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The gravity survey and the gravimetric map of the territory of Lithuania

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Abstract. We presented a concept of a modern gravimetric-geodetic survey, the data processing and analysis of gravimetric observations and, ultimately, a new gravimetric map of the territory of Lithuania. In this connection, we outlined the applied algorithms for calculating free-air gravity anomalies and Bouguer anomalies, as well as assessed their accuracy and the accuracies of other parameters. The following accuracies were obtained: 0.021 mGal for uncertainties of gravity acceleration according to differences detected at control points, 0.025 m for coordinates, 0.015 m for ellipsoidal heights, 0.073 mGal for Bouguer anomalies, and 0.326 mGal for interpolated Bouguer anomalies. We further described the content of the gravimetric map. The map shows gravity measurement points together with their recorded value of Bouguer anomaly. Isoanomalies of gravity acceleration are drawn every 2 mGal. The scale of the map is 1:200,000. The printed version of the gravimetric map of the territory of Lithuania consists of 15 pages (50 × 50 cm).

Keywords: *gravity acceleration; gravimetric measurements; gravimetric network; gravity anomalies; gravimeter; calibration coefficients*

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INTRODUCTION

Geodetic measurements carried out on the Earth are affected by the Earth's gravity field. Therefore, information on the gravity field is required for adequate and accurate measurement data processing and any reductions of gravimetric observations. The gravity field describes the surfaces of the geoid and the quasigeoid of the accepted system of altitudes used as a basis for calculating the altitudes of the points on the Earth's surface. A detailed gravity survey that establishes gravity accelerations in points on the Earth's surface and the coordinates of these points are required to obtain a gravity field that can be used in geoscientific applications.

Such applications include exploration of oilfields and other mineral deposits, geophysical and geodynamic studies (Märdla *et al.* 2017), determination of orbits of all objects flying in the space around the Earth and precise navigation. However, the accuracy of all these applications depends eventually on the particularity and the accuracy of a gravity survey that provides data for the gravity field model, i.e., a gravimetric map.

The first gravity survey that covered the whole territory of Lithuania was performed in 1951–1962 (Petroškevičius 2004; Šliaupa *et al.* 2012). Gravimetric measurements were carried out in more than 10,000 points. On their basis, gravimetric maps of Bouguer anomalies with a scale of 1:200,000 were arranged and issued. An assessment of the accuracy of these maps with new gravimetric measurements showed that the uncertainties of the map's gravity anomalies are at a level of 0.7 mGal; however, errors in some points of the map achieve 3 mGal (Birvydiene *et al.* 2010; Šliaupa *et al.* 2012).

Some efforts to improve gravity control and to perform gravity surveys could be noted in neighbouring countries. Poland, for example, performs research and controls the national gravity standard with a superconducting and absolute gravimeter for strengthening their gravity reference system (Krynski, Rogowski 2018; Krynski *et al.* 2019a, b). In Estonia, a new gravity system EG2000 was introduced, and gravity surveys are directed to fill in the gaps, mostly in swamps, areas without roads and border zones (Kollo *et al.* 2017). Another big effort is digitising and checking historical gravity data (Oja *et al.* 2019; Ellmann *et al.* 2020). In Latvia, historical gravity maps at a scale of 1:200,000 were digitized as well, providing a total of about 12,000 gravity points (Morozova *et al.* 2021). New gravity measurements with the SCINTREX CG-5 relative gravimeter were carried out at more than 4,800 gravity points to fill gaps and improve the network (Morozova *et al.* 2021). Under the umbrella of the Nordic Geodetic Commission, the participating countries Sweden, Norway, Denmark, Finland, Iceland, Estonia, Latvia and Lithuania are managing the special gravity points data base, covering an area of 52º to 74º N and 2º to 36º E and containing both land and marine information of gravity observations (Märdla *et al.* 2017). Another important and very recent gravity project in the region is FAMOS, which deals with gravity measurements, gravity field and geoid modelling in the Baltic Sea (Famos 2020; Ågren *et al.* 2017).

In 1992–2015, a new base for gravimetric and geodetic measurements was formed in the territory of Lithuania upon applying modern gravimetric devices and space geodetic systems: absolute gravity acceleration measurements had been performed, new Lithuanian systems of gravity (LSS07, epoch 2007.0), normal gravity (GRS80), geodetic coordinates (LKS94) and altitudes (LAS07) had been adopted and a network of a permanently operating Global Navigation Satellite System (GNSS) stations (LitPOS) had been formed (Parseliunas 2008; Baniulis *et al.* 2017). Consequently, an opportunity for a more detailed and accurate research of the gravity field in Lithuania and the formation of a modern gravity survey appeared (Birvydiene *et al.* 2010, 2009; Paršeliūnas *et al.* 2010; Petroskevicius *et al.* 2014; Šliaupa *et al.* 2012). The geodetic and gravimetric measurements were carried out in 32,951 points in 2016–2018. Automated relative gravity meters (gravimeters) of Scintrex CG5 type were used for detecting gravity acceleration, while the LitPOS service RTKNet was applied for measuring coordinates of the points. The normal altitudes of the points were calculated according to the quasigeoid model of the territory of Lithuania (LIT15G).

THE GRAVITY SURVEY

The design of the survey

The gravity survey design covered the territory of Lithuania (an area of 65,286 km²) by an even network of about 30,000 gravimetric points, except for regions of intensive variation of the gravity field where the densification of gravimetric points was expected. Points of the gravity survey were designed with the QGIS programme on the orthophotographic map of Lithuania; it was strived to ensure the density of at least one gravimetric point per 2.4 km^2 and ca. 1.6 km distance between adjacent points. In densified zones, the distance between gravimetric points was reduced to 1.0 km. As the gravimetric and geodetic base was considered and in view of the accuracy of modern gravimeters and GNSS, the following expected mean square errors of the measurements in points of the gravity survey should not be exceeded: 0.060 mGal for the gravity acceleration of LSS07 system, 0.20 m for coordinates of the LKS94 system using the network of permanently operating GNSS stations (LitPOS), and 0.15 m for normal altitudes of the LAS07 system calculated upon applying the geoid model LIT15G and the ellipsoidal heights obtained upon applying GNSS. The accuracies of gravity acceleration and coordinates should ensure the suitability of the points for a more detailed gravity survey.

