Report on availability and re-processing procedure of the historical marine gravity data of the southern and eastern Baltic Sea

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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, over twelve historical marine gravimetric sources are identified for further re-processing and homogenization of these data with nowadays surveys of the gravity field in the Baltic Sea region. Guidelines and methods are developed to re-calculate historical gravimetric data to modern geodetic and gravimetric reference systems.

2 Historical marine gravity data

Nowadays, most of the marine gravimetric measurements from the Balitc Sea region are stored in the Nordic Geodetic Commission (NKG) gravity database (in short: the NKG gravity DB), maintained by the DTU Space (institute of the Technical University of Denmark). The historical gravimetric data re-processed during the BalMarGrav project, which is not yet included in this database, will be available there under the BalMarGrav license.

2.1 Denmark

The national gravity database of Denmark is hosted by the regional NKG gravity database – the historical marine gravity data in Danish waters is labelled as a source #**42**.

The origin of the data source #42 is described by Andersen and Engsager (1977) in an extensive monograph of the official 3rd series of the former Geodetic Institute of Denmark. The monograph (written in English) is not easily available and only exists as a hard copy report. The description of the data source #**42** in the NKG gravity DB is rather sparse and deficient and will be corrected/extended in the future:

> *Publication 42*
> *Database public_dk*
> *42*
> *Andersen, Ole Bedsted and Karsten Engsager: Surface-Ship*
> *Gravity Measurements in Danish Waters 1970,*
> *Vol. XLIII, 1977.*

In general, the description of the digital data sources in the NKG gravity DB varies strongly in quality as well as in the degree of detail. In fact, the description is often sparse and sketchy for the old data. Originally, the idea behind the short data source description in a digital form was to point to the specific publication in hard copy on the bookshelf. This idea is of course much outdated today as most publications exist in digital form.

Nevertheless, one important and probably relevant detail concerning the published and the digital form of the same data source is that the data source in digital form may deviate from the original published version due to the unreported corrections. In other words, the gravity data in the digital form may have been corrected without updating the description.

According to the monograph of Andersen and Engsager (1977), the marine surveys were conducted from the Royal Danish Navy inspection vessels "Fylla" and "Ingolf" during five periods (1970: May 19 – June 17; 1971: June 7 – June 19 and August 23 – September 4; 1972: September 25 – October 8; 1975: June 1 – June 18). The gravimeter used was Graf-Askania marine gravimeter Gss2-14 mounted on the Anschütz oil-erected gyrostabilization. The idea was to cover the waters around Denmark with the gravity data. The collected data were extended with few extra profiles from marine surveys in 1966 in Kattegat (Andersen, 1966) and from surveys in 1968 in Skagerrak (Andersen, 1975).

The source #**42** (Fig. 1), in its current version, has been for years regarded as the main marine data source in Danish waters. The gravity data from this source were used in all national-, regional- and global geoid computations from the area. However, in connection with the latest FAMOS/BSCD2000 quasi-geoid model of the Baltic Sea (Schwabe et al., 2020) this data source was excluded. One reason was the availability of new modern marine- and airborne surveys collected within the FAMOS project and covering the same area, but also because a detailed quality check (QC) of the data sources revealed some inconsistencies with modern surveys. For example, some big discrepancies between modern Swedish marine surveys and the source #**42** based on 20 crossings were reported (Olsson et al., 2022).

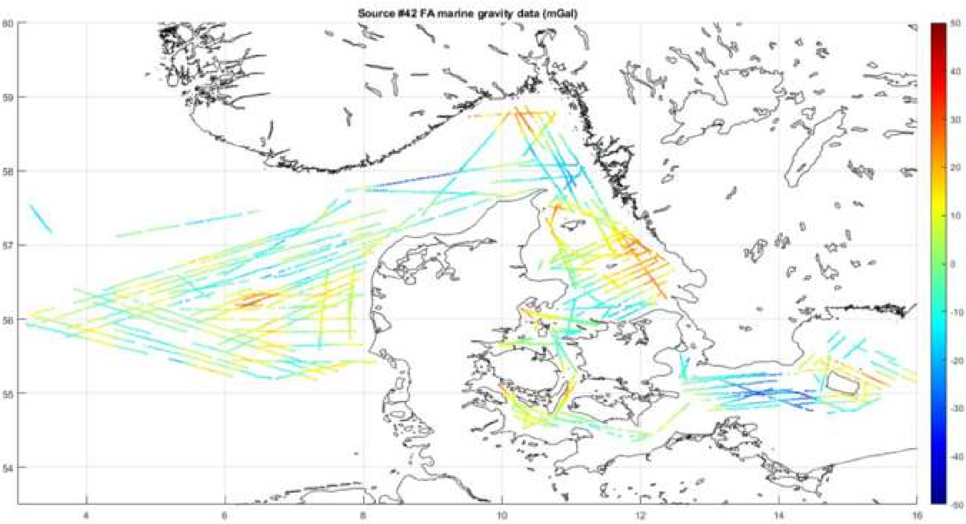


Figure 1: A source #**42** from the NKG gravity DB Free-air gravity anomalies (mGal)

As stated above the source #**42**, shown on Fig. 1 is not one single marine survey, but rather a number of different surveys. The quality of these different surveys is not necessarily uniform. It is quite possible that the observed inconsistencies with modern surveys for the source #**42** vary from place to place. The area east of Bornholm (except areas very close to the shore) is of particular interest for the source #**42** as it has only sparsely been crossed by modern surveys. Furthermore, because this area is geographically convenient for planned surveys within the BalMarGrav project, it seems to be deliberate to verify these measurements in the project. So, a part of source #**42** will be included in the historical data modernization of the BalMarGrav project.

In the original manuscript of Andersen and Engsager (1977) there is a section in which the final gravity anomalies are being assessed. The free-air gravity anomalies and Bouguer gravity anomalies were calculated for approximately 7000 positions from the total number of 256 profiles. Currently, in the NKG/FAMOS gravity DB, the source #**42** consist of 5753 data records. The profile structure is not preserved in the record numbering.

The marine surveys were linked via harbor ties to the Kneissl-Marzahn European Gravimeter Calibration line (Kneissl and Marzahn, 1963). In the original manuscript it is mentioned that for anomaly computation the International Gravity Formula of 1930 was used. A mass density of 2.67 g/cm^3 for the terrain (read: the sea bottom or the pier in harbors) was used. The mass density of the sea water is not explicitly mentioned but is probably 1.00 g/cm^3. Furthermore, the tidal corrections and terrain corrections were ignored.

A Decca Navigator System – a hyperbolic radio navigation system was used for positioning. After removal of the obvious blunders, a positioning accuracy of 200 m is claimed. Often it is much better. The accuracy of the bathymetric data is assessed to be 2% of the recorded depth. The recorded depth is in meters (no decimals).

In the original manuscript, Table III shows the internal consistency of the survey results at, in total, 335 profile crossings. This simple crossing statistics provides only the mean crossing discrepancy between the profiles, i.e. there is no std, rms, min and max values. The mean crossing discrepancy is specified individually for five main marine areas in Danish waters and lies between 2.1 and 3.0 mGals. Based on the table, the overall mean crossing discrepancy for these results is assessed to 2.5 mGal.

The accuracy level of Gss-2 Graf-Askania marine gravimeter claimed by Andersen and Engsager (1977) is of the order of 1.0 mGal. However according to Dehlinger (1978) a lot of effort in the improvement of instrumental design in 1960s went to correct the so called cross-coupling error, a misreading of the gravimeter caused by the horizontal and vertical accelerations of the ship movement. The cross-coupling error is not mentioned by Andersen and Engsager (1977). However, Dehlinger (1978) states the following for Gss-2 Graf-Askania instruments: "Extensive experience has shown that these meters usually provide measurements accurate to within a few milligals, and better at low sea states".

The source #**42** in the NKG gravity DB, being the main marine gravity data source for Denmark, has without any doubt undergone several historical corrections, which, however, are not well documented. One obvious consequence of these corrections is that the number of records for this source has been reduced to the current 5753. Formally, the gravity free-air and Bouguer anomalies in the NKG gravity DB refer to the GRS80 International Gravity Formula. Consequently, a conversion from the 1930 International Formula to GRS80 was most certainly applied. Also, the famous Potsdam correction of 14.0 mGals, which corrects for the error in the fundamental pendulum gravity value, most certainly has been applied. This ensures that g values are expressed in IGSN71. Current gravimetric systems defined according to ITGRF standards are an improvement on IGSN71 and differ from it at the level of 0.1 mGal, a value that can be disregarded when considering historical marine gravity data. The profile structure of the data is not preserved in the current station numbering but can, most probably, be reconstructed.

2.2 Germany

Two major historical datasets from the 1960s and 1970s exist in the maritime area of the former GDR, each with individual status regarding available original data sources, re-processing, ownership and, thus, availability for the BalMarGrav project. They are shown in Fig. 2.

Due to the individual ownership of the data, recovery and re-processing of the datasets was done individually. The *OST* dataset was reprocessed at BKG, while GGD Geophysik mbH was contracted already in 2013 to recover and re-process the *GGD* dataset.

Simplified comparisons with modern shipborne data, e.g. gridding, sampling of differences along ship tracks, were carried out at BKG. In this report, only conclusions are outlined. Detailed figures and statistics have been shared with the BalMarGrav partners.

(OST) Ocean-bottom gravimetric campaign (1966-1968)
The observations were made using Soviet-made DGK-EMK, GDK II and GAK-7DT seafloor gravimeters in water depths of 4–30 m (typically, max. 50 m). The distance between

the stations was ca. 2 km, in some areas 2–4 km. Two different instruments were used with a nominal accuracy better than 0.5 mGal. Positions were determined by radio triangulation (system "Poisk") with larger uncertainties off the coast. This information was obtained by personal communication from Geophysik GGD mbH in connection with the shallow-water gravimetry dataset (see below).

Digital records of point data are partly preserved: gravity at the sea floor in the Potsdam gravity system and depth. In the transition phase around the German reunification, these data accrued to the Institute for Applied Geodesy (IfAG) in Leipzig, which is now the Federal Agency for Cartography and Geodesy (BKG). Archived communication from 1991 states that positions were already transformed to WGS84 and that the original measurement data are not anymore available. There is indication about original positions referring to the Pulkovo datum (system "42/83", EPSG:4178, in a later realization), however, this cannot be definitely confirmed.

The data have been reprocessed to modern standards as follows and are available for further comparisons and merging in the BalMarGrav project.

The absolute gravity values were converted to the system IGSN71 and computationally lifted to the sea surface by means of the free-air gradient and the Prey gradient (correction $+4\pi G\rho D$ using the archived depths D and a water density of $\rho = 1010$ kg/m^3). Some points along singular profiles in the territories of Denmark and Poland (see Fig. 2) or

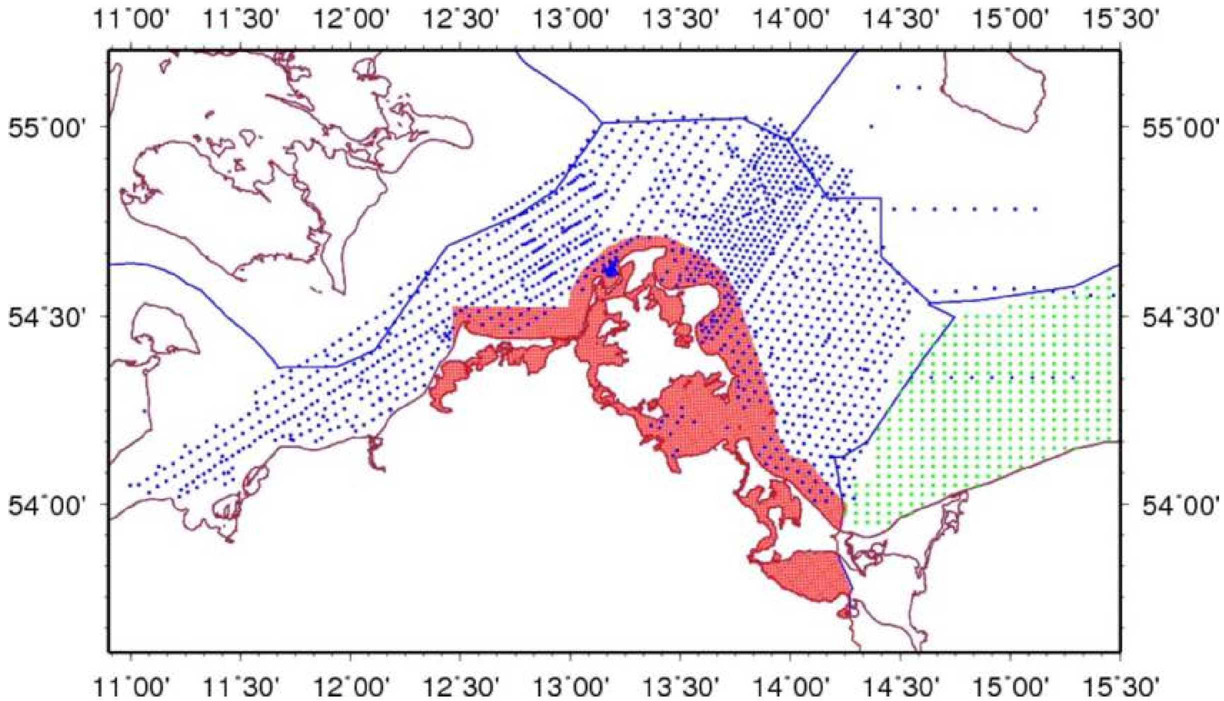


Figure 2: Overview plot of historical data in the former GDR area of the Baltic Sea. Blue dots are the ocean-bottom measurements (1966-1968, OST). The red area localizes the area of the shallow-water campaigns (1969-1973, GGD). Green dots in the Polish exclusive-economic zone represent the current gridded marine gravity data provided by IGiK and is shown for illustration purposes only.

with obvious errors in the position were discarded from the re-processed dataset. Current gravimetric systems defined according to ITGRF standards are an improvement on IGSN71 and differ from it at the level of 0.1 mGal, a value that can be disregarded when considering historical marine gravity data.

Comparison with new shipborne data measured by BKG between 2013 and 2018 confirmed an overall statistical agreement at the 1 mGal level (standard deviation, statistically insignificant offset), which is also typical for the internal consistency of modern shipborne gravimetry. Thus, the reprocessed dataset is suitable for geophysical or geological mapping in the maritime areas, and also for geoid modeling with centimeter accuracy.

Shallow-water gravimetry (1969-1973)

Following upon the 1966–1968 measurements, adjacent and partly overlapping parts were observed by the state-owned company "VEB Geophysik Leipzig" in altogether 6 campaigns between 1969 and 1973. Depending on the water depth, measurements were carried out using two different setups (GGD, 2013):

- setup A: close to the water level in depths between 1 and 4.5 m, using special tripods and a land gravimeter Sharpe CG2 with an accuracy between 0.02 and 0.05 mGal. The station distance ranged between 250 and 1000 m, with the majority at 500 m. The equipment might have been transferred to Poland in 1975 for further use;
- setup B: ocean bottom (> -5 m depth), using a sea-floor gravimeter GAK 7DT dropped by crane and observed on ship using a galvanometer with an estimated uncertainty between 0.2 and 0.4 mGal. Station distance ranged between 500 and 1000 m.

Positions were determined by triangulation with uncertainties (standard deviation) of up to 8 m (setup A) and 27 m (setup B). Gravity values were connected to the gravity base network of the GDR (Potsdam datum). Computation of Bouguer anomalies was done based on the Helmert 1901 normal gravity formula and a reduction density from 1.0 g/cm^3 (water) to 2.0 g/cm^3 (rock). To this end, depths were observed by rod with the accuracy of 0.05 m (setup A) and by plumb with the accuracy of 0.5 m (setup B).

