

Research Article

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Geodetic advances in Estonia 2018–2022

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Abstract: Geodetic advances in Estonia within the Nordic Geodetic Commission activity term 2018–2022 are reviewed. The new Estonian height and gravity systems and a new geoid model, EST-GEOID207, have been implemented. A national global navigation satellite system (GNSS) satellite data centre (ESTPOS) was established at the Estonian Land Board (ELB). ELB has also acquired instruments capable of detecting GNSS interference. ELB and Latvian Geospatial Information Agency conducted the Interreg-funded joint Estonian–Latvian cross-border project “Harmonization of Estonian and Latvian geodetic systems in the border areas” within 2021–2022.

Keywords: Nordic Geodetic Commission, Estonian Land Board, ESTPOS, EH2000, GNSS, CORS

1 Introduction

The major renovation of the Estonia geodetic infrastructure started after the Republic of Estonia regained its independence in the early 1990s. In particular, emerging accurate geodetic measurement techniques, e.g., global navigation satellite system (GNSS), required modernization of the national geodetic networks. The concept and the implementation strategy (summarised, e.g., in Rüdja, 2004) of the integrated geodetic networks were developed. The national geodetic GNSS network is hierarchically and accuracy-wise divided into first- and second-order networks, which are further densified by the GNSS densification network. The Estonian Land Board (ELB), a governmental agency responsible for the development and maintenance of geodetic networks in Estonia, initiated the establishment of a new Estonian national geodetic GNSS network in 1995. The fieldworks of the new national geodetic GNSS network were completed between 1996 and 1997 (Rüdja, 1999). A resolution of the

EUREF (International Association of Geodesy [IAG] Reference Frame Sub-Commission for Europe) Prague Symposium in 1999 (EUREF, 1999) approved the results (Rüdja, 1999) of the new first-order GNSS network to correspond to the class B accuracy (1 cm at the epoch of observations). Hence, the national geodetic system EUREF-EST97 is a realisation of the European Terrestrial Reference System 1989 (ETRS89).

As a result of the cooperation between ELB and the Finnish Geospatial Research Institute (FGI), the first GNSS permanent station in the north-west of Estonia (Suurupi) became operational in 1996. Starting from 2008, four Estonian Continuously Operating Reference Stations (CORS) have been incorporated into the EUREF permanent GNSS network (EPN). During the years 2014–2015, the modernization of the GNSS CORS in Estonia was carried out. The number of national GNSS CORS increased to 29 (Metsar et al., 2018). These national GNSS satellite data centre (ESTPOS) stations were interconnected to the first-order national geodetic network by a special GNSS field campaign in 2017 (Metsar et al., 2019).

Estonia has been participating actively in regional and international collaboration projects, e.g., with the Nordic Geodetic Commission (NKG) and EUREF. Among others, this gave the possibility to establish the Estonian first-order gravity network, which is based on absolute gravity observations. The new gravity sites were repeatedly measured in five absolute measurement campaigns from 1995 to 2017 within international cooperation by FGI and the Institute of Geodesy and/or Leibniz Universität of Hannover (Oja et al., 2021). Further densification of the gravity network was conducted using relative gravity measurements (Oja et al., 2021). The density and accuracy of the historic and new gravity points (cf. Oja et al., 2019) allow 5 mm accuracy for the new Estonian geoid model (Ellmann et al., 2020).

Estonia conducted the reconstruction of the national high-precision levelling network between 2003 and 2016. The network comprises 3,144 benchmarks, with the total length of levelling lines as 4,238 km, the average distance between levelling benchmarks is thus 1.4 km. Estonia is situated in the postglacial Vertical Land Motion region, where the land uplift varies from 0 mm/year in south-east Estonia to up to 3 mm/year in north-west Estonia. The NKG2005LU land uplift model (Ågren and Svensson, 2007) was used to refer the levellings of different years to the

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common time epoch 2000.0. The final adjustment yielded an average uncertainty of ± 1.76 mm for the resulting normal heights. This created the preconditions for the nationwide implementation of a new national height system in Estonia.

The management of geodetic point databases and geodetic marks is important for the preservation of geodetic infrastructure. This includes updating the information in the geodetic point database as well as the field maintenance of geodetic points.

Geodetic metrology has been a part of geodetic activities in the ELB as we maintain the geodetic calibration baseline in Vääna, near Tallinn. The full length of the calibration line is 1.3 km, consisting of 13 measurement pillars. The baseline has been repeatedly measured by the FGI metrology laboratory, with the latest in 2017.

Hence, by 2018, the modern geodetic infrastructure in Estonia had been established. However, the advancements of new surveying technologies require continuous updates of the geodetic infrastructure.

Accordingly, this review article focuses on the advances and development of the geodetic infrastructure within the NKG activity term 2018–2022. The activities including the change of the geodetic system, the reconstruction of geodetic infrastructure, the computation of GNSS networks, and geodetic activities in the Estonian–Latvian border region and in the field of geodetic metrology are presented. More detailed descriptions of the individual components of the national geodetic infrastructure can be found in the referred research publications.

2 Implementation of Estonian geodetic system

The update of the Estonian geodetic system was enforced on 1 January 2018 by a governmental decree (Geodetic System, 2018). The system comprises a new height system EH2000, a gravimetric system EG2000, and a geoid model EST-GEOID2017, as well as legislative changes for the Estonian GNSS permanent station network ESTPOS.