Gravity anomalies are calculated upon applying the normal gravity field GRS80 and a crustal density of 2.67 g/cm^3. The uncertainties of Bouguer anomalies at gravimetric points should not exceed 0.080 mGal, while those of interpolated Bouguer anomalies should not exceed 1.00 mGal.

The gravimetric and geodetic base of the survey

The gravimetric base of the territory of Lithuania is formed by the gravimetric network (Birvydiene *et* *al.* 2009; Paršeliūnas *et al.* 2010; Petroskevicius *et al.* 2014) that connects 686 points, where the gravity acceleration of the LSS07 system is established. The network covers evenly the territory of the country. The network includes 3 absolute acceleration measurement points where the measurements were carried out in 1994, 2002 and 2017, and 51 first order points. The first order network was observed by 6 LaCoste & Romberg relative gravimeters, and the second order network by 2 SCINTREX CG-5 gravimeters. The internal uncertainties of gravity accelerations at these 51 points do not exceed 0.010 mGal. A detailed analysis of the stability of absolute gravity points is done in Olsson *et al.* (2019). For example, the gravity rate of change at the VILNIUS absolute gravity point is –0.33 μGal yr^{-1} (see Table 6 in Olsson *et al.* (2019), which is negligible for gravity survey observations. All measured gravity values and their rates of change at three absolute gravity points in Lithuania are given in Tables 1 and 2. To obtain the gravity rates of changes, the land uplift model NKG2016LU_abs (Vestøl *et al.* 2019) and formula (1) (Olsson *et al.* 2019) were used.

The distribution of the gravity control points in Lithuania is shown in Fig. 1.

The geodetic base for the positioning of the gravity survey points was formed by a network of 31 permanently operating GNSS stations (LitPOS) (Baniulis *et al.* 2017; Moritz 1984).

For establishing normal heights, the quasigeoid model LIT15G was used (Puškorius *et al.* 2019; Paršeliūnas *et al.* 2013; Obuchovski *et al.* 2017). The mean square error of geoid heights of this quasigeoid model is 0.02 m.

Table 1 Observed absolute gravity values at absolute gravity points in Lithuania

Year of observations	Instrument	g_0 μGal
Vilnius		
1994	JILAg-5	981459087.60
2002	JILAg-5	981459076.70
2007	FG5-221	981459077.00
2013	FG5X-221	981459078.15
2017	FG5X-221	981459081.30
Klaipėda		
1994	JILAg-5	981547770.54
2002	JILAg-5	981547766.07
2017	FG5X-221	981547765.51
Panevėžys		
1994	JILAg-5	981527063.58
2002	JILAg-5	981527059.22
2017	FG5X-221	981527055.55

Calibration of SCINTREX CG-5 relative gravimeters

The special gravimetric basis uniting the gravimetric stations Vilnius, Panevėžys, Eišiškės, and Saločiai (Fig. 1) was used for the calibration of the gravimeters. The points of the gravimetric basis are located in the direction of a meridian. The length of the basis is 270 km. The gravity increment between the marginal points of the base, i.e., Eišiškės and Saločiai, is 201 mGal. The same calibration basis was used when establishing the first and second order gravimetric networks.

The points Vilnius and Panevėžys on lower levels of buildings are parts of the gravimetric network of zero-category where absolute gravity acceleration measurements were carried out with free-fall absolute gravimeters of different types (see Table 1). The two other points (Eišiškės and Saločiai) are arranged outdoors. They are parts of the first order gravimetric network. They were observed with LaCoste & Romberg and SCINTREX CG-5 relative gravimeters.

The calibration was done with measurements according to the following sequence: Vilnius, Panevėžys, Saločiai, Panevėžys, Vilnius, Eišiškės, Vilnius. In each point, two 10-cycle measurements (the duration of each of them was 55 s) were carried out. The duration of a passage of measurements was 12 hours. Results of the measurements were processed applying the procedures of the GRAVSOFT software package (Forsberg *et al.* 2008; Parseliunas *et al.* 2013).

Gravimetric measurements and data processing

Measurements in points of the gravity survey were carried out with one single SCINTREX CG-5 relative gravimeter. A passage of any day was started and ended in points of gravimetric control. Also, in the middle of a passage, control measurements were carried out in a point of gravimetric control. For the measurements, five Scintrex CG-5 gravimeters (Nos. 182, 183, 184, 185, and 825) were used. In each point of the survey, two 5-cycle measurements were carried out. The duration of a cycle was 25 s. When an even

Table 2 Rates of changes at absolute gravity points in Lithuania. $\dot{g}_{av}$ is the observed average gravity change, $\dot{h}_{LU}$ is the absolute land uplift according to the NKG2016LU_abs model and $\dot{g}_{LU}$ is the gravity change according to the NKG2016LU_gdot model

Code	Name	Longitude	Latitude	Normal height, m	$\dot{g}_{av}$, μGal yr^{-1}	$\dot{h}_{LU}$, mm yr^{-1}	$\dot{g}_{LU}$, μGal yr^{-1}
VLNS	Vilnius	25.33722	54.72111	147.88	–0.08	–0.03	0.08
KLPD	Klaipėda	21.17528	55.72333	15.64	–0.30	0.37	–0.58
PNVZ	Panevėžys	24.35861	55.73500	52.37	–0.40	0.22	–0.34