Only Bouguer gravity maps (1:25000, 1:50000), partly digital, were archived, but no original locations and heights. Copyright of these data originally archived at "VEB Geophysik" remains unclear because the original data owners and their legal succession can no longer be retraced. These sources are available in the archives of GGD Geophysik mbH, the legal successor of VEB Geophysik, but not at BKG.

The reprocessing carried out by GGD Geophysik mbH consisted in the following steps (GGD, 2013):

- gridding at 500 m regular interval in the system PD/83 (Potsdam datum, a.k.a. DHDN as ensemble datum) in GK4 projection (EPSG:31468), and subsequent transformation (EPSG:15948) to ETRS89. Remark: PD/83 is reported in GGD (2013) as the original system, however this system realization did not yet exist at the time of the measurement. Thus, it cannot be confirmed with certainty if the original measurements referred to an earlier realization of the DHDN datum, and/or if they were transformed in an intermediate step;

- transformation of the gravity system from Potsdam datum to IGSN71;
- reversal of the normal gravity reduction.

The reversal of the Bouguer reduction was then made by BKG using the same density assumption and charted depths from a 10 m resolution digital elevation model.

Despite the reconstruction from a Bouguer grid and the uncertainty regarding the datum of the original positions, the reprocessed surface gravity values show the same level of agreement with the new shipborne gravity measurements like the ocean-bottom dataset *OST* (1 mGal standard deviation, statistically insignificant offset).

Copyright of the revitalized data belongs to Geophysik GGD mbH. However, permission has been granted recently to share and use the data internally in the BalMarGrav project.

2.3 Poland

Two major historical datasets from the 1970–1980s exist in the maritime area of Poland, each with individual status regarding available original data sources, re-processing, ownership and, thus, availability for the BalMarGrav project.

In 1970-1972 the Institute of Geodesy and Cartography in the cooperation with the Academy of Sciences of USSR conducted the marine gravity measurements within four surveying campaigns:

A) campaigns on Zaria in 1970, 1971 and 1972;

B) campaign on Jan Turlejski in 1972.

The gravity data are shown in Fig. 3.

There are two sources of historical gravity data from the Baltic Sea region from the 1970–1980s in the National Geological Archives (NAG) maintained by the Polish Geological Institute – National Research Institute. The license of NAG allows only to share products made on data basis, e.g. in the form of anomaly grids. These two datasets are:

C) Petrobaltic ocean-bottom campaign from 1978 to 1979;

D) Ustka–Rozewie ocean-bottom campaign from 1976 to 1981.

The gravity data are shown in Fig. 4.

Zaria campaign in 1970
The works were carried out from 8 to 13 August 1970 (Popow et al., 1971). Gravimetric measurements at sea were carried out by the Institute of Earth Physics (IPE) of the USSR Academy of Sciences and the Institute of Geodesy and Cartography (IGiK) from Poland.

The position of the ship during the campaign was determined using coastal landmarks. The bearing (direction) to a coastal landmark was determined using a gyrocompass, and the distance – using a radar. A total of 100 ship's location on profiles were determined on the surveyed polygon. The mean square error of the layout of profiles on the polygon, taking into account all position determinations, was ±0.2 nautical miles, i.e. ±370 m. In total, 15 profiles were surveyed on the polygon: 8 profiles parallel to the coastline at a distance of 2 miles from each other and 7 profiles secant. Weather conditions during the period of work on the surveyed area were generally favourable.

In order to link the marine gravity measurements to gravity control, a reference point on the quay near the mooring point of the R/V Zaria in the port of Kołobrzeg was established.

Three strongly damped, gyroscopically stabilized GAL-M gravimeters were used to measure gravity at sea. The sensor of the GAL-M-type gravimeter was a double quartz system, the operating principle of which was based on the use of elastic properties of twisted fibers. Gravimeter readings were recorded on a photographic film. All three gravimeters were installed on the ship in the same room and operated under the same conditions. During offshore operations, gravimeter readings were recorded continuously along the routes, excluding short breaks for cassette reloading (5–10 minutes after 4 hours of recording). The records of one GAL-M gravimeter, due to insufficient damping of the elastic system, turned out to be strongly disturbed and were not included in data processing. Due to insufficiently reliable linkage of profiles, ship course deviations and unfavourable weather conditions, a few profiles were also excluded from data processing.

During data processing, gravimeter readings were averaged over 10-minute intervals. A MIG microscope was used to measure the photograms. As the final value of Δg, the average of the readings from two instruments was taken. Further Faye and Bouguer anomalies were calculated.

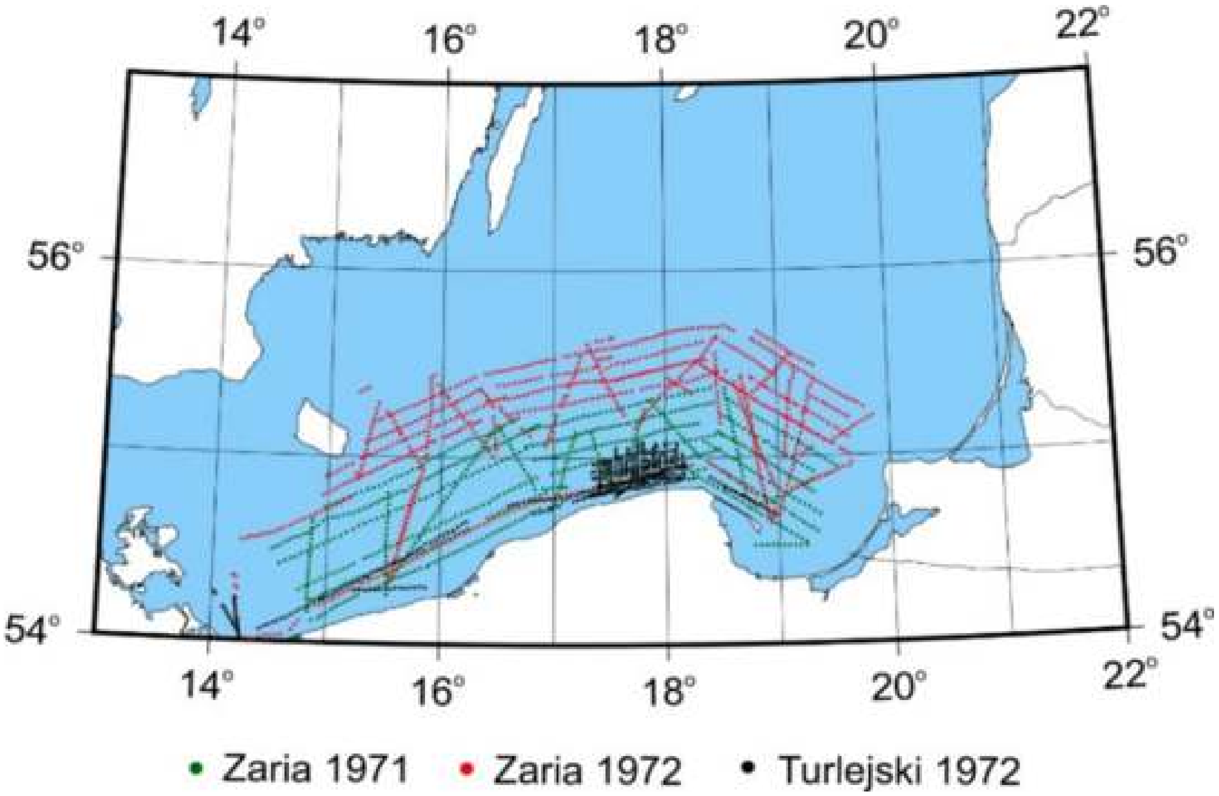


Figure 3: IGiK's historical marine gravity data

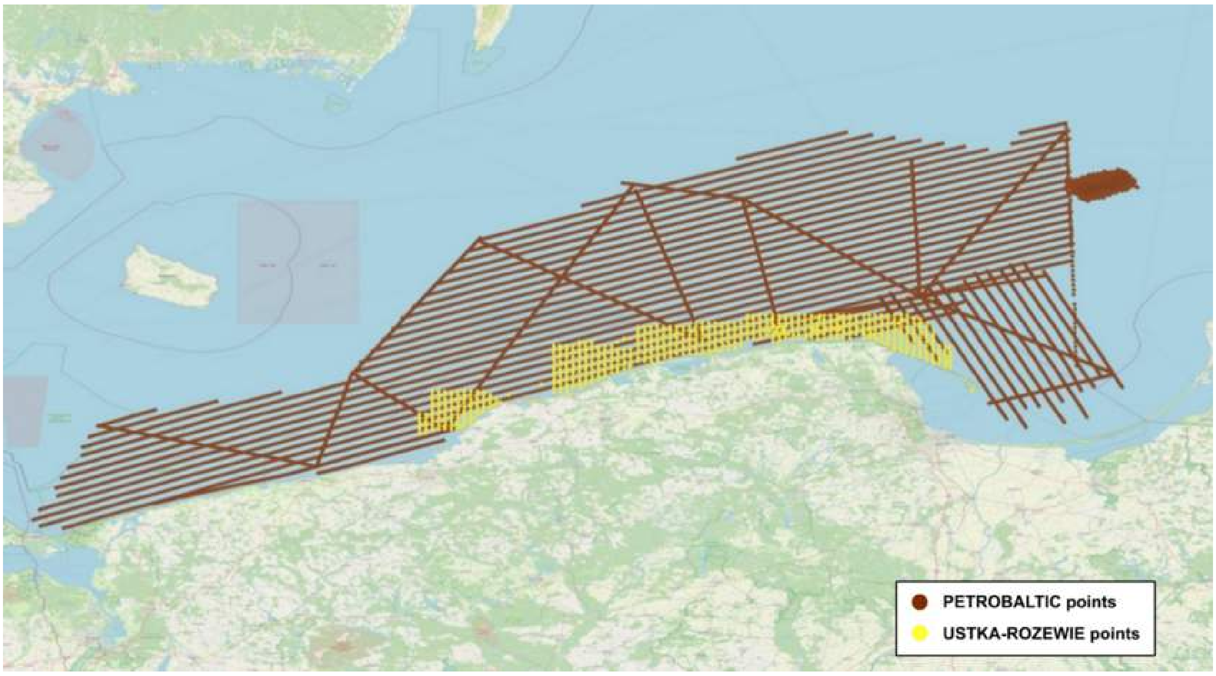


Figure 4: Location of measurement points of PETROBALTIC and USTKA–ROZEWIE campaigns

Based on the results of the gravimetric survey a catalogue of gravimetric points and maps of gravity, Faye anomaly and Bouguer anomaly at a scale of 1:200 000 with a contour cut of 5 mGal were developed. The Faye and Bouguer anomalies depicted on the maps were calculated using the Helmert formula 1901–1909.

The mean square error, estimated on the basis of the consistency of determinations of gravity at the intersection points of the profiles was +1.7 mGal.

The original documentation of Zaria campaign in 1970 will be deposited in the National Geological Archives (NAG) maintained by the Polish Geological Institute – National Research Institute at the end of the BalMarGrav project.

Zaria campaign in 1971
The expedition on R/V Zaria provided gravimetric measurements in the Baltic Sea along the Polish coast from the mouth of the Vistula river to the mouth of the Oder river, in a strip about 35 nautical miles wide (Popow et al., 1972). The works were carried out in June–July 1971. A total of 2010 nautical miles were covered by measurements. Gravimetric measurements at sea were carried out by the Institute of Earth Physics (IPE) of the USSR Academy of Sciences and the Institute of Geodesy and Cartography (IGiK) from Poland as well as the Gdynia Maritime University (navigation measurements and their processing).

Determination of coordinates
The location of the ship during the works off the Polish coast was determined using the Decca radionavigation system. The southern Swedish chain Decca Igoa whose transmitting stations cover the southern Baltic with a network of positional hyperbolas was used.

A Decca Matchk-12 radionavigation system receiver was installed on the ship and readings were taken every 15 minutes with an accuracy of 1 second; the receiver and chronometer readings were photographed. Corrections were then made to these readings. A catalogue of coordinates of surveyed points was developed, which, in addition to the moment of observation, latitude and longitude, also provided the mean square error of the ship's position in meters. The average error of the ship's position was ±224 m, with the maximum value equal to ±960 m. In the study area, 1153 ship positions were determined using the Decca radionavigation system.

Instruments
A set of three strongly damped gyroscopically stabilized gravimeters GAL-M were utilized. The sensor of the GAL-M gravimeter was a double quartz system, the operating principle of which was based on the use of elastic properties of twisted fibers. Gravimeter readings were recorded on a photographic film. The sensitivity axis of the gravimeter was stabilized by the gyroscope along the plumb line. All three devices were installed on the ship in the same room and operated under the same conditions.

Reference measurements
Two reference gravity measurements were conducted in the port of Gdynia (points Zaria-1 and Zaria-2) and in the port of Kołobrzeg (point Kołobrzeg). In order to link marine gravity measurements to the gravimetric network of control points located on land, reference gravimetric points were determined in the ports visited by the ship, and regular gravity measurements were conducted (twice a day) using spring gravimeters. The gravimetric points in ports were connected with the gravimetric points of the Polish gravimetric control network. The gravimetric points at the Gdynia port were tied to the 1^{st} class gravimetric point located in Gdańsk, and additionally connected to the gravimetric point in Gdynia, established by Przedsiębiorstwo Poszukiwań Geofizycznych in the area of the sea-port. The value of gravity at the gravimetric points in Gdynia were determined in the "1968" system. The gravimetric point located in the port in Kołobrzeg was connected to the 2^{nd} class gravimetric control network point in Kołobrzeg, and to two neighbouring intermediate points of the Polish gravimetric network.

Marine surveys
The entire study area was divided into three separate polygons, partially overlapping at the borders. Marine gravity measurements were conducted on them as follows: at each polygon, 6–8 profiles were measured parallel to the shoreline, 5 nautical miles apart, and 13 transverse profiles. In total, 106 points of intersection of profiles were obtained.

All gravity measurements at sea were completed within 12 days. While moving along the profiles, gravity measurements were carried out continuously, except for small breaks related to the need to load the photo-recorder cassettes. The average speed of the ship was 7 knots. In order to stabilize the gravimeter indications, the observations were started 30–40 minutes after turning to the next profile. During processing, continuous gravimetric measurements were averaged over each 15-minute interval. As a result of averaging, gravity measurements along the routes were reduced to discrete points, spaced approximately every 1.7 miles.

The total number of points where gravity was measured, excluding route sections unsuitable for gravimetric measurements (turns from profile to profile, manoeuvring, deviations, etc.) was 940. 15% of the entire observational material, i.e. 145 points, was discarded. The gravimetric point coverage density at the measured area, excluding rejected measurements, was 1 point per 5 square miles.

Results and assessment of their accuracy
The final gravity value was calculated as the average of the gravity values from the three gravimeters. Then Faye and Bouguer gravity anomalies were determined. Finally, a catalogue of gravimetric points and gravimetric maps at a scale of 1:200 000 with a contour cut of 5 mGal of the measured values of gravity, Faye anomaly and Bouguer anomaly were developed.

The accuracy of gravity measurements was assessed in several ways: 1) on the basis of the internal consistency of the readings of three gravimeters, 2) by comparing the results of measurements at the intersection points of the profiles, 3) by comparing the results obtained in 1971 with the results from 1970, 4) by checking the consistency of the results of marine and land gravimetric measurements. The root mean square error of a single gravity determination was assessed as ±1.6 mGal. The mean square error of a single gravity determination from the comparison of the measurement results at the intersection points of the profiles is equal to ±2.2 mGal. The adjusted gravity values at the intersection points were characterized with an error of ±1.6 mGal. Comparing the results of gravimetric measurements from 1971 and 1970 showed that the discrepancies in the eastern part of the 1970 research area are small (1–2 mGal), while in the western part they reach 3–5 mGal. These discrepancies were mainly due to errors in the coordinates of points on the map from 1970 located at a distance from the coast that would allow visual linking to reference points on the coast. The marine and field gravity measurements performed showed good agreement, which indicated the lack of noticeable systematic errors in marine gravity measurements.

