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Case Study: One Centimeter Precision Regional Quasi-geoid

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Abstract— an attempt has been made to develop the one centimeter precision regional quasi-geoid model for transformation of the ellipsoidal GNSS height, h, to the standard height, H. For this purpose the densification of the GNSS/levelling point regional network has been performed in Latvia. Differential GNSS processing strategy, IGS/EPN reference station network and Helmert transformation 7 parameter method used to reduce the daily results of Latvian continuously operating station network to the ETRS89 fixed epoch. The same Helmert transformation 7 parameters are applied for the corresponding date GNSS/levelling point ellipsoidal height reduction to the same fixed epoch in order to avoid the daily unresolved network deformations. The new geoid model based on LAS-2000,5 normal height system, ellipsoidal heights and global gravimetric models (EGG97 and EGM2008) was computed using DFHRS v 4.0 software.

Index Terms **ETRS89, EVRF2007, GNSS/levelling network densification, regional quasi-geoid.**

I. INTRODUCTION

The Latvian first order levelling was carried out in time span 2000 – 2011. The Latvian national levelling network had been aligned to the epoch 2000.5 [1], [17] due to the unification of the national levelling datum in Europe to the EVRF2007 datum. The new height system LAS-2000,5 had been enacted by Latvian authority Latvian Geospatial Information Agency (LGIA) as the European Vertical Reference System's EVRF2007 [3] realization in Latvia. The request to modify the national geoid model arisen as well and the new quasi-geoid model LV'14 had been developed by LGIA [18] which is used in industry now instead of previous geoid model LV98. The precision of the new quasi-geoid model LV'14 is estimated of about 3 centimeters. GNSS applied measuring and navigation technologies are crucial for all of the engineering processes and therefore the need for high quality quasi-geoid model is very important. One of the objectives of this article is to search a road for approaching to one centimeter quasi-geoid model design by improving the quality of GNSS/levelling fitting points.

The GNSS-based ellipsoidal height, h, refers to an ITRF-based datum definition (e.g. ETRS89 in Europe) with the GRS80 ellipsoid as reference surface, while the standard height, H, refers to a physically defined Height Reference Surface EVRF2007. Therefore, a transformation of the ellipsoidal GNSS height, h, to the standard height, H, is the objective.

II. DENSIFICATION OF THE GNSS/LEVELLING NETWORK FOR GEOID CONTROL

High precision homogeneous GNSS/levelling network is required in order to achieve the reliable geoid fitting, testing and control quality. The attempt to develop such a network has been performed at the Institute of Geodesy and Geoinformatics (GGI) for the development of new one centimeter precision geoid model which mainly aimed to be used for ground based GNSS normal height measurements. The GNSS careful static measurement 4 hour sessions were carried out in order to significantly densify the GNSS/levelling network for test area of Eastern part of Latvia. The measurements were performed at the 138 sites of the first order levelling network and at the 42 sites of the second order levelling network. Additionally, for 120 sites the measuring results were obtained from LGIA where the GNSS measurements were performed in time span 2010-2014 and the results in *LKS-92* system (Latvian realization of *ETRS89*) were computed.

III. OBSERVATION REDUCTION

According to the EUREF Resolution No.1 of EUREF Meeting 1990 the *ETRS89* is an official reference system in EU. Consequently, the international IGS/EPN reference network data should be applied for the computation of the ellipsoidal heights of GNSS/levelling points for the *EVRF2007* realization in epoch 2000. As mentioned above, this has to be done in national level. However, the Latvian levelling network data had been reduced to the epoch of 2000.5. [18]

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There are two continuously operating GNSS reference networks developed in Latvia in 2006: LatPos 24 station network which has been developed and operated by LGIA [22] and EUPOS®-Riga 5 station network which has been developed and operated by both Riga municipality and GGI. The *ETRS89* SINEX weekly solutions are regularly computed for both LatPos and EUPOS®-Riga networks by GGI and forwarded to EUPOS® Combination Centre [15], [16] for European intraplate deformation analysis. The daily obtained GNSS station results are used in GGI for the network control and deformation analysis [2], [5]. However, the *LKS-92* system coordinates fixed by LGIA are used for the cadaster and land surveying in national solutions. The national *LKS-92* system is the *ETRS89* realization in Latvia which has been updated by LGIA for LatPos network in year 2011.

Regional geoid or quasi-geoid models, broadcasted as RTCM-transformation messages [23], are an important component of GNSS-services like LatPos.

EUPOS®-Riga network is tied in LatPos defined *LKS-92* system for services in Latvia. GNSS observation reduction process of the transformation from *ITRF2008* of current epoch to *ETRS89* of current epoch is performed in GGI. However, GGI performed transformation does not take into account the internal velocities within European plate due to the lack of information on the LatPos and EUPOS®-Riga internal coordinate velocities. LatPos and EUPOS®-Riga network stations were installed just in year 2006. However, it is important to take into account the internal velocities of the European plate and the local network deformations to achieve high accuracy of the GNSS measured ellipsoidal heights. The information of the network local deformations [4], [8] is not available for period from 2000-2006.

Different authors have given mention of 2-3 cm accuracy for GNSS measured ellipsoidal heights [4], [8]. However, higher accuracy is requested for one cm geoid model [6].

IV. ATTEMPT TO ACHIEVE 1 CM PRECISION FOR ELLIPSOIDAL HEIGHTS

Daily computations were performed for the Latvian GNSS permanent network stations in IGS/EPN network using Differential GNSS processing strategy together with Precise Point Positioning. The Up component variations during year 2014 for all of the LatPos and EUPOS®-Riga stations are depicted in Fig. 1. The daily variations of the Up and Down from yearly average changes similarly for all of the stations. Bernese 5.0 software was used by computing in PPP mode. The GNSS receiver has been changed for the IGS/EPN station Riga whose Up variations are appeared on the bottom in Fig. 1.

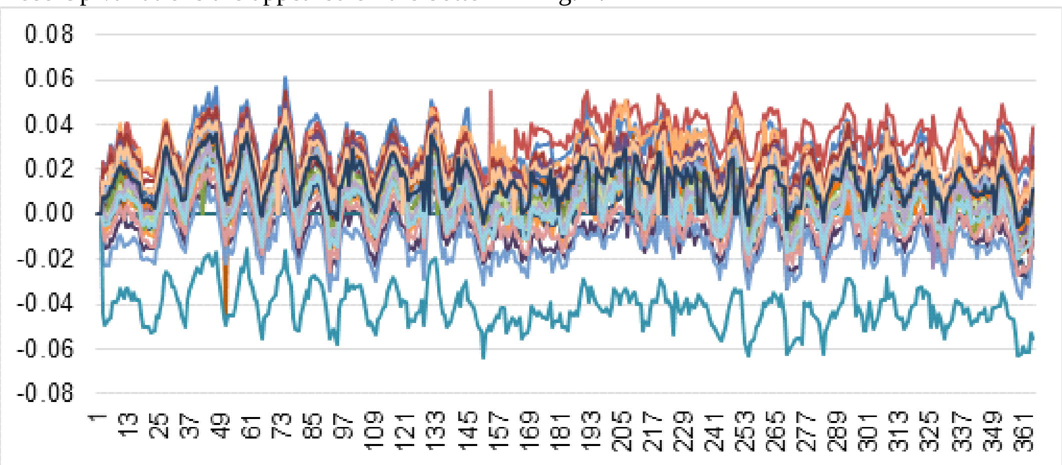

Fig. 1. LatPos and EUPOS®-Riga station daily Up variations (m)

ETRS89 in epoch of 2015.0 was computed for each station by applying the linear approximation of the corresponding coordinates of year 2014. In order to demonstrate the height variations in details in daily solutions the station ALUK (Fig. 2) and station LIMB (Fig. 3) height coordinate variations are shown.