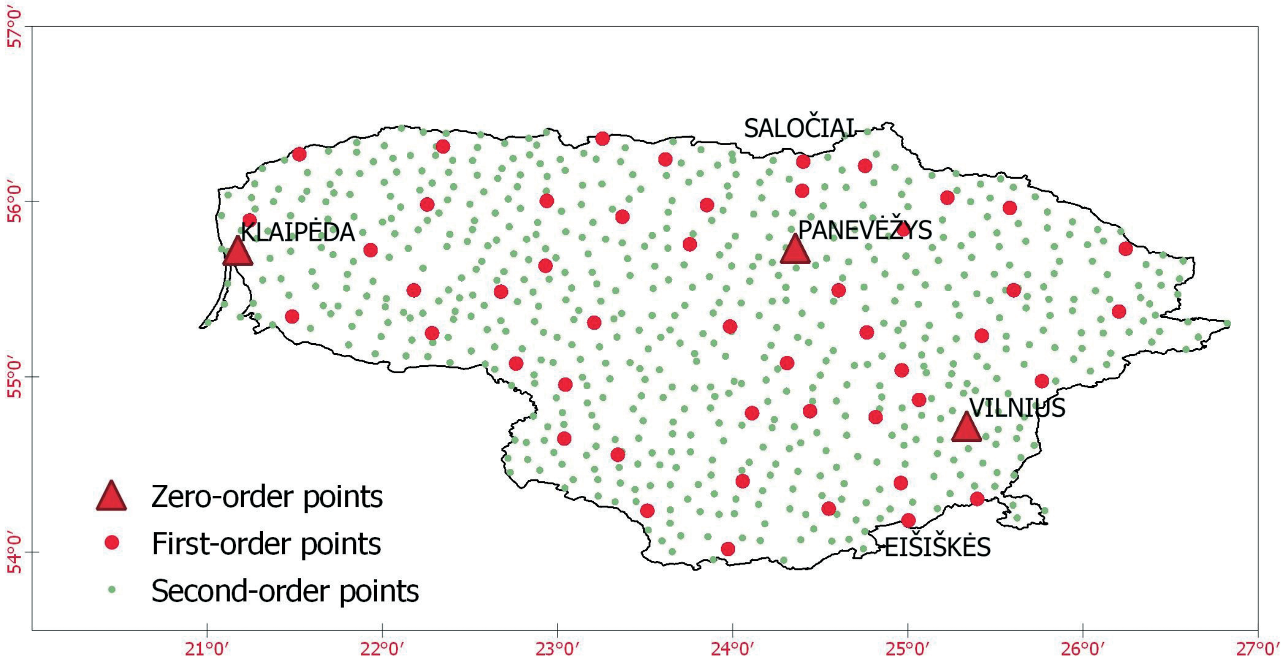

Fig. 1 Gravity control points in Lithuania

change (exceeding 15 μGal) was found in the readings of the gravimeter, additional 5-cycle measurements were carried out.

The gravimetric measurement data were processed applying the procedures of the GRAVSOFT software package (Forsberg, Tscherning 2008). The data were reduced upon assessing the values of calibration coefficients of the gravimeters as well as the influence of the Moon and the Sun.

Calculation of gravity anomalies

After the measurement of the gravity acceleration g_z in the point of the Earth's surface, i.e., ellipsoidal height H, its free-air anomaly is (Petroškevičius 2004; Moritz 1984; Torge 1989)

$$(g-\gamma_{80}) = g_z - \gamma_{80}^0 + \Delta\gamma_{80}(H) + \Delta g_a(H), \quad (1)$$

whereas γ_{80}^0 – acceleration of the GRS80 normal gravity field:

$$\gamma_{80}^0 = \gamma_{80\mathrm{e}}^0 \frac{1+k_{80}\sin^2 B_{94}}{\sqrt{1-e_{80}^2\sin^2 B_{94}}}, \quad (2)$$

with $\gamma_{80\mathrm{e}}^0$, e_{80}, and k_{80} being the coefficients of the GRS80 normal gravity field: $\gamma_{80\mathrm{e}}^0$ = 978032.67715 mGal, e_{80}^2 = 0.00669438002290, k = 0.001931851353, and B_{94} – geodetic latitude in the LKS94 system. The third term in Eq. (1)

$$\Delta\gamma_{80}(H) = 0.30877(1 - 0.00142\sin^2 B_{94})H - 0.75\cdot 10^{-7}H^2 \quad (3)$$

is the height correction in the GRS80 normal field, while the fourth term in Eq. (1)

$$\Delta g_a(H) = 0.874 - 0.99\cdot 10^{-4}H + 0.356\cdot 10^{-8}H^2 \quad (4)$$

is the atmosphere attraction correction.

Pure Bouguer anomaly is then calculated with

$$(g-\gamma_{80})_\delta = (g-\gamma_{80}) - \Delta g_\delta(H) + \Delta g_r, \quad (5)$$

with an endless interlayer correction:

$$\Delta g_\delta(H) = 2\pi G\delta H, \quad (6)$$

where the sphericity of the Earth is neglected.

If the sphericity of the Earth is taken into account, then

$$\Delta g_\delta(H) = 2\pi G\delta\left(\frac{1}{3R^2}(R^3 - R_0^3 + dL - d_0L_0) - R\sin^2\alpha\cos\alpha\ln\frac{d+R-R\cos\alpha}{d_0+R_0-R\cos\alpha}\right), \quad (7)$$

with R_0 the radius of the Earth (6371.032 km) and $\alpha = \frac{S}{R_0}$ with S the radius of the area around the gravimetric point (200 km). Further:

$$R = R_0 + H;$$

$$d = R\sqrt{2(1-\cos\alpha)};$$

$$d_0 = \sqrt{R^2 + R_0^2 - 2RR_0\cos\alpha};$$

$$L = R^2(\cos\alpha + 3\cos^2\alpha - 1);$$

$$L_0 = R_0^2 + RR_0\cos\alpha + 3R^2\cos^2\alpha - 2R^2.$$

δ is the Earth's crustal density, here set to 2.67 g cm^{-3}, and the gravitational constant G = 6.67259 · 10^{-11} m^{3}kg^{-1}s^{-2}. The third term in Eq. (5), Δg_r, is the terrain correction. Terrain corrections were calculated applying the standard procedure TC of the GRAVSOFT package (Forsberg, Tscherning 2008).

