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Gravity anomaly field over Estonia

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Abstract. Different gravity reference frames, methods and instruments have been used by several institutions for conducting gravimetric measurements in Estonia within the past 70 years. Accordingly, a careful evaluation of the obtained gravity data is required before their use in applied science and scientific research. The focus of this study is on (*i*) the determination and elimination of discrepancies between different gravity datasets and (*ii*) the prediction of a high-quality gravity anomaly grid for the Estonian territory and adjacent areas.

About 144 000 gravity points were evaluated with outlier detection and removal. Some high-resolution data sets were also low-pass filtered to meet the requirements of geodetic applications like the determination of regional and national geoid models. Remaining 31 850 high-quality data points (22% of initial data) with additional metadata were used in the compilation of the Estonian Gravity Database (EGDB). Recent international cooperation (NKG2015 geoid and FAMOS marine survey projects) resulted in additional 17 339 points in the neighbouring countries and marine areas. These were used as auxiliary data to the EGDB in the computation of gravity anomaly grids.

The conversion of gravity data to the residual terrain model anomaly (RTMA) values is a novel approach to improve the prediction accuracy of the regional gravity anomaly grids in Estonia. The resulting RTMA model obtained for the Estonian territory from the least-squares collocation prediction indicates high accuracy (low uncertainty) according to the statistical estimates and geostatistical analysis. As examples, some gravity field-related products were derived from the RTMA model for possible application in geosciences and other fields.

Key words: gravity reference frame, gravimetric database, gravity anomaly, residual terrain model anomaly, stochastic spatial prediction, least-squares collocation.

List of main abbreviations

CV2M – 2nd-order isotropic Markov model
DEM – digital elevation model
EGDB – Estonian Gravity Database
ELB – Estonian Land Board
EULS – Estonian University of Life Sciences
FAA – free-air anomaly
FAMOS – Finalising Surveys for the Baltic Motorways of the Sea
GGM – global geopotential model
GSE – Geological Survey of Estonia
GV-EST95 – Estonian gravity net based on the absolute gravity measurements made in 1995
IAGBN – International Absolute Gravimeter Basestation Network
IG – Institute of Geology of the Estonian Academy of Sciences
IGSN71 – International Gravity Standardization Net 1971
LSC – least-squares collocation
NKG – Nordic Geodetic Commission (Nordiska Kommissionen för Geodesi)
NKG WG-GHS – NKG working group of geoid and height systems
PGS1955 – Potsdam Gravity System realization in 1955
PGS1960 – Potsdam Gravity System realization in 1960
RTM – residual terrain model
RTMA – residual terrain model anomaly
SBA – simple Bouguer anomaly
SRTM – Shuttle Radar Topography Mission
STDEV – standard deviation
TalTech – Tallinn University of Technology

INTRODUCTION

The magnitude $g = \|\boldsymbol{g}\|$ of the gravity acceleration vector $\boldsymbol{g}$ along the plumb line is observed on (land, marine), above (air- and spaceborne) or below (sea bottom, borehole, mines) the Earth's surface. The gravimetric information is required for numerous applications and researches not only in Earth sciences but also in metrology, planetary and space sciences. The gravity (also the gravity anomaly) values are commonly expressed in the CGS (centimetre–gram–second) acceleration unit of mGal (1 mGal = 10 μm/s^2).

Terrestrial gravimetric measurements to map the gravity field over the Estonian territory have been conducted since 1939 (Sildvee 1998). The data are used in geosciences (e.g. geodesy, geology and geodynamics). On local and national scale, gravity data have been applied to gravimetric geoid modelling (Maasik 1952; Vermeer 1994; Jürgenson 1998; Ellmann 2001; Märdla et al. 2017, 2018; Ellmann et al. 2019), the realization of the national height system (Ellmann 1999; Rüdja 2016) and the geological mapping and geophysical modelling purposes (Maasik 1950; Gromov & Gromova 1968; All et al. 2004; Dmitrijeva et al. 2018). Estonian gravity data have also been used in international projects like Fennoscandian geophysical mapping (Korhonen et al. 1999), the European geoid models EGG07 and EGG2015 (Denker et al. 2009; Denker 2015), as well as in the Nordic–Baltic geoid models NKG96, NKG2004 and NKG2015 (Forsberg et al. 1997, 2004; Ågren et al. 2016), and in the development of Earth Gravitational Models EGM96 and EGM2008 (Lemoine et al. 1998; Pavlis et al. 2012).

Gravity data in Estonia have been collected by different institutions over the past 70 years (see a review in Ellmann et al. 2009). The data collected by different methods and equipment, following different standards, conventions and specifications, require evaluation before their use in the applications and the aforementioned scientific studies. All undesired systematic biases need to be detected and eliminated, followed by a conversion to a common gravimetric reference frame. Hence, a rigorously defined gravity system and a nationwide gravity network are needed. Nowadays, an accurate gravity network, based on absolute gravity values determined by modern free-fall gravimeters, provides an important reference frame for the quality check and the transformation of historical data to a modern gravity frame.

The present study was partly motivated by the Nordic Geodetic Commission (NKG) that is using the gravity field data in geoid modelling for the needs of geospatial community and industry. A new NKG geoid modelling project NKG2015 was conducted within 2011–2016 in cooperation between the Nordic–Baltic national mapping agencies and universities, coordinated by the NKG Working Group of Geoid and Height Systems (NKG WG-GHS; Ågren et al. 2016). The updated NKG gravity database (consisting of more than 500 000 points from participating countries) was used for gravity anomaly field and geoid modelling computations over the Nordic and Baltic countries and adjacent areas (Märdla et al. 2017). The responsibility of national representatives was quality check and submission of their national gravity data to the NKG gravity database. The majority of the present study gravity data were prepared within the frames of updating the NKG gravity database. Another important contribution to the national gravity database originates from the Finalising Surveys for the Baltic Motorways of the Sea (FAMOS) international cooperation project (FAMOS Consortium 2014). The shipborne gravimetric campaigns in 2016–2017 added nearly 6000 new gravity survey points along the Estonian western and northern coasts. The improvements due to new marine data on coastal gravity field modelling are presented in this paper.

The gravity values measured on or near the Earth's physical surface are commonly converted to gravity anomalies by subtracting the normal gravity of the reference ellipsoid. The gravity data can be represented in several ways such as free-air or topographically corrected gravity anomalies. A regular grid of gravity anomalies is often needed for the aforementioned scientific and practical applications. Either deterministic methods or geostatistical approaches are used to predict the gravity anomaly values from irregularly scattered survey data.

The motivation of this contribution was to provide input data in a model computation of gravimetric quasigeoid with uncertainty better than 1 cm. Two kinds of errors that propagated from the gravity data to the geoid modelling could be distinguished: (1) the omission error related to the spatial resolution of data and (2) the commission error related to random and systematic (correlated) noise components in data (see e.g. Jekeli 2012; Farahani et al. 2017). To assess the effect of these errors, all gravity values transformed from the historical to the modern gravity frame were analysed to estimate their prior uncertainties and spatial properties (e.g. data resolution and autocorrelation). Different methods and different types of gravity anomalies have already been tested by Märdla et al. (2017) to predict the high-quality gravity anomaly grid over the entire Nordic–Baltic region. The present study uses the same gridding methods, but with the parameters adapted to the study area (Estonia and the border regions). The surface with location-related uncertainties of residual terrain model (RTM) gravity anomalies is modelled. The results are used for assessing the suitability of available gravimetric information for accurate geoid modelling but also for geoscientific and other kinds of applications over the study area.

ESTONIAN GRAVITY NETWORK

The nationwide gravity network, developed and maintained by the Estonian Land Board (ELB), is based on the results of contemporary absolute gravimeters (Mäkinen et al. 2009; Oja 2012) and the International Absolute Gravimeter Basestation Network (IAGBN) standards (Boedecker 1988). The gravity network solution GV-EST95 was implemented in 2006 (Oja 2008). Correspondingly, the gravity network of Estonia consists of 1st-, 2nd- and 3rd-order (designated as I, II and III order in Estonian classification, see EME 2017) points, divided according to the estimated uncertainty of gravity values, and the stability and construction of the point. The accurate gravity reference values with uncertainty equal to or better than 0.01 mGal at the 1st-order points using different types of absolute (free-fall laser) gravimeters have repeatedly been determined from 1995 to 2017. The first absolute gravity campaign at three points (Suurupi, Tõravere and Kuressaare) was conducted in 1995 with the free-fall gravimeter JILAg-5 operated by Finnish Geodetic Institute (Sildvee 1998). The acquired data were processed according to the IAGBN standards (FGI 2003). The used gravimeter JILAg-5 had been monitored periodically at the Finnish reference station Metsähovi (Olsson et al. 2019) and at international comparison campaigns (Marson et al. 1995; Robertsson et al. 2001) to ensure long-term stability, repeatability and traceability to the SI (International System of Units). Presently the 1st-order network consists of seven absolute points (see Fig. 1), whereas the gravity measurements with newer types of absolute gravimeters FG5 and FG5X have been performed in 2007, 2008, 2013 and 2017 (Oja et al. 2009, 2017). These new absolute gravity determinations are forming the base for the new nationwide gravity frame EG2000 (EME 2017). The differences between previous GV-EST95 and new EG2000 gravity frames have not been accurately determined yet, however, they remain within ±0.015 mGal according to the rough estimation based on the 1995–2017 absolute gravity results.

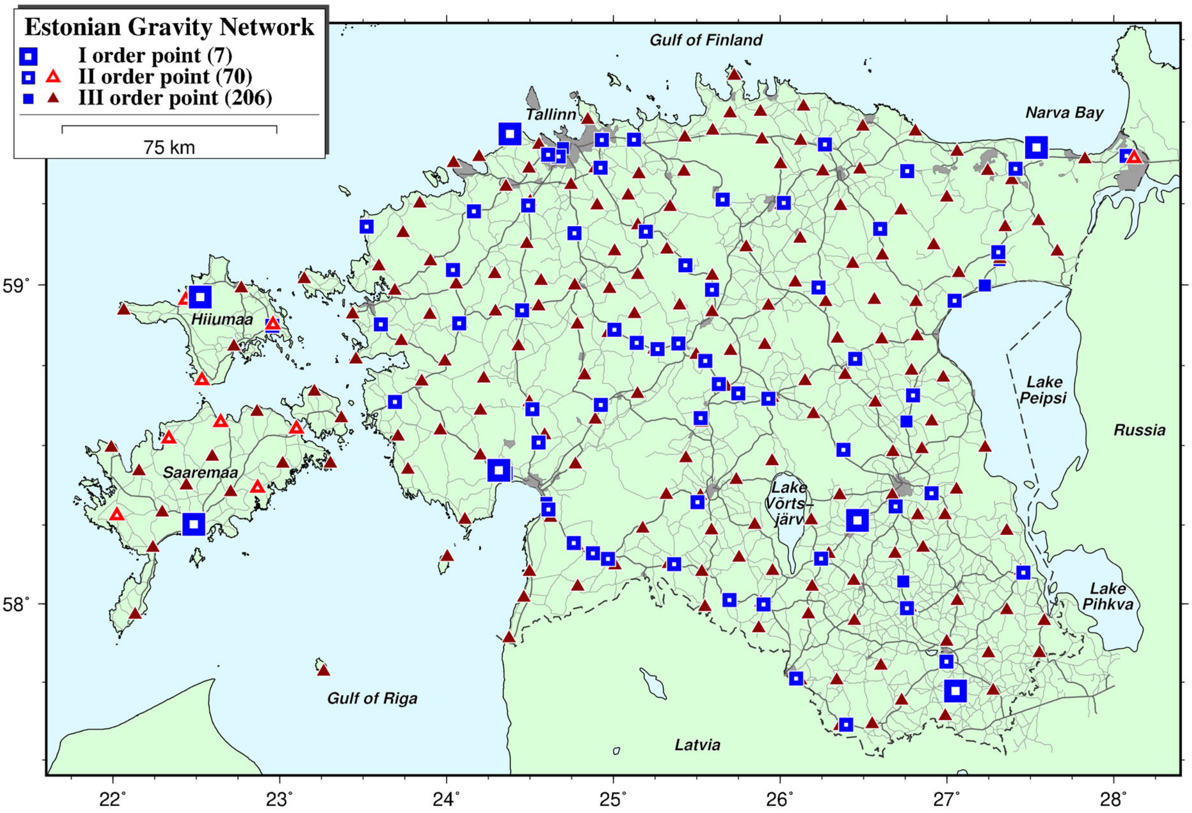

Fig. 1. Configuration of the Estonian gravity network. The present 2nd- and 3rd-order (II and III) networks include also the geodetic network points (red triangles). The geographic regions with labels referred in the text are also denoted. The distribution of major roads is shown in the background (also in the figures to follow). This figure and the following ones were generated using the Generic Mapping Tools software (Wessel et al. 2013).

The 1st-order network gravity values (with an uncertainty of ±6 μGal, according to the 1σ or 68.3% confidence intervals) served as a reference for the densification of the GV-EST95 2nd- and 3rd-order national gravity networks. The relative gravity connections between the 1st-, 2nd- and 3rd-order network points were repeatedly measured by using several LaCoste&Romberg G and Scintrex CG-5 spring gravimeters in 2001–2006 (Oja 2012). The scale of these relative gravimeters has been regularly checked along the gravimetric calibration lines in Estonia and Finland (Oja 2016). The gravity values at the national gravity network points were adjusted by using (*i*) the results of absolute gravimeters at the 1st-order points and (*ii*) the calibration corrections of relative gravimeters in a weighted least-squares adjustment of the 2nd- and 3rd-order networks. The uncertainty (1σ) of gravity at values on the 2nd- and 3rd-order points was estimated to be equal to or lower than ±50 μGal (Ellmann et al. 2009; Oja 2012). More than 280 1st-, 2nd- and 3rd-order network points (Fig. 1) form a national gravity frame to check the quality of historical data and make transformations (from historical to modern gravity datum) as well as for conducting new gravity surveys.

