additionally, few tracks remain in the data from measurements made at high speeds (< 10 knots), unfavourable conditions, or while the ship was adrift for repairs. At some tracks, high-frequency undulations of measure values were seen, representing instrument errors. Track crossover analysis results seemed to show the extreme values grouped around such biased tracks; because of this, it was decided that additional dataset filtering should be done.

Table 1. Data count before and after clean-up. More track crossovers grant better data control

Campaign	*n*, original	*n*, post-CV	% of data eliminated
2023	21 821	15 171	30.47523028
1977	2030	1996	1.674876847

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

When looking at CV results along data acquisition conditions, we see that most crossover values exceeding the standard deviation are associated with ship manoeuvres, excessive speed or bad weather conditions. This can be seen from the short track records, track point density or written field reports. However, multiple planned tracks visibly stand out in the data set, either at the first half of the track, or in the entire track length; one possible explanation for such behaviour could be the Eotvos effect lingering in the gravimeter data post-turn. Currently, the best option would be to eliminate bad tracks from the final solution further; alternative data should be introduced in the new voids, or correctional values should be calculated from validation measurements.

5. Modern and historical data comparison

After data filtering and uniform digitisation, comparisons were made between the re-digitised historical data and the filtered and unfiltered version #612 (Figure 3). The base statistics of all comparisons (including comparisons of historical sources overlapping each other) are given in Table 2. As is visible, historical data re-digitising has improved data performance, and all data sources now show decreased differences from the 2023 data.

Table 2. Statistics of dataset comparisons between modern and historical datasets and overlapping historical datasets. The mean value increases with filtered data, implying a more accurate comparison

Modern and historical dataset comparisons					
Source	*n*	mean	SD	Min	Max
621_unfiltered-1968	2186	–0.04	0.56	–2.03	2.17
621_filtered-1968	1722	–0.02	0.54	–2.03	1.57
621_unfiltered-1974	794	–0.04	0.77	–2.63	1.46
621_filtered-1974	714	0.06	0.67	–2.48	1.36
621_unfiltered-1976	4521	0.04	0.82	–4.72	3.47
621_filtered-1976	2830	0.16	0.65	–4.72	2.61
621_unfiltered-1977	12251	–0.56	1.31	–10.07	4.97
621_filtered-1977	7333	–0.64	1.06	–6.79	4.97
621_unfiltered-1991	1143	–0.10	0.94	–2.60	4.20
621_filtered-1991	751	–0.12	0.75	–2.46	4.20
Historical campaign inter-comparisons					
1977–1991	36	1.59	1.09	–0.63	3.51
1991–1977	42	–1.67	1.12	–1.05	3.57
1977–1976	81	0.99	1.07	–1.27	6.22
1968–1969	19	0.89	0.34	0.35	1.57
1968–1974	11	0.02	0.42	–0.68	0.68

In theory, the unfiltered data comparison should be close to the values observed by Wilde-Piorko et al. (2024) during the BalMarGrav project. Data filtering seems to increase mean and median differences between modern and historical data, as with all data sets, except 1968. An 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.

When comparing datasets 1968/1969, we see the same bias, which was first identified between sources #338 and #372 (–0.77...–0.88 μGal). Again, when comparing the dataset 1968 to modern data, both filtered and unfiltered data provide good agreement. Since data has been independently digitised and transformed throughout this research, we can conclude that the bias of dataset #372 is most probably due to errors within the observed values. To the problem that bias is present in the entire source #372, not just southern part (surveyed in 1969), we can hypothesise that at some point after digitisation of both 1969 and 1968 data, 1968 data must have been recalculated, using correction values from biased 1969 dataset, creating the biased data source #338. Since the data source was isolated and there was no reliable way of data validation, the error has been propagated into further work. Such findings especially underline the value and opportunities given to the scientific community by projects like BalMarGrav.

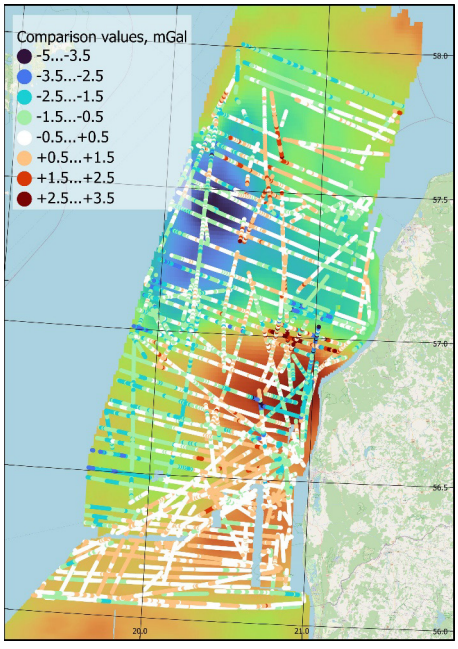


Figure 3. Dataset comparison values. Historical dataset points as coloured dots; gridded free air anomaly surface used in comparison as background

6. Conclusions

Digitisation and modernisation of older and new field reports have provided an opportunity to determine inter- and intra-dataset biases more precisely. Gross and biased data elimination has potentially improved the 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 for 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 can help tighten the effect, making discrepancies in the anomaly surface easier to identify.

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

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GRAVITACIJOS DUOMENŲ SUDERINIMAS RYTINĖJE BALTIJOS JŪROJE

V. ZUSEVICS

Santrauka. Jūrų gravitacijos duomenų rinkinius, apimančius valstybinio masto teritorijas, paprastai sudaro kelių kampanijų metu surinkti duomenys. Šios kampanijos nevyksta dažnai, o jų raiška ir tikslumas skiriasi. Taip yra dėl to, kad jūrinių kampanijų vykdymas yra daug brangesnis ir užtrunka ilgiau nei sausumos; todėl senesnių duomenų patvirtinimas ir korekcija turi pridėtinę vertę. 2023 m. vykdant jūrinės gravitacijos projektą „BalMarGrav“, buvo ištirta Latvijos išskirtinės ekonominės zonos dalis ir surinkti aukštos kokybės, tankūs gravitacijos duomenys. Jie buvo lyginami su ankstesnėmis kampanijomis siekiant tiek patvirtinti naujuosius matavimus, tiek įvertinti senesnių rinkinių paklaidas. Nauji duomenys padengė anksčiau neapimtus regionus, ypač pakrančių zonoje, kur trūko tikslių matavimų. Tai leido sumažinti geoido modelio paklaidas probleminėje pereinamojoje zonoje tarp sausumos ir jūros duomenų. Tyrimų ataskaitos, kuriose pateikiami XX a. jūrų gravitacijos taškų duomenys, buvo suskaitmenintos naudojant optinį simbolių atpažinimą, jų vertės buvo perkeltos į dabartinius ataskaitos rėmus, o rinkinio patikimumas patikrintas taikant *Leave-one-out Cross Validation* metodą. Palyginus senus ir naujus duomenis nustatytos paklaidas tarp kampanijų, o atliktos korekcijos pagerino geoido modeliavimo tikslumą seklioje zonoje, kurioje tradiciškai trūksta aukštos kokybės duomenų.

Reikšminiai žodžiai: aukštumos, navigacija, geoidas, gravitacija.