Data conversion to currently used reference frames
The conversion of the gravimetric reference level of Zaria 1971 measurements from the IGiK-68 system (realization of the Potsdam System) to the International Terrestrial Gravimetric Reference System was necessary. During this research it has been shown, that less accurate gravimetric data, e.g. marine data, can be transformed into the ITGRF with sufficient approximation using the relationship:

$$g_{ITGRF} = g_{IGSN71} = g_{IGiK-68} - 14.0 \text{ mGal}.$$

The following procedure led to the above formula. In the preserved documentation, only the absolute value of g at the reference points (Zaria-1, Zaria-2, Kołobrzeg) in the IGiK-68 system are given. Unfortunately, there is no information on the location of these points,

Table 1: The g values in mGal at the Gdańsk (1^{st} class point: 54°24.16' N, 18°37.78' E) and Kołobrzeg (2^{nd} class point: 54°10.62' N, 15°35.3' E) points of Polish gravimetric control network in gravimetric reference systems

	IGiK-66	IGiK-68	IGiK-IGSN71	POGK99	PBOG14
Gdańsk	981454.459	981454.375	981440.377	981440.377	981440.390
Kołobrzeg	981455.154	981455.070	981441.106	981441.096	981441.104

except for the some general statement that measurements were taken at the ports. Therefore, it was assumed that the difference in g between the reference points in the ports and the points of Polish gravimetric control network remained constant throughout all these years. So, the determination of gravimetric level conversion formula is derived based on gravity values at points of Polish gravimetric control network, i.e. Gdańsk (1^{st} class point) and Kołobrzeg (2^{nd} class point). The g values at the Gdańsk and Kołobrzeg points in subsequent gravimetric reference system are shown in Table 1.

Additional explanations: The gravity values g at the Gdańsk and Kołobrzeg points in IGiK-68 have not been found. However, for these points g values in the IGiK-66 gravity reference frame were found. The scale factor of the conversion from IGiK-66 to IGiK-68 is:

$$k = \Delta g_{IGiK-68} / \Delta g_{IGiK-66} = 0.999616.$$

Taking a Warszawa Okęcie point (52^o10.85' N, 20^o57.94' E) of the international gravity network as a reference point and $g_{IGiK-66}$(Waw) = 981 236.650 mGal, gravity differences Δg between points Gdańsk and Warszawa Okęcie, and Kołobrzeg and Warszawa Okęcie can be calculated as:

$$\Delta g_{\textit{IGiK-66}}(\text{Gd-Waw}) = 217.809 \text{ mGal},$$
$$\Delta g_{\textit{IGiK-66}}(\text{Koł-Waw}) = 218.504 \text{ mGal}.$$

So, the g values in the IGiK-68 gravity reference frame can be calculated as follows:

$$g_{\textit{IGiK-68}}(\text{Gd}) = g_{\textit{IGiK-66}}(\text{Waw}) + 0.999616 \cdot 217.809 \text{ mGal} = 981\,454.375 \text{ mGal};$$
$$g_{\textit{IGiK-68}}(\text{Koł}) = g_{\textit{IGiK-66}}(\text{Waw}) + 0.999616 \cdot 218.504 \text{ mGal} = 981\,455.070 \text{ mGal}.$$

The difference between g values referred to IGiK-IGSN71 and POGK99 gravity reference frames at the Gdańsk and Kołobrzeg points can be determined based on the map of the differences between IGiK-IGSN71 and POGK99 published by Kryński (2007) (p. 106), providing values of 0.00 mGal and 0.01 mGal for the Gdańsk and Kołobrzeg points, respectively.

The difference between g values referred to POGK99 and PBOG14 gravity reference frame, which is equivalent to the International Terrestrial Gravity Reference Frame (ITGRF) at the Gdańsk and Kołobrzeg points can be determined based on documentations of the Head Office of Geodesy and Cartography (GUGiK), providing values of 0.013 mGal and 0.008 mGal for the Gdańsk and Kołobrzeg points, respectively.

The average value of differences between gravity referred to ITGRF and IGiK-68 at the Gdańsk and Kołobrzeg is -13.976 mGal. The 14.0 mGal was accepted as the value for the conversion from the marine gravity data of Zaria 1971 campaign to the currently used gravity reference frame ITGRF. The accuracy of 0.1 mGal for the conversion formula is relevant with the accuracy of gravity values given in Zaria 1971 documentation for historical marine gravity measurements.

In the report of Zaria 1971 campaign the coordinate reference frame is not specified. However, it is stated that the data were given in the current reference frame. So, the positions of gravity points most probably refer to the "1942" system (Kryński, 2007, p. 106). The

Table 2: The statistics of differences between depths measured within the Zaria 1971 campaign and those from the ETOPO22 [m] (NOAA, 2022)

Campaign	Min	Max	Mean	Std. dev.
Zaria 1971	-90.5	107.4	2.9	14.6

conversion of coordinates φ, λ of gravimetric points from the reference frame "1942" to the European Terrestrial Reference Frame ETRF2000 was conducted by the employees of Polish Geological Institute – National Research Institute (PGI-NRI).

The reference frame for depths data was not specified. The depths values given in the documentation were compared with the ETOPO22 global relief model (NOAA, 2022). The statistics of this comparison are shown in Table 2.

Standard deviation of depths differences given in Table 3.2 are 14.6 m and it is much higher than the respective one for depths differences from the Petrobaltic or Gdansk University Navigator campaigns (1.0–1.5 m). So, depth values from Zaria 1971 campaign seems to be unreliable, thus they will not be incorporated into the BalMarGrav.

The original documentation of Zaria campaign in 1971 will be deposited in the National Geological Archives (NAG) maintained by the Polish Geological Institute – National Research Institute at the end of the BalMarGrav project.

Zaria campaign in 1972

Documentation concerning this campaign was not found either in the archives of IGiK or in the archive of Main Office of Geodesy and Cartography in Poland. However, in the computer resources of the Centre of Geodesy and Geodynamics of IGiK the files Green-71.dat, file Red-72.dat and Black-72.dat were found. The files Green-71.dat and Black-72.dat contain gravimetric data from the Zaria 1971 and Turlejski 1972 campaigns, respectively (the values in the files were compared with the original documentation). The Red-72.dat file was considered a reliable source of gravity data from the Zaria 1972 campaign, for which documentation has not been found. For each gravity point in Red-72.dat file the following information is given: point number, latitude [°], longitude [°], gravity [mGal], depth [m].

Transformations of IGiK's marine gravity data from the Zaria 1972 campaign into ITGRF and ETRF2000 were conducted in the same way as the one described in the section "Zaria campaign in 1971".

Jan Turlejski campaign in 1972

In June–August 1972 marine gravity measurements were carried out on the Polish ship Jan Turlejski (Popow et al., 1973; Chowańska-Otyś, 1974, 1977). The aim of those measurements, i.e. increasing the accuracy of the measurement results, was achieved by increasing the accuracy of navigation and determining the ship's coordinates, reducing the distance between the measurement profiles and performing repeated determinations of gravity. The work was conducted by the Institute of Geodesy and Cartography in Poland and the Institute of Earth Physics (IPE) of the USSR Academy of Sciences. Navigational measurements were conducted by the Gdynia Maritime University.

As a result of the works carried out within that campaign, the following were made:

a) measurements in the basin of 1300 km^2 near the port of Łeba in order to refine the gravimetric map developed on the basis of observations in 1971 on board the R/V Zaria;

b) measurements along separate routes in the Pomeranian Bay, in the area not covered by the measurements on R/V Zaria;

c) measurements during the voyage of Jan Turlejski ship on the Gdynia-Świnoujście and Świnoujście-Gdynia routes in order to control the measurements conducted on R/V Zaria;

d) measurements during berths in the ports of Gdynia and Świnoujście.

In order to determine coordinates of gravity points measured on the profiles, Decca and "Siffix" radionavigation systems receivers were installed on the ship. The Decca system was a hyperbolic phased radionavigation system that was based on measuring the phase difference of two electromagnetic oscillations sent by two transmitting stations and recorded by a receiver. In the case of gravity measurements performed in 1972 on a Polish ship, the signals of the south-Swedish chain of this system were used. The Sea-fix system was a short-range radionavigation system (approximately 20 nautical miles above the surface of sea water), which was a variant of the Hi-fix system. The set of stations of this system could operate in a hyperbolic or circular system. The maximum location accuracy in this system was 2 meters.

During the campaign, the port of Gdynia was visited four times and the port of Świnoujście once. During stops in those ports, measurements were carried out regularly (twice a day) with marine gravimeters. The gravimetric point on the seaside wharf at the mooring place of the Jan Turlejski ship in the port of Gdynia was used to link the marine gravity measurements to the national gravimetric control network.

The gravimetric equipment consisted of two TGG-1 exemplary gyro-stabilized gravimeters GAL-M and one TGG-1 experimental gyro-stabilized gravimeter. The sensor of these gravimeters was a double quartz system, the principle of which is based on the use of elastic properties of twisted threads and a viscous damping fluid.

The Łebski polygon covered the area of 50×25 km located 10 km north of the port of Łeba in Polish territorial waters. The whole area was divided into two separate parts, overlapping at the border. Measurements were conducted on each separate part of the area, on profiles parallel to the coastline at a distance of 2 km from each other and on secant profiles located meridionally at a distance of 3 km from each other. In addition, gravity measurements were conducted on two diagonal secant profiles 8 and 24. Gravimetric measurements were repeated on four profiles. Thus, they were carried out on 41 profiles (including repeated ones) with a total length of 1100 km. All gravity measurements were carried out within 6 days. In order to exclude the influence of the transient process on the gravimeter readings, the observations were started 30–40 minutes after turning to the next measurement profile. The speed of the ship during the measurements was 7 knots.

Records of gravimeter readings during data processing were averaged over each 10-minute interval. As a result of averaging, continuous gravity measurements on profiles are reduced to discrete points, 2 km apart from each other. Average gravity values from three gravimeters were calculated. Differences in gravity at nodal points (points of intersection of profiles) were determined, and then the gravimetric observations were adjusted. Next, Faye and Bouguer gravity anomalies were calculated.

The results of gravimetric measurements, after processing gravimeter readings in accordance with the method described above, were presented in the form of a catalogue of gravimetric points, which contains 91 nodal points and 134 intermediate points, and gravimetric maps at a scale of 1:200,000 with a contour cut of 2.5 mGal: observed gravity values, Faye and Bouguer anomalies.

To assess the accuracy of the gravimetric measurements (1) Comparison of gravimeter readings on each profile, (2) Comparison of gravimetric measurements on profiles, (3) Comparison of gravimeter readings at profile intersections, and (4) Comparison of gravity measurements at sea with available gravity measurements on the coast, were used. The estimates showed that marine gravimetric measurements, after adjustment, meet the accuracy requirements of gravimetric maps at a scale of 1:200,000 with a contour cut of 2.5 mGal.

In order to carry out the planned gravimetric works in the Pomeranian Bay, a cruise from Gdynia to Świnoujście was carried out and then the ship returned to Gdynia. In the Pomeranian Bay the measurements were performed on five profiles with a total length of ~400 km. During the voyage, the ship's speed was 9–10 knots, and during work in the Pomeranian Bay 6 knots. Continuous measurements were averaged in 10-minute intervals and reduced to discrete points 2–3 km apart.

The assessment of the accuracy of the measurements in the Pomeranian Bay was carried out according to consistency of gravimeter readings on routes and comparison of the results of repeated measurements. The accuracy was assessed as to be at the level of 0.9 mGal. The accuracy of marine gravity measurements during the voyage from Świnoujście to Gdynia was estimated on the basis of the gravimeter readings and the comparison of the obtained results with the gravimetric map developed on the basis of measurements from 1971 made on board of R/V Zaria. It was assessed to be at the level of 1.6 mGal.

It has been found that the values of gravity obtained from the measurements on the Jan Turlejski ship were on average 2 mGal lower than the corresponding values obtained from the measurements on the R/V Zaria ship. The random error of a single measurement was determined to be ±1.4 mGal.

There is no information about the reference systems for the data acquired within Turlejski 1972 campaign. It is reasonable to assume that the gravity data refer to the same reference frames as in Zaria 1971 campaign, i.e. gravity refers to the IGiK-68 system (realization of the Potsdam System), and positions to "1942" system.

The reference frame for depths data was not specified. The depths values given in the documentation were compared with the ETOPO22 global relief model (NOAA, 2022).

Table 3: The statistics of differences between depths measured within the Turlejski 1972 campaign and those from the ETOPO22 [m] (NOAA, 2022)

Campaign	Min	Max	Mean	Std. dev.
Turlejski 1972	-79.4	34.8	-34.5	26.3

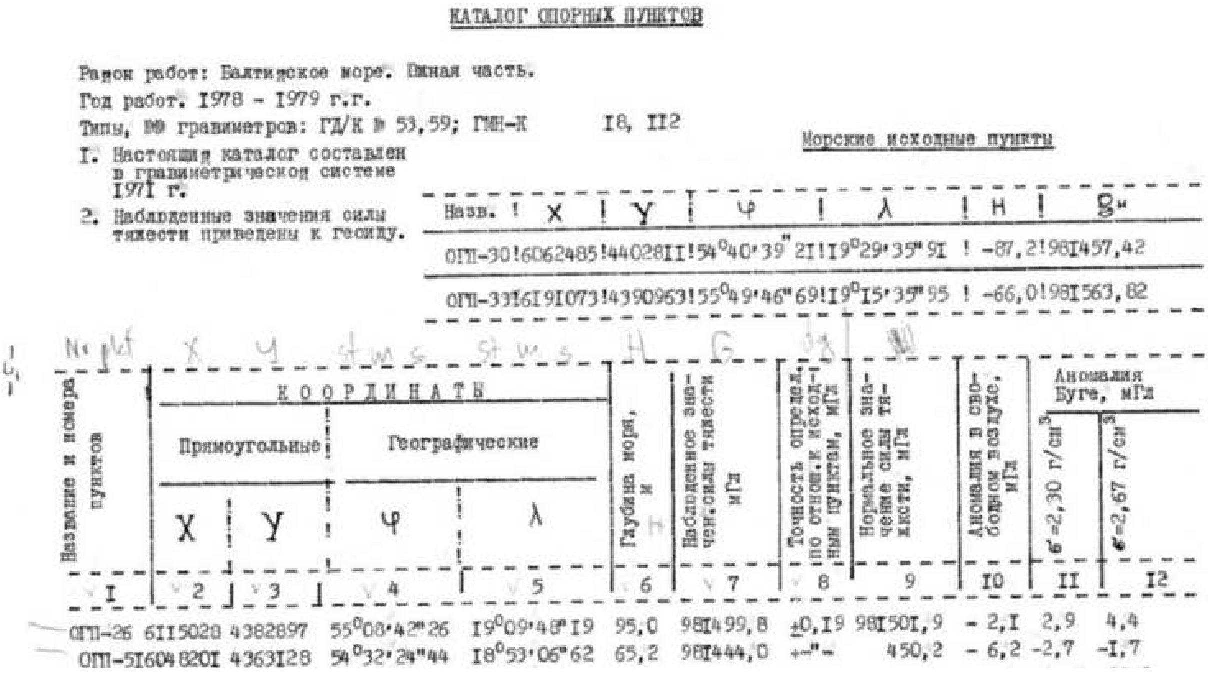
The statistics of this comparison are shown in Table 3.

Standard deviation of depths differences given in Table 3 is 26.3 m and it is much higher than the respective depths differences from the Petrobaltic or Gdansk University Navigator campaigns (1.0–1.5 m). So, depth values from the Turlejski 1972 campaign seem unreliable, thus they will not be incorporated into the BalMarGrav database.