REVIEW OF GRAVITY DATA

Gravity surveys in 1949–2017

The first nationwide gravity survey was conducted along roads by the Institute of Geology (IG) of the Estonian Academy of Sciences in 1949–1958 (Maasik 1959; Ellmann et al. 2009). The uncertainties from ±0.5 to ±0.8 mGal for gravity values, ±0.5 to ±1.5 m for height and about ±50 to ±100 m for the map-based horizontal positioning of the 4195 survey points were estimated (Sildvee 1998). The corresponding reference network was established in 1955–1957 by connecting it with the USSR gravity datum points in the international Potsdam Gravity System (Maasik 1958). This realization of the Potsdam system is hereinafter referred to as PGS1955. In 1999 the systematic difference of +15.4 mGal between the historical PGS1955 and modern frame GV-EST95 was found by Sildvee & Oja (1999). Accordingly, the constant correction of –15.4 mGal was added to the historical gravity values, whereas 110 erroneous survey points were removed during the 2007 update of the IG database (Ellmann et al. 2009). For decades the IG regional gravity database has been extensively used for geological mapping and geoid modelling purposes (Maasik 1952; Vermeer 1994; Lemoine et al. 1998; Ellmann 2001; Jürgenson 2003; All et al. 2004).

Another gravity survey programme that supported geological mapping was initiated in 1965 by the Geological Survey of Estonia (GSE) (Gromov & Gromova 1968). This programme ended in 2007 and resulted in extremely dense gravity data (about 3–4 points per km²) over the northern and western parts of Estonia, including the largest islands of Saaremaa and Hiiumaa. Initially, the GSE surveys were based on a realization of the Potsdam Gravity System established in the USSR in the 1960s, hereinafter referred to as PGS1960. In the 1980s the gravity values of USSR reference points in the international gravity system IGSN71 were used and older datasets were converted to the IGNS71 by using the constant correction of –14.0 mGal, determined in Potsdam (Morelli et al. 1971; Oja 2007). In 2005 another conversion of GSE data from IGSN71 to GV-EST95 was done by removing an offset of 0.08 mGal (e.g. All & Gromov 2005). In 2008 the GSE gravity database contained information on about 126 609 survey points. Their estimated uncertainties are from ±0.1 to ±0.5 mGal for gravity values, ±0.15 m for height and from ±10 to ±50 m for the horizontal position (Ellmann et al. 2009).

According to an evaluation by Ellmann et al. (2009), the IG database gravity values in some areas appeared to be inaccurate, systematically biased and therefore unusable for accurate prediction of gravity anomaly grids and geoid modelling. As a result, the majority of the IG database was removed from the present study. Only a few hundred historical IG survey points (about 10% of the initial data set) were retained in border areas and remote regions of Estonia where sparse or no other data are available. Conversely, the GSE gravity measurements proved to be a usable data source with ±0.2 to ±0.5 mGal uncertainty of gravity values (ibid.).

Gravity datasets for the areas with limited access (Gulf of Riga, lakes Võrtsjärv and Peipsi–Pihkva, Estonian–Russian border, see Fig. 1) have been digitized from the historical gravimetric maps of the Ministry of Geology of the USSR (Jürgenson 2003). These historical maps presented either survey points with observed values (Gulf of Riga, lakes Peipsi–Pihkva and Võrtsjärv) or measured/interpolated gravity anomaly values (Estonian–Russian border, Russian territory).

In 2006–2017 several new gravity surveys were conducted by the specialists and students from the ELB, Estonian University of Life Sciences (EULS) and Tallinn University of Technology (TalTech) to replace unreliable IG survey data and to fill data voids in the SW, southern, central and SE parts of Estonia (Ellmann et al. 2009; Türk et al. 2011). Several gravity surveys on the ice of frozen water bodies (lakes Võrtsjärv and Peipsi–Pihkva, Gulf of Riga, Narva Bay, West Estonian Archipelago) were conducted in 2009–2013 to validate historical data and fill data gaps over the coastal marine areas (Oja et al. 2011; Märdla et al. 2016). In 2006–2017 approximately 3200 new gravity survey points were observed within the territory of Estonia and along the Estonian–Latvian border (Table 1).

Estonian gravity database

The process of collecting and analysing the existing gravity data (together with relevant metadata) in Estonia was initiated in 2008 (Ellmann et al. 2011). A national gravity database with 136 195 points covering the Estonian territory was compiled in 2010–2011. In 2013 this work was continued with the compilation of the Estonian gravity database (EGDB) and delivery of the updated gravity data to the NKG2015 geoid modelling project. In 2014 more than 143 000 gravity data points were collected, evaluated and prepared as input data to the EGDB (Talvik & Oja 2014). During gravity field and geoid model computation it became evident that the density of GSE gravity data distribution was higher than needed in geoid determination and caused computational burden in data processing. Therefore a downsampling filter was applied to select the most reliable single data point (by using the uncertainty of the gravity value) in every 1 km² cell. Figure 2 demonstrates that within each cell the gravity data point with the lowest uncertainty value is retained after the downsampling which thinned the original data set by 84%, from 128 781 points to 20 841 points (Talvik & Oja 2014; Märdla 2017).

In the EGDB the following attributes were attached to each gravity point: unique id and project id (survey job) numbers, position (latitude, longitude), normal and ellipsoidal heights, gravity and uncertainty for the last five quantities. Also other metadata, including project description and references to original publication, were attached if such information was available (Talvik & Oja 2014). The original gravity observations were converted to the contemporary gravity frame GV-EST95 (see the section ‘Estonian gravity network’). Conversion parameters for different datasets were applied for that purpose (see Table 1). The geodetic latitude and longitude were referred to the Estonian realization of the European Terrestrial Reference System ETRS89. The heights were referred to the Baltic Height System 1977 (BHS77), i.e. to the conventional zero of the Kronstadt tide gauge. It should be noted that the Estonian territory is affected by the Fennoscandian post-glacial rebound (e.g. Kall et al. 2014). Even though the gravity measurements have been performed over a relatively long time span, any temporal

Table 1. The main data sets comprising the Estonian gravity database (EGDB)

No.	Data set (Nordic Geodetic Commission – NKG gravity database source No.)	Observation time	Observed points/Stored in the EGDB	Uncertainty of the position, height and gravity (with lower and upper limits)	Original gravity datum (constant correction to GV-EST95)
1	Institute of Geology of the Estonian Academy of Sciences (No. 339)	1949–1958	4195/435 (10%)	±50 to ±100 m, ±0.5 to ±1.5 m, ±0.5 to ±0.8 mGal	PGS1955 (–15.4 mGal)
2	Geological Survey of Estonia (No. 681)	1965–2007	128781/20834 (16%)	±10 to ±50 m, ±0.15 to ±0.50 m, ±0.1 to ±0.5 mGal	PGS1960 (–14.08 mGal)
3	Ministry of Geology (MG) of the USSR (northwestern Russia, Gulf of Riga) (Nos 618, 620, 689)	1960–1970	6561/6158 (94%)	±20 to ±80 m, ±1.5 to ±4.5 m, ±2.0 mGal	PGS1960 (–14.0 mGal)
4	MG (lakes Peipsi–Pihkva, Võrtsjärv) (No. 619)	1987–1988	891/882 (99%)	±60 m, ±2.0 m, ±0.60 mGal	PGS1960 (–14.0 mGal)
5	Surveys by the ELB, EULS, TalTech (Nos 310, 311, 315–318, 324, 334, 682–688)	2006–2017	2822/2821 (99.96%)	±0.10 m, ±0.15 m, ±0.10 mGal	GV-EST95 (0.0 mGal)
6	Surveys by the ELB, EULS (not included in the NKG database)	2014–2017	720/720 (100%)	±0.10 m, ±0.15 m, ±0.10 mGal	GV-EST95 (0.0 mGal)

Remarks: New surveys from 2006 to 2017 have been conducted by the Estonian Land Board (ELB), Estonian University of Life Sciences (EULS) and Tallinn University of Technology (TalTech). PGS1955 and PGS1960 represent the realizations of the Potsdam Gravity System in 1955 and 1960 in Estonia. GV-EST95 denotes the Estonian national gravity system.

changes in the position, height and gravity components were not considered in this study. This is due to the fact that the accuracy of these components of the most of gravity survey points is generally poorer than the overall range of the land rebound effect – the largest impact is expected on the height component, with a maximum of about 15–20 cm over 50 years in Estonia.

In June 2014 the EGDB extracted dataset (consisting of about 31 130 gravity points) was delivered to the NKG gravity database (to be introduced below). Additional 720 gravity survey points, measured by the gravity teams of the ELB, EULS and TalTech in 2014–2017, were included in the EGDB in 2017 (Table 1).

Gravity data from the international cooperation and global gravity field models

The accurate prediction or gridding of a gravity field model needs gravity data also from the adjacent regions of the study area. For instance, according to Ellmann (2005), gravity data are needed 2°–3° outside the target area for the accurate determination of the gravimetric geoid. Therefore substantial effort has been put into the collection of gravity data over coastal marine areas and the digitization of the historical gravity anomaly maps (e.g. northwestern parts of Russia). Another effort to gain up-to-date, accurate data from neighbouring countries (Finland, Latvia, Lithuania, Russia and Sweden) has been made through the international cooperation, e.g. in the working group of geoid and height systems of the Nordic Geodetic Commission (NKG WG-GHS). New marine gravity data have been acquired within the international FAMOS project.

Gravity data along the western and northern coasts of Estonia were collected during the Baltic Sea airborne survey organized by the NKG in 1999 (Forsberg et al. 2001). About 17 400 points with formal uncertainty of ±0.15 m for the 3D position and ±2 mGal for gravity values were collected. However, comparisons of different data sets revealed that the discrepancies between aerogravimetric and land gravity control data exceeded 2 mGal along the western islands and northern Estonian coast (Oja 2018). The 1999 airborne campaign took place in relatively hot summer conditions, with turbulent flight conditions over land, but more smooth conditions over sea (Forsberg et al. 2001). Apparently, this explains the increased noise level of aerogravimetric data. The respective parts of the tracks (altogether 132 airborne survey points) nearby the coast and over land were flagged as outliers and removed from further analysis and computations.

Additional gravity data were obtained by two FAMOS marine gravity campaigns conducted along the Estonian coasts in 2016–2017 (Ellmann et al. 2016; Varbla et al. 2017). In cooperation with Danish National Space Institute (DTU Space, Technical University of Denmark), two shipborne gravity surveys were conducted with the Russian manufactured Chekan-AM marine gravimeter and Global Navigation Satellite System (GNSS) receivers on ship. The uncertainties of the 3D position and gravity were estimated to be around ±15 cm and ±1 mGal, respectively (Olesen & Kasenda 2016; Olesen 2017). The marine gravity data of 2016 included many repetitive measurements since the gravity campaign was collocated with the hydrographic surveys in the West Estonian Archipelago. The hydrographic vessel was often anchored or slowly drifting. As a result, the 2016 survey points were low-pass filtered (not to be confused with the filtering used in raw data processing) by averaging the value over the 0.005° N × 0.01° E cell size, which reduced the data set from 8421 to 2530 points. There was no need to apply such a low-pass filter to the 2017 marine data (consisting of 3450 points) since the sole purpose of the shipborne campaign was gravimetric survey (lasted 72 h with vessel's velocity of 8–9 knots).

An international project for modelling a new NKG geoid NKG2015 for the Nordic–Baltic region was initiated by the NKG WG-GHS in 2011 (Ågren et al. 2016; Märdla et al. 2017). During the project every participating country modernized, updated and quality checked the national gravity data before the delivery to the NKG gravity database. Relevant geodetic reference systems and epochs were treated as rigorously as possible. Further analysis of the NKG database coverage revealed a large data void in the eastern end of the Gulf of Finland (see Figs 3–5). No gravity data over the region stretching from 59.5° to 61.5° N and 25° to 30° E were available for the study. To improve the gravity anomaly prediction in the region, a patch was created to fill the data void using one of the latest global gravity field models. The GOCE (short for Gravity field and steady-state Ocean Circulation Explorer), GRACE (Gravity Recovery and Climate Experiment) and LAGEOS (Laser Geodynamics Satellite) based satellite-only global geopotential model (GGM) GO_CONS_GCF_2_DIR_R5 (Bruinsma et al. 2013) was selected and series expansion with degree and order of 240 was evaluated to fill the data void with 'pseudo-observed' data in a regular 0.1° × 0.2° grid (Märdla 2017).