The Estonian height system EH2000 is based on the European Vertical Reference System (EVRS). The EVRS is a kinematic reference system with a datum defined by the Normaal Amsterdam Peil in Amsterdam, whereas a solid Earth zero tide system is adopted. The heights are initially expressed as geopotential numbers, whereas the normal gravity values of the Geodetic Reference System 1980 reference ellipsoid are used for calculating normal heights (Geodetic System, 2018). The EH2000 normal heights at epoch 2000 are based on the recently reconstructed national

levelling network, and the benchmark height values are derived from the EVRS implementation EVRF2007 (Rüdja, 2016). This datum change and the selected time epoch 2000.0 caused the previous heights (belonging to the obsolete 1977 Baltic Height System) numerically to increase from 14 to 25 cm towards north-western direction. The corrected tide gauge (TG) records (Kollo and Ellmann, 2019), complemented by the GNSS CORS time series, help to determine the magnitude of land uplift velocities, thus enabling to monitor (and account for) the deformations in the vertical datum.

The new Estonian geoid model EST-GEOID2017 (Ellmann et al., 2020) is used to convert EUREF-EST97 ellipsoidal heights into EH2000 normal heights and vice versa. The 5 mm accuracy of the geoid model ensures the requested accuracy for most of the land surveying works and also the offshore engineering demands (Varbla et al., 2020; Liibus et al., 2022; Varbla et al., 2022). The geoid model is distributed to the users free of charge, but the licence agreement must be signed. Currently, ELB has issued more than 220 licences to governmental bodies, educational institutions, software developers, and foreign/domestic surveying companies.

The new Estonian gravity system is denoted as EG2000, and it is based on the gravity values of the first-order gravity network. Gravity values at epoch 2000.0 are based on the results of absolute gravity measurements performed according to the International Absolute Gravity Basestation Network standards in 1995, 2003, 2013, and 2017 (Oja et al., 2021).

The ground-buried first-order geodetic GNSS network points are complemented by the network of ESTPOS GNSS-CORS. This ensures consistent deformation monitoring of the national geodetic network and geodetic system. In addition, ESTPOS-based GNSS real-time kinematic (RTK) or real-time network (RTN) measurements are widely used for land surveys, machine control, and mobile robot guidance. With RTN, it is rather straightforward and accurate (within 1 cm to 2 cm) to carry out geodetic measurements such as topographic/engineering surveys and less demanding stake-out tasks. Nowadays, the surveying industry uses CORS data also for kinematic applications, e.g., determining airborne laser scanning or mobile laser scanning trajectories. Hence, GNSS CORS-based services have become a crucial part of the modern surveying industry, and these need to be updated continuously.

3 National GNSS centre ESTPOS

The modern ESTPOS network consists of 29 sites by fall 2022 (Figure 1). ELB is responsible for ESTPOS management,

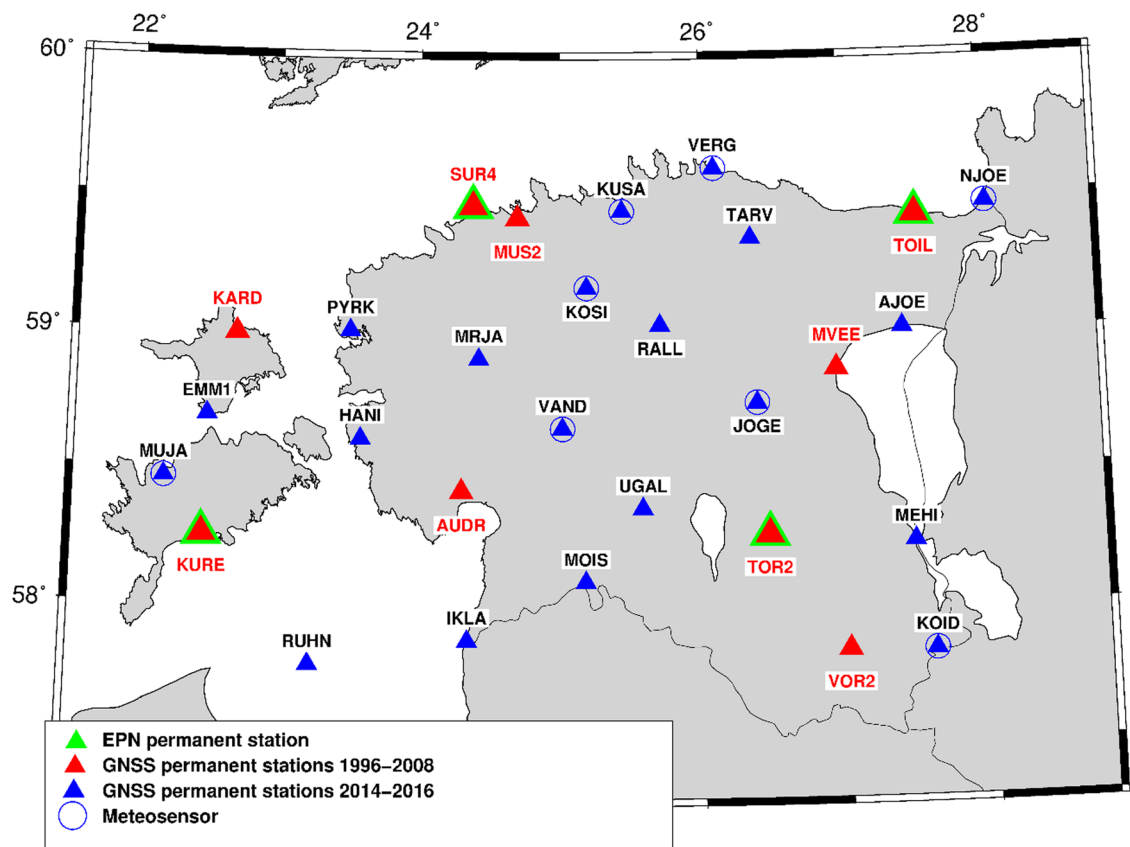


Figure 1: ESTPOS GNSS CORS network in 2022. See the legend for the used symbols.

including equipment maintenance and updates, the management of ESTPOS users, and data services (Metsar et al., 2018).