Accuracy of gravity and gravity anomalies

The uncertainties m_g of gravity accelerations at gravimetric points according to gravity acceleration differences d in control points of the gravimetric network were calculated by

$$m_g = \sqrt{\frac{[d^2]}{n}}, \tag{8}$$

with n the number of points.

The uncertainty of a single measurement is

$$m_{dg} = \sqrt{m_g^2 - m_{ga}^2}, \tag{9}$$

with m_{ga} – the uncertainty of gravity acceleration at gravimetric points.

The uncertainties of Bouguer anomalies m_{Ba} can be determined with

$$m_{Ba} = \sqrt{m_g^2 + m_{Bp}^2 + m_{\gamma_0}^2 + m_r^2}, \tag{10}$$

where m_{Bp} is the mean square error of the Bouguer anomaly [mGal], m_{Bp} = $(0.3084 - 0.0419258\delta)m_H$, with m_H the mean square error of the ellipsoidal height [m]. m_{γ_0} is the mean square error of the normal gravity, $m_{\gamma_0} = 0.00081308 sin2Bm_x$, with B the average latitude and m_x the mean square error of the coordinate x [m]. m_r is the mean square error of the terrain correction.

The uncertainty m_{iBa} of interpolated values of Bouguer anomalies is

$$m_{iBa} = \sqrt{\frac{[((g-\gamma_{80})_\delta - (g-\gamma_{80})_{\delta i})^2]}{n}}, \tag{11}$$

where $(g - \gamma_{80})_\delta$ is the value of the Bouguer anomaly measured in a gravimetric point and $(g - \gamma_{80})_{\delta i}$ is the value of the Bouguer anomaly interpolated in the same point.

ASSESSMENT OF THE QUALITY OF THE GRAVITY SURVEY

Results of gravimeter calibration

Calibration of five gravimeters was arranged prior to, during, and after the gravity survey. In 2016–2018, eight calibrations were performed in total. The detected changes of the calibration coefficients of the gravimeters are presented in Fig. 2.

These calibration coefficients were used in the gravimetric data processing.

Accuracy of the gravity survey

The internal uncertainties of the adjusted values of gravity acceleration vary in the range between 0.002 mGal and 0.009 mGal (Fig. 3).

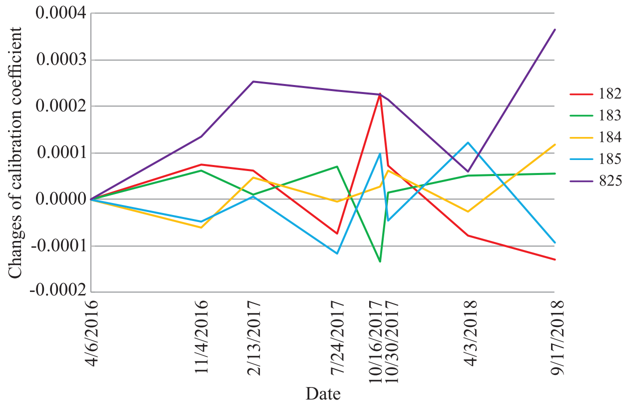

Fig. 2 The changes of the calibration coefficient in respect of the value fixed on 06 April 2016

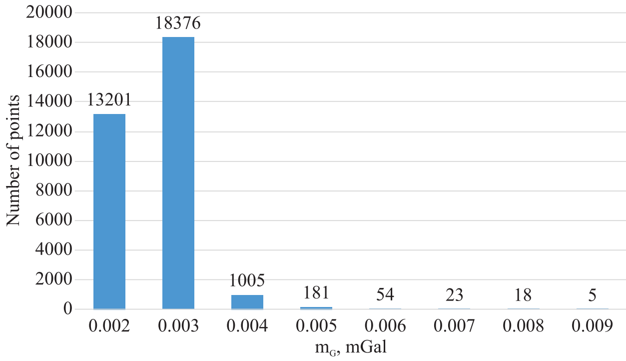

Fig. 3 The histogram of the internal uncertainties of adjusted values of gravity acceleration

The mean square errors calculated on the basis of double differences of GNSS measurements in gravimetric points are as follows: 0.025 m for LKS94 coordinates in x-direction, 0.018 m for coordinates in y-direction, and 0.015 m for ellipsoidal heights. If we keep in mind that the mean square error of the geoid model LIT15G is 0.020 m, the mean square error of LAS07 normal heights will be 0.025 m. These parameters fulfil the precision requirements presented in paragraph 2.1.

The accuracy of gravity acceleration was determined with gravimetric measurements in 1917 control points of the gravimetric network. The differences between the measured and known values of gravity acceleration at the control points are shown in Fig. 4.

The uncertainty of gravity acceleration was calculated with Eq. (8) and is $m_g = 0.0213$ mGal.

If we assume that the uncertainty m_{ga} of gravity acceleration at control points is 0.010 mGal, we find with Eq. (9) that the uncertainty of one single measurement is $m_{dg} = 0.0188$ mGal.

The mean square error of Bouguer anomalies is, using Eq. (10), m_{Ba} = 0.0732 mGal, with $m_H = 0.015m$, m_x = 0.025, m_{Bp} = 0.0033 mGal, and $m_r = 0.070$ mGal.

The differences between the interpolated and the measured values of Bouguer anomalies (at 506 points) are shown in Fig. 5.

The mean square error of interpolated values of Bouguer anomalies m_{iBa} = 0.326 mGal using Eq. (11).