Spatial distribution and analysis of data

The present review and analysis of gravity data from Estonia and adjacent areas were carried out in 2017 with the aim of preparing input data necessary for the modelling of a new national geoid model EST-GEOID2017 (Ellmann et al. 2019). Both the national and international data sources with metadata (with source description)

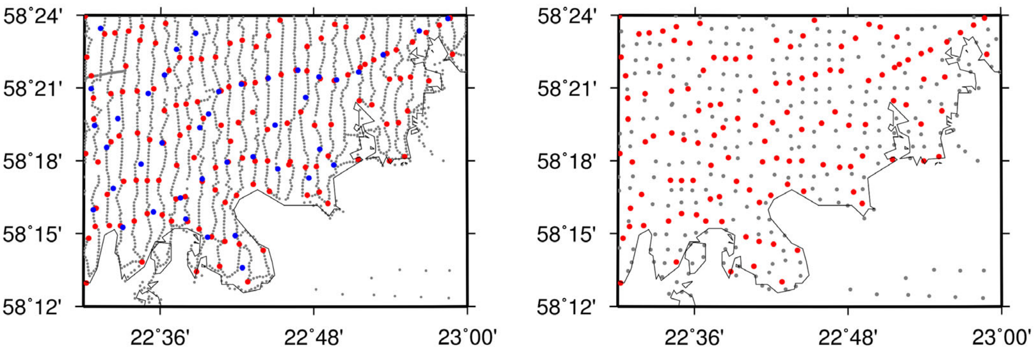

Fig. 2. The Geological Survey of Estonia gravity data before (left-hand side) and after (right-hand side) downsampling using the formal uncertainty estimates of gravity points: red –0.2 mGal, grey –0.3 mGal, blue –0.5 mGal (from Märdla 2017, p. 42).

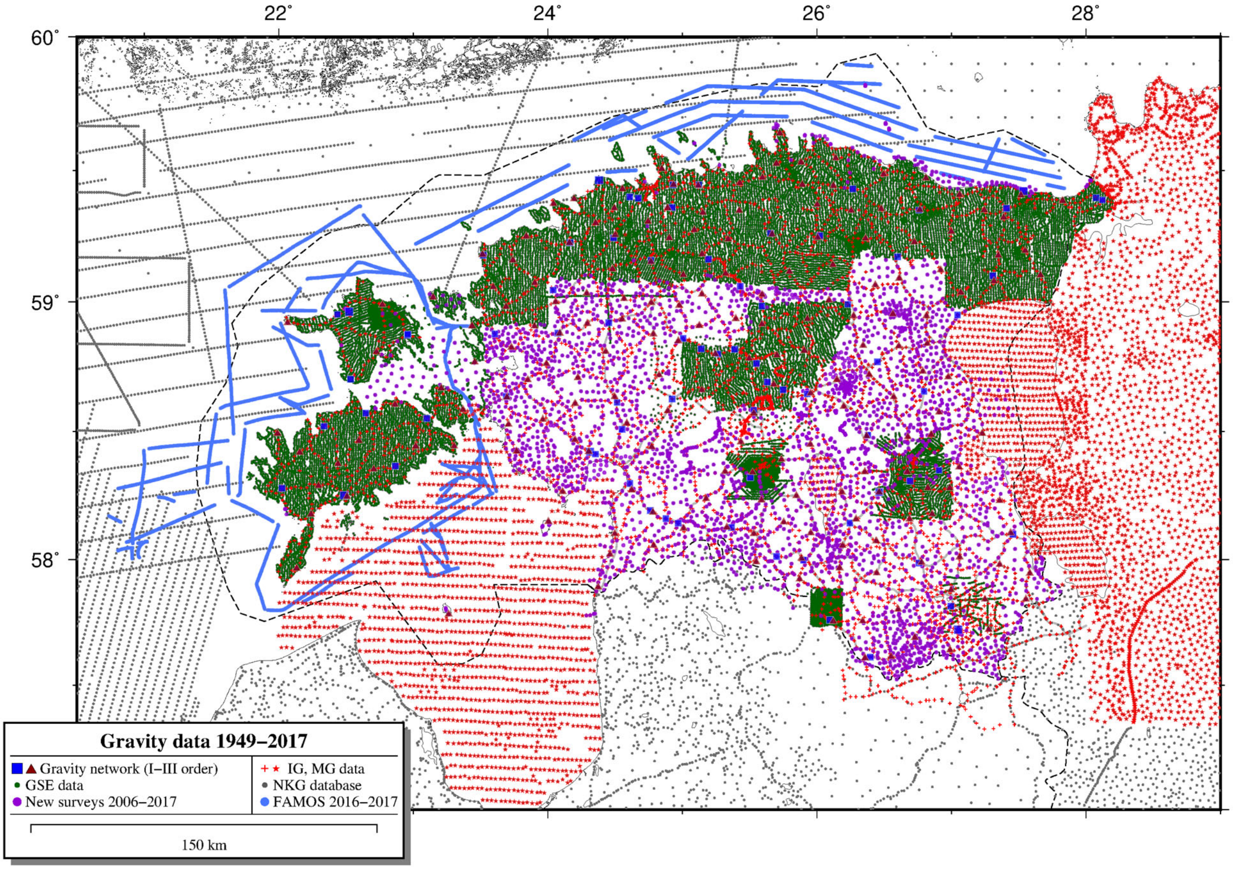

Fig. 3. Distribution of gravity data sets acquired in 1949–2017 in Estonia and its surroundings (see Table 1). Data have been measured by the Institute of Geology of the Estonian Academy of Sciences (IG), the Ministry of Geology of the USSR (MG) and the Geological Survey of Estonia (GSE). Gravity data from neighbouring countries and marine areas have been gained from the database of Nordic Geodetic Commission (NKG) and the Finalising Surveys for the Baltic Motorways of the Sea (FAMOS) project.

were inspected to avoid duplicate data points and detect possible biases between different data sets. For data analysis and gravity field modelling the study area around Estonia (with 49 189 gravity data points) was selected for latitude from 56.5° to 60.5° N and for longitude from 20° to 30 E°. The geographic distribution of the available land, lacustrine and marine (on ice and at the bottom, shipborne) and airborne gravity data points is shown in Fig. 4. Their formal uncertainties in Fig. 5 reveal expectedly that the most accurate data have

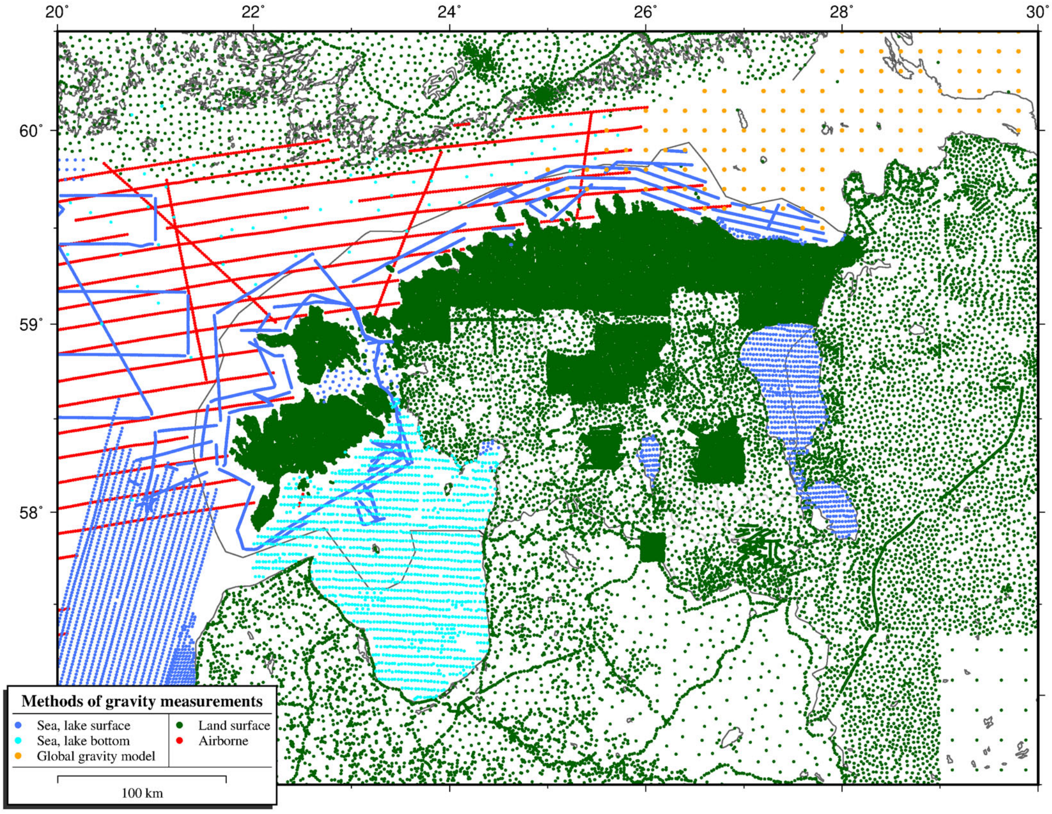

Fig. 4. Types of gravity observation methods.

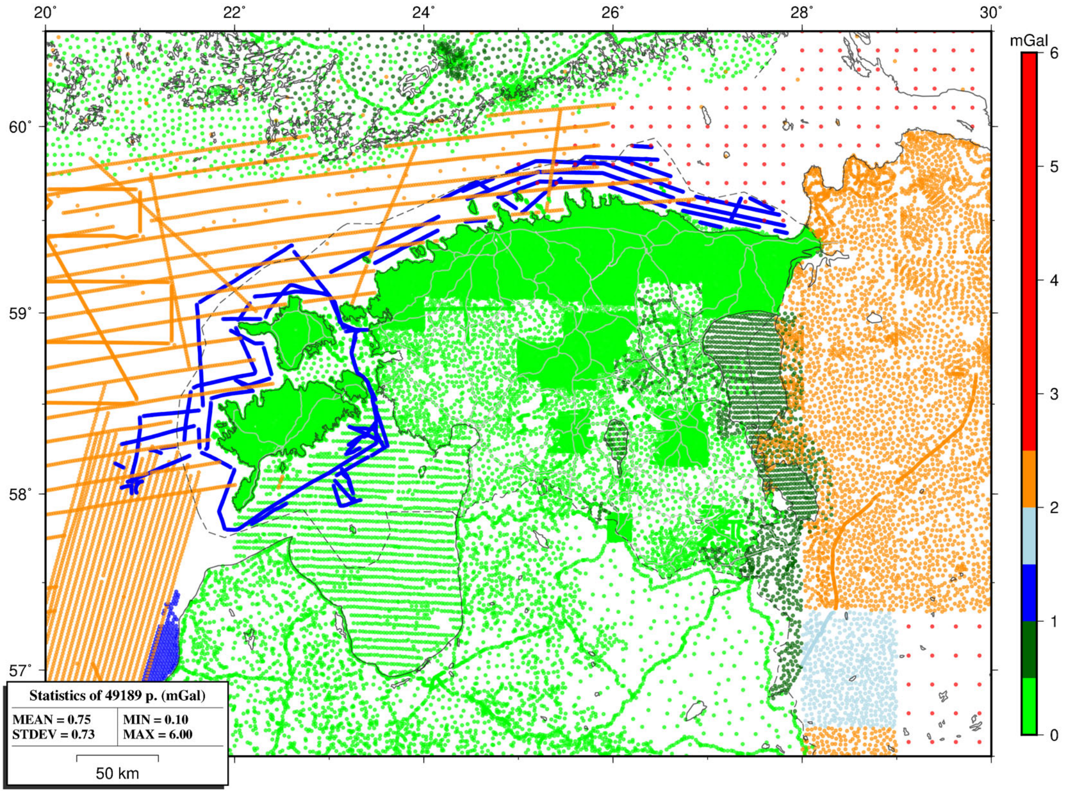

Fig. 5. The formal uncertainty estimates of gravity data in the national/international gravity databases.

been measured on land (mean uncertainty 0.54 mGal). Less accurate results have been obtained from shipborne (mean uncertainty ±0.8 mGal) and airborne (uncertainty ±2.0 mGal) gravity measurements over the Baltic Sea. Within the Estonian land and maritime (territorial waters) boundaries the mean uncertainty of gravity survey data is about 0.48 mGal, which is lower than the mean uncertainty 0.75 mGal of all data (see Fig. 5).

The data density over the majority of the mainland and the islands of the West Estonian Archipelago is rather good (more than 1 point per 10 km², see Fig. 6) and should satisfy the requirements for geoid modelling with 5 mm precision (e.g. Ellmann et al. 2019). The data density is less satisfactory over the southern mainland and some marine regions (less than 4 points per 100 km²) where the accurate gravity anomaly prediction could be problematic. This problem aggravates in areas where the gravity field is rough or demonstrates large horizontal gradient values.

PREDICTION OF GRAVITY ANOMALIES

The gravity measured on or nearby the Earth's physical surface deviates from the theoretical normal gravity which models the gravity acceleration of the reference ellipsoid. The observed gravity values can be represented in several ways – via free-air, Bouguer or topographically corrected gravity anomalies. Observations are reduced to gravity anomalies in such a way that the subsurface geophysical features under study stand out as correctly as possible.

For applications like regional geoid modelling a regularly spaced gravity anomaly grid is generally needed as input data (e.g. Jürgenson 2001; Ellmann 2002; Märdla et al. 2017). Either spatial 2D interpolation functions (deterministic methods) or geostatistical modelling (stochastic methods) are used to predict the gravity anomaly values at the grid nodes. In Märdla et al. (2017) continuous curvature splines, triangulated irregular network, kriging and least-squares collocation (LSC) were tested to predict the gravity anomaly grids over the Fennoscandian and Baltic regions. The same study also evaluated free-air, Bouguer and residual terrain model (RTM) anomalies to investigate the stochastic behaviour and the prediction accuracy of these types in grid computation. It was concluded that RTM anomalies coupled with the LSC prediction method lead to a gravity grid with the highest quality (ibid.). It will be shown here that similar conclusions with RTM anomalies predicted by using the LSC method hold over Estonia as well.