The original documentation of Jan Turlejski campaign in 1972 will be deposited in the National Geological Archives (NAG) maintained by the Polish Geological Institute – National Research Institute at the end of the BalMarGrav project.

PETROBALITC ocean bottom campaign (1978-1979)

Observations of gravity on the bottom of the Baltic Sea were conducted with the use of GAK-EMK bottom gravimeters. Those relative measurements were linked to the bottom points of the Russian gravimetric control points in Klaipeda and Kaliningrad. Some Polish gravimetric points were connected to the gravimetric control network of PGI-NRI from 1980, i.e. the implementation of the Potsdam system in Poland used by PGI-NRI. Location of the measured points was determined with the accuracy of about 80 m in the Pulkovo 1942 system using the Poisk radio-navigation system, and the depths were determined using the Halibut echo-sonde with an accuracy of 1.4 m. The area of measurements covers about 27,180 km^2. It contains 8,878 points with an average distance of



КАТАЛОГ ОПОРНЫХ ПУНКТОВ

Район работ: Балтийское море. Южная часть.
Год работ. 1978 – 1979 г.г.
Типы, №№ гравиметров: ГД/К № 53,59; ГМН-К 18, 112
1. Настоящий каталог составлен в гравиметрической системе 1971 г.
2. Наблюденные значения силы тяжести приведены к геоиду.

Морские исходные пункты

Назв.	X	Y	φ	λ	H	g_н
ОГП-30	6062485	4402811	54°40'39"21	19°29'35"91	-87,2	981457,42
ОГП-33	6191073	4390963	55°49'46"69	19°15'35"95	-66,0	981563,82

Название и номера пунктов	Координаты: Прямоугольные X	Координаты: Прямоугольные Y	Координаты: Географические φ	Координаты: Географические λ	Глубина моря, м	Наблюденное значение силы тяжести мГл	Точность определ. по отнош. к исходным пунктам, мГл	Нормальное значение силы тяжести, мГл	Аномалия в свободном воздухе, мГл	Аномалия Буге, мГл: σ=2,30 г/см^3	Аномалия Буге, мГл: σ=2,67 г/см^3
1	2	3	4	5	6	7	8	9	10	11	12
ОГП-26	6115028	4382897	55°08'42"26	19°09'48"19	95,0	981499,8	±0,19	981501,9	- 2,1	2,9	4,4
ОГП-51	6048201	4363128	54°32'24"44	18°53'06"62	65,2	981444,0	-"-	450,2	- 6,2	-2,7	-1,7

Figure 5: Example of the PETROBALTIC final report containing records of gravity data.

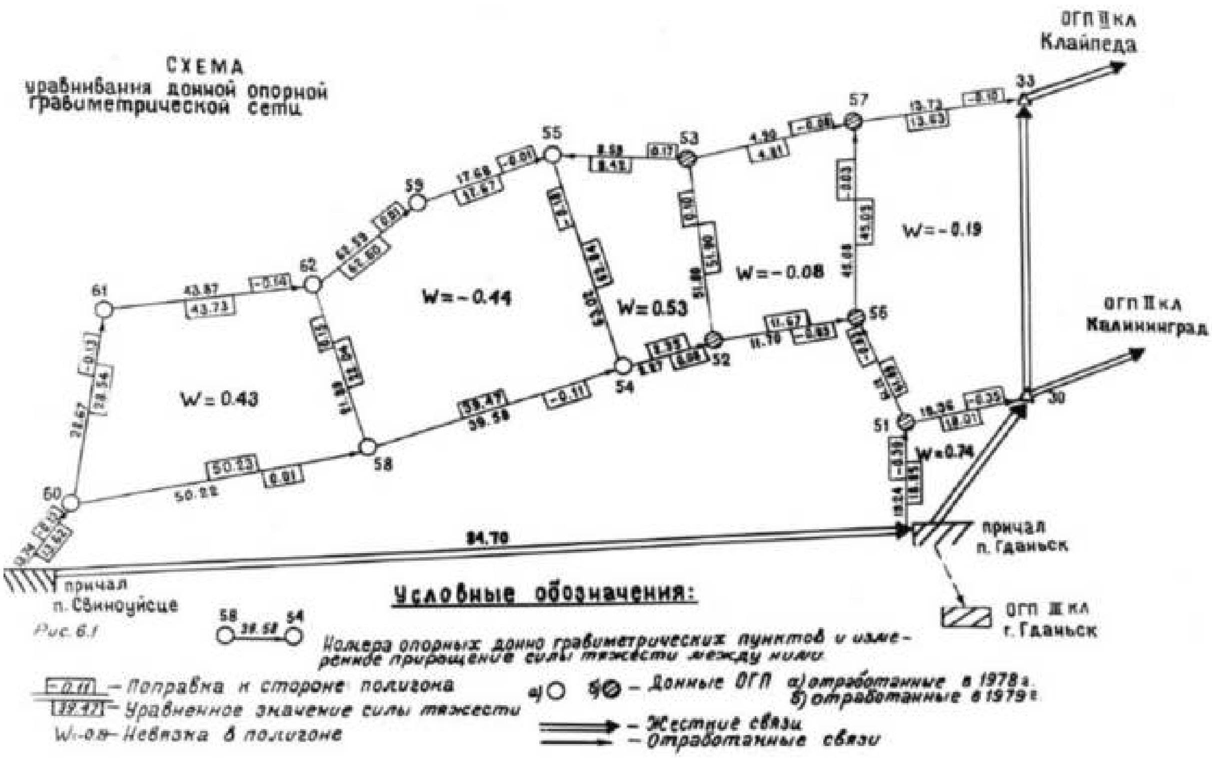


Figure 6: PETROBALTIC sea bottom control network with links to the Polish land control network

about 1 km along the profile and 4 km between the profiles. About 4.2% of the points were selected for control measurements and showed the accuracy of 0.7 mGal on the sea surface after Prey reductions from the bottom. The database contains coordinates of points in the Pulkovo system, sea depth in the Kronstadt system, the value of the gravity in the Potsdam system implemented by the Russian gravimetric network, and free-air and Bouguer anomalies on the sea surface. The original documentation was scanned and digitised (Fig. 5).

In addition to gravimetric measurements, a geomagnetic measurements were also conducted as a part of this campaign. All documentation is in Russian and contains not only a technical description but also a geological description of the area and interpretation of the results of both potential fields and anomaly maps.

Originally, gravity in the PETROBALTIC campaign was related to the Russian gravity reference frame, based on No. 33 (Klajpeda) and No. 30 (Kaliningrad) points of the 2^{nd} class of marine gravity control network. After finishing of the work and completing documentation, two spans connected the Polish Geological gravity control network and Russian marine gravity control network were added (Fig. 6). Świnoujscie and Gdańsk points were defined in the PIG-68 frame by this way.

Because a relationship between old Russian and Polish Geological gravity control networks is not known, additional computation concerning transformation of all Petrobaltic dataset to PIG-68 frame were done:

- re-adjustment of sea bottom network (points OGP from sketch in Fig. 6) by least square method based on gravity values at the points Gdańsk and Świnoujście in the PIG-68 system; obtained parameters of adjustment: redundancy number 5, a-posteriori error of a single span of 0.105 mGal, mean value of adjusted gravity value of 0.025 mGal;

- based on old gravity values at the point of gravity control in original Russian frame and defined by re-adjusted gravity values in PIG-68 frame, a simple mathematical model of transformation was proposed after the tests, based on simple linear polynomial formula of relationship with geodetic latitude φ and longitude λ in such $\Delta g = p_{00} + p_{10} \cdot \varphi + p_{01} \cdot \lambda$. Statistical analysis gave root mean square error of this model as 0.035 mGal with maximum value of residuals -0.08 mGal for the Klajpeda station. The errors of more advanced polynomials were decreasing not significantly (less than 10%), so the simplest model is sufficiently good to transform gravity with uncertainty of 0.7 mGal. An error budget of transformed gravity values is only 5%.

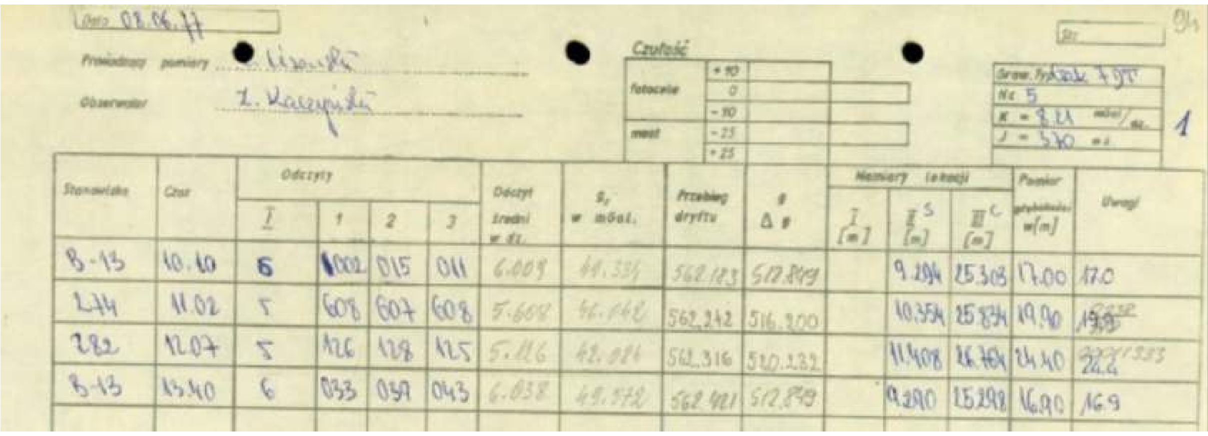
The difference between gravity values in Russian and Polish gravity frames was about 14 mGal. The last step of the transformation will be available after surveys in October 2023 which link the harbour stations to gravity system in Poland realised by the International Terrestrial Gravity Reference Frame.

The spatial coordinates of point surveyed in the PETROBALTIC campaign was transformed to ETRF2000 (2011 epoch) by using seven-parameters Bursa-Wolf transformation derived based on the Polish geodetic control network. The transformation error for land areas is below 1 cm. In the case of extrapolation of these parameters for Baltic Sea area, a precision of this transformation will be slightly lower, but the maximum error of transformation should not exceeded 10 cm. To find another source of errors, the difference between the measured depths and the respective once from the ETOPO22 global relief model was analysed (NOAA, 2022). A mean value of residuals was ±5 m, as expected according to the ETOPO22 model precision.

USTKA ROZEWIE ocean bottom campaign (1976-1981)

In 1976–1981, in the coastal areas of Poland, gravimetric measurements, known as the USTKA ROZEWIE study, were carried out as a complementary survey to the far sea PETROBALTIC campaign (Lisowski, 1980, 1981; Okulus, 1977, 1978, 1979). The USTKA ROZEWIE measurements covered an area up to 10 km from the coast, excluding the Gulf of Gdańsk and the areas of navy training grounds. The GAK-7 DT and GD-K sea bottom gravimeters sea and a light cutter weighing 50 tons were used. Geolocation was determined using the radio navigation method (RYM-2 probe), with the accuracy of ±20 m, while the depths of the points were determined using the Krupp probe with the accuracy of 0.1 m. In total, measurements at 690 points in a grid with average distance of 2 km. The reference network consisted of several dozen sea points was linked to the PIG-68 3 class ground network in the Potsdam system. Eac year about 2-3% of the points were re-surveyed, providing mean square error of 0.24 mGal of difference of gravity values at re-surveyed points.

The documentation of the campaign is in Polish and includes observation logs of the control network measurements and a detailed reports. As part of the preparations to the BalMarGrav project implementation, all materials were transferred to a digital form.



Stanowisko	Czas	I	1	2	3	Odczyt średni w dz.	g w mGal	Przebieg dryftu	Δg	I [m]	II [m]	III [m]	Pomiar głębokości w[m]	Uwagi
8-13	10.10	6	002	015	011	6.009	[illegible]	562.183	512.849		9.194	25.308	17.00	17.0
274	11.02	5	608	607	608	5.608	[illegible]	562.242	516.300		10.354	25.834	19.90	19.9
282	12.07	5	126	128	125	5.126	[illegible]	562.316	520.232		11.408	26.764	24.40	24.4
8-13	13.40	6	033	039	043	6.038	[illegible]	562.421	512.848		9.290	25.298	16.90	16.9

Figure 7: USTKA–ROZEWIE observation logs

The availability of measurement logs allows to recompute gravity values. Several steps were applied in this process:

- adjustment of the whole control network by the least squares method;
- re-calculation of observation logs with linear gravimeter drift corrections to determine g values.

A created database contains coordinates of points in the Pulkovo system, a sea depth in the Kronstadt system and the value of the gravity in the Potsdam system, implemented by the PIG-68 network of the 3^{rd} class.

Each of the data sets was prepared for conversion to the modern ETRF2000 reference frame (accuracy in meters) and for conversion of gravity measurement from the archival gravimetric system to the modern IGSN71 and ITGRF standards (accuracy of 0.2 mGal). The last step of the transformation will be available after surveys in October 2023, which links the harbour stations to the current Polish gravimetric system PBOG14, the realisation of the International Terrestrial Gravimetric Reference Frame in Poland.

2.4 Lithuania

Gravity survey in the Baltic Sea (in Lithuanian waters)

In 1968–1970 scientific research Institute of Marine Geology and Geophysics (Soviet Union) carried out the gravity survey in the Baltic Sea in the Lithuanian waters. Gravity survey covers about 80 km area along the offshore territory (Fig. 8). Density of gravity points is 2×4 km (1 point in 8 km^2). The geodetic coordinates of the points were detected by radio-navigation system *Poisk*, and depths were observed by echo sounder. Gravimetric measurements were carried out by GDK-EMT and GAK-7DT bottom gravimeters, transporting them by ship. Two reference gravity points were used: No. 384 in Kaliningrad (Russia Federation) and No. 383 in Klaipeda (Lithuania). The standard deviations of geodetic coordinates are declared about 32 m, depths – about 0.5 m, and gravity – about 0.37 mGal.

Report containing catalogue of the gravity points was compiled (Fig. 9).