In 2019, the ESTPOS network coordinates were recomputed using the time span of more than 12 past years (GPS weeks 1408–2034) of GNSS measurements. For computations, Bernese 5.2 software was used, and the selected computational parameters are presented in Table 1.

The aim of the study was to validate the multi-year solution for the ESTPOS and establish further EUREF densification sites in Estonia. Cumulative coordinate solutions were calculated according to the EUREF guidelines (Legrand et al., 2022). The resulting formal average coordinate root mean square error (RMSE) for the ESTPOS network was 0.12, 0.10, and 0.35 mm for the North, East, and Up (NEU) components, respectively (cf. Figure 2).

The new multi-year solution for ESTPOS was accepted by the EUREF2019 Symposium to correspond to Class A standard for a national realisation of ETRS89 in Estonia (EUREF, 2019). Class A designates the stations’ positions within 1 cm accuracy at all epochs of the used observations (EPN, 2022).

Table 1: Computational parameters for ESTPOS

Software	Bernese GNSS 5.2
Satellite system	GPS + GLONASS
Elevation cut-off angle	3° and 10°
Orbits	Final products from centre for orbit determination for Europe (CODE) epn_14.atx
Antenna calibration model	
Positioning mode	Network DD
Baseline definition	Maximum observation strategy
Ambiguity resolution strategy	Quasi ionospheric free
Troposphere model	Vienna mapping function
Ionosphere model	CODE
Ocean tide loading model	Finite element solution tidal model, developed in 2004
Atmospheric tidal model	Compiled in Bernese
Stacking daily solutions	Minimum constraints using three translations
Reference frame	International GNSS service 2014 (IGS14)
Exclusion threshold for the outliers	10, 10, and 30 mm for NEU components, respectively (daily solutions)

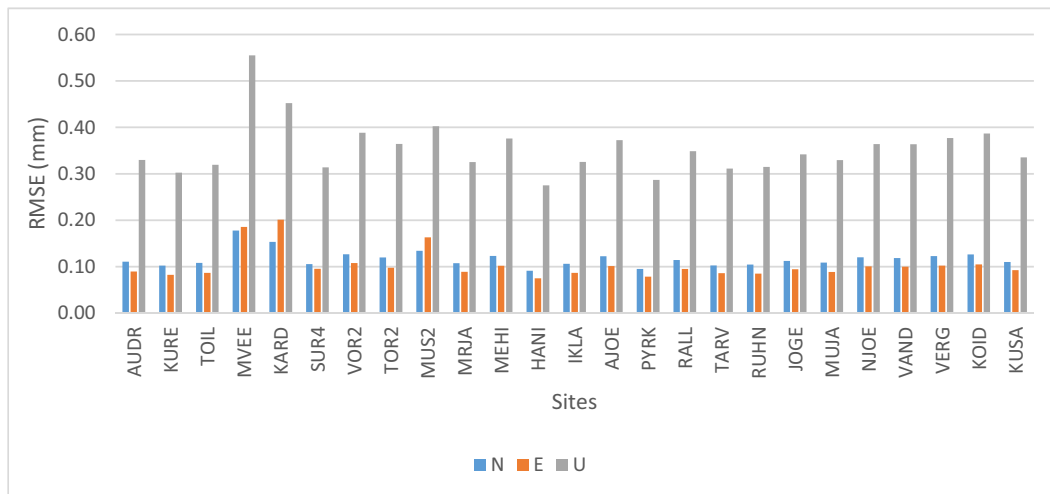


Figure 2: Average RMSE of the NEU coordinate components based on weekly (GPS weeks 1408–2034) solutions for the ESTPOS stations. Consult Figure 1 for the locations of the ESTPOS stations.

Final ESTPOS coordinates and velocities were computed for epoch 2013.0 (the middle epoch of the used GNSS observation series), whereas coordinates and velocities (Figure 3) were computed in IGS14 and afterwards transformed into the ETRS89 coordinate system. The resulting velocity rates and directions are compatible with the study of Brockmann (2009), Kollo et al. (2019), and Lahtinen et al. (2019).

Some site-based measurement noise occurrences were identified at certain GNSS stations. For instance, the occurrence of short signal interference episodes was detected in some of the GNSS data streams. To eliminate this, an “anti-bird” antenna spike (cf. Figure 4a) was mounted on the antennae radome of the ESTPOS site MUS2 in 2020. Such a modification eliminated further GNSS signal disturbances at the site.