As a first step, the free-air or surface Δg_P^{FA} (FAA) and simple Bouguer Δg_P^{SBA} (SBA) anomalies are conventionally computed (e.g. Heiskanen & Moritz 1967, Eqs 7–8, 3–19):

$$\Delta g_P^{FA} = g_P - \gamma_Q = g_P - \gamma_0 + 0.3086 \cdot H_P^* \qquad (1)$$

and

$$\Delta g_P^{SBA} = \Delta g_P^{FA} - 2\pi G \rho H_P^* = \Delta g_P^{FA} - 0.11196 \cdot H_P^*, \quad (2)$$

where g_P is the gravity value on or above the topography at the point P (at the normal height H_P^* relative to quasigeoid, unit in metres), γ_0 and γ_Q are the normal gravity on the International Geodetic Reference System 1980 (GRS80) ellipsoid and at the point Q on the telluroid (at the height $h = H_P^*$ above the ellipsoid), $G \approx 6.674 \times 10^{-11}$ m³/s²kg is the gravitational constant and ρ is the density (set to the constant value $\rho \approx 2670$ kg/m³) of an infinite Bouguer plate with thickness H_P^*. Although reduced in magnitude (compared to the initial gravity value itself), the free-air and Bouguer anomaly fields can still be rough and correlated with height. That is why the gridding with these types of anomalies is not optimal. Thus, a further reduction of gravity anomalies is often needed to facilitate a better gridding outcome. Both short and long wavelength features are often removed to yield a suitable (e.g. smoother and spatially less variable) gravity anomaly field. Topographic, bathymetric, isostatic and global geopotential models can be used for that purpose.

As a next step, the RTM anomalies Δg_P^{RTM} (RTMA) are computed from the FAA by removing the contributions of a GGM and a RTM

$$\Delta g_P^{RTM} = \Delta g_P^{FA} - \Delta g_P^{GGM} - \delta g_P^{RTM} - \delta g_P^{ATM}, \quad (3)$$

where Δg_P^{GGM} is the gravity anomaly calculated from a GGM by a standard formula (e.g. Heiskanen & Moritz 1967, p. 89), δg_P^{RTM} and δg_P^{ATM} are the gravitational effect of residual terrain correction (Forsberg 1984) and the atmospheric masses above the point. Note that the bathymetric correction in marine areas is not considered in this study. Details about the computation of RTMA and its components in Eq. (3) can be found in Märdla et al. (2017). For the terrain correction δg_P^{RTM} estimation the Estonian 3" × 3" digital elevation model (DEM) EST-DEM2013 (Oja 2014) was used which was compiled from airborne laser scanning data (see Gruno et al. 2013). Similar national DEMs were used for estimating the RTM correction for Latvian and Finnish data points, but global Shuttle Radar Topography Mission (SRTM; Farr et al. 2007) had to be applied in Russia. The spherical harmonic coefficients of GOCO05c (Fecher et al. 2017) up to a maximum degree and order of 300 were expanded to compute the Δg_P^{GGM} correction in Eq. (3).

According to the estimated statistics (Table 2) of different types of gravity anomalies at survey points, the variance of RTMA is smaller than the corresponding estimates of FAA and SBA. The smaller spatial variability of RTMA relative to FAA can also be noticed in Fig. 7. Moreover, the mean value of RTMA is nearly zero, whereas the mean values of FAA and SBA are biased. As a conclusion, the RTMA signal demonstrates superiority above other anomaly types in the light of assumptions generally assumed in geostatistics like unbiasedness (e.g. zero mean), weak stationarity and isotropy (see Cressie 1993). The GGM and RTM contributions in RTMA computation (Eq. (3)) represent the long- and short-wavelength parts in the gravity anomaly signal, respectively. The removal of these parts from the observed gravity signal results in the smooth residual RTMA signal with reduced spatial variability. These findings demonstrate the improved stochastic properties of RTMA and its suitability for geostatistical modelling.

The spatial variability and correlation of the data in question are described by an empirical autocovariance (hereafter covariance) curve to which a theoretical model is fitted. The estimated covariance of gravity anomaly data in the following grid computation (Fig. 8) was approximated by a 2nd-order isotropic Markov model (CV2M) (see Kasper 1971; Andersen 2013):

$$C(l) = C_0\left(1+\frac{l}{\alpha}\right)e^{-l/\alpha}, \tag{4}$$

where $C(l)$ is the modelled covariance value over the distance l, C_0 is the signal variance and α is a parameter related to the correlation length $X_{1/2}$ approximately as $\alpha \approx 0.595X_{1/2}$. The correlation length is defined as the distance at which the covariance function reaches a half of the initial C_0 value.

Smaller covariance values (near 0° spherical distance, see Fig. 8) of RTMA compared to FAA yield that the predictable quantity is smoother (i.e. it varies less, see also Table 2) and needs fewer nearby data points to predict the anomaly values at grid's nodal points. In other words, the higher spatial variability of the FAA point values (see Figs 7 and 8) due to the high-frequency components in the FAA signal implies that a much denser distribution of observation points near the grid's node is needed to obtain the grid prediction accuracy comparable to that of RTMA. Evidently, FAA is less suitable for the gravity anomaly surface modelling and therefore the RTMA values are to be used in the subsequent gravity anomaly gridding.

Before grid computation additional downsampling of input data was applied to select a single point with the smallest uncertainty estimate within each 0.01° × 0.02° cell (Märdla et al. 2017) which is about 1.1 km × 1.2 km in Estonia. Note that data resolution of nearly 1 point per km² is sufficient for the accurate regional gravity field modelling, which is one of the main purposes of this study. The optimal RTMA anomaly grid was predicted using a method of weighted LSC with noise (Moritz 1980). The weights were assigned from the formal uncertainties of gravity values (Fig. 5). Dermanis (1984) noted that the LSC with a priori modelled covariance is similar to the kriging prediction method (with semivariogram modelling). For the weighted LSC prediction of the unknown gravity anomaly signal at regular grid nodes the following matrix equation was solved [Moritz 1980, (14.27)]:

$$\Delta\boldsymbol{g}_s = \boldsymbol{C}_{st}\left(\boldsymbol{C}_{tt}+\boldsymbol{C}_{nn}\right)^{-1}\Delta\boldsymbol{g} = \boldsymbol{C}_{st}\boldsymbol{C}_{\Delta\boldsymbol{g}\Delta\boldsymbol{g}}^{-1}\Delta\boldsymbol{g}\,, \tag{5}$$

where $\Delta\boldsymbol{g}$ and $\Delta\boldsymbol{g}_s$ are the vectors of known and predicted anomaly values, respectively (representing the known signal t at observation points and the predicted signal s at grid points), $\boldsymbol{C}_{st}$ is the cross-covariance matrix of signals s and t, $\boldsymbol{C}_{tt}$ and $\boldsymbol{C}_{nn}$ are the autocovariance matrices of the signal t and the noise n, and since $\Delta\boldsymbol{g} = t + n$, the variance–covariance matrix of observed values is $\boldsymbol{C}_{\Delta\boldsymbol{g}\Delta\boldsymbol{g}} = \boldsymbol{C}_{tt} + \boldsymbol{C}_{nn}$. Note that $\boldsymbol{C}_{nn}$ is a

Table 2. The statistics of free-air, residual terrain model, Bouguer anomalies (denoted as FAA, RTMA and SBA, respectively) evaluated at 49 189 points over the target area. It was complemented with the statistics of corrections computed from global gravity field, residual terrain and atmospheric models (denoted as GGM, RTM, ATM corrections, respectively). *Units of gravity anomalies in mGal (for variance mGal²) and heights in m

Anomaly type/Correction	Mean	Standard deviation	Variance	Min.	Max.
FAA	–13.14	±16.55	273.9	–73.82	44.05
GGM corr.	*–12.86*	*±14.62*	*213.7*	*–61.94*	*22.79*
RTM corr.	*0.09*	*±1.50*	*2.3*	*–7.84*	*14.54*
ATM corr.	*0.87*	*±0.01*	*0.0*	*0.84*	*0.87*
RTMA	0.45	±7.83	61.3	–30.64	33.67
SBA	–17.43	±15.20	213.0	–73.82	30.37
*Height**	*38.2*	*±40.6*	*1648.4*	*–0.1*	*283.7*

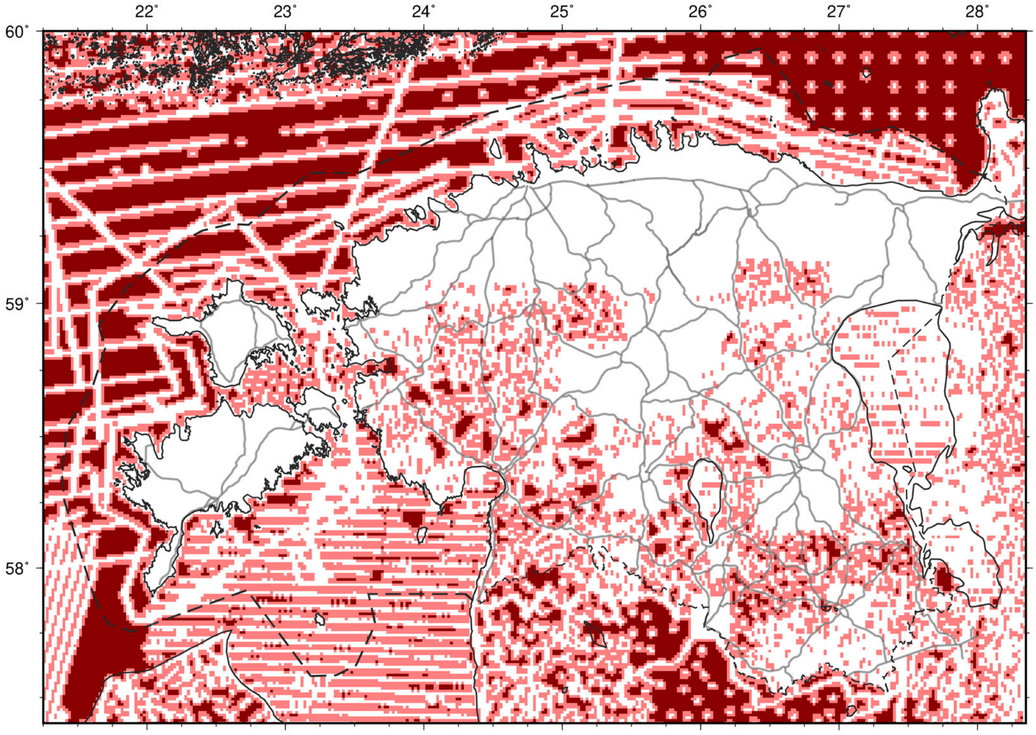

Fig. 6. Distribution of data voids and data density. The 0.01° × 0.02° grid (about 1.1 km × 1.2 km in Estonia) with coloured cells where no data points are available within the radius of 1.5 km (marked with light red) and 2.5 km (dark red) from the cell centre. In other words, the distance between data points is equal to or larger than 3 and 5 km over the areas marked with light and dark red, respectively.

diagonal matrix that contains observational errors. The variance–covariance (also the error covariance) matrix $\boldsymbol{C}_{\Delta \boldsymbol{g}_s}$ of predicted quantity results from the matrix equation [Moritz 1980, (14.42)]:

$$\boldsymbol{C}_{\Delta \boldsymbol{g}_s} = \boldsymbol{C}_{ss} - \boldsymbol{C}_{st} \boldsymbol{C}^{-1}_{\Delta \boldsymbol{g} \Delta \boldsymbol{g}} \boldsymbol{C}^{\mathrm{T}}_{st}, \tag{6}$$

where $\boldsymbol{C}_{ss}$ is the auto-covariance matrix of the predicted signal s. This relation allows us to estimate the uncertainties of gravity anomaly grid values and describes (*i*) the combined effect of formal uncertainties of input data (Fig. 5), (*ii*) the distribution and density of gravity points (Fig. 6) and (*iii*) the modelled spatial correlation described by Eq. (4) with parameters from Fig. 8. The LSC predicted RTMA grid with the CV2M model ($X_{1/2} = 23$ km) from Eq. (5) and estimated uncertainties from Eq. (6) are shown in Figs 9 and 10, respectively. The software 'geogrid' from physical geodesy software package GRAVSOFT (Forsberg & Tscherning 2008) was used for computing the weighted LSC solution.

Applications derived from the RTMA model

The generated high-quality RTMA prediction model can be used for deriving specific types of gravity anomalies. For instance, by restoring the GGM and RTM parts in Eq. (3) the RTMA grid is converted into the FAA surface model (Fig. 11). Similarly the Bouguer, Faye, Prey and isostatic anomalies can be derived from the RTMA grid by using the corresponding DEM, bathymetry and crustal density models with the accuracy and resolution necessary for specific application.

Within the entire target area the FAA surface model varies from –73 to +44 mGal with the overall range of 117 mGal. The FAA grid values are predominantly negative (with a mean of –14.6 mGal), especially over large portions of the sea. The grid also reveals rather rough variations with standard deviation (STDEV) of 19.2 mGal. Correlation between the FAA and topography can be identified over the land masses, e.g. over the eastern part of the Estonian mainland but also in Latvia, Russia and Finland.

In general the free-air anomalies are needed as input data for the geoid computation, therefore the primary outcome of the present study is the FAA model. Yet, SBA can be computed from the FAA surface model (Fig. 11) by using relation (3), whereas the normal height of topography (at the nodal point of the FAA grid) can be interpolated from regional or global digital terrain models like EST-DEM2013 or SRTM.