Paper catalogues of gravity points were digitised and gravity values were recalculated from the Potsdam gravity system to IGNS71. Current gravimetric systems defined according to ITGRF standards are an improvement on IGSN71 and differ from it at the level of 0.1 mGal, a value that can be disregarded when considering historical marine gravity data. Coordinates of gravimetric points at the time of observation were in the

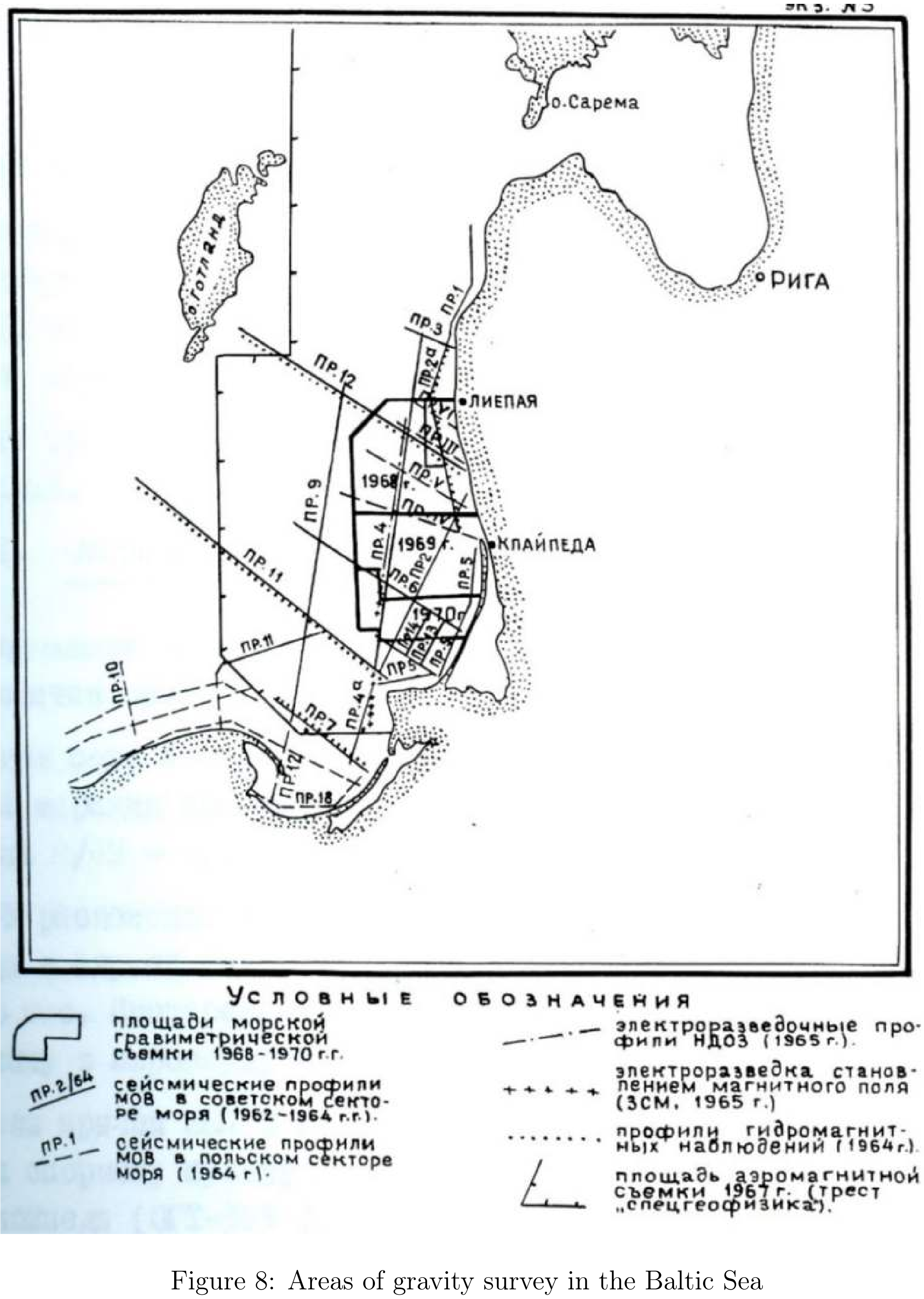


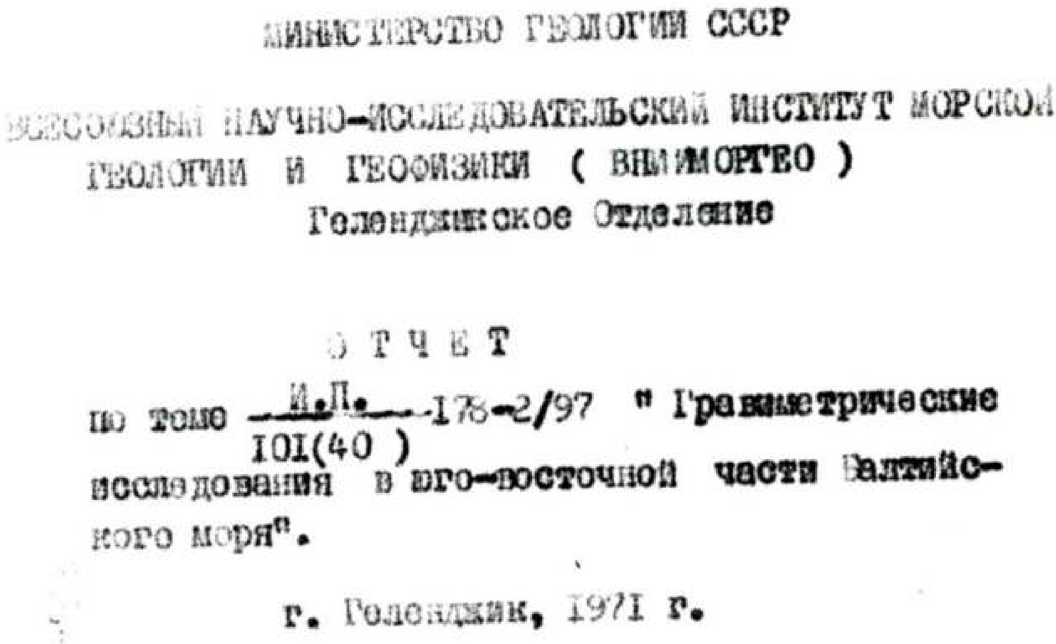
Figure 8: Areas of gravity survey in the Baltic Sea

Soviet Union Pulkovo system (1942). Data were stored in the text files using NKG 80 characters gravity data format. Nowadays the number of Baltic Sea gravity points set, in the NKG/FAMOS DB, is #372.

Nowadays, the data are supervised by the National Land Service under the Ministry of Environment. Original reports can be found at the archive of the Geological Survey of Lithuania.

Gravity survey in the Curonian Lagoon
In 1973–1974 Oil Search Expedition of Geological Board (Soviet Union) carried out the gravity survey in the Curonian Lagoon in the Lithuania waters (Fig. 10). Density of gravity points is 1 × 1 km or even 0.5 × 1 km. The geodetic coordinates of the points were detected by theodolites using intersection method. Gravimetric measurements were carried out by GAK-4M, GDK, GRK-"Delta-2" and GRK bottom gravimeters. Gravimetric measurements were carried out on the bottom of the lagoon or on tripods above the water level, when depths were less than 2 m. The standard deviations of geodetic coordinates are declared about 30 m, depths – about 0.1 m, and gravity – about 0.15 mGal.
Report containing catalogue of the gravity points was compiled (Fig. 11).

Paper catalogues of gravity points were digitised and gravity values were recalculated from the Potsdam gravity system to IGNS71. Current gravimetric systems defined according to ITGRF standards are an improvement on IGSN71 and differ from it at the level of 0.1 mGal, a value that can be disregarded when considering marine gravity data. Coordinates of gravimetric points at the time of observation were in the Soviet Union Pulkovo system (1942). Data were stored in the text files using NKG 80 characters gravity data format. Nowadays the number of Curonian Lagoon gravity points set, in the NKG/FAMOS DB, is #373.


МИНИСТЕРСТВО ГЕОЛОГИИ СССР

ВСЕСОЮЗНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ МОРСКОЙ
ГЕОЛОГИИ И ГЕОФИЗИКИ (ВНИИМОРГЕО)
Геленджикское Отделение

ОТЧЕТ

по теме И.Л. 176-2/97 / 101(40) "Гравиметрические исследования в юго-восточной части Балтийского моря".

г. Геленджик, 1971 г.

Figure 9: Title page of the report on the gravity survey in the Baltic Sea (in Lithuanian waters)

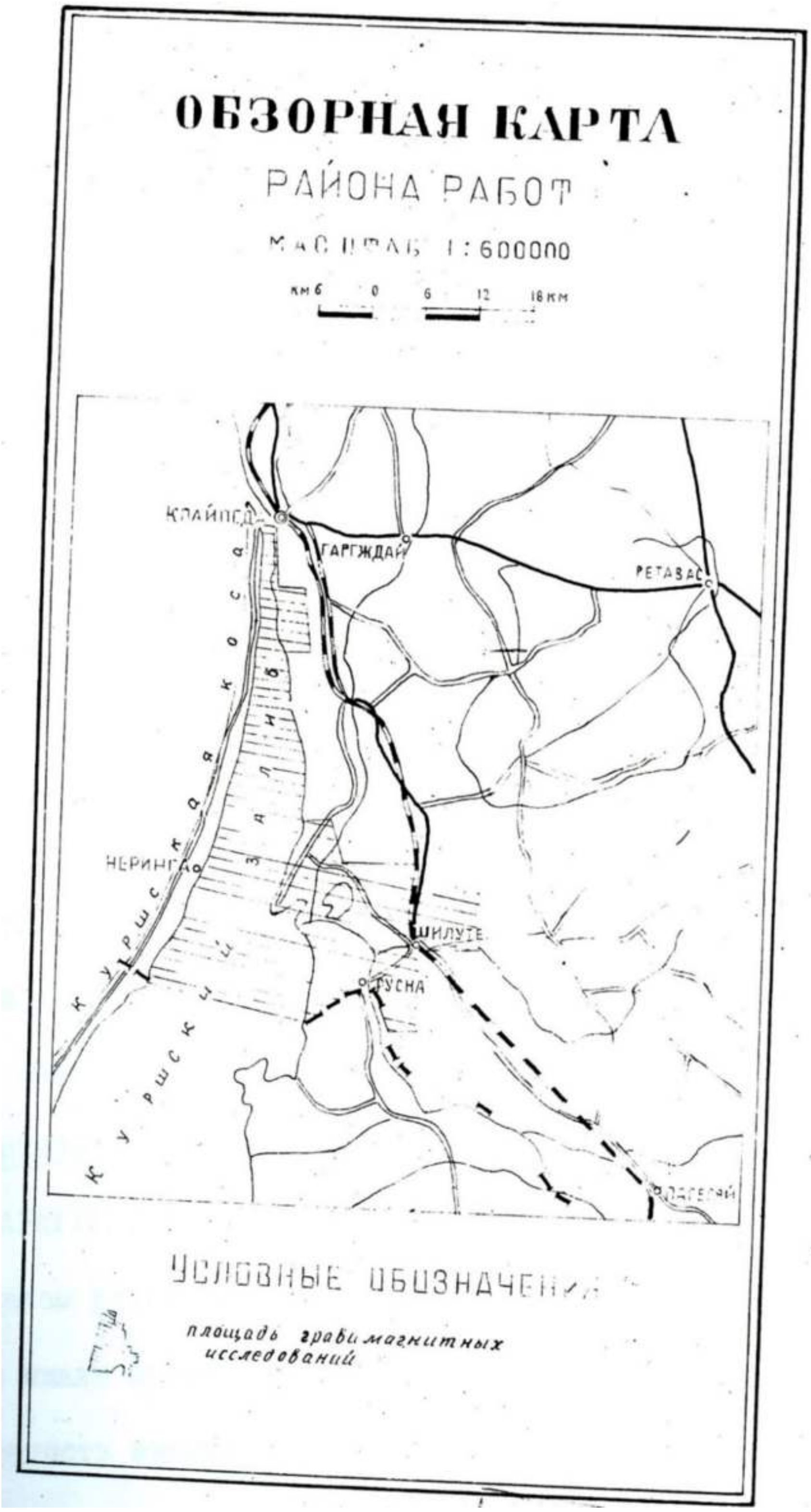
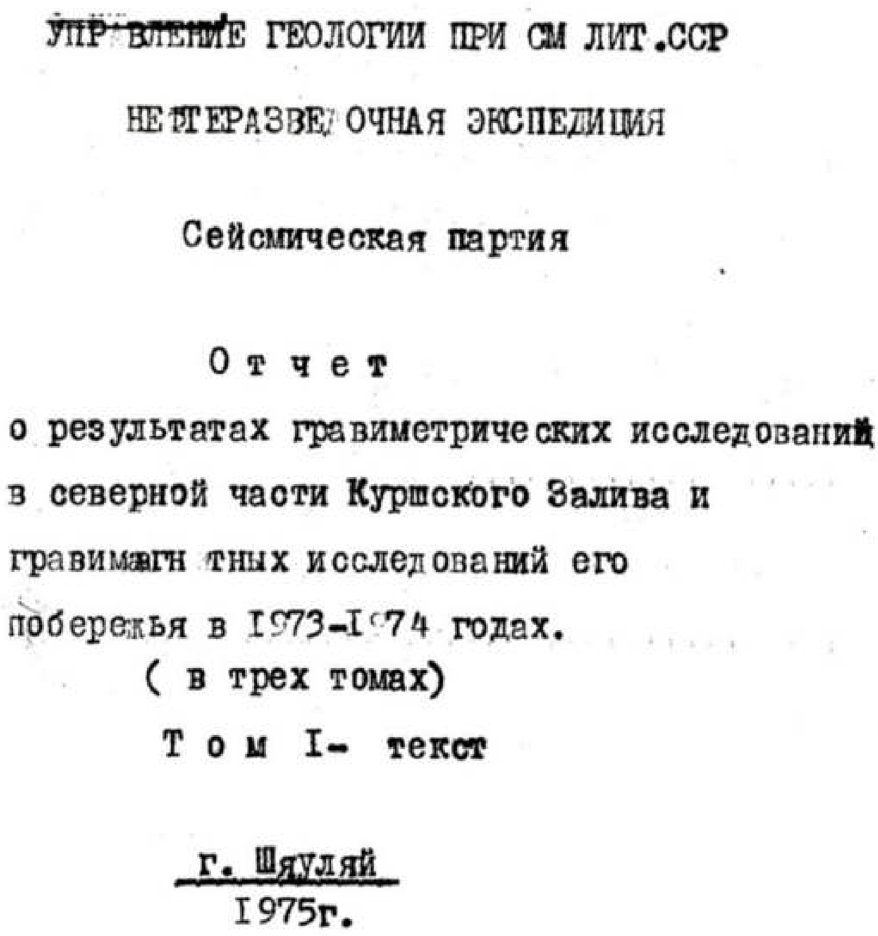


Figure 10: Area of gravity survey in Curonian Lagoon



УПРАВЛЕНИЕ ГЕОЛОГИИ ПРИ СМ ЛИТ.ССР

НЕФТЕРАЗВЕДОЧНАЯ ЭКСПЕДИЦИЯ

Сейсмическая партия

Отчет

о результатах гравиметрических исследований
в северной части Куршского Залива и
гравимагнитных исследований его
побережья в 1973-1974 годах.
(в трех томах)
Том I- текст

г. Шяуляй
1975г.

Figure 11: Title page of the report on the gravity survey in the Curonian lagoon

Nowadays, the data are supervised by the National Land Service under the Ministry of Environment. Original reports can be found at the archive of Geological Survey of Lithuania.

2.5 Latvia

Gravimetric surveying campaigns in the south-eastern part of the Baltic Sea and in the area of the Baltic Sea shelf were actively carried out in the period from 1969 to 1979. The works were executed by USSR enterprises Specgeofizika, Povarovka and Marine Engineering Geology, Riga. All reports, more than 10, are stored at the State Limited Liability Company "Latvian Environment, Geology and Meteorology Centre". Examples of cover pages of reports are shown in Fig. 12 and 13.

The description states that due to the detection of magnetic anomalies, the area of gravimetric measurements has been increased by more than 3 thousand square kilometers. The total area measured within the project with a sea surface gravimeter is 15,400 square kilometers (Fig. 14 and 15).