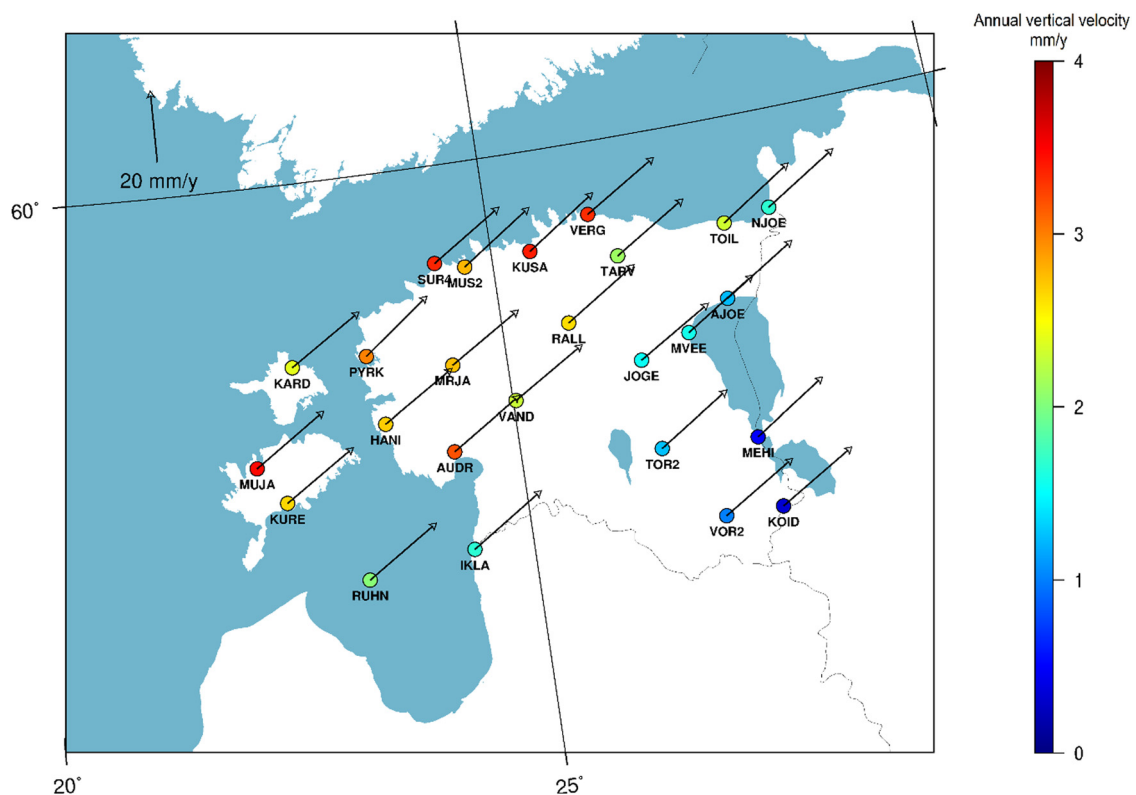


Figure 3: ESTPOS stations' velocities and directions in the IGS14 coordinate system (pers. comm. J. Metsar).

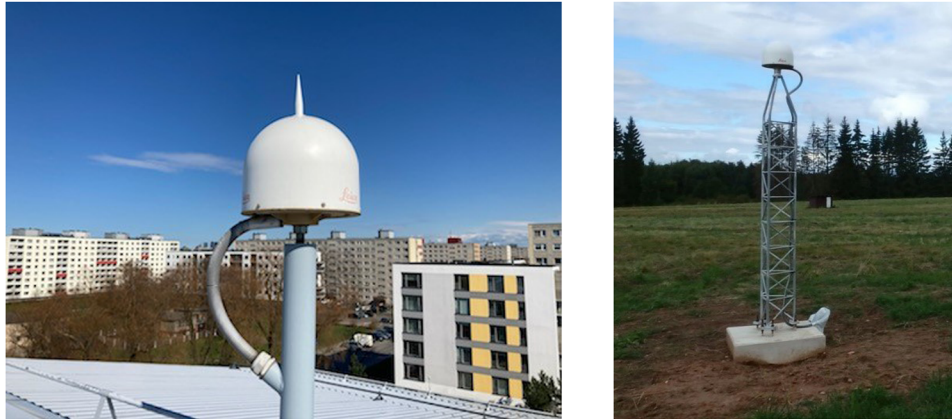


Figure 4: (a) “Anti-bird” modification of the GNSS antenna radome in the ESTPOS site MUS2. (b) TOR3 pillar in South Estonia.

In 2020–2021, within the framework of the Estonian–Latvian cooperation project GeoRefAct, ELB acquired two additional GNSS receivers with signal interference detection capability (ELB, 2022), see Section 6 for further details.

In 2022, the EPN and European Plate Observing System site TOR2 in South Estonia had to be relocated from a building (to be demolished) rooftop to a nearby metallic pillar (Figure 4b), which is located ca 40 m south from the previous location. The old site TOR200EST was decommissioned on 31 August 2022, whereas the new site TOR300EST data streams were already activated on 7 October 2022.

Estonia participates actively in the work of NKG GNSS Analysis Centre (NKG-AC), which is one of the dedicated computational centres (Lahtinen et al., 2018). For NKG-AC coordinate solutions, ELB has developed semi-automatic scripts. New developments are ongoing towards the change to the new International Terrestrial Reference Frame 2020 (ITRF2020). Most of the changes are due to the usage of the new Bernese 5.4 software version.

Currently, ESTPOS-based GNSS real-time corrections are accessible to governmental institutions and universities. The usage statistics is shown in Figure 5.