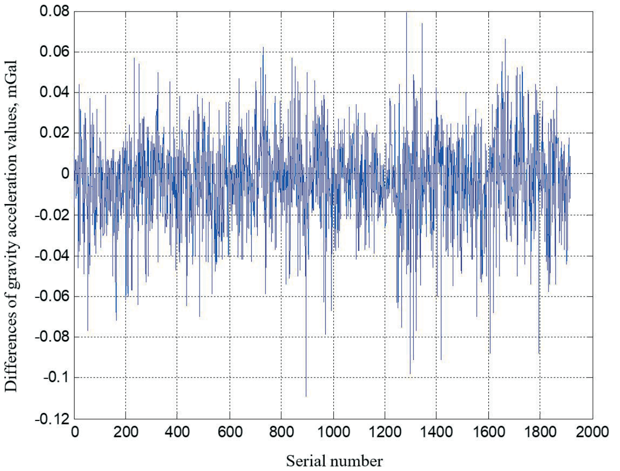

Fig. 4 The differences of values of gravity acceleration at the control points

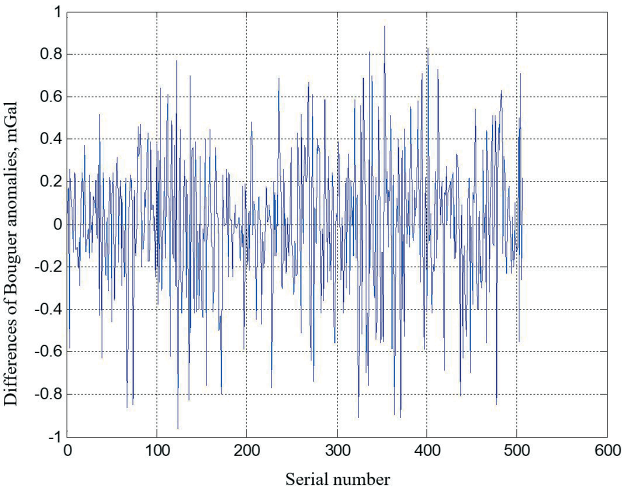

Fig. 5 The differences between the interpolated and measured values of Bouguer anomalies

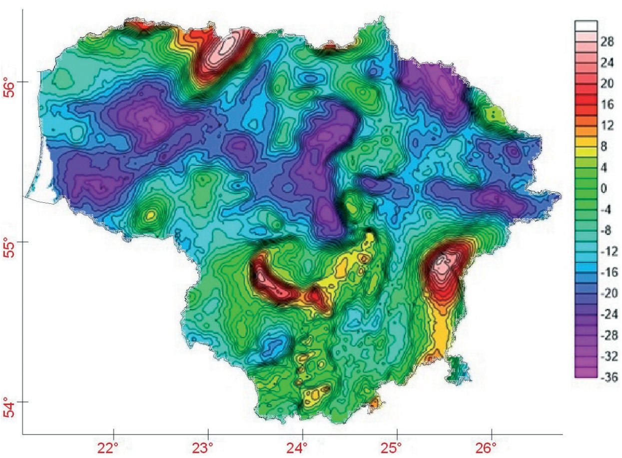

Fig. 6 Pure Bouguer anomalies in the territory of Lithuania (isoanomalies are drawn every 2 mGal)

The pure Bouguer anomalies in the territory of Lithuania (if the density of 2.67 g/cm³ is applied) are shown in Fig. 6.

In the territory of Lithuania, pure Bouguer anomalies vary in the range between –30 mGal and +30 mGal.

THE GRAVIMETRIC MAP

On the basis of data from the gravity survey, a gravimetric map of Lithuania territory was produced. The geodetic coordinate system LKS94 was applied. So, the system of rectangular plane coordinates of the map was formed in the transversal cylindrical Mercator projection with the central meridian Lo = 24° and the scale of projection at the central meridian mo = 0.9998. The zero point of coordinates coincides with the intersection of the central meridian and the equator in the plane of the projection. The projection of the central meridian is the x-axis, which is oriented to the North. The y-axis is oriented to the East. The ordinate of the x-axis (false easting) is 500,000 m.

In the gravimetric map, the following national spatial databases were used:

- The Data Set of the National Geodetic Base (Lithuanian abbreviation: GPDR);
- The Georeferential Spatial Data Set of the Territory of the Republic of Lithuania, scale M 1:250,000 (GDR250LT).

The terrain corrections were calculated applying the TC procedure of the GRAVSOFT package (Forsberg *et al.* 2008). The following three digital terrain models were used:

LIT27E.gri, which is a detailed digital terrain model with a mesh size of 0.00028 degrees ×0.00028 degrees, developed based on the LiDAR data of the territory of Lithuania and "ALOS Global Digital Surface Model (DSM) "ALOS World 3D-30m" (AW3D30) Ver. 3.1". The model covers the range from 53º North latitude to 57º North latitude and from 20º East longitude to 27º East longitude (Fig. 7).

DEM_83-90m0.gri, which is a rough digital terrain model with a mesh size of 0.00083 degrees ×0.00083 degrees, generated with the model LIT27E and the global model AW3D30; it covers the range from 52º North latitude to 59º North latitude and from 18º East longitude to 30º East longitude.

DEM_1800m0.gri, which is a reference digital terrain model with a mesh size of 0.017 degrees × 0.017 degrees, generated with the DEM_83-90m0 model.