Nowadays, the historical gravity measurements in the Latvian water are supervised by the

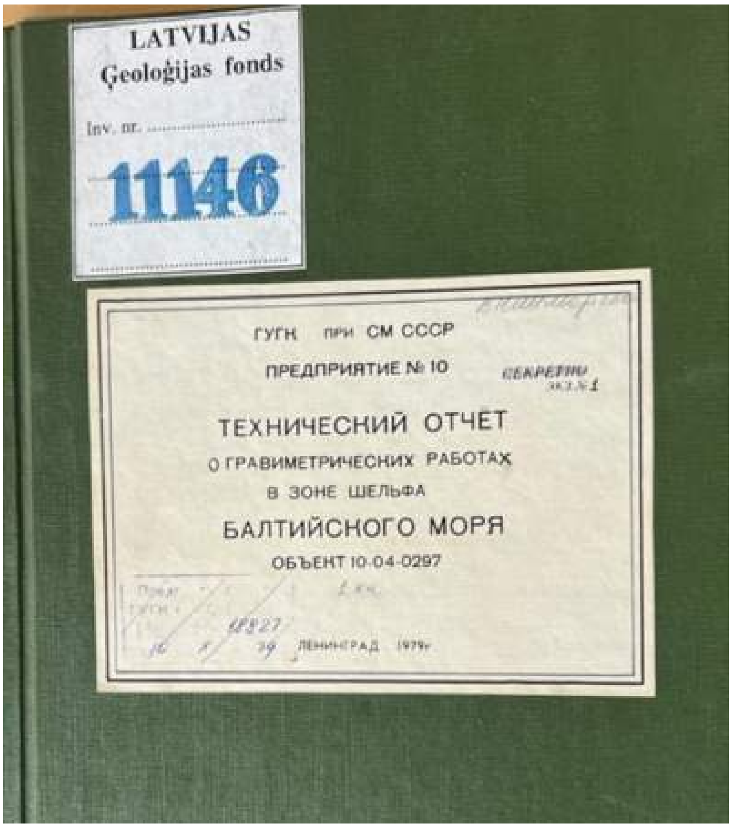


Figure 12: Title page of the technical report

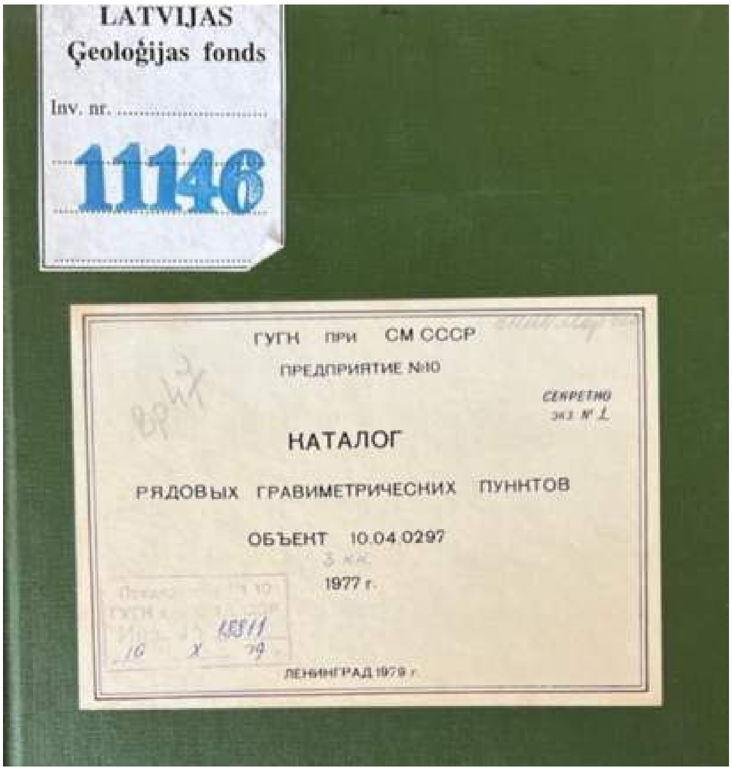
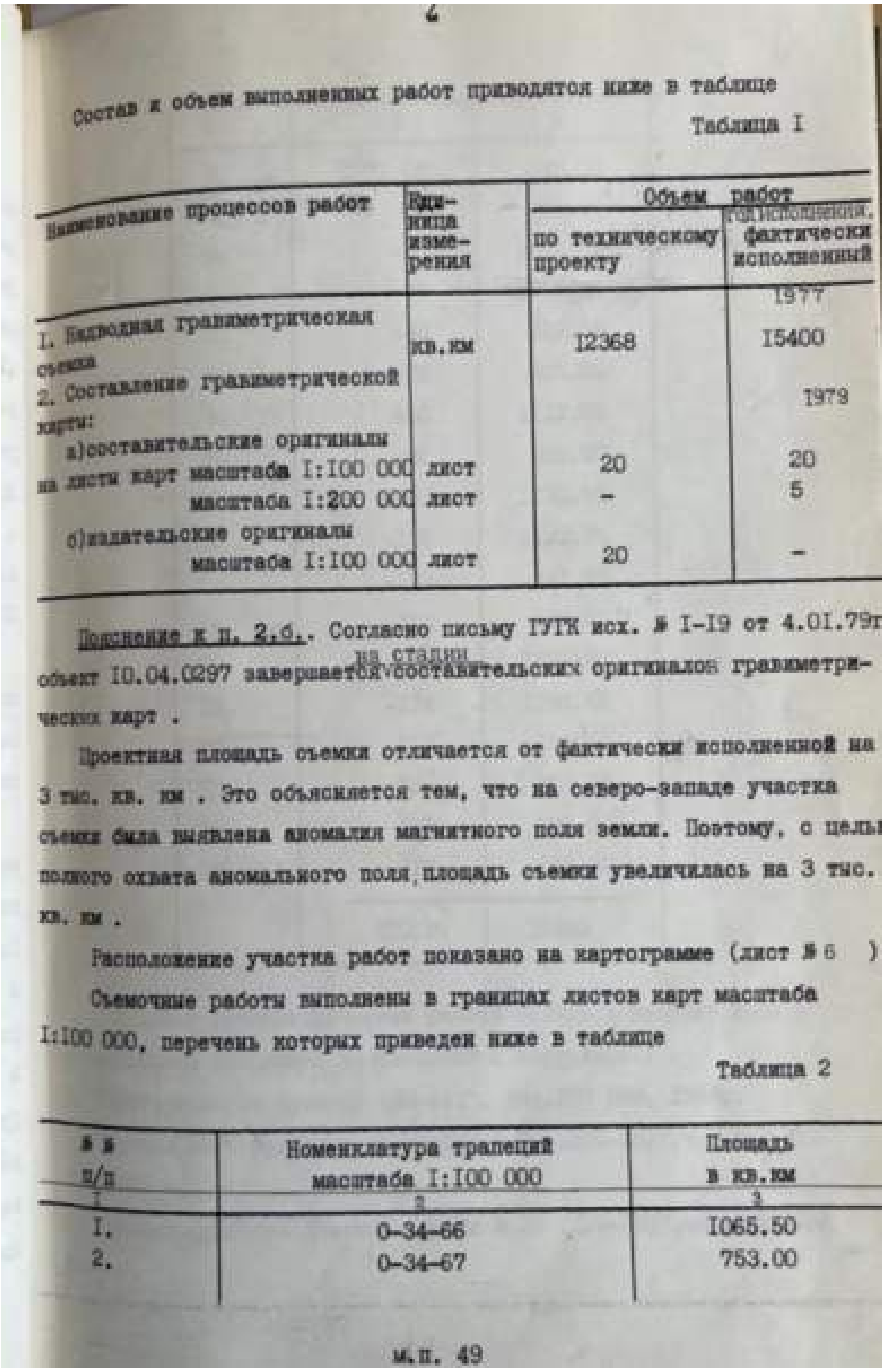


Figure 13: Points catalog cover page



2

Состав и объем выполненных работ приводятся ниже в таблице

Таблица I

Наименование процессов работ	Единица измерения	Объем работ: по техническому проекту	Объем работ: год исполнения, фактически исполненный
I. Надводная гравиметрическая съемка	кв.км	I2368	1977 I5400
2. Составление гравиметрической карты:			1979
а) составительские оригиналы на листы карт масштаба I:100 000	лист	20	20
масштаба I:200 000	лист	-	5
б) издательские оригиналы масштаба I:100 000	лист	20	-

Пояснение к п. 2.б. Согласно письму ГУГК исх. № I-I9 от 4.01.79г объект I0.04.0297 завершается на стадии составительских оригиналов гравиметрических карт.

Проектная площадь съемки отличается от фактически исполненной на 3 тыс. кв. км. Это объясняется тем, что на северо-западе участка съемки была выявлена аномалия магнитного поля земли. Поэтому, с целью полного охвата аномального поля, площадь съемки увеличилась на 3 тыс. кв. км.

Расположение участка работ показано на картограмме (лист № 6)

Съемочные работы выполнены в границах листов карт масштаба I:100 000, перечень которых приведен ниже в таблице

Таблица 2

№ № п/п	Номенклатура трапеций масштаба I:100 000	Площадь в кв.км
1	2	3
I.	0-34-66	I065.50
2.	0-34-67	753.00

м.п. 49

Figure 14: An example of description of the historical marine gravity measurements on the Baltic Sea shelf

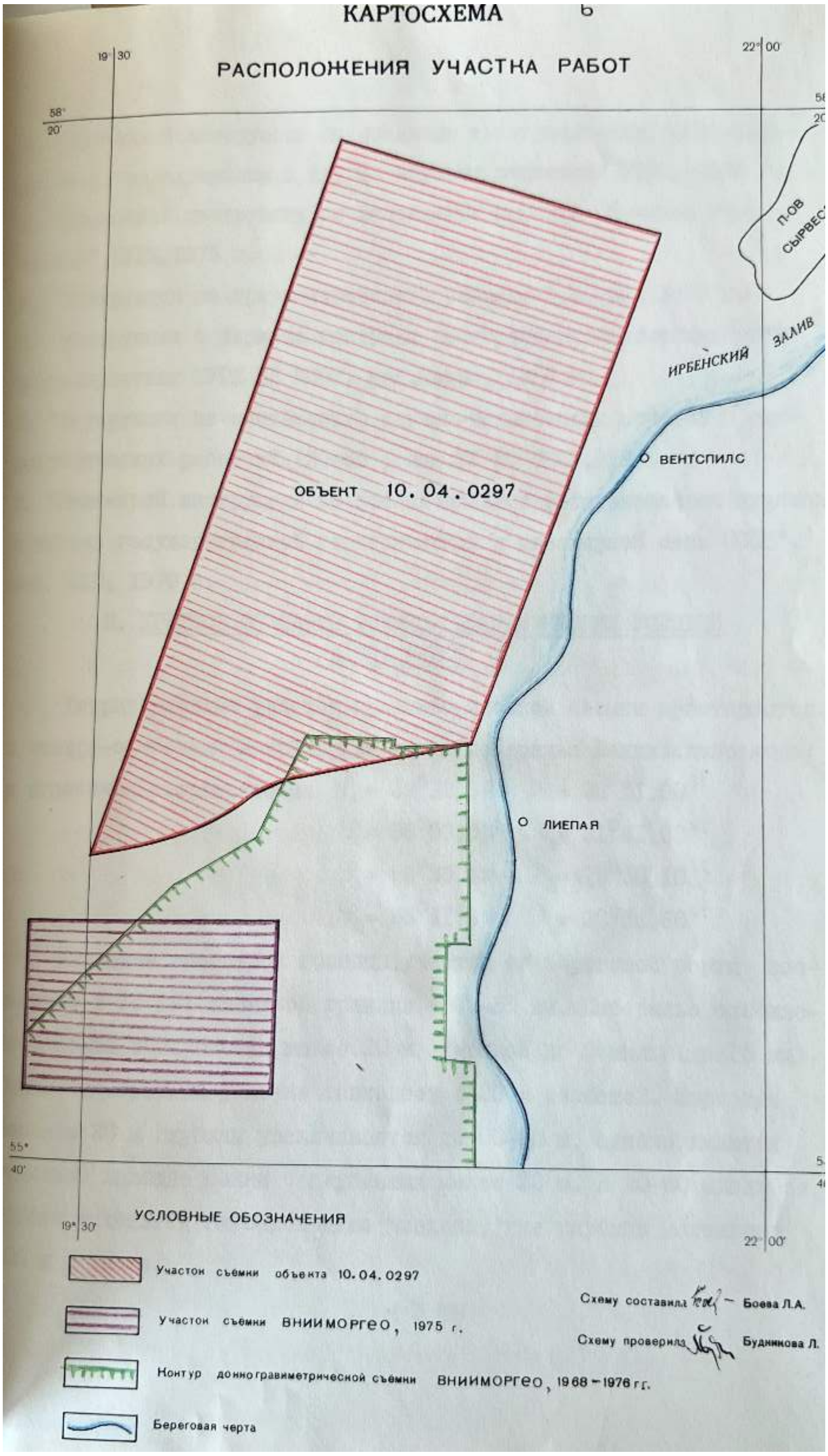


Figure 15: Territories surveyed until 1979 in the vicinity of the Latvian sea coast

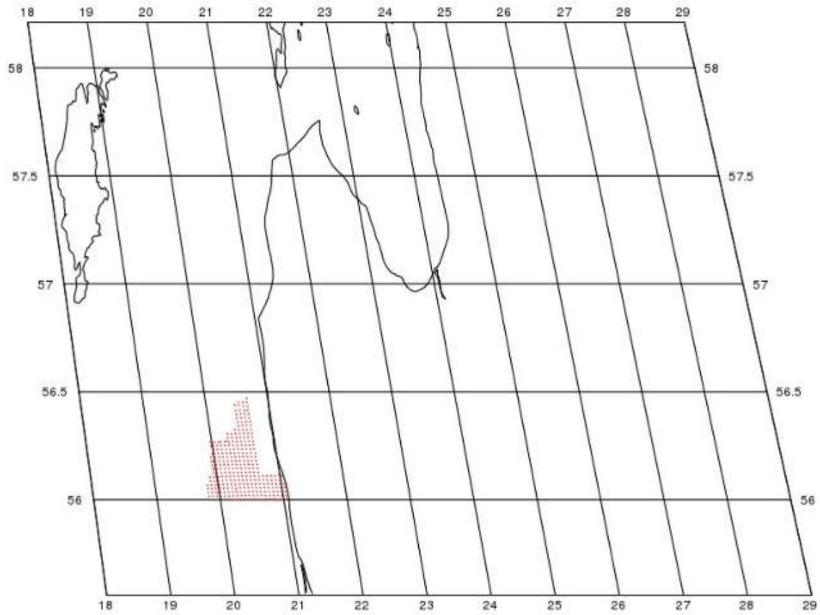


Figure 16: Source #338 depicted as a schematic location of NKG's gravity DB points

Latvian Geospatial Information Agency (LGIA). They are stored in the NKG/FAMOS DB as sources numbered #338 (Fig. 16), #615 (Fig. 17) and #345 (Fig. 18). They have been considered the main source of marine gravity data in the territorial waters of Latvia for several decades since 1998. #338, #615 and #345 contain 292 1847, and 303 gravimetric observation points, respectively. Initially, altimetric observations of ERS-1 were used, which were later replaced by gravity data. Gravity data from those source were used in all national-, regional- and global quasi-geoid computations from the area, starting from LV'98 untill current model LV'14.

The latest gravimetric measurements of Latvia (source #345) were carried out so far in Latvian waters in 1990, with a support base located in Liepaja and Ventspils in a strip almost 100 km wide along the western coast of Latvia. The works were carried out by the USSR (or state-owned) enterprise Specgeofizika by order of the Department of Geology, Geodesy and Cartography of the Council of Ministers of the Republic of Latvia. In order to link marine gravity measurements to the ground-based gravimetric support network, the exploration vessels regularly visited the ports and reference gravimetric points were determined, and regular gravimetric measurements were conducted using relative spring gravimeters. The locations of historical reference points (Liepaja and Ventspils) are known and used in many cases. The location of the ship during the works on the west coast of Latvia was determined using GLONASS (Russian) or GPS Navstar (USA) positioning systems, depending on when it was operational due to the number of available artificial Earth satellites. This could be the first such case in Latvian territorial waters, determining the coordinates of a ship with the help of modern satellite technologies. And the depths were observed by an echo sounder. Gravimetric measurements were performed by bottom gravimeters, transporting them by a geophysical research vessel.