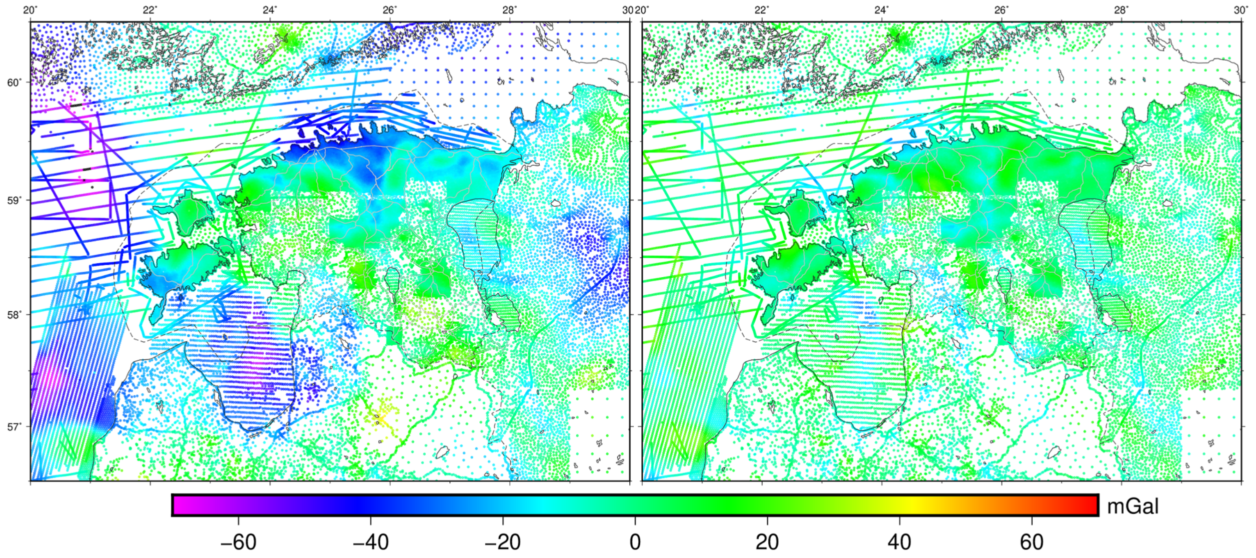

Fig. 7. The gravity point data with the assigned free-air (left-hand side) and residual terrain model (right-hand side) anomaly values.

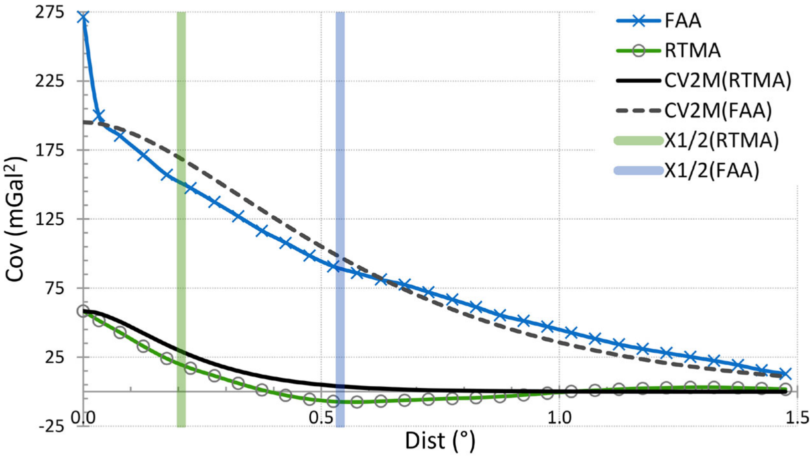

Fig. 8. Empirical autocovariogram curves estimated for free-air and residual terrain model gravity anomaly (denoted as FAA and RTMA, respectively) point values (by using the pairs of 49 189 points up to 1.5° spherical distance). The least-squares fit with the 2nd-order Markov function (Eq. (4), labelled as CV2M) yields optimum autocovariance models for RTMA ($C_0 = 58.4$ mGal², $X_{1/2} = 0.21° \approx 23$ km) and FAA ($C_0 = 195.1$ mGal², $X_{1/2} = 0.54° \approx 60$ km). The vertical bars indicate correlation lengths $X_{1/2}$ of the models. The unit of the horizontal axis is arc-degrees.

The misfit between the predicted RTMA and FAA models and initial data point values in Fig. 12 describes the effect of different error sources in the observation data and the prediction models, but also the actual variability of the anomaly field. The larger variability is associated with the FAA residuals. The STDEV of residuals over the entire target area are 0.65 mGal and 0.73 mGal for RTMA and FAA anomalies, respectively. Large residuals (up to 16 mGal) that occur over marine areas (indicating possible outliers in data) could corrupt the statistics (e.g. STDEV of residuals). Oja (2018) identified discrepancies over the western marine areas (mean and STDEV –1.7 and ±2.7 mGal, min. and max. –11.6 and 7.4 mGal) and along the northern coast (–2.5 and ±3.3 mGal, –16.4 and 6.2 mGal). These values indicate disagreement between airborne (measured in 1999) and shipborne (2016–2017) gravity data sets. These discrepancies also imply that the formal uncertainties of the RTMA model in Fig. 10 could apparently be too optimistic for marine areas. To avoid biased results, the STDEV of residuals was estimated separately over land and marine areas. As a result, the RTMA-related STDEV of 0.45 mGal and 1.00 mGal, and the FAA-related STDEV of 0.58 mGal and 1.01 mGal were

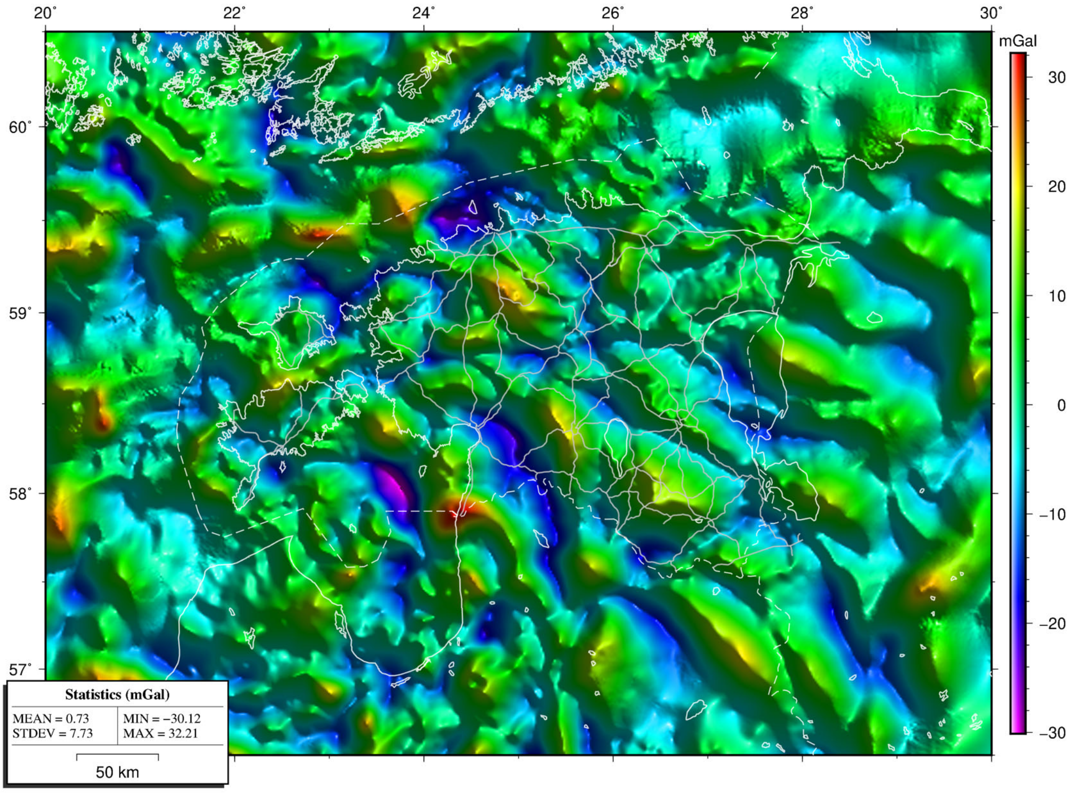

Fig. 9. The least-squares collocation predicted residual terrain model gravity anomaly grid.

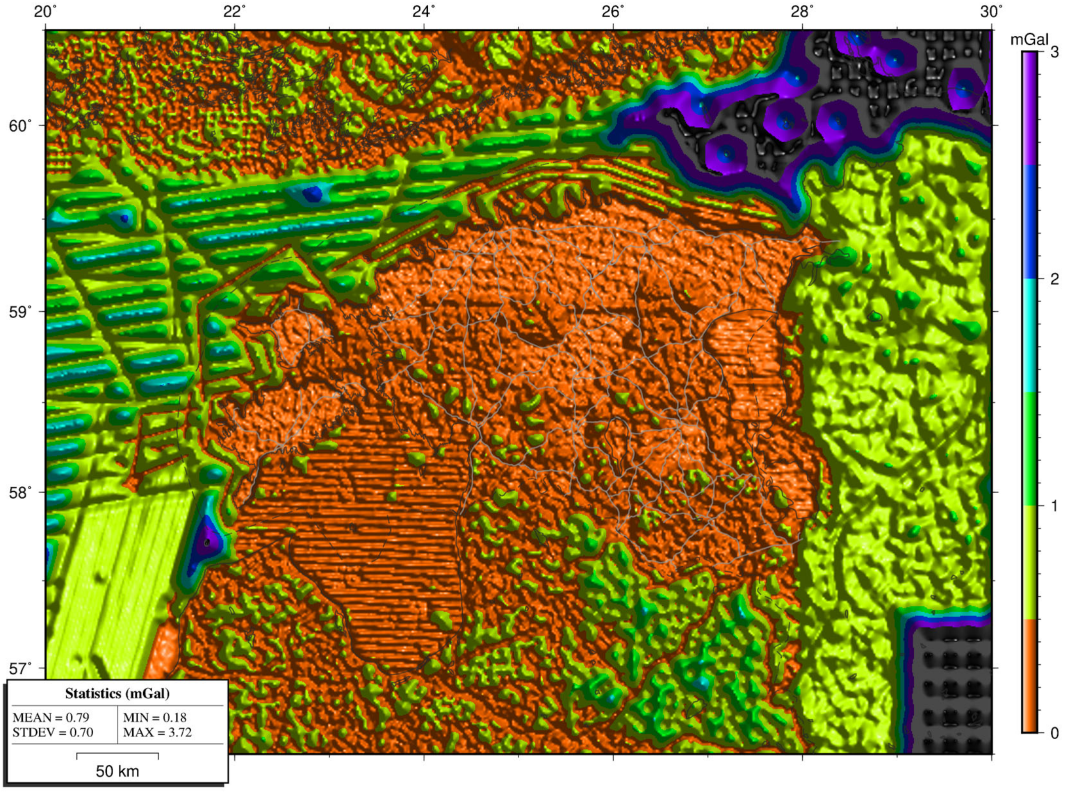

Fig. 10. The estimated LSC uncertainties of predicted residual terrain model gravity anomaly values. The grey and black shades indicate the areas with uncertainties exceeding 3 mGal.

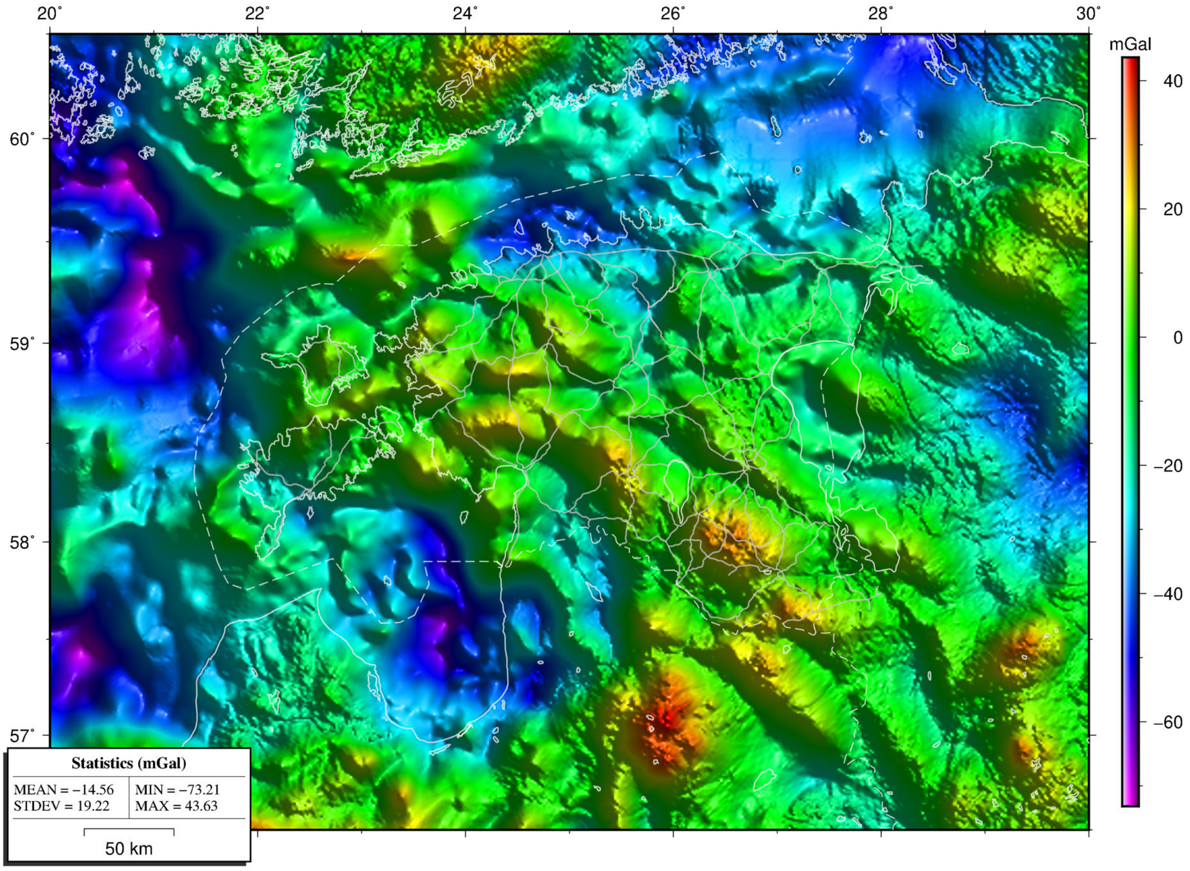

Fig. 11. The free-air anomaly model derived from the predicted residual terrain model gravity anomaly grid after restoring the components of global gravity and residual terrain models.