The limitations applicable to the calculations include: the radius of the near zone is 6 km and the radius of the total zone is 200 km. The obtained average value of terrain corrections for land points is 0.043 mGal, its minimum value is –0.082 mGal, its maximum value is +0.724 mGal, and the median is

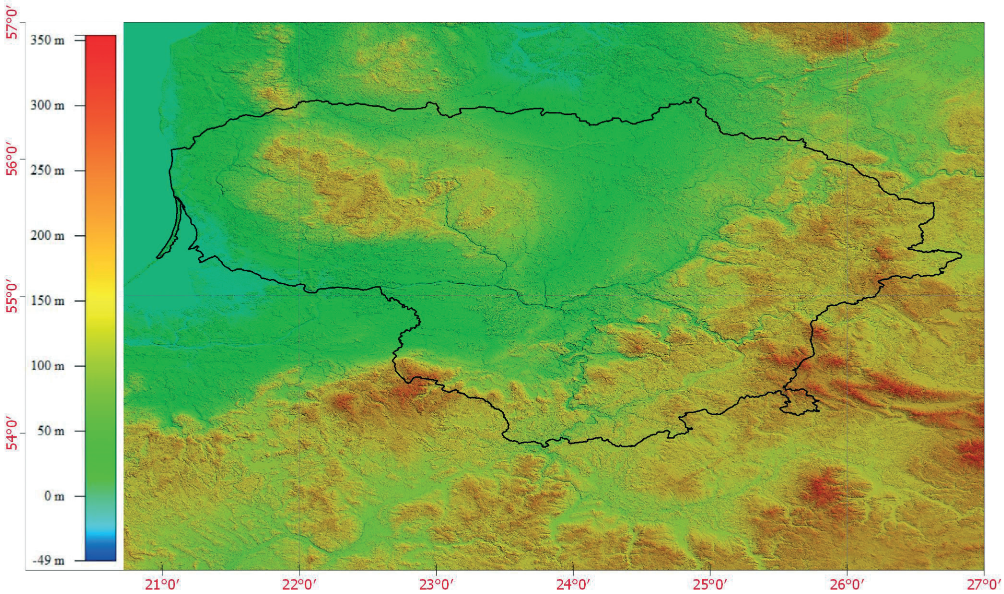

Fig. 7 The detailed digital terrain model LIT27E

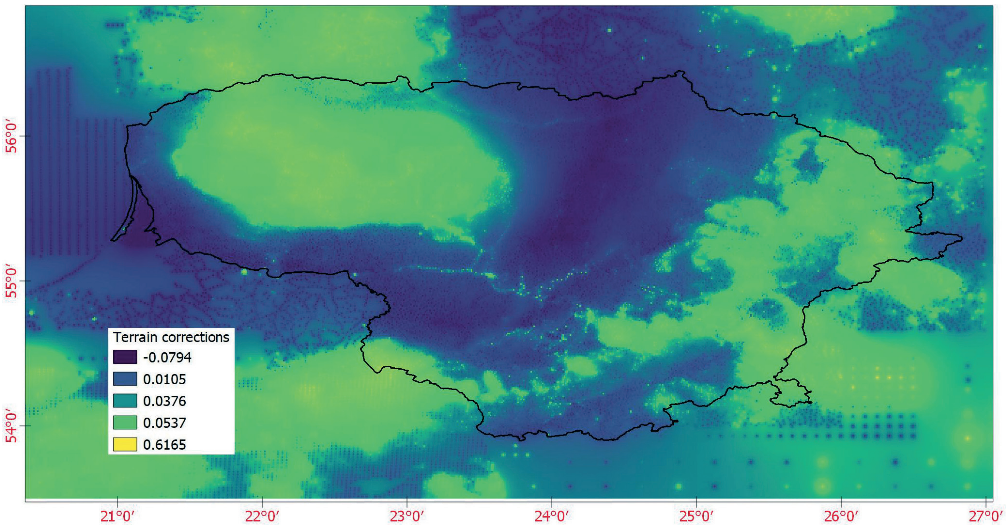

Fig. 8 Terrain corrections applied in the generation of the gravimetric map of Lithuania

+0.031 mGal. The calculated values of terrain corrections are positive at hills (greenish yellow colour) and negative at lowlands (blue colour) (Fig. 8).

In the gravimetric map, measurement points of gravity acceleration are shown with the recorded value of Bouguer anomaly in mGal, two digits after the decimal point. Isoanomalies of gravity acceleration are drawn every 2 mGal. Every fifth isoanomaly is thickened. Numbers on the isoanomalies can bear a plus or a minus sign. Gravity anomalies are expressed by colours as well. Warm colours (yellow, red or brown) are used for positive anomalies, and cold colours (green or blue) for negative anomalies. Cutouts of the gravimetric map are presented in Figs 9 and 10 below.

The printed gravimetric map of the territory of Lithuania consists of 15 pages (50 × 50 cm).

CONCLUSIONS

1. An improved methodology for the formation of a gravity survey by applying the recent automated Scintrex CG5 gravimeters and a network of permanently operating GNSS stations as well as algorithms for the calculation of gravity anomalies and assessment of accuracy were presented.

2. Applying the proposed methodology of the formation of a gravity survey, the following accuracies were obtained: 0.021 mGal for uncertainties of gravity acceleration according to differences detected at control points, 0.025 m for coordinates, 0.015 m for ellipsoidal heights, 0.073 mGal for Bouguer anomalies, and 0.326 mGal for interpolated Bouguer anomalies.

3. The gravity survey provides new opportunities for improving the accuracy of the quasigeoid of the territory of Lithuania.