Historical gravimetric marine measurement data play a role in the additional testing of new gravimetric measurements in order to obtain a stable result and judge further

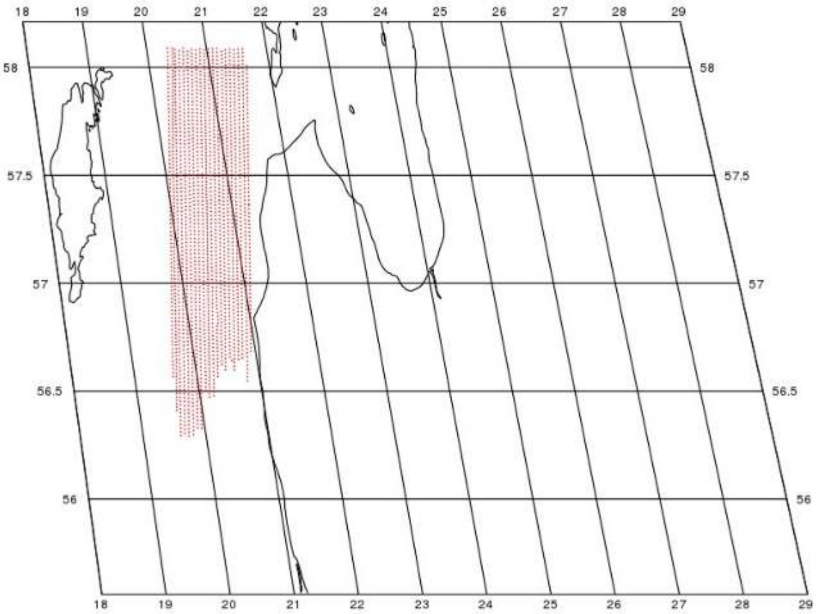


Figure 17: Source #615 depicted as a schematic location of NKG's gravity DB points

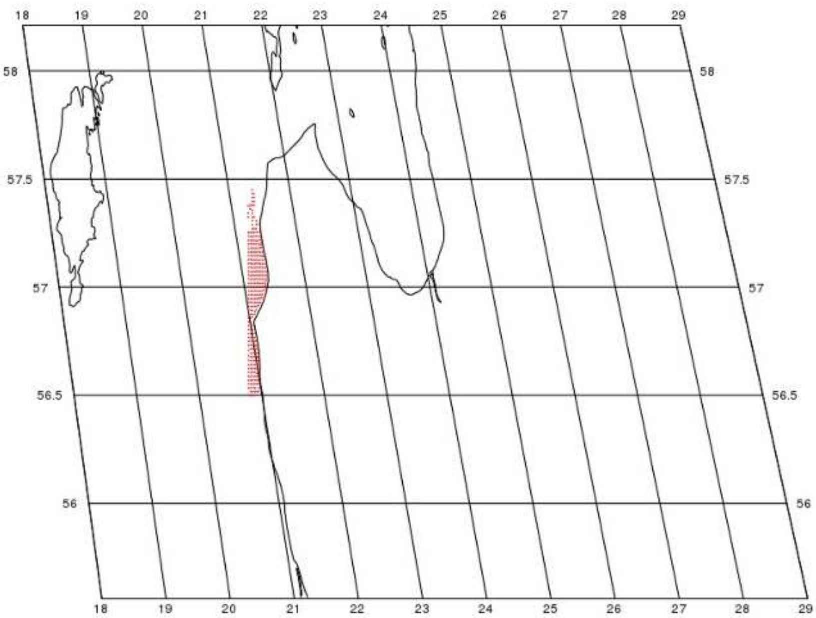


Figure 18: Source #345 depicted as a schematic location of NKG's gravity DB points

developments.

2.6 Estonia

Gravity measurements within Gulf of Riga in 1966-1967

Sea bottom gravity measurements in the Gulf of Riga were conducted in 1966-1967 (detailed description in Jürgenson (2003); also, the references therein) – in the southern Gulf of Riga in 1966 and the northern Gulf of Riga in 1967 (Fig. 19). Over 2000 gravity points were surveyed using soviet manufactured KDG-P and GAK-7DT marine gravimeters (Fig. 20) with an average root mean square error of ±0.4 mGal in a row of survey points. These data points formed roughly a 2×5 km gravity data grid. Gravity surveys were connected to the USSR 2^{nd} order gravity network points in Kuressaare, Pärnu, Riga, and Virtsu. Coordinates of these network points were retrieved from 1:25 000 and 1:50 000 scale topographic maps with the accuracy of ±20 and ±40 m, respectively. Lo-

Figure 19: Gulf of Riga gravity survey regions in 1966 (south) and 1967 (north)

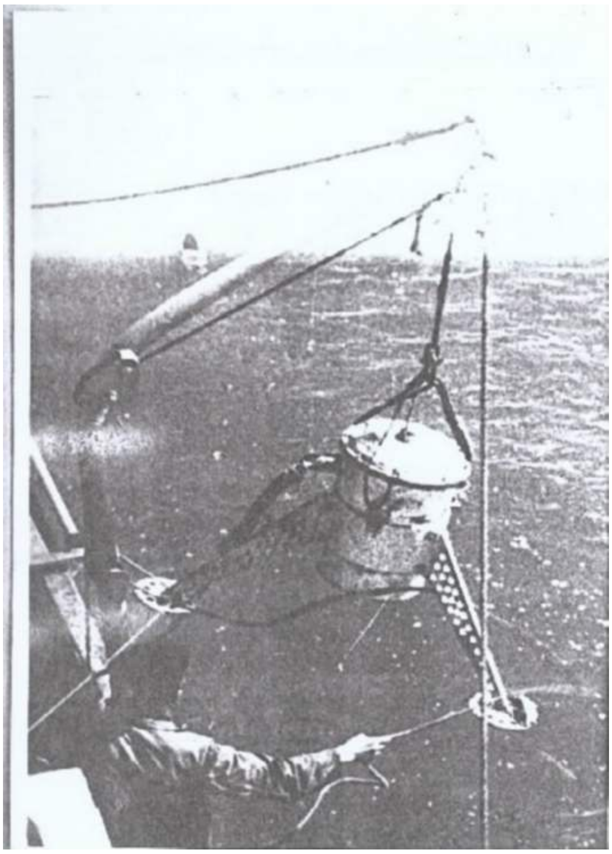


Figure 20: Marine gravimeter used in the Gulf of Riga during the sea bottom gravity survey

cations of survey points were determined using the radio-geodetic system Poisk. It is estimated that the accuracy of coordinates of these gravity points was ±80 m. Sea depth measurement accuracy employing echo sounding was estimated at around ±1.0 to ±1.5 m.

As a result of these gravity surveys, 1:200 000 scale paper maps of the Ministry of Geology of the USSR were compiled, depicting Poincaré-Prey gravity anomalies. These maps depicted gravity anomalies as survey points with observed values and isolines – only data presented as observed values have been digitized. It is estimated that the coordinate errors associated with data digitization are around ±70 m. The initial coordinates were given in the Pulkovo-42 coordinate system, so later coordinates were transformed into the ETRF89 frame.

Free-air gravity anomalies at the sea surface (i.e., $H = 0$) were computed from Poincaré-Prey gravity anomalies. Original sea bottom depth data (used for computing the initial Poincaré-Prey gravity anomalies) was assessed using the sea depths obtained from AS Regio. Differences were generally around a few meters. The conversion to free-air gravity anomalies was conducted using AS Regio sea depth data. For the conversion from the initial Potsdam gravity system to the IGSN71, a constant of −14 mGal was considered. Current gravimetric systems defined according to ITGRF standards are an improvement on IGSN71 and differ from it at the level of 0.1 mGal, a value that can be disregarded when considering historical marine gravity data. Ellipsoidal heights of these gravity data points were determined using the EST-GEOID2011 geoid model (Talvik and Oja, 2014).

Currently, 1493 gravity data points are in use (Fig. 21). Details regarding gravity data are presented in the Table 4. The uncertainty associated with gravity data is ±2.0 mGal (instead of the initial ±0.4 mGal of surveys) due to errors associated with data digitization

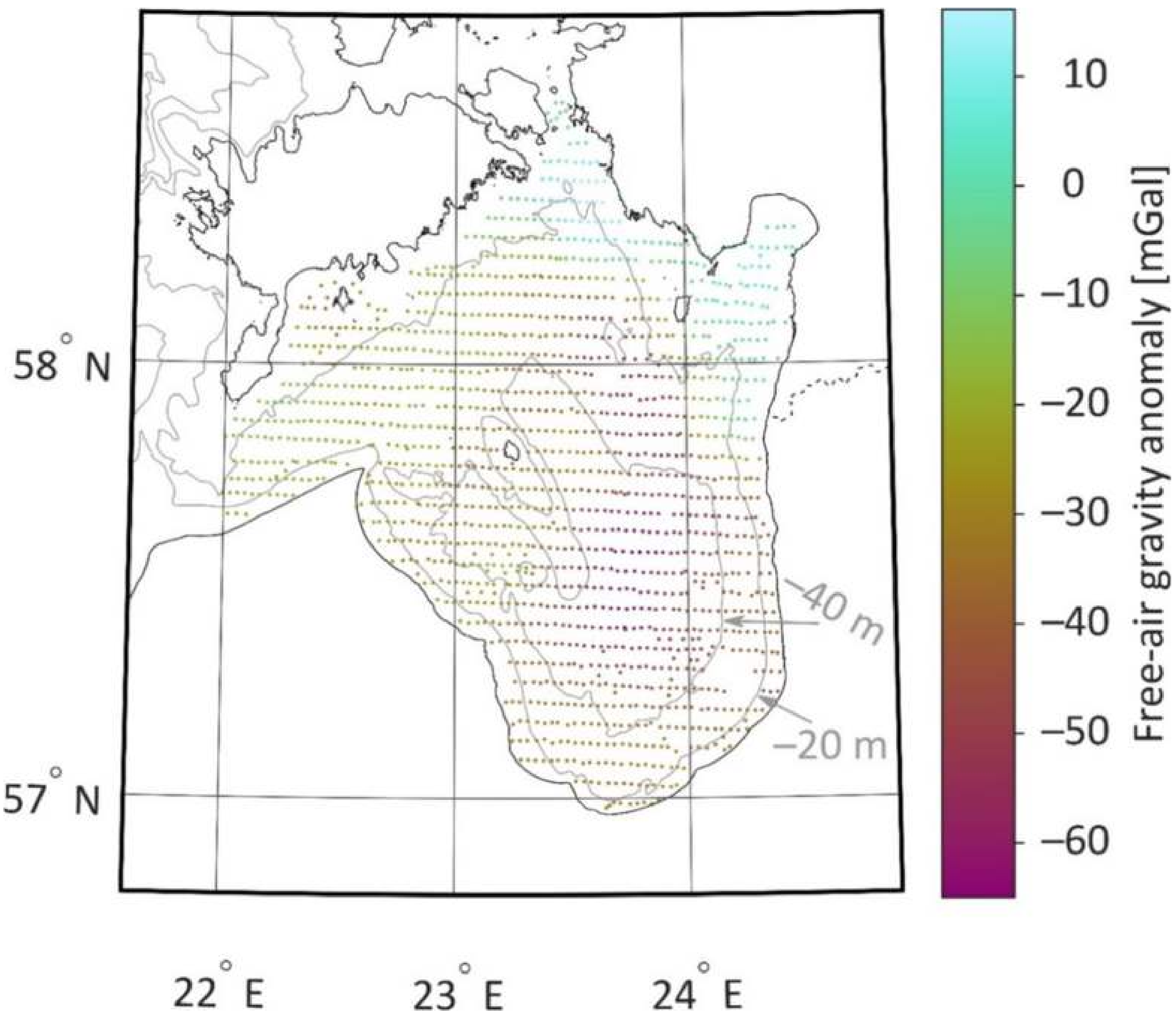


Figure 21: Marine gravity measurements in the Gulf of Riga and the corresponding free-air gravity anomaly values (see the colour bar): min = –65.0 mGal, max = 16.1 mGal, mean = –28.7 mGal, SD = 16.7 mGal. The greyish isolines denote the sea bottom depths.

Table 4: Details about the historical gravity data at the Gulf of Riga

NKG gravity database source No	Historic data set, survey agency and area	Obs. time	Number of obs. points	Uncertainty of position, height and gravity (with lower and upper limits)	Original gravity datum, constant correction to Gravity system of Estonia 1995 (GV-EST95)
618	Ministry of Geology of the USSR, Gulf of Riga	1966-1967	1493	±20...±80 m, ±1...1.5 m (sea depth meas.) ±2.0 mGal	PGS1960 (–14.0 mGal)

and conversions. Comparison with the 1998 aerogravity survey data reveals differences up to 1.8 mGal.

Nowadays, the historical gravity measurements in the Estonian waters are supervised by the Estonian Land Board. They are stored in the NKG/FAMOS DB as a source numbered 618. Original documentations (paper copy, paper maps) can be found most probable in the archives of the Estonian Land Board.

2.7 Finland

Bottom gravimetry in Baltic Sea, 1956

The Finnish Geodetic Institute (FGI), being now the part of the National Land Survey of Finland, carried out bottom gravimetry in the Baltic Sea in 1956 (Fig. 22). The measurements were done from the research vessel Aranda with the Gulf underwater gravimeter

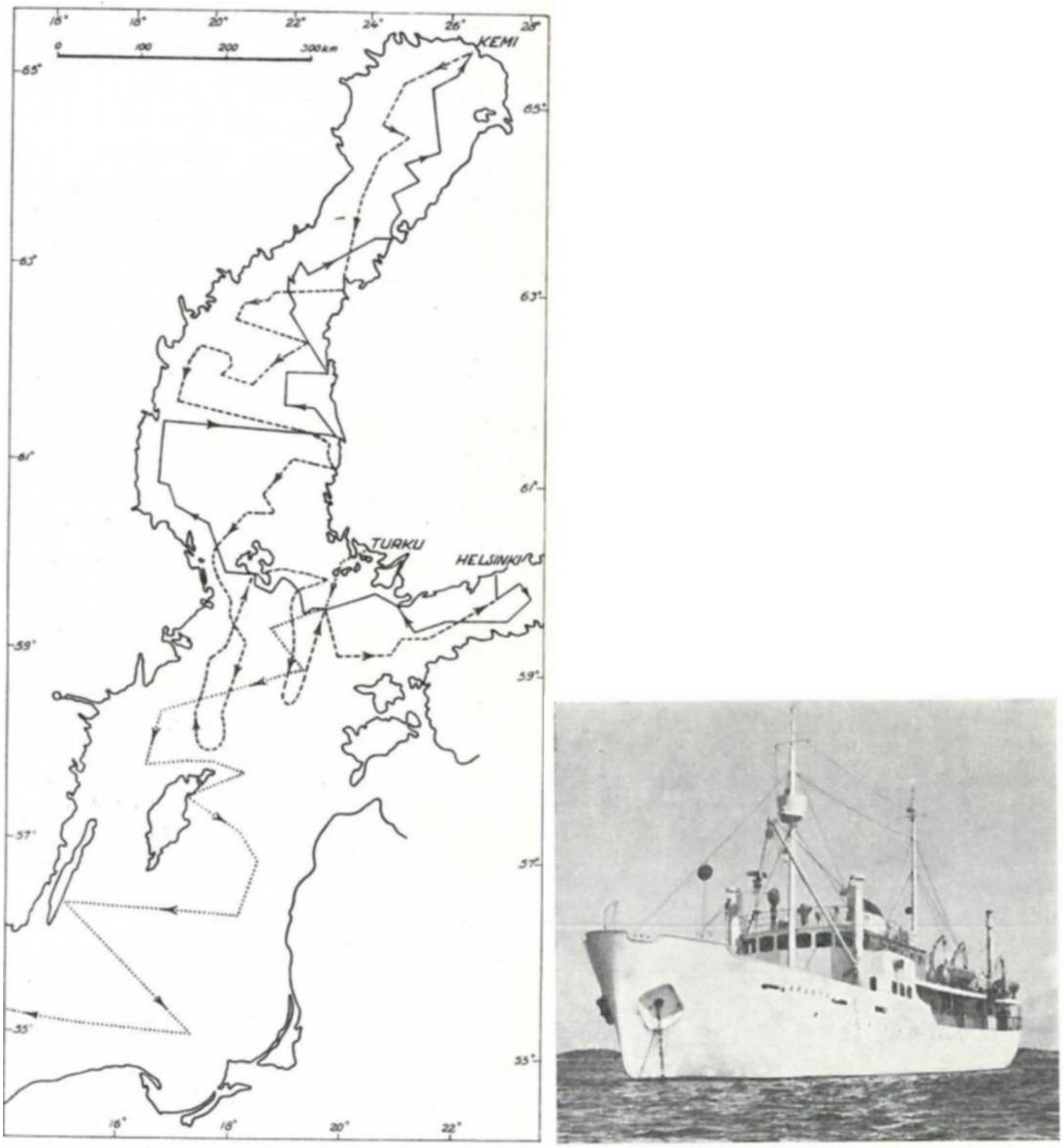


Figure 22: The route of the M/S Aranda during the bottom gravity measurements in July and August 1956 (left) and The M/S Aranda (right) (Honkasalo, 1956)