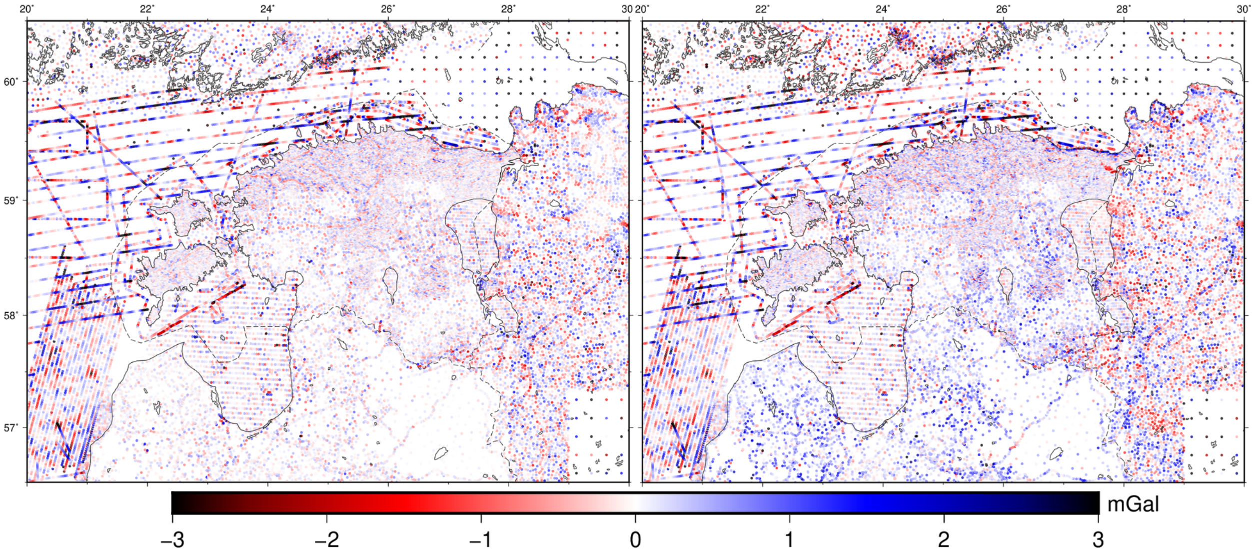

Fig. 12. The discrepancies of the residual terrain model (left) and free-air (right) gravity anomaly surface grids at the locations of gravity data points (bicubic method used for interpolation).

estimated over land and marine areas, respectively. Thus, over land the agreement between the point values and the RTMA model is clearly better than for FAA. Over the marine areas the residuals of RTMA and FAA are practically same, which is not surprising since no corrections due to bathymetry have been modelled and added there.

The roughness of the gravity field can be assessed from the magnitude map of the horizontal gradient (estimated as a directional derivative) of the RTMA grid (Fig. 13). The horizontal gradient reaches 3 mGal/km over the land masses, but 4–5 mGal/km in marine areas (Gulf of Riga, northwestern coast near Tallinn). It can be concluded that in the areas with an intense and variable gradient the spatial distance between gravity points more than 2–3 km might aggravate the prediction accuracy considerably and the resulting omission errors may be up to 3–5 mGal. Accordingly, in combination with the data density map (cf. Fig. 6), the horizontal gradient mapping would be an important source for designing future gravity surveys.

Another product of the present study, and useful for e.g. metrological research, is the surface gravity model derived from the RTMA grid (Fig. 14). To compile that model, the expected gravity values on the topography or water surface g_P were derived from Eq. (3) by restoring the normal gravity, GGM, RTM and other components. The surface gravity model revealed that gravity acceleration g_P on topography was changing by 220 mGal (0.0022 m/s^2 or 2.2 mm/s^2) within the Estonian land and maritime borders, the mean value being 981 796 mGal (9.81796 m/s^2). By considering only land areas, the surface gravity varies from 981 674 to 981 864 mGal (9.81674–9.81864 m/s^2), with the mean of 981 792 mGal (9.81792 m/s^2) and the maximum range of about 190 mGal (1.9 mm/s^2). The surface gravity reflects similar features found also on gravity anomaly maps (Figs 9 and 11), with a strong south–north direction positive trend due to the Earth's flattening and rotation. These gravity field maps (Figs 11, 13, 14) correlate also with geological structures within the crystalline basement (see details in All et al. 2004; Sildvee & Vaher 1995; Puura & Flodén 1999; Karell et al. 2014).

The FAA model predicted in this study coincides with the FAA model used for the national geoid EST-GEOID2017 modelling (Ellmann et al. 2019), only the geographical boundaries of grid areas differ slightly. To identify the impact of new gravity data, DEM and methods of gravity anomaly modelling, the differences between FAA models of this and previous study (the computation of a previous geoid model EST-GEOID2011, see Ellmann et al. 2011) were estimated (Fig. 15).

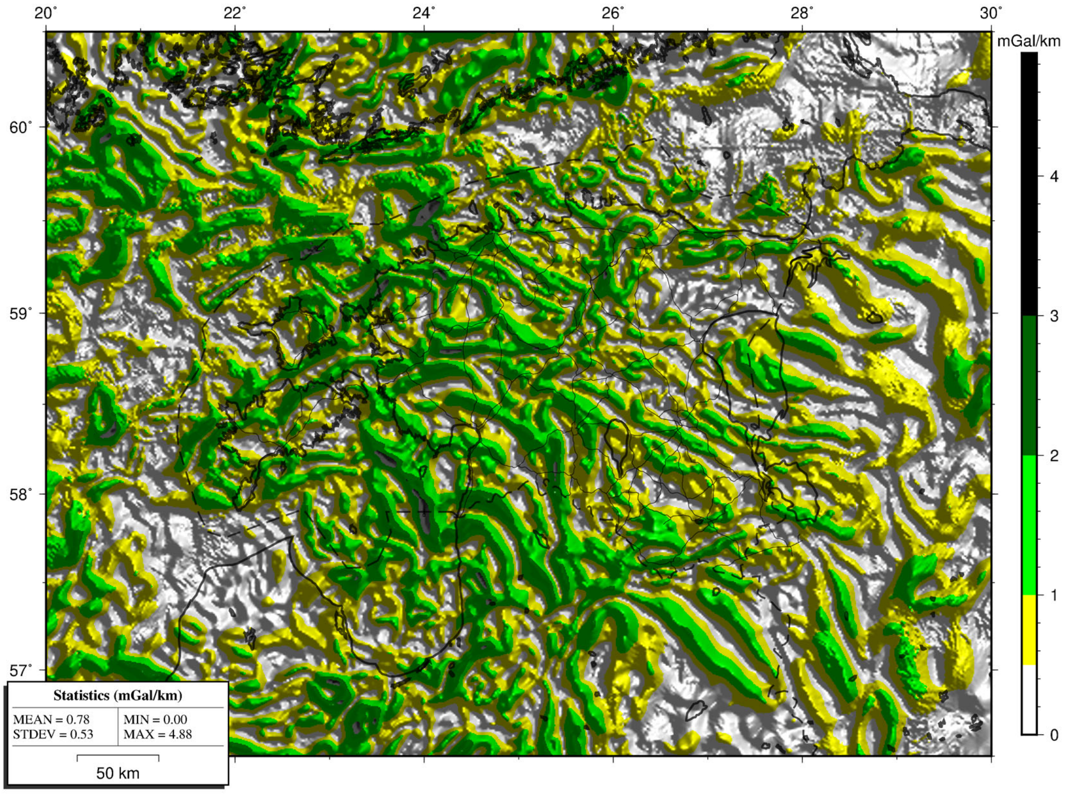

Fig. 13. The magnitude of the horizontal gradient estimated as a directional derivative of the residual terrain model anomaly prediction model.

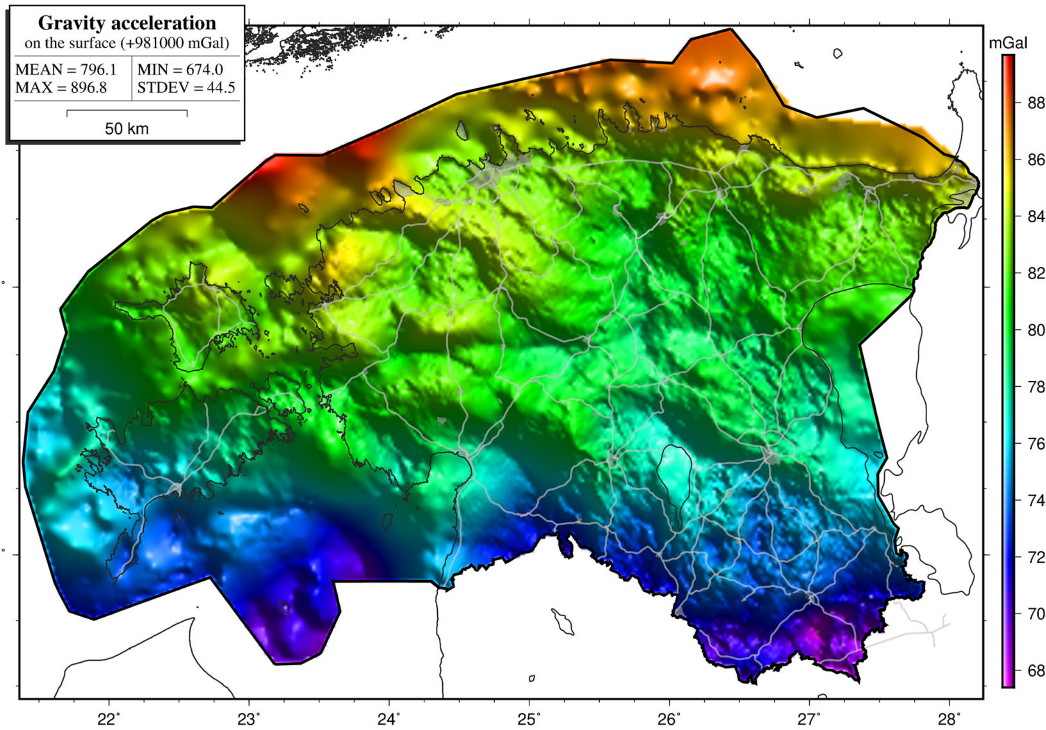

Fig. 14. The gravity acceleration g_P on topography (on land and water surfaces) derived from the residual terrain model anomaly grid within the Estonian land and maritime borders.

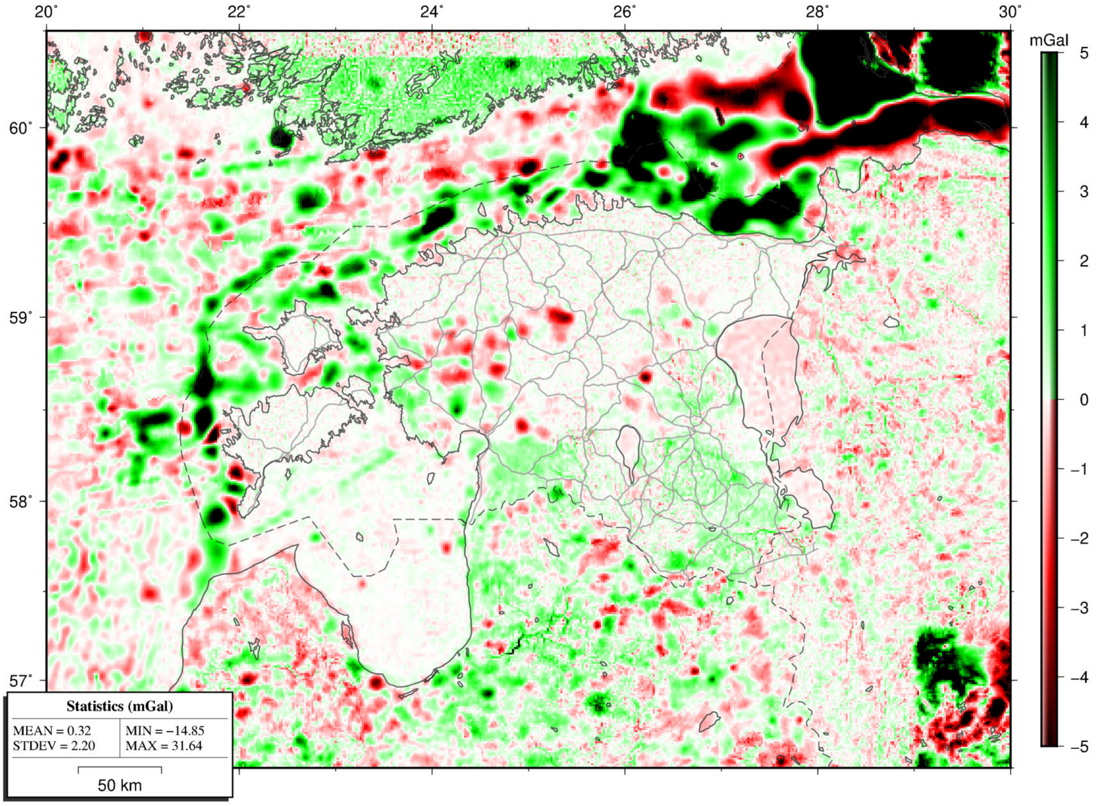

Fig. 15. The difference between the free-air gravity anomaly grids computed in 2011 and in this study ($\Delta g^{FA}_{2011} - \Delta g^{FA}_{2017}$). Within the black areas the differences are larger than 5 mGal.