In 2021, the vision for the new generation of ESTPOS (Kollo et al., 2021) was elaborated. Vision gives an overview of global GNSS trends and their implication for Estonia in the next decade. The foresight for the future modernization of the Estonian GNSS CORS equipment and data processing workflows was developed. The realisation of the new vision may open the ESTPOS RTK corrections to the public. ESTPOS offers real-time data streams from 20 mountpoints in Radio Technical Commission for Maritime Services 3.x or Multi Satellite Message 4/5 formats. Different correction methods are used, like virtual reference station, master-auxiliary corrections, and individualised master-auxiliary corrections.

3.1 GNSS signal interference studies

ELB possessed commercial GNSS receivers (Leica GR50) with interference detection capability, which were mounted at two ESTPOS sites. With the Interference Toolbox support, it is possible to monitor and analyse the signal interference in real time. It is also possible to record data for later analysis. An example of signal interference is given in Figure 6.

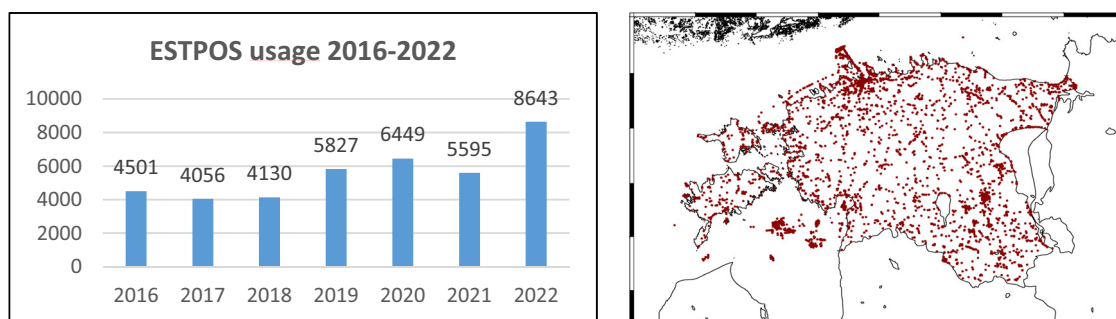


Figure 5: Statistics in 2016–2022 (left) and spatial distribution of ESTPOS usage in 2022 (right).

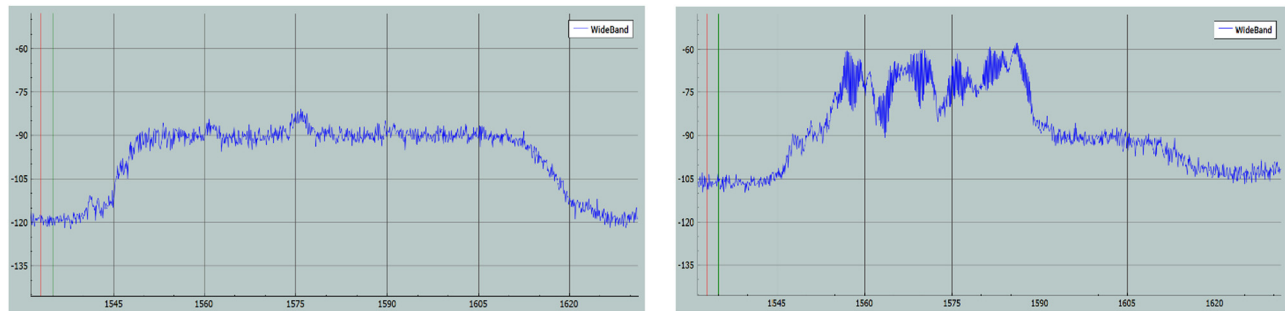


Figure 6: Samples of GNSS signal L1 frequency before interference (left) and during the interference (right). The vertical axis is in units of dB, and the horizontal axis is in units of hh:mm.

So far, we have detected signal interference events only in real time, but no further analysis has been initiated. We are planning to build up a corresponding service in the coming years.

The interference detection option notifies about any detected interference event via email, which contains information about the time, frequency, and power of detected interference. A new generation ESTPOS is planned to have nationwide GNSS signal interference capability already within the next NKG activity period.

4 Re-measurements of national geodetic network

The aim for the re-measurement of ground-buried national geodetic GNSS network was to perform quality assessment, validate the coordinate transformations, and integrate with ESTPOS GNSS CORS using a similar methodology.

Altogether, there have been seven field campaigns in 2020–2022 (Figure 7). Static GNSS methodology was used, with an observation session length of 6 h. Data processing was done with Bernese 5.2 software (Dach et al., 2015).

In 2020 and 2021, high-precision levelling was outsourced for certain levelling lines. In 2020, a total of 12 km

was levelled near the harbours of the West-Estonian islands to connect TG stations to the nearest benchmark of the national height network. In 2021, 33 km was levelled to connect national geodetic GNSS network points into a high-precision levelling network for the future needs of the new Rail Baltic railway construction.

5 Geodetic point database and field maintenance of geodetic marks

In the national geodetic point database, there is currently information available for 35,000 geodetic points, of which only 45% belong to national networks and 55% to local networks. Currently, the revision of the geodetic point database is ongoing in order to update the information. In July 2022, the new web-based interface for geodetic database was launched, which was the first step in the revision process.

Note that more than half of the points in the geodetic point database belong to local geodetic networks, thus increasing the workload for ELB. De jure, local municipalities are obliged to take decisions on local geodetic infrastructure, but in practice, their capacities and interests are

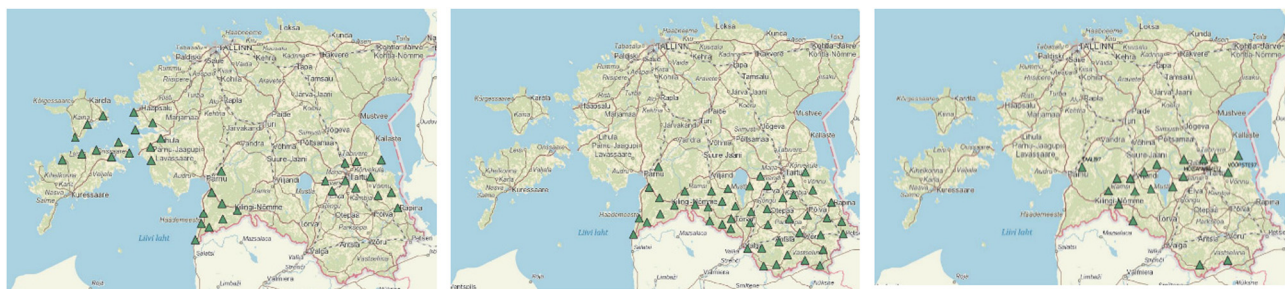


Figure 7: GNSS measurement field campaigns in 2020 (left), 2021 (middle), and 2022 (right).

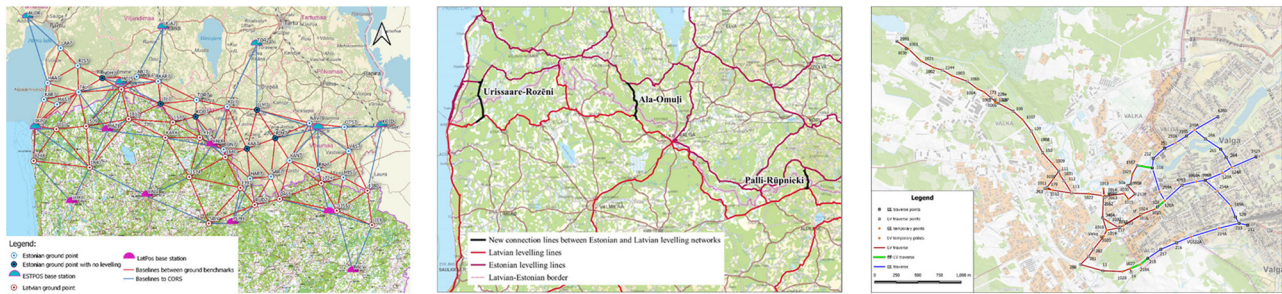


Figure 8: (a) GeoRefAct GNSS measurements (Zuševics et al., 2022). (b) GeoRefAct high-precision connection lines (Zuševics et al., 2022). (c) GeoRefAct local geodetic network in Valga/Valka (Zuševics et al., 2022).

quite heterogeneous. Therefore, legislative changes are planned to entitle the local authorities' clearer responsibility for the geodetic infrastructure.

Previously, the field maintenance of geodetic marks was outsourced to private companies. Starting from 2021, ELB performs this task with its own manpower. In 2021 and 2022, field checks and documentation were conducted for approximately 100 and 200 geodetic points, respectively. Within the revision of the geodetic point database, we intend to finalise the list of geodetic points that are crucial for the future geodetic infrastructure in Estonia. These geodetic marks shall be maintained at least once every 2 years.

Maintenance of geodetic marks includes the review of civil engineering structure design projects in order to preserve or remove national geodetic marks. Altogether, approvals for engineering plans and projects in terms of geodetic marks reach about 160 annually, and approvals for projects and reports of geodetic works reach about 130.

6 Estonian-Latvian cross-border geodetic activities

In 2021, ELB and Latvian Geospatial Information Agency initiated the Interreg-funded Estonian–Latvian cross-border programme. The project “Harmonization of Estonian and Latvian geodetic systems in border areas” (GeoRefAct) was launched in order to harmonise the geodetic systems in the border region (ELB, 2022).

The European Geodetic Reference System ETRS89 and the European Vertical Reference System EVRS are on the basis of geodetic systems in Europe, which is required by the Infrastructure for Spatial Information in Europe directive. However, the geodetic systems of the countries of the European Union may differ to some extent from the

European reference systems because there are practical differences in the values of heights and coordinates in neighbouring countries (i.e., national geodetic systems are based on slightly different input data). Therefore, accurate and seamless geodetic data must be available in cross-border areas to ensure the proper establishment of cross-border engineering projects, such as Rail Baltic.

In Latvia, the officially used coordinate system is LKS-92, which was established in 1992 (Likumi, 2011). The Latvian height system LAS-2000.5 was implemented in 2014 as a realisation of the EVRS (Likumi, 2015). In Estonia, the geodetic reference system EUREF-EST97 is officially in use, which is the basis for the rectangular coordinate system L-EST97 (Estonian Geodetic System, 2018). The Estonian height system EH2000 was implemented in 2017 as a realisation of the EVRS (Estonian Geodetic System, 2018). The numerical differences between these coordinate systems had to be identified and eliminated. For this purpose, within the frame of the GeoRefAct project, several geodetic instruments were upgraded or acquired: digital level Trimble DiNi, total station Leica TS60, three meteosensors, electronic field book for measurements, and two new GNSS permanent station receivers, Leica GR50.

The activities performed within the project were as follows: (1) development and harmonisation of methodologies for the GNSS, high-precision levelling, relative gravity, and traverse measurements in Valga/Valka twin city; (2) measurements and computations of national GNSS (Figure 8a) and levelling networks (Figure 8b) in border area, local GNSS/traverse network of twin-city Valga/Valka (Figure 8c) and gravity survey in Northern Latvia; and (3) calculation of transition models for the height and coordinate systems in the border corridor as well as transition model for coordinates in the border twin-city Valga/Valka.

The resulting coordinate and height transformation models, including web-based services, were created and made publicly accessible on the project partners' web pages in 2022.

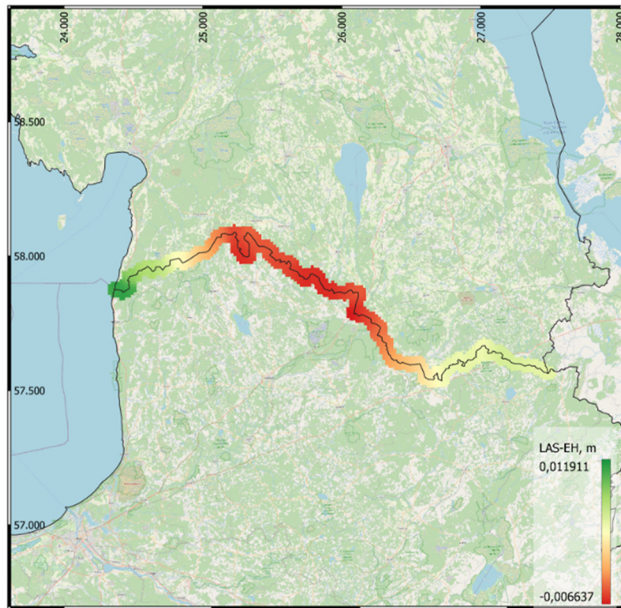


Figure 9: Height transition model for EH2000 and LAS2000.5 height systems (Zuševics et al., 2022).

For the height transition model, the levelling network adjustment was done as a minimally constrained solution, keeping the height for one single levelling benchmark #2128, which had normal height values both in the Latvian LAS-2000.5 ($H = 51.07090$ m) and Estonian EH2000 height systems ($H = 51.07834$ m), fixed. For the international border area, the EH2000 heights and those obtained from the GeoRefAct network were considered, so the height differences between the LAS-2000.5 height system and the GeoRefAct final computations were used to create the height transition model (cf. Figure 9).

For the coordinate transition model, GNSS adjustment for the across-border GNSS network was performed. The calculations were done in two steps. First, the coordinates for ESTPOS and LatPos CORS were referred to certain IGS and EPN CORS, and the resulting coordinates were obtained in the IGB14 reference system at the GNSS measurement mid-epoch 2021.05.23. Second, the coordinates for the GNSS points were calculated using ESTPOS/LatPos CORS as a reference in the EUREF-EST97 and LKS-92 coordinate systems. The obtained results were used to calculate transformation parameters and generate transition models (Figure 10).

The Valga/Valka traverse network was adjusted both in the L-EST97 and LKS-92 coordinate systems; the coordinates for the adjustment reference points were obtained from GNSS measurements. The results were used to calculate the transformation parameters between the L-EST97 and LKS-92 systems and to create a transition model (Figure 11).

7 Geodetic metrology

ELB maintains a 1.3-km-long high-precision calibration line (Figure 12) in Vääna, near Tallinn. This calibration line has latest been reconstructed in 2016–2017 and certified by the FGI in 2017. As from 2020, ELB has intentions to start the geodetic instrument calibration service. For this, in 2020–2022, several preparations have been made. First, the necessary precise meteorological instruments have been acquired, and the devices were equipped with hardware and software. Second, the data processing software is updated, and calibration measurement routines have been

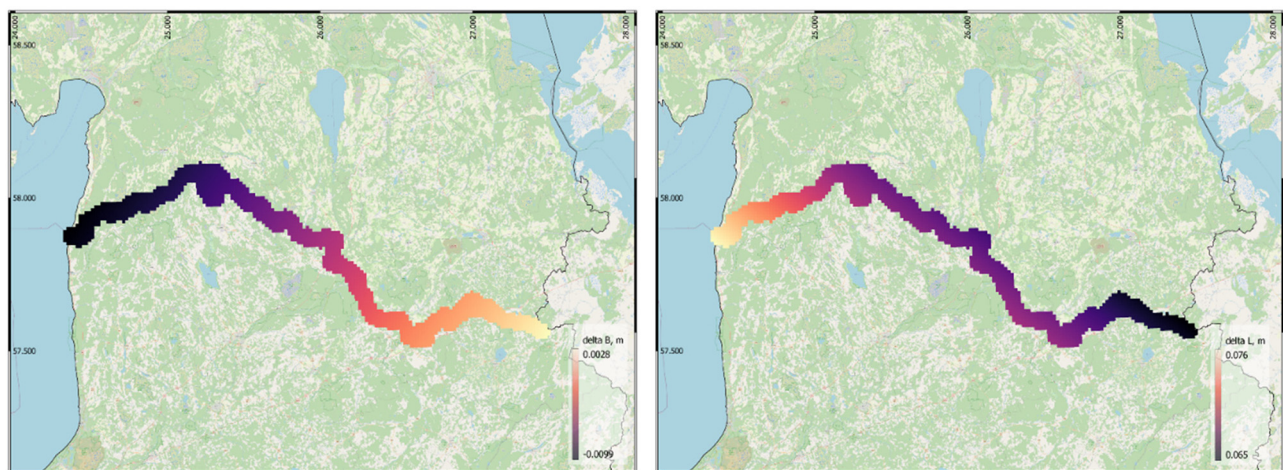


Figure 10: Coordinate transition model for L-EST92 and LKS-92 coordinate systems. The model for latitude is on the left, and the model for longitude is on the right-hand side (Zuševics et al., 2022).

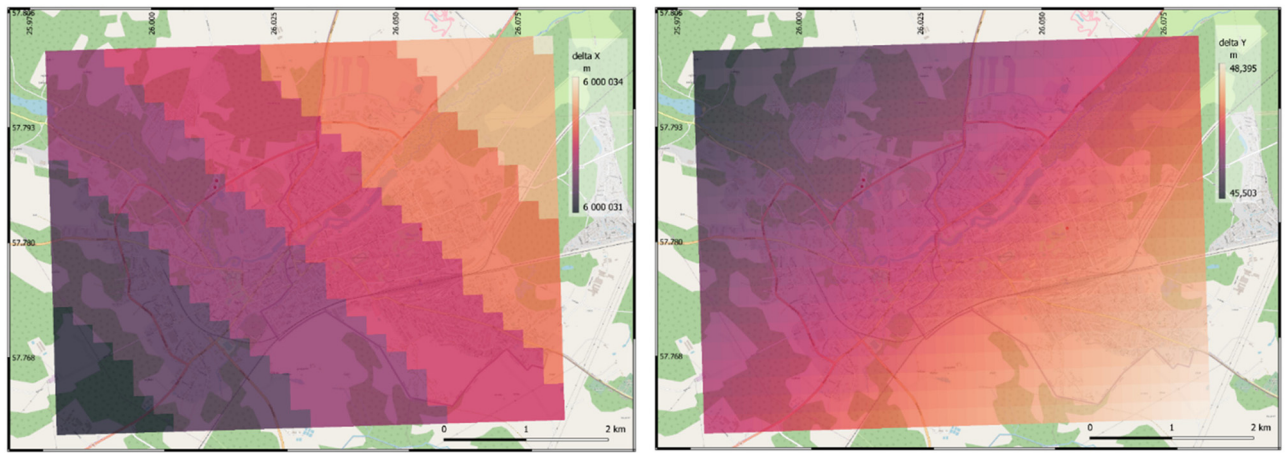


Figure 11: Coordinate transition model for L-EST92 and LKS-92 coordinate systems in Valga/Valka twin city. Model for the x-coordinate on the left and for the y-coordinate on the right-hand side (Zuševics et al., 2022).

developed. The first calibration measurements were conducted within the framework of the GeoRefAct project (ELB, 2022). The Latvian Geospatial Information Agency's and the ELB's equipment were calibrated in November 2021 and May 2022, respectively.

Regarding the future developments in the geodetic metrology laboratory, several consultations were held with the Estonian Ministry of Justice on legal analysis, with the FGI on practical arrangements, and with AS Metrosert (the provider of metrological services in Estonia). In 2023, we start with the development of corresponding methodologies and developing procedures for issuing the calibration certificates.

Table 2: Major changes in the Estonian geodetic system and national infrastructure in 2018–2022

Topic	Old model/version	New model/version
Height system	BK77	EH2000
	Kronstadt TG	Normaal Amsterdam
	Obsolete system	Peil, based on EVRF2017
Gravimetric system	GV-95	EG2000
	Based on absolute gravity measurements 1995	Based on absolute gravity measurements from 1995–2017
Geoid model	EST-GEOID2011	EST-GEOID2017
	Accuracy 1.3 cm	Accuracy 5 mm



Figure 12: Calibration line in Vääna; on the left, the map view; and on the right, the photo of aligned measurement pillars.

8 Concluding remarks

Geodetic advances in Estonia in recent years were reviewed and discussed. Table 2 gives an overview of the major changes in the Estonian geodetic system.

For the new Estonian height system EH2000, we have changed from the obsolete former height system BK77 to the new and well-defined EH2000. For the new gravimetric system, enhancements were made by incorporating additional absolute gravity measurements, this provided the opportunity to update the existing gravimetric system. As well, we have unified the epoch for both the height and the gravimetric system, which is now 2000.0. The change in height and gravimetric systems brought about the need to update the geoid model as well. The new EST-GEOID2017 model has an outstanding accuracy of 5 mm achieved due to the involvement of more precise levelling and gravimetric data. For the GNSS computations, we have a prolonged time span for computations, thus giving a more consistent time series and better monitoring options for the ESTPOS.

ELB, as the administrator and manager of the geodetic system, is continuing the implementation of future innovative geodetic technologies in Estonia. For instance, in the coming years, even more space geodesy methods, e.g., interferometric synthetic aperture radar, will be available to regular users. The introduction of dynamic reference systems is gaining momentum, which means that users shall be well-oriented in both international reference systems and the corresponding transformation algorithms. As the accuracy of various spatial applications increases, one of the most important issues will be the calibration of different geodetic instruments.

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