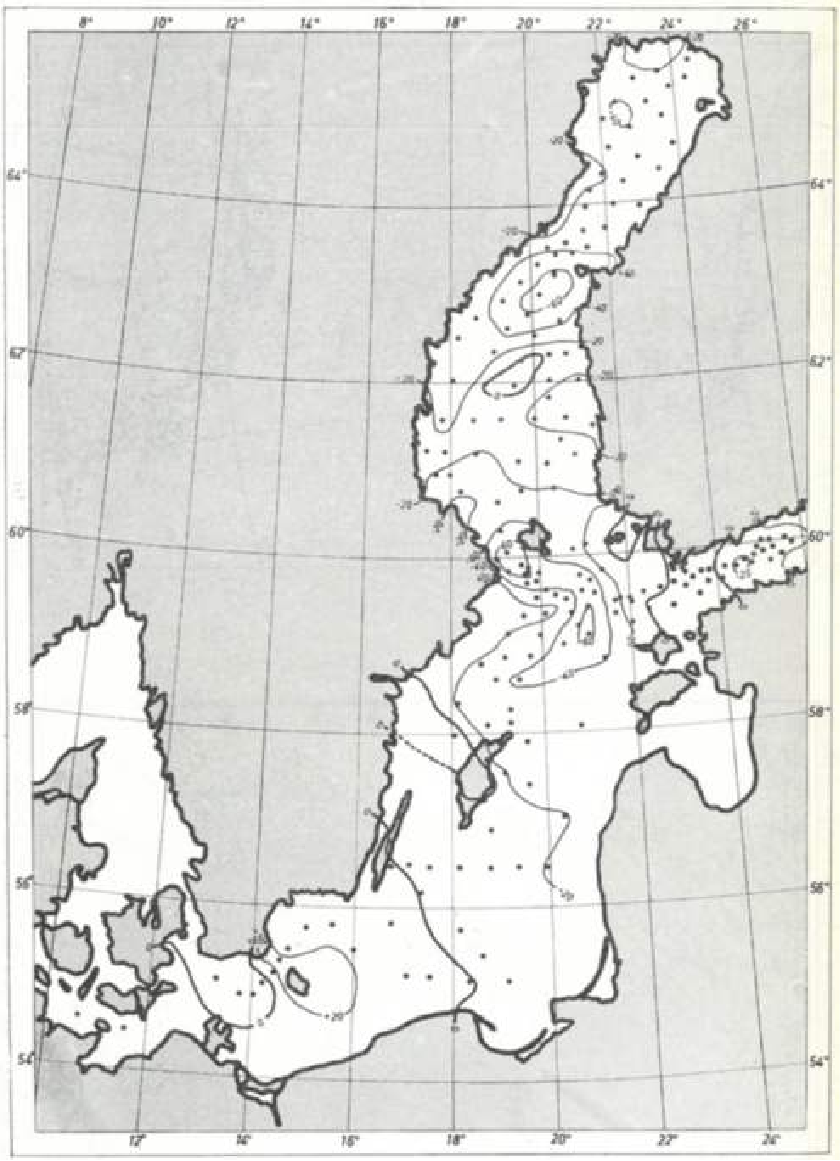


Figure 23: Gravity measurements in the Baltic with Gulf underwater gravimeter in 1956. The stations and free-air anomalies (Honkasalo, 1962)

GM3 that was on loan from Gulf Research & Development Co. The measurements are described in detail in Honkasalo (1956, 1959). A summary is given here.

When sonar measurements showed that the sea bottom was suitable, a token flag was anchored next to which the vessel was kept stationary. Then the gravimeter was lowered with a metal wire to the bottom. The gravimeter was remotely levelled by use of photocells and the reading was done photographically on film. The instrument temperature was kept stable with an accuracy of 0.01°. Depths were measured using echo sounding and plump line measurements. Echo sounding accuracy was estimated to be ±0.7 m (Honkasalo, 1962). Positioning was done using the DECCA system. Harbour ties were done every 3 days. The quadratic mean of the harbour closures was ±1.1 mGal and drift of the instrument was comparable to the drift on land. A total of 170 points were measured with the largest depth being 151 m (Fig. 23).

Original calculation documents can be found in the archive of the National Land Survey of Finland (Document Number 590_M6109). Original results in the form of point gravity values and free-air anomalies at sea level are listed in Honkasalo (1959).

The measurements were tied to the Helsinki reference station, that was station of the 1^{st} order world gravity network at that time. The Helsinki station was tied to reference stations abroad using pendulum and relative gravimeter measurements (Honkasalo, 1962). After the establishment of the First Order Gravity Net of Finland, FOGN (Kiviniemi, 1964), all gravity data, including the bottom gravity measurements of 1956, were readjusted (Kiviniemi, 1980). The resulting gravity values are in the IGSN71 system and have epoch 1963 and are in the mean tide system (Kääriäinen and Mäkinen, 1997).

For geoid modelling purposes the coordinates have been transformed to modern systems. The horizontal coordinates were transformed from the original frame for latitude and longitude, KKJ (with the international ellipsoid of 1924 (Hayford), $f = 1/297$), to the current Finnish reference frame EUREF-FIN (Finnish ETRF89 realization) using the coordinate transformation service provided by the National Land Survey.

The gravity values have been transformed from mean tidal system to the zero tidal system using:

$$g_{zero} = g_{mean} + 30.4 - 91.2 sin^2\varphi \;\; [\mu\text{Gal}]. \tag{1}$$

Then the data were transformed from the 1963 land uplift epoch to the epoch 2000.0 using the follow equations:

$$\frac{dh}{dt}_{absolute} = \left(\frac{dh}{dt}_{apparent} + 1.32\right) \cdot 1.06 \;\; [\text{mm/yr}], \tag{2}$$

$$\frac{dg}{dt} = -0.154 \cdot \frac{dh}{dt}_{absolute} \;\; [\text{Gal/yr}], \tag{3}$$

where $\frac{dh}{dt}_{apparent}$ is obtained using the vertical component of the model NKG2005LU: NKG_RF03vel.

The bottom measurements were then converted to zero height using:

$$g_{h=0} = g_{bottom} + \left(\frac{dg}{dz} - 4\pi G\rho\right) \cdot H = g_{bottom} + 0.2248H, \tag{4}$$

where H is negative.

The data is part of the NKG database item #322 as subset #322_5. Owner of the data is the National Land Survey of Finland. The dataset includes also bottom measurements made in the Barents Sea in 1957, which is out of the scope of this project. These measurements in the Barents should not be used.

Sea ice measurements – not for re-processing

The sea-ice measurements are not in the target area of the BalMarGrav project. This data is not reprocessed, but it can be used for checking and aligning with the FAMOS

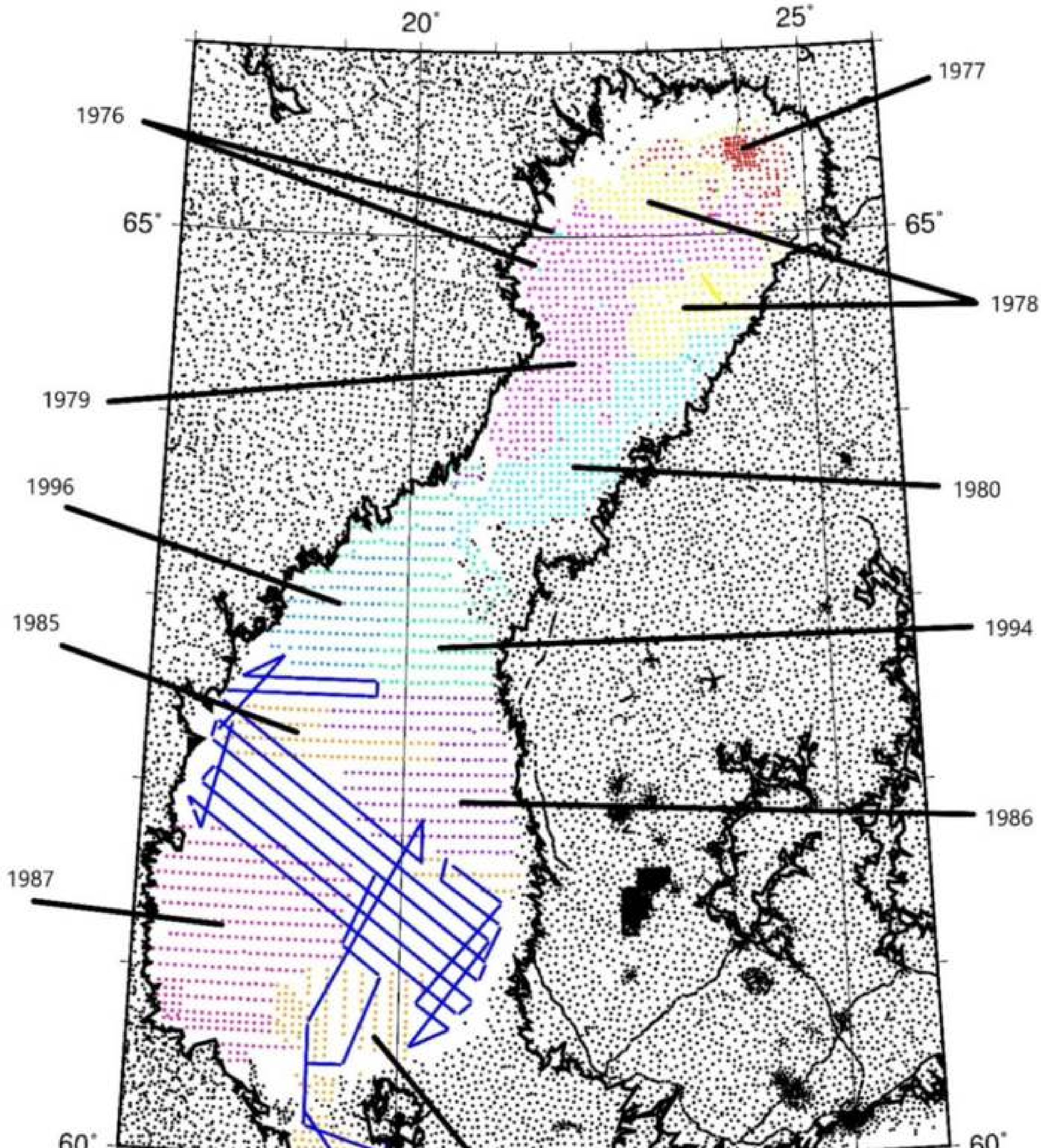


Figure 24: Sea-Ice measurements in the Gulf of Bothnia in different years between 1976 and 1996. The blue line are the 1996 ship-born measurements.

data and input for final map products and geoid calculation.

Extensive surveys on the ice were started in 1976 when the 5×5 km^2 nation-wide network approached completion (Lehmuskoski, P. and J. Mäkinen , 1978). Measurements in the Bothnian Bay took place between 1976 and 1980, in the Åland Sea in 1985, and in the Bothnian Sea again in 1985-1987, 1994 and 1996 (Kääriäinen and Mäkinen, 1997). In total 2219 points were measured on the sea ice (Fig. 24). These measurements were conducted in cooperation with the National Land Survey of Sweden and the Geological Survey of Sweden.

On the ice the gravity measurements are complicated by the movements of the ice. In the early years, when a Worden gravimeter was used, the accuracy of the gravity observations was estimated to be 0.10 mGal in the North of the Bothnian Bay (Lehmuskoski, P. and J. Mäkinen , 1978). When moving more to the south, where conditions were worse, the accuracy deteriorated to between 0.15 and 0.4 mGal (Kääriäinen and Mäkinen, 1997). Starting from 1985, overdamped LCR gravimeters were used, and the accuracy was estimated to be 0.1 mGal (Kääriäinen and Mäkinen, 1997). The ice thickness was measured, and the gravity values were reduced to sea level, which introduced an additional uncertainty to the gravity values of 0.02 mGal.

In the early years, coordinates were obtained using the Decca navigation system. The standard error in 1977 was determined to be 50 m, which corresponds to 0.10 mGal uncertainty in the calculation of anomalies (Lehmuskoski, P. and J. Mäkinen , 1978). Later the Decca positioning accuracy deteriorated to 100 – 300 m. Since 1994 the position was determined with GPS (Kääriäinen and Mäkinen, 1997). Up till 1987 depths of the points were determined from sounding charts, whereas from 1987 on the depths were measured by echo sounding. Lehmuskoski, P. and J. Mäkinen (1978) estimate the that the sounding chart readings have an accuracy of ± 2 m, which causes an error in the Bouguer reduction of 0.14 mGal.

When the ice moves, the Coriolis force causes an additional vertical component of the acceleration, called Eötvös effect. Lehmuskoski, P. and J. Mäkinen (1978) estimated the effect to be at most 0.16 mGal for the 1976 and 1977 measurements. However, no Eötvös corrections were applied to the data of these years. In later years Eötvös corrections, calculated from wind-models, were applied. In 1996 DGPS was used to measure the ice movements and calculate the Eötvös corrections. The corrections in 1996 varied between 0 and 0.14 mGal according to Ruotsalainen (1997b), but a maximum value of 0.493 mGal was reported in Ruotsalainen (1997a).

All these data were original in the KKJ coordinates system and measurements on the ice were reduced to zero height in the N60 height system. All horizontal coordinates were converted to the current Finnish reference frame EUREF-FIN (Finnish ETRF89 realization) using the coordinate transformation service provided by the National Land Survey. The gravity data was converted from mean to zero tidal system using equation 1. For the transformation to the new height system, heights were kept at zero, but the gravity values were transformed from zero height in the N60 system to zero height in the N2000 system, using the vertical change, dH, from 1960 to 2000 of the nearest Finnish tide gauge:

$$g_{new} = g_{old} + 0.2667 \cdot dH \tag{5}$$

The data are given as point data in the NKG DB and are divided into subsets according to the year of observations:

- #322, sub-dataset #322_3 1976-1980 Sea ice measurements in Bothnian Bay (Finnish waters). Described in Lehmuskoski, P. and J. Mäkinen (1978) and Kääriäinen and Mäkinen (1997), and above.
- #330, sub-dataset #330_3 1986 Sea ice measurements in Bothnian Sea (Finnish waters). Described in Kääriäinen and Mäkinen (1997), and above.
- #332, sub-dataset #332_3_1 1985 Sea ice measurements in Åland Sea and Bothnian Sea (Finnish waters). Described in Kääriäinen and Mäkinen (1997), and above.
- #332, sub-dataset #332_3_2 1987 Sea ice measurements in Åland Sea and Bothnian Sea (Finnish waters). Described in Kääriäinen and Mäkinen (1997), and above.
- #358, sub-datasets #358_3_1 1994 Sea ice measurements in Bothnian Sea (Finnish waters). Described in Kääriäinen and Mäkinen (1997), and above.
- #358, sub-datsets #358_3_2 1996 Sea ice measurements in Bothnian Sea (Finnish waters). Described in Kääriäinen and Mäkinen (1997), and above.

Owners of all these datasets are the National Land survey of Finland, the National Land Survey of Sweden, and the Geological Survey of Sweden.

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