A rather good agreement was found between the new and old FAA models over northern Estonia and the West Estonian Archipelago islands. Such a result was expected because the dense GSE gravity data (from the geological mapping, see Table 1) are the same in both modelling. Slight discrepancies indicate the effect of low-pass filtering of very dense data before the prediction of the new FAA model, whereas the modelling in 2011 included all the GSE observations. Larger discrepancies over central and southern Estonia represent the effects of new gravimetric surveys (red, green spots) and an improved DEM (greenish background) used in the computation of a new FAA grid through RTMA. Dark green, red and black areas along the northern and western coasts and marine areas represent the large impact of FAMOS shipborne data and the GGM-derived gravity anomaly patch in the Gulf of Finland.

SUMMARY

This contribution reviews the ongoing improvement of the spatial distribution and accuracy of gravity data in Estonia within the last 70 years. The results and reference metadata of many gravity surveys (see Table 1) have lately been compiled into the Estonian gravity database (EGDB). This work included evaluation, the conversion of historical data sets from the original gravity datum to the modern gravity frame and outlier detection. The EGDB has been used successfully in the national Estonian geoid model EST-GEOID2017 and the international NKG2015 geoid model projects. The geoid modelling needs gravity data from a wider region than the area under study. Therefore extensive international cooperation to obtain gravity data from neighbouring countries and the Baltic Sea has been carried out. As a result, new and improved gravity data from the NKG gravimetric database and the FAMOS marine gravity campaigns have been available for domestic and international researches and applications.

The Estonian gravity data combined with international data sets resulted in nearly 50 000 gravity points over the study area (with latitude from 56.5° to 60.5° N and longitude from 20° to 30 E°). The mean of the formal uncertainty (obtained from databases) of all gravity data is 0.75 mGal, which is a bit worse than the corresponding value of 0.48 mGal of Estonian gravity data. The data uncertainty over marine areas (on average 1.3 mGal) is about 2–3 times worse than the uncertainty on the land (0.54 mGal).

The spatial data density in the Estonian mainland is satisfactory, especially over the northern and western parts of Estonia where the resolution of survey points from geological mapping is better than 1 point per 10 km². Such data resolution should be enough for regional applications like geoid modelling, the processing of precise levelling, etc. However, this conclusion may not hold in the regions with a rough, variable gravity field.

An improved gravity field model over Estonia was obtained by applying RTM anomalies and the LSC prediction method. The statistics and spatial covariance analysis suggest that the RTM anomaly signal is more suitable for the modelling of the gridded surface than free-air and Bouguer anomaly signals. Nevertheless, the predicted RTMA model can be converted to other anomaly type models that may be useful for different applications in geodesy, geology, geophysics and metrology. The results of this contribution should be useful input for the study of the Earth's crustal properties over Estonia and its neighbouring areas, including the modelling of the basement structures and the crustal thickness (e.g. All et al. 2004) and the inverse modelling of local causative sources in the crystalline basement (Dmitrijeva et al. 2018). The gravity data used and anomaly models predicted in this study might be insufficient for the determination of the properties of the upper sedimentary cover (e.g. to locate buried valleys) due to the spatial density of data points (filtered down to 1 point per km²) and the resolution of prediction models (0.01° × 0.02°).

There are still areas where measurements are needed to improve the accuracy of gravity anomaly prediction models. Both the density and uncertainty should be improved over coastal marine areas. Large discrepancies over 3–5 mGal between the airborne and shipborne data along the northwestern coast need further research in the future. The large data void in the eastern Gulf of Finland, currently filled with GGM-derived 'pseudo-observed' data, is definitely a complicated area for the grid prediction and the geoid modelling methods. More accurate and dense data could be obtained from the international cooperation (data exchange and joint marine campaigns with Finnish and Russian institutions) or by using some remote sensing techniques like satellite radar altimeters (e.g. Birgiel et al. 2018).

The high quality of Estonian gravity data and the anomaly models of this study is supported by the fact that recent Estonian geoid computation resulted in the EST-GEOID2017 model with an uncertainty of about 5 mm (Ellmann et al. 2019). The high-resolution geoid model EST-GEOID2017 is officially imposed by the Estonian Ministry of Environment as a part of the Estonian national geodetic datum.

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REFERENCES

Ågren, J., Strykowski, G., Bilker-Koivula, M., Omang, O., Märdla, S., Forsberg, R., Ellmann, A., Oja, T., Liepinš, I., Paršeliunas, E., Kaminskis, J., Sjöberg, L. & Valsson, G. 2016. *The NKG2015 gravimetric geoid model for the Nordic-Baltic region*. Presented at the 1st Joint Commission 2 and IGFS Meeting International Symposium on Gravity, Geoid and Height Systems. Thessaloniki, Greece.

All, T. & Gromov, O. 2005. *Geoloogilise baaskaardi Vaida (6341) lehe gravimeetrilise teemakihi täiendamine* [*Complementing the gravimetric layer of the geological base-map Vaida (6341) sheet*]. Technical report, Eesti Geoloogiakeskus, EGF, 20 pp. [in Estonian].

All, T., Puura, V. & Vaher, R. 2004. Orogenic structures of the Precambrian basement of Estonia as revealed from the integrated modelling of the crust. *Proceedings of the Estonian Academy of Sciences, Geology*, **53**, 165–189.

Andersen, O. B. 2013. Marine gravity and geoid from satellite altimetry. In *Geoid Determination* (Sansò, F. & Sideris, M. G., eds), *Lecture Notes in Earth System Sciences*, **110**, 401–451.

Birgiel, E., Ellmann, A. & Delpeche-Ellmann, N. 2018. Examining the performance of the Sentinel-3 coastal altimetry in the Baltic Sea using a regional high-resolution geoid model. In *2018 Baltic Geodetic Congress (BGC Geomatics), Olsztyn, Poland, 21–23 June, 2018*, pp. 196–201. IEEE Computer Cociety.

Boedecker, G. 1988. International Absolute Gravity Basestation Network (IAGBN). Absolute gravity observations data processing standards and station documentation. *Bureau Gravimétrique International (BGI), Bulletin d'Information*, **63**, 51–57.

Bruinsma, S. L., Förste, C., Abrikosov, O., Marty, J.-C., Rio, M.-H., Mulet, S. & Bonvalot, S. 2013. The new ESA satellite-only gravity field model via the direct approach. *Geophysical Research Letters*, **40**, 3607–3612.

Cressie, N. 1993. *Statistics for Spatial Data*. John Wiley & Sons, New York, 900 pp.

Denker, H. 2015. *A new European gravimetric (quasi)geoid EGG2015*. Poster presented at XXVI General Assembly of the International Union of Geodesy and Geophysics (IUGG), 22 June–02 July 2015, Prague, Czech Republic, www.isgeoid.polimi.it/Geoid/Europe/IUGG_2015_EGG2015.pdf [accessed 20/03/2019].

Denker, H., Barriot, J.-P., Fairhead, R., Forsberg, D., Ihde, J., Kenyeres, A., Marti, U., Sarrailh, M. & Tziavos, I. N. 2009. The development of the European Gravimetric Geoid model EGG07. In *Observing Our Changing Earth, IAG Symposia Series Vol.* 133 (Sideris, M., ed.), pp. 177–186. Springer, Berlin.

Dermanis, A. 1984. Kriging and collocation – a comparison. *Manuscripta Geodetica*, **9**, 159–167.

Dmitrijeva, M., Plado, J. & Oja, T. 2018. The Luusika potential field anomaly, eastern Estonia: modelling results. *Estonian Journal of Earth Sciences*, **67**, 228–237.

Ellmann, A. 1999. Eesti kõrgtäpse nivelleerimisvõrgu mõõtmistulemuste andmetöötlus ja tasandamine [Data processing and adjustment of the Estonian high-precision levelling network]. *Geodeet*, **20**, 6–8 [in Estonian, with English abstract].

Ellmann, A. 2001. *Least Squares Modification of Stokes Formula with Applications to the Estonian Geoid*. Division of Geodesy, Royal Institute of Technology, Report No. **1056**, Stockholm, viii+98 pp.

Ellmann, A. 2002. An improved gravity anomaly grid and a geoid model for Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **51**, 199−214.

Ellmann, A. 2005. Two deterministic and three stochastic modifications of Stokes's formula: a case study for the Baltic countries. *Journal of Geodesy*, **79**, 11–23.

Ellmann, A., All, T. & Oja, T. 2009. Towards unification of terrestrial gravity data sets in Estonia. *Estonian Journal of Earth Sciences*, **58**, 229–245.

Ellmann, A., Oja, T. & Jürgenson, H. 2011. Kosmosetehnoloogia rakendused geoidi ja gravitatsioonivälja täpsustamiseks Eesti alal [Application of space technologies to improve geoid and gravity field models over Estonia]. *Geodeet*, **41**, 22–25 [in Estonian].

Ellmann, A., Väling, P. & Oja, T. 2016. Meregravimeetrilised mõõdistused Lääne-Eesti vetes FAMOS projekti raames [Marine gravimetric surveys in the West-Estonian waters under the FAMOS project]. *Geodeet*, **45/46**, 80−82 [in Estonian].

Ellmann, A., Märdla, S. & Oja, T. 2019. The 5 mm geoid model for Estonia computed by the least squares modified Stokes formula. *Survey Review*, DOI: 10.1080/00396265.2019.1583848.

[EME] Estonian Ministry of Environment. 2017. Geodeetiline Süsteem [Geodetic system]. In *Legal Acts of Estonia, Decree No. 64, Riigi Teataja I*, https://www.riigiteataja.ee/akt/128102011003?leiaKehtiv [in Estonian, accessed 26/11/2018].

[FAMOS] FAMOS Consortium. 2014. *The FAMOS Project*. Available at http://www.famosproject.eu/famos [accessed 09/11/2018].

Farahani, H. H., Klees, R. & Slobbe, C. 2017. Data requirements for a 5-mm quasi-geoid in the Netherlands. *Studia Geophysica et Geodaetica*, **61**, 675–702.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. & Alsdorf, D. 2007. The Shuttle Radar Topography Mission. *Reviews of Geophysics*, **45**, RG2004.

Fecher, T., Pail, R., Gruber, T. & the GOCO Consortium. 2017. GOCO05c: A new combined gravity field model based on full normal equations and regionally varying weighting. *Surveys in Geophysics*, **38**, 571–590.

[FGI] Finnish Geodetic Institute. 2003. *Certificate of Calibration No. 6/2003*. Finnish Geodetic Institute, National Standards Laboratory.

Forsberg, R. 1984. *A Study of Terrain Reductions, Density Anomalies and Geophysical Inversion Methods in Gravity Field Modelling*. The Ohio State University, Report No. OSU/DGSS-355, 129 pp.

Forsberg, R. & Tscherning, C. C. 2008. *Geodetic Gravity Field Modelling Programs. An Overview Manual for the GRAVSOFT*. Second Edition, 77 pp.

Forsberg, R., Kaminskis, J. & Solheim, D. 1997. Geoid for the Nordic and Baltic region from gravimetry and satellite altimetry. In *Gravity, Geoid and Marine Geodesy* (Segawa, J., Fujimoto, H. & Okubo, S., eds), *International Association of Geodesy Symposia*, **117**, 540–547.

Forsberg, R., Olesen, A. V., Keller, K., Møller, M., Gidskehaug, A. & Solheim, D. 2001. Airborne gravity and geoid surveys in the Arctic and Baltic Seas. In *Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS-2001), Banff 2001*, pp. 586–593.

Forsberg, R., Strykowski, G. & Solheim, D. 2004. NKG2004 geoid of the Nordic and Baltic area. In *Proceedings on CD-ROM from the IAG, Gravity, Geoid and Satellite Gravity Missions*, August 30–September 3, Porto, Portugal.

Gromov, O. & Gromova, G. 1968. *Otchet o gravimetricheskoj s"emke masshtaba 1 : 25 000 na territorii Tsentral'noj Éstonii za 1965–1967 gody* [*Gravity mapping at a scale of 1 : 25 000 in the central part of Estonia, 1965–1967*]. Tallinn, EGF 2994, Technical report, 128 pp. [in Russian].

Gruno, A., Liibusk, A., Ellmann, A., Oja, T., Vain, A. & Jürgenson, H. 2013. Determining sea surface heights using small footprint airborne laser scanning. In *Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions 2013* (Bostater, C., Mertikas, S., Neyt, X. & Bruyant, Y.-P., eds), pp. 88880R-1–88880R-13. Dresden.

Heiskanen, W. A. & Moritz, H. 1967. *Physical Geodesy*. W. H. Freeman & Co., San Francisco, 374 pp.

Jekeli, C. 2012. Omission error, data requirements, and the fractal dimension of the geoid. In *VII Hotine-Marussi Symposium on Mathematical Geodesy* (Sneeuw, N., Novák, P., Crespi, M. & Sansò, F., eds), *International Association of Geodesy Symposia*, **137**, 181–187.