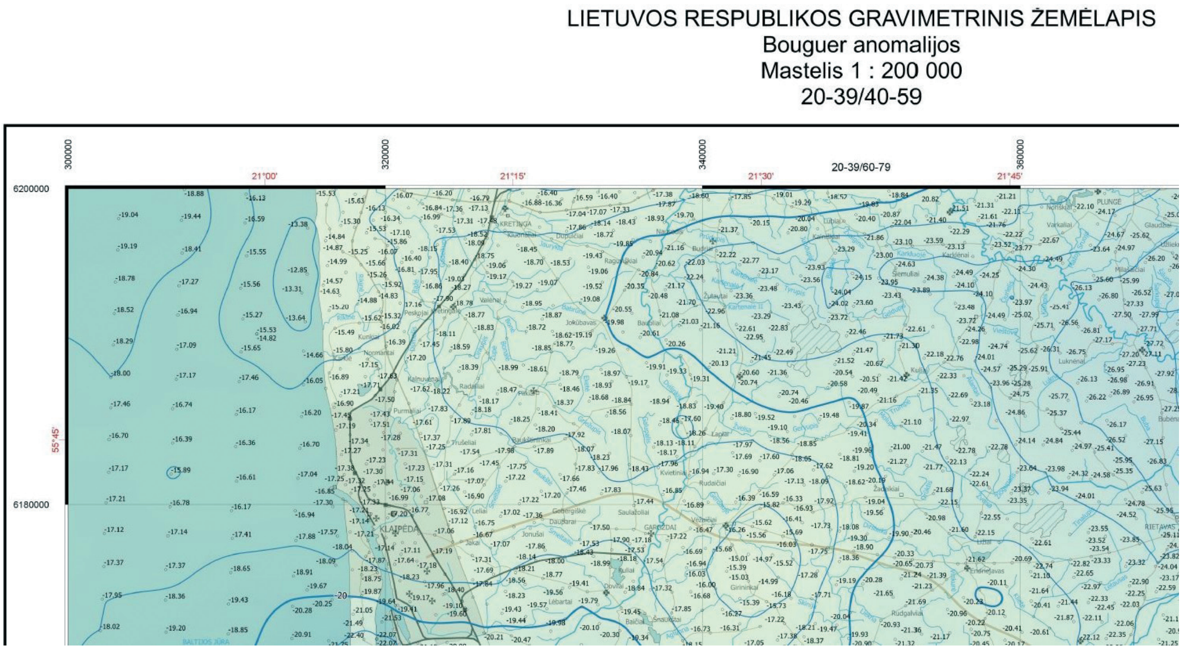

Fig. 9 A fragment of the printed page 20–39/40–59 of the gravimetric map

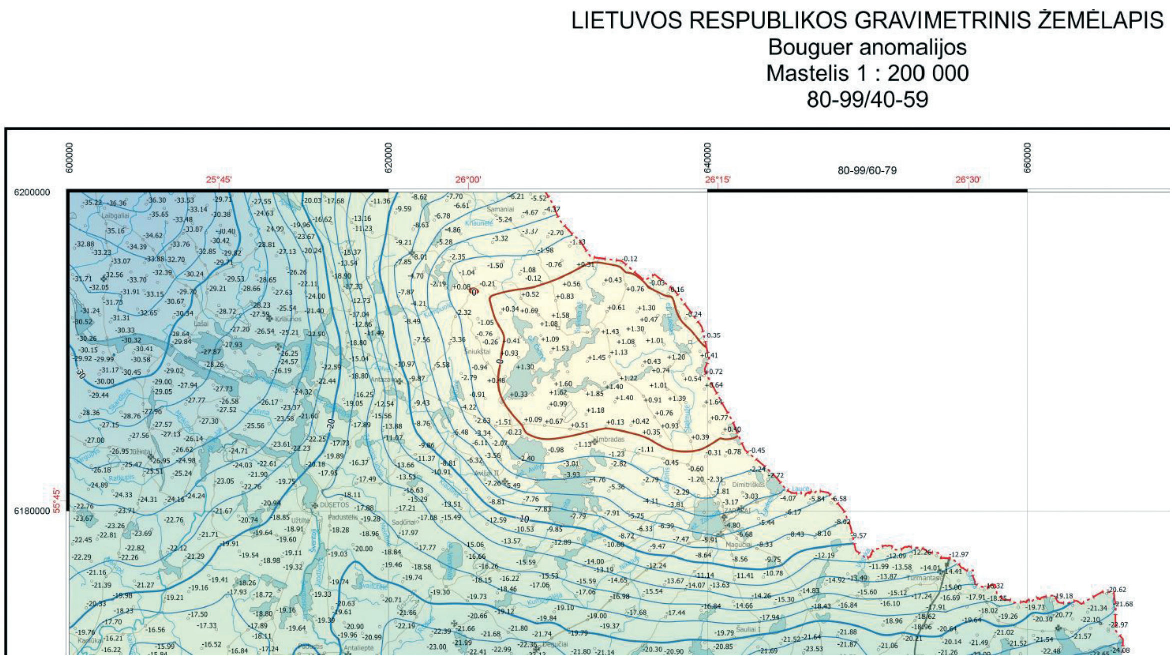

Fig. 10 A fragment of the printed page 80–99/40–59 of the gravimetric map

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REFERENCES

Ågren, J., Schwabe, J., Strykowski, G., Forsberg, R., Liebsch, G., Förste, C., Barthelmes, F., Bilker-Koivula, M., Ellmann, A., Märdla, S. 2017. Overview of the FAMOS efforts to improve the Baltic Seageoid model by new marine gravity measurements. *IAG-IASPEI 2017*, Kobe, July 30 – August 4, 2017. https://doi.org/10.13140/RG.2.2.34378.67521

Baniulis, R., Galinauskas, K., Marozas, L., Parseliunas, E., Petniunas, M., Puskorius, V. 2017. An Analysis of the Performance and Coordinates Time Series of CORS Network LitPOS. *2017 Baltic Geodetic Congress (BGC Geomatics)*. https://doi.org/10.1109/BGC.Geomatics.2017.39

Birvydiene, R., Obuchovski, R., Paršeliūnas, E., Petroškevičius, P., Šlikas, D., Viskontas, P.