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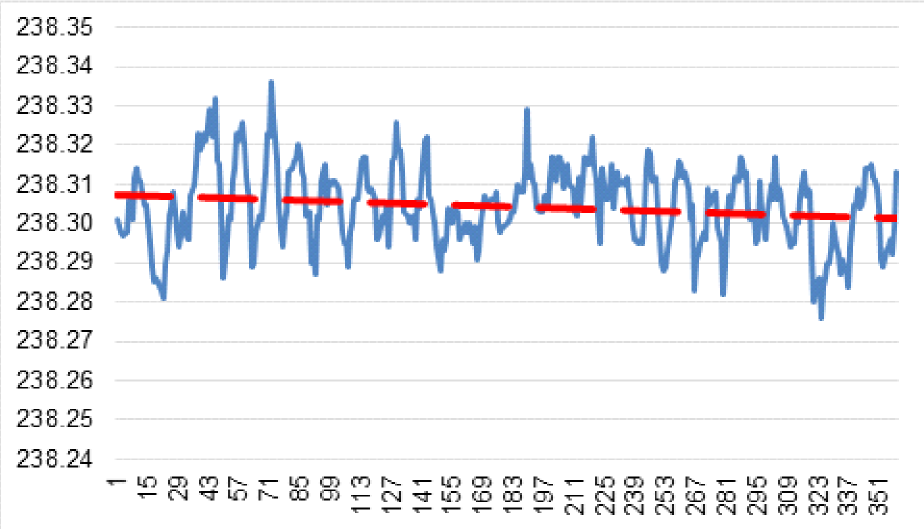

Fig. 2. LatPos network ALUK station daily height variations (m) and linear trend line in 2014

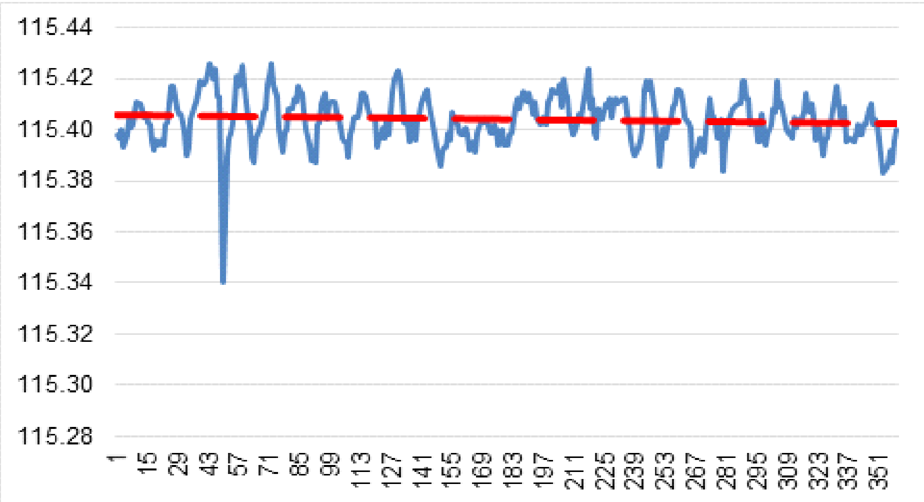

Fig. 3. LatPos network LIMB station daily (hor.) height variations (m) and linear trend line in 2014

The differences of the ellipsoidal heights between *ETRS89* in 2015.0 and *LKS-92* in 2011 are depicted in Fig. 4. After the analysis of 9 year time series of LatPos stations the conclusion of GGI is that the reference station *LKS-92* coordinates are outdated [2].

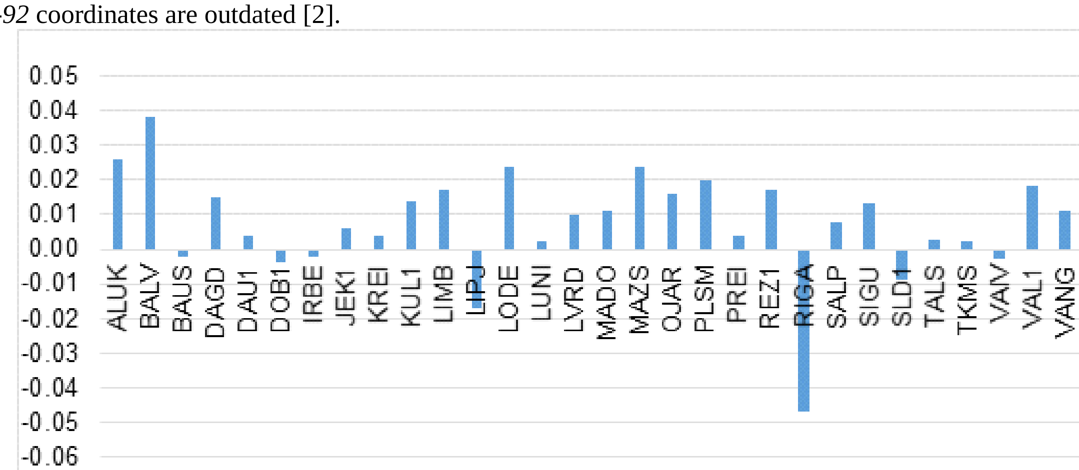

Fig. 4. LatPos and EUPOS®-Riga station ellipsoidal height differences (m) between ETRS89 and LKS-92

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Over the selected national network levelling points the GNSS applied ellipsoidal height careful static measuring sessions (Fig. 5) were performed by GGI staff in years 2014 and 2015.

Fig. 5. The practice of static GNSS ellipsoidal height measuring with fixed antenna height

The standard Benese 5.2 software and methods, recommended by EUREF were used to compute the *ITRF2008* coordinates to current date and then reduced to *ETRS89* framework. The IGS/EPN reference stations were used for the computation of the set of coordinates of GNSS/levelling point(s) and the set of all the 29 LatPos and EUPOS®-Riga stations. The height values of LatPos and EUPOS®-Riga stations were changing in various days within ± 12 mm (Fig. 6 and Fig. 7).

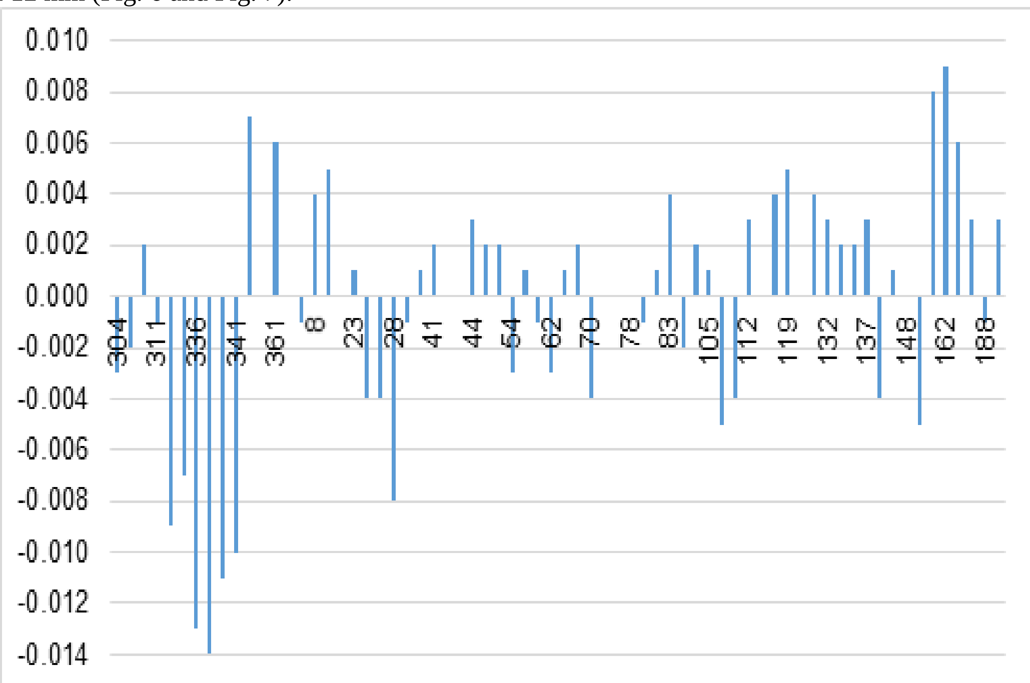

Fig. 6. ALUK station Up variations (m) for geoid control measurements in 2014 and 2015

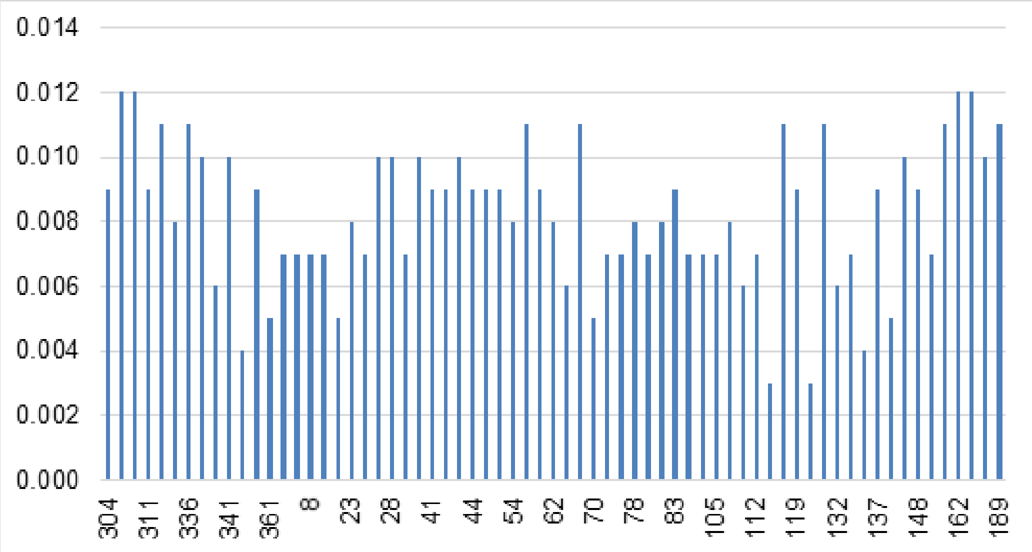

Fig. 7. LIMB station Up variations (m) for geoid control measurements in 2014 and 2015

The results are affected by the local conditions of ionosphere, troposphere, multipath and other eventually undiscovered deformations. Obviously, similarly were affected the ellipsoidal height values of GNSS/levelling points (Fig. 5) measured in corresponding days. The Up variations are depicted for station ALUK in Fig. 6 and for station LIMB in Fig. 7.

Assuming the height variation similarity like in Fig. 1 the LatPos and EUPOS®-Riga *ETRS89* to current day coordinates were used for the daily Helmert 7-parameter transformation model to reduce all in the corresponding day obtained coordinates to epoch 2015.0 (Formula (1)).
where,
X – translation along the X-axis,
Y – translation along the Y-axis,
Z – translation along the Z-axis,
R_X – rotation about the X-axis,
R_Y – rotation about the Y-axis,
R_Z – rotation about the Z-axis,
S – scale factor.

Typical transformation RMS for X, Y, Z are 0.5, 0.4, 0.8 (mm) correspondingly. These Helmert transformation 7 parameters are applied for the corresponding date GNSS/levelling point ellipsoidal height reduction to the same fixed epoch of 2015.0 in order to avoid the daily unresolved network deformations. Additionally, the data of 120 GNSS/levelling points from LGIA has been received. The LGIA performed computation of ellipsoidal heights of these points were based on LatPos network in system *LKS-92* of the epoch 2011. In order to achieve the homogeneity with a set of GGI measured points the Helmert transformation was applied to reduce the ellipsoidal heights of LGIA measured points to the *ETRS89* system to the epoch of 2015.0. The set of obtained GNSS/levelling points was used as fitting points for one centimeter precision geoid development.

V. GGI/DFHRS GEOID COMPUTATION

In order to compute one centimeter precision quasi-geoid model DFHRS (*Digital Finite element Height reference surface*) software v. 4.0 [7] was used, which was developed in Karlsruhe University of Applied Sciences (Germany). DFHRS concept is based on parameter modeling and height reference surface (HRS) computation using geometrical and physical components by hybrid adjustment approach [23]. A HRS is represented by the height N of the HRS above the reference ellipsoid. The main aim of DFHRS is the direct conversion of the ellipsoidal height h determined at the earth surface into the physical earth gravity field based standard "sea-level" height.

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In the concept of the FEM (Finite Element Method), the area is subdivided into a grid of FEM meshes. The HRS surface is approximated by local Taylor series within each mesh and derived at the center point of each mesh. Computation strategy is described in publication [13].

VI. GLOBAL GRAVIMETRIC MODELS

Global gravimetric geoid models, for example the EGG97 [14], comprise both geoid heights and the deflections of the vertical. Due to the genesis of the models, the determined anomalous gravity potential suffers from long-wave systematic errors that mainly result from two sources. Once, from datum inconsistencies in the original gravity observations and twice from the so-called "weak-forms". The weak forms are related to the maximum and some subsequent eigenvectors of the covariance-matrix as carrier functions and occur in extended networks [9], [13].

On the territory of Latvia EGM2008 [19], [20], [21] is based on gravimetric data from EGG97 geoid and digitized data by J.Kaminskis (approx. 12000 points) and approx. 200 new measured data within Danish-Baltic sector program in geodesy [10].

VII. DFHRS GEOID MODEL DESIGN

One mesh area is 5 x 5 km, total amount of meshes – 2304 (Fig.8). In order to reduce the effect of medium- or long-wave systematic shape deflections, the natural and stochastic "weak-shapes" in the geoid-height observations N_{grav} and vertical deflections (ξ,η) are obtained from geoid-model. These observations are subdivided into a number of patches [11]. Patch areas are different due to inhomogeneous point location (Fig. 8), but it must be at least 4 points per patch in order to determine system definition. Minimum patch area – 35 x 60 km, maximal patch area – 55 x 110 km. Total number of patches – 17. In order to reach 1 cm geoid 50 fitting-point density should be used in the area of 100 × 100 km and mesh size should be 5 × 5 km (Fig. 8.) [12].

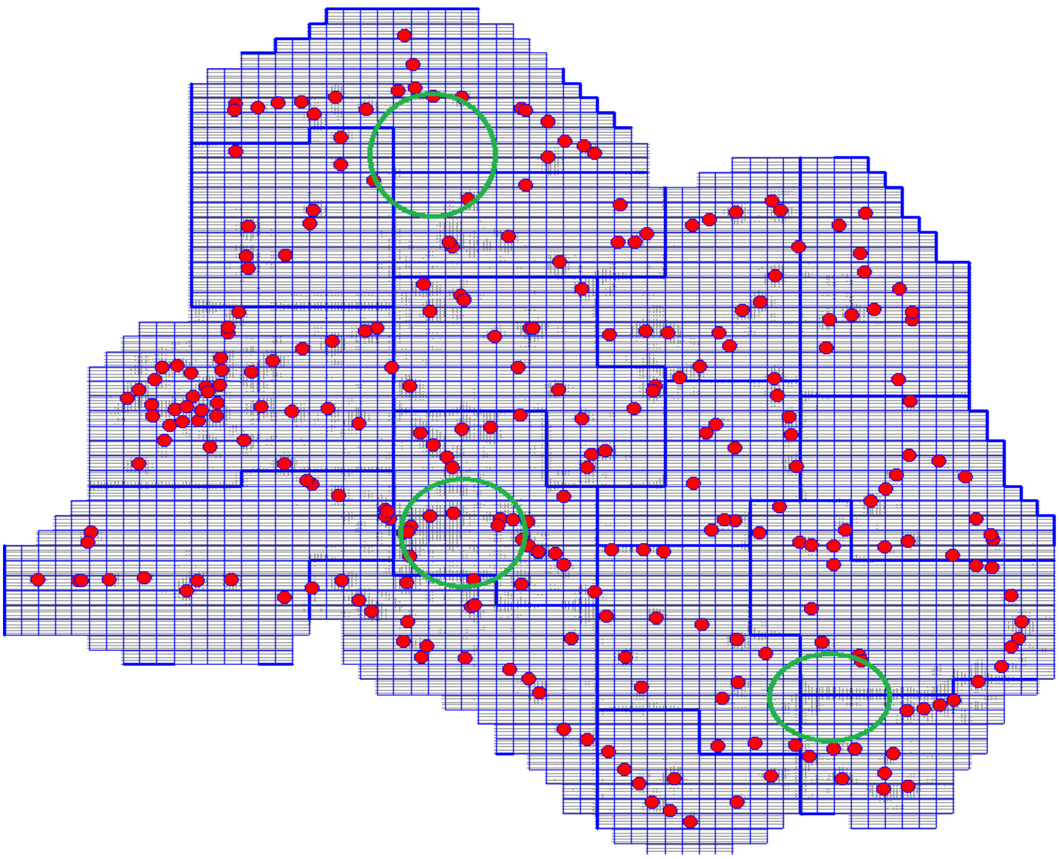

Fig. 8. Computation design for Eastern part of Latvia with a 5 km mesh-size. (thin blue lines), patches (thick blue lines), fitting points (B,L,h|H) (red circles), the most inconsistent places between EGG97 and EGM2008 (green ellipses)

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In order to compute geoid grid file DFHRS – tools was used. As input data latitude, longitude and approximate ellipsoidal heights are needed. Approximate ellipsoidal heights were computed using EGG97 or EGM2008 model geoid heights, correspondingly, and RIWI_TOPO_2012_plusGRS80 topographical model file from ICGEM Calculation service with a grid step of 0,025 degrees. (http://icgem.gfz-potsdam.de/ICGEM/). Two versions were computed - DFHRS/GGI/EGG97 and DFHRS/GGI/EGM2008. Obtained geoid is depicted in Fig. 9.

VIII. COMPUTATION RESULTS

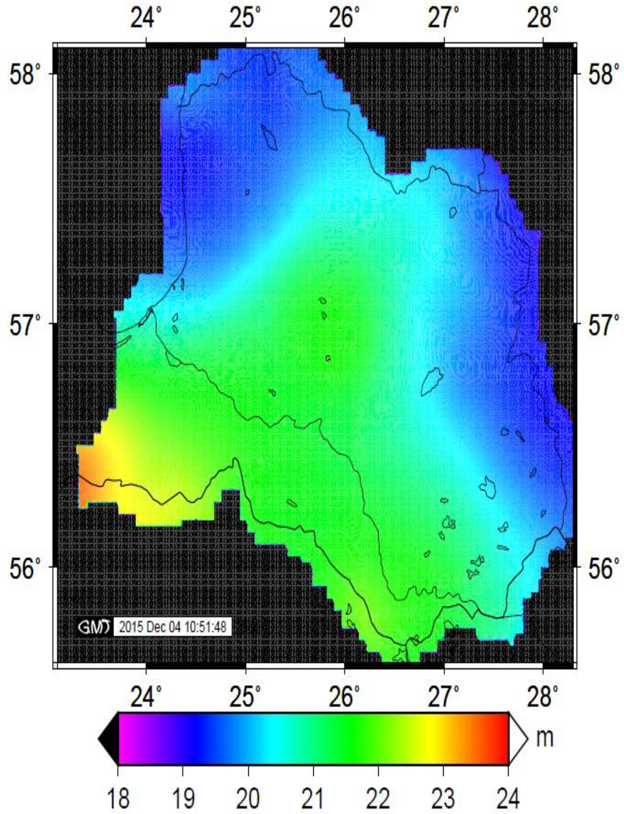

Fig. 9. DFHRS/GGI geoid

Fig. 10 shows normality plot and distribution of residuals from DFHRS report, where x axis shows the residuals in mm and y axis shows the amount of points. Analyzing DFHRS/GGI/EGG97 solution's residual distribution (Fig. 10) 112 points are under 0.004 m residuals, 283 points (from 300) or 94.7% are under 0.012 m, standard deviation – 0.009 m.

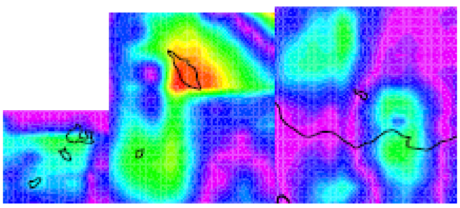

Fig. 10. The distribution histogram of the discrepancies of DFHRS/GGI/EGG97 (mm) and normality plot
Analyzing GGI/DFHRS/EGM2008 model the residuals (Fig. 11) for 120 points are in the interval of 0.004 m. Total amount of the points – 300. 284 points or 94.6% are under 0.016 m, 268 points or 89.3% are under 0.012 m. Standard deviation for GGI/DFHRS/EGM2008 – 0.01 m.

Fig. 11. The distribution histogram of the discrepancies of DFHRS/GGI/EGM2008 (mm) and normality plot

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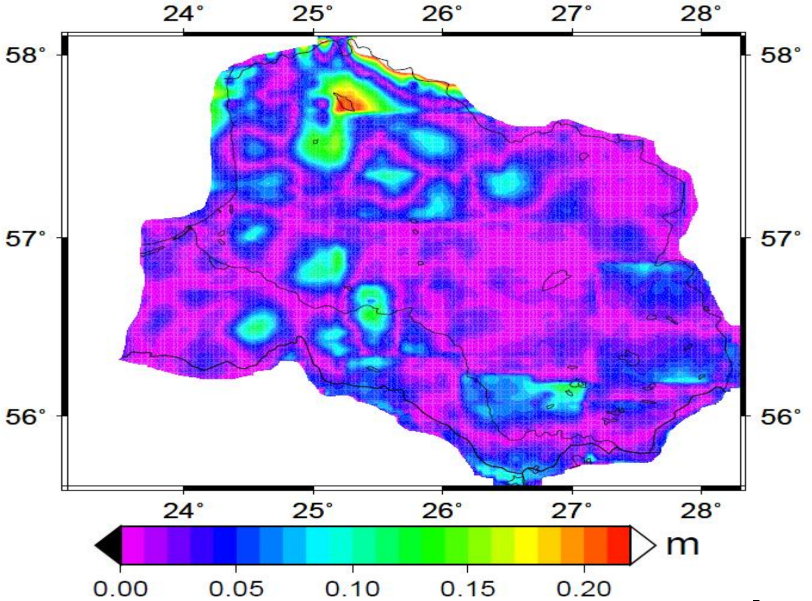

Fig. 12. Comparison of the solutions DFHRS/GGI/EGM2008 and DFHRS/GGI/EGG97

Analyzing the comparison of two computed geoids based on EGG97 and EGM2008 global gravimetric models, correspondingly, there are three places inconsist most (Fig. 12). One of them is the northen part of Latvia between Mazsalaca, Puikule and Valmiera towns (the Burtnieks lake), this inconsistence can be explained by the lack of the GNSS/levelling points in this region, and the solution could be continuation of the 1st order levelling from Valmiera to Mazsalaca, or the 2nd order levelling from Puikule to Valka.

Analyzing the second from left place of inconsistence near Koknese town (from both sides of the Daugava river), the possible explanation is unprecise EGG97 model in that place, because one point (point 1691) had inconsistence in report of DFHRS of about 17 cm, that is why ellipsoidal height for this point was determined twice and the difference between the results was 1 mm what means that ellipsoidal height