Jürgenson, H. 1998. Gravimeetrilise põhivõrgu mõõtmised 1998. a. suvel ja geoidi pinna arvutus [Gravimetrical measurements in 1998 and new determination of the geoid surface]. *Geodeet*, **17**, 8−15 [in Estonian].

Jürgenson, H. 2001. Geoid computations in Estonia. *IGeS Bulletin*, **11**, 21–29.

Jürgenson, H. 2003. *Eesti täppisgeoidi arvutus* [*Determination of Estonian precision geoid*]. Thesis (PhD), Estonian University of Life Sciences, Tartu, Estonia, 157 pp. [in Estonian, with English summary].

Kall, T., Oja, T. & Tänavsuu, K. 2014. Postglacial land uplift in Estonia based on four precise levelings. *Tectonophysics*, **610**, 25–38.

Karell, F., Ehlers, C. & Airo, M.-L. 2014. Emplacement and magnetic fabrics of rapakivi granite intrusions within Wiborg and Åland rapakivi granite batholiths in Finland. *Tectonophysics*, **614**, 31–43.

Kasper, J. F. Jr. 1971. A second-order Markov Gravity Anomaly Model. *Journal of Geophysical Research*, **76**, 7844–7849.

Korhonen, J., Koistinen, T., Elo, S., Säävuori, H., Kääriäinen, J., Nevanlinna, H., Aaro, S., Haller, L. Å., Skilbrei, J. R., Solheim, D., Chepik, A. K., Zhdanova, L., Vaher, R., All, T. & Sildvee, H. 1999. Preliminary magnetic and gravity anomaly maps of the Fennoscandian shield 1 : 10 000 000. *Geological Survey of Finland Special Paper*, **27**, 173–179.

Lemoine, F. G., Kenyon, S. C., Factor, J. K., Trimmer, R. G., Pavlis, N. K., Chinn, D. S., Cox, C. M., Klosko, S. M., Luthcke, S. B., Torrence, M. H., Wang, Y. M., Williamson, R. G., Pavlis, E. C., Rapp, R. H. & Olson, T. R. 1998. *The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96*. Greenbelt, Md.: National Aeronautics and Space Administration, Goddard Space Flight Center, NASA/TP-1998-206861, 584 pp.

Maasik, V. 1950. *Eesti NSV maa-alal 1949. aastal teostatud gravimeetrilised mõõdistamise tulemused* [*Gravimetric survey results done in the Estonian SSR territory in 1949*]. ENSV TA Geoloogia Instituut, Tallinn, 97 pp. [in Estonian].

Maasik, V. 1952. *Gravimeetrilised loejoone kõrvalekalded ja geoidi pind Eesti NSV keskosas* [*Gravimetric plumb line deflections and geoid surface in the middle of Estonian SSR*]. ENSV TA Geoloogia Instituut, Tallinn, 32 pp. [in Estonian].

Maasik, V. 1958. *Gravimetricheskie issledovaniya territorii Éstonskoj SSR (Opredelenie mestnykh iskhodnykh gravimetricheskikh punktov 1957 g)* [*Gravimetric studies on the territory of the Estonian SSR (Establishment of the local gravity reference points in 1957)*]. Institut Geologii AN ESSR, Tallinn, 103 pp. [in Russian].

Maasik, V. 1959. *Gravitatsionnoe pole na territorii Éstonskoj SSR i ego primenenie. Opredelenie sily tjazhesti i poluchennye rezul'taty* [*Gravitational field in the territory of the Estonian SSR and its application. Determination of gravity and the received results*]. Institut Geologii AN ESSR, Part 1, Tallinn, 156 pp. [in Russian].

Mäkinen, J., Bilker-Koivula, M., Falk, R., Gitlein, O., Kaminskis, J., Lapushka, K., Oja, T., Paršeliunas, E., Petroškevičius, P. & Timmen, L. 2009. Gravity change from repeated absolute measurements in Estonia, Latvia and Lithuania 1994–2008. *Geophysical Research Abstracts*, **11**, EGU2009-13286-1. EGU General Assembly 2009, Vienna, Austria.

Märdla, S. 2017. *Regional Geoid Modelling by Least Squares Modified Hotine Formula*. Doctoral thesis, Tallinn University of Technology, 210 pp.

Märdla, S., Ellmann, A., Oja, T. & Jürgenson, H. 2016. Improving and validating gravity data over ice-covered marine areas. *International Association of Geodesy Symposia*, **143**, 263–270.

Märdla, S., Ågren, J., Strykowski, G., Oja, T., Ellmann, A., Forsberg, R., Bilker-Koivula, M., Omang, O., Paršeliunas, 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.

Märdla, S., Ellmann, A., Ågren, J. & Sjöberg, L. 2018. Regional geoid computation by least squares modified Hotine's formula with additive corrections. *Journal of Geodesy*, **92**, 253–270.

Marson, I., Faller, J. E., Cerutti, G., De Maria, P., Chartier, J.-M., Robertsson, L., Vitushkin, L., Friederich, J., Krauterbluth, K., Stizza, D., Liard, J., Gagnon, C., Lothhammer, A., Mäkinen, J., Murakami, M., Rehren, F., Schnüll, M., Ruess, D. & Sasagawa, G. S. 1995. Fourth international comparison of absolute gravimeters. *Metrologia*, **32**, 137–144.

Morelli. C., Gantar, C., Honkasalo, T., McConnell, R. K., Tanner, I. G., Szabo, B., Uotila, L. J. & Whalen, C. T. 1971. The International Gravity Standardization Network (IGSN71). *Bulletin Géodésique, Special Publication*, **4**, 1–194.

Moritz, H. 1980. *Advanced Physical Geodesy*. Herbert Wichmann Verlag, Karlsruhe, Abacus Press, Tunbridge Wells, Kent, 500 pp.

Oja, T. 2007. Gravimeetrilised süsteemid ja võrgud Eestis: IGNS71 ja EGS ajavahemikus 1975–2007 [Gravity systems and networks in Estonia: IGSN71 and EGS from 1975 to 2007]. *Geodeet*, **35**, 11–20 [in Estonian].

Oja, T. 2008. New solution for the Estonian gravity network GV-EST95. In *The 7th International Conference, Environmental Engineering Selected Papers*, **3**, 1409–1414.

Oja, T., 2012. Gravity system and network in Estonia. In *Geodesy for Planet Earth* (Kenyon, S., Pacino, M. & Marti, U., eds), *International Association of Geodesy Symposia*, **136**, 315–322.

Oja, T. 2014. *Compilation of Estonian Digital Elevation Model EstDEM2013*. Unpublished technical report (ver. 2014-10-08), Estonian Land Board, Tallinn, 10 pp.

Oja, T. 2016. *Unstable calibration factor of CG-5 relative gravimeter*. Presented at the 1st Joint Commission 2 and IGFS Meeting International Symposium on Gravity, Geoid and Height Systems. Thessaloniki, Greece, www.researchgate.net/publication/316739992_Unstable_calibration_factor_of_CG-5_relative_gravimeter [accessed 20/03/2019].

Oja, T. 2018. *EST-GEOID2017 sisendandmete ettevalmistus ja GRAV-GEOID2017 sobitamine GNSS/nivelleerimise andmetega* [*Preparation of EST-GEOID2017 input data and GRAV-GEOID2017 fitting with GNSS-levelling points*]. Unpublished technical report, Estonian Land Board, Tallinn, 59 pp.

Oja, T., Timmen, L. & Gitlein, O. 2009. 2007. a raskuskiirenduse mõõtmised Suurupi ja Tõravere punktidel absoluutgravimeetriga FG5-220 [Determination of the gravity acceleration at the Estonian stations Suurupi and Tõravere with the absolute gravimeter FG5-220 in 2007]. *Geodeet*, **38/39**, 16–27 [in Estonian, with English abstract].

Oja, T., Türk, K., Ellmann, A., Gruno, A., Bloom, A. & Sulaoja, M. 2011. Relative gravity surveys on ice-covered water bodies. In *Selected Papers of the 8th International Conference on Environmental Engineering*, pp. 1394–1401. Vilnius Gediminas Technical University Press "Technika".

Oja, T., Bilker-Koivula, M. & Mäkinen, J. 2017. Raskuskiirenduse mõõtmised gravimeetrilise võrgu I klassi punktidel 2017. a. suvel [Absolute gravity measurements on the I order points of the Estonian gravity network in summer 2017]. *Geodeet*, **47**, 35–38 [in Estonian, with English abstract].

Olesen, A. V. 2017. *Marine Gravity Onboard MS Sectori July 2017*. Processing report, DTU Space, 7 pp.

Olesen, A. V. & Kasenda, F. 2016. *Marine Gravity Onboard Jakob Prey June/July 2016*. Processing report, DTU Space, 6 pp.

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**, 1141–1156.

Pavlis, N. K., Holmes, S. A., Kenyon, S. K. & Factor, J. K. 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research*, **117**, B04406.

Puura, V. & Flodén, T. 1999. Rapakivi-granite–anorthosite magmatism – a way of thinning and stabilisation of the Svecofennian crust, Baltic Sea Basin. *Tectonophysics*, **305**, 75–92.

Robertsson, L., Francis, O., van Dam, T. M., Faller, J., Ruess, D., Delinte, J.-M., Vitushkin, L., Liard, L., Gagnon, C., Guo You Guang, Huang Da Lun, Fang Yong Yuan, Xu Jin Yi, Jeffries, G., Hopewell, H., Edge, R., Robinson, I., Kibble, B., Mäkinen, J., Hinderer, J., Amalvict, M., Luck, B., Wilmes, H., Rehren, F., Schmidt, K., Schnüll, M., Cerutti, G., Germak, A., Zabek, Z., Pachuta, A., Arnautov, G., Kalish, E., Stus, Y., Stizza, D., Friederich, J., Chartier, J.-M. & Marson, I. 2001. Results from the Fifth International Comparison of Absolute Gravimeters, ICAG97. *Metrologia*, **38**, 71–78.

Rüdja, A. 2016. *Kõrgusvõrgu rekonstrueerimine. Tasandusarvutused* [*Reconstruction of Height Network. Adjustment Computations*]. Unpublished geodetic report, part I, AS Planserk, Tallinn, 103 pp. [in Estonian].

Sildvee, H. 1998. Gravity measurements of Estonia. *Reports of the Finnish Geodetic Institute*, **98**:3, 1–8.

Sildvee, H. & Oja, T. 1999. Eesti gravimeetriline põhivõrk [Estonian gravity base network]. *Geodeet*, **21**, 10–13 [in Estonian].

Sildvee, H. & Vaher, R. 1995. Geologic structure and seismicity of Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **44**, 15–25.

Talvik, S. & Oja, T. 2014. *Eesti gravimeetriline andmebaas* [*The Estonian Gravity Database*]. Unpublished report, Tallinn University of Technology, Estonian Land Board, 27 pp. [in Estonian].

Türk, K., Sulaoja, M., Oja, T., Ellmann, A. & Jürgenson, H. 2011. Precise gravity surveys in South-Estonia from

2009 to 2010. In *Selected Papers of the 8th International Conference on Environmental Engineering* (Cygas, D. & Froehner, K. D., eds), pp. 1499–1505. Vilnius, Lithuania.

Varbla, S., Ellmann, A., Märdla, S. & Gruno, A. 2017. Assessment of marine geoid models by ship-borne GNSS profiles. *Geodesy and Cartography*, **43**, 41–49.

Vermeer, M. 1994. A fast delivery GPS-gravimetric geoid for Estonia. *Reports of the Finnish Geodetic Institute*, **94**:1, 1–7.

Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J. F. & Wobbe, F. 2013. Generic mapping tools: Improved version released. *EOS, Transactions of the American Geophysical Union*, **94**, 409–410.

Raskuskiirenduse anomaalvälja mudel Eestis

Tõnis Oja, Artu Ellmann ja Silja Märdla

On käsitletud raskuskiirenduse anomaalvälja mudeli täpsustamist Eestis, võttes aluseks viimase 70 aastaga mõõdistatud gravimeetrilised andmed. Arvesse võeti ajaloolised gravimeetrilised daatumid ja nende seos praeguse riikliku gravimeetrilise raamistikuga – kasutatud spetsifikatsioonid, meetodid, seadmed jne –, et erinevaid andmekogumeid korrektselt valideerida ning ühtsesse Eesti gravimeetrilisse andmebaasi (EGA) koondada. 2014. aasta sisaldas EGA infot ligikaudu 144 000 gravimeetrilise andmepunkti kohta. Geodeetiliste tööde jaoks (riikliku geoidi modelleerimine ja kõrgusvõrgu arvutus) vähendati andmepunkte 78%, eemaldades vähem täpsed ja varasemalt mõõdistatud punktid. Rahvusvahelise koostöö kaudu (projektid NKG2015 geoid ja FAMOS) täiendati EGA andmeid gravimeetriliste punktidega naaberriikidest ja Läänemerelt. Statistiliste omaduste tõttu eelistati raskuskiirenduse anomaalvälja modelleerimisel jääkpinnamudeli ehk RTM-i anomaaliaid (RTMA). Vähimruutude kollokatsiooni meetodiga modelleeriti optimaalne RTMA prognoospind koos määramatuse pinnaga. Kombineerides RTMA mudelit täpse kõrgusmudeliga (DEM), tuletati mudelpinnad veel vabaõhu ja Bouguer' anomaaliatele ning maapinna raskuskiirenduse jaoks. Erinevatel raskuskiirenduse prognoospindadel on mitmeid rakendusi nii geoteadustes kui ka metroloogias.