2009. Lietuvos gravimetrinio tinklo charakteristikos. *Geodesy and Cartography 35*, 131–136. https://doi.org/10.3846/1392-1541.2009.35.131-136
Birvydiene, R., Krikštaponis, B., Obuchovski, R., Paršeliūnas, E., Petroškevičius, P., Šlikas, D. 2010. Lietuvos teritorijos gravimetrinio žemėlapio tikslumo vertinimas. *Geodesy and Cartography 36*, 20–24. https://doi.org/10.3846/gc.2010.03
Ellmann, A., Märdla, S., Oja, T. 2020. The 5 mm geoid model for Estonia computed by the least squares modified Stokes's formula. *Survey Review 52 (373)*, 352–372. https://doi.org/10.1080/00396265.2019.1583848
FAMOS Consortium (2014–2017). *Finalising surveys for the Baltic motorways of the sea – FAMOS*. Accessed November 20, 2020. https://transport.ec.europa.eu/system/files/2020-06/2020-mos-dip.pdf.
Forsberg, R., Tscherning, C.C. 2008. *Overview Manual for the GRAVSOFT Geodetic Gravity Field Modelling Programs, 2nd ed., Technical Report*, DTU-Space: Kongens Lyngby, Denmark.
Kollo, K., Pihlak, P., Oja, T. 2017. National report: Estonia. In: *Symposium of the IAG Sub-commission for Europe (EUREF), Symposium of the IAG Subcommission for Europe (EUREF)* held in Wroclaw, Poland, 17–19 May 2017.
Krynski, J., Rogowski, J.B. 2018. National Report of Poland to EUREF 2018. In: *Symposium of the IAG Sub-commission for Europe (EUREF), 30 May – 1 June 2018*, Amsterdam, Netherlands.
Krynski, J., Rogowski, J.B., Liwosz, T. 2019a. Research on reference frames and reference networks 2015–2018. *Geodesy and Cartography 68 (1)*, 5–29. https://doi.org/10.24425/gac.2019.126093
Krynski, J., Dykowski, P., Olszak, T. 2019b. Research on gravity field modelling and gravimetry in Poland in 2015–2018. *Geodesy and Cartography 68 (1)*, 31–63. https://doi.org/10.24425/gac.2019.126096
Märdla, S., Ågren, J., Strykowski, G., Oja, T., Ellmann, A., Forsberg, R., Bilker-Koivula, M., Omang, O., Paršeliūnas, E., Liepinš, I., Kaminskis, J. 2017. From Discrete Gravity Survey Data to a High-resolution Gravity Field Representation in the Nordic–Baltic Region. *Marine Geodesy 40*, 416–453. https://doi.org/10.1080/01490419.2017.1326428
Moritz, H. 1984. Geodetic reference system 1980. *Bulletin Géodésique 58*, 388–398. https://doi.org/10.1007/BF02519014
Morozova, K., Jäger, R., Zarins, A., Balodis, J., Varna, I., Silabriedis, G. 2021. Evaluation of quasi-geoid model based on astrogeodetic measurements: case of Latvia. *Journal of Applied Geodesy 15 (4)*, 319–327. https://doi.org/10.1515/jag-2021-0030
Obuchovski, R., Petroskevicius, P., Parseliunas, E., Puskorius, V., Slikas, D., Viskontas, P., Zigmantiene, E. 2017. On the Quality Parameters of the Modern Gravity Survey of the Lithuanian Territory. 2017. *Baltic Geodetic Congress* (*BGC Geomatics*). https://doi.org/10.1109/BGC.Geomatics.2017.16
Oja, T., Ellmann, A., Märdla, S. 2019. Gravity anomaly field over Estonia. *Estonian Journal of Earth Sciences 68 (2)*, 55. https://doi.org/10.3176/earth.2019.06
Olsson, P.-A., Breili, K., Ophaug, V., Steffen, H., Bilker-Koivula, M., Nielsen, E., Oja, T., Timmen, L. 2019. Postglacial gravity change in Fennoscandia – three decades of repeated absolute gravity observations. *Geophysical Journal International 217(2)*, 1141–1156. https://doi.org/10.1093/gji/ggz054
Parseliunas, E. 2008. LitPOS – A service for precise positioning in real time. In: *The 25th International Symposium on Automation and Robotics in Construction.* ISARC-2008. https://doi.org/10.22260/ISARC2008/0057
Paršeliūnas, E., Obuchovski, R., Birvydienė, R., Petroškevičius, P., Zakarevičius, A., Aksamitauskas, V.Č., Rybokas, M. 2010. Some issues of the national gravimetric network development in Lithuania. *Journal of Vibroengineering 12*, 685–690.
Paršeliūnas, E.K., Birvydienė, R., Petroškevičius, P., Aksamitauskas, V.Č., Papšienė, L. 2013. Анализ гравиметрических данных для уточнения квазигеоида. In: *Інженерна геодезія: науково-технічний збірник = Engineering geodesy: scientific and technical collection*. Київ: Київський національний університет будівництва і архітектури, *60*, 39–45. [In Russian].
Parseliunas, E., Petroškevičius, P., Obuchovski, R., Birvydiene, R. 2013. An Investigation of the Automatic Relative Gravimeters. *Solid State Phenomena 199*, 261–266. https://doi.org/10.4028/www.scientific.net/SSP.199.261
Petroškevičius, P. 2004. *Gravitacijos lauko poveikis geodeziniams matavimams*. Vilnius: Technika, 290 pp.
Petroskevicius, P., Parseliunas, E., Birvydiene, R., Popovas, D., Obuchovski, R., Papsiene, L. 2014. The quality analysis of the national gravimetric network of Lithuania. *Geodetski vestnik 58*, 746–755.
Puškorius, V., Paršeliūnas, E.K., Petroškevičius, P., Obuchovski, R., Šlikas, D. 2019. Modern gravity survey of the Lithuania territory. Geophysica: Special Issue of the General Assembly of the Nordic Geodetic Commission, dedicated to the meeting organized by the Finnish Geospatial Research Institute FGI of National Land Survey of Finland on September 3 to 6, 2018. Helsinki: *Geophysical Societyof Finland 54* (1), 39–49.
Šliaupa, S., Dėnas, Ž., Korabliova, L. 2012. Bouguer Anomalijų Žemėlapio Patikslinimas GIS Priemonėmis. *Geodesy and Cartography 31*, 41–46. https://doi.org/10.1080/13921541.2005.9636663
Vestol, O., Ågren, J., Steffen, H., Kierulf1, H., Tarasov, L. 2019. NKG2016LU: a new land uplift model for Fennoscandia and the Baltic Region. *Journal of Geodesy 93*, 1759–1779. https://doi.org/10.1007/s00190-019-01280-8
Torge, W. 1989. *Gravimetry*. Berlin, New York: de Gruyter, 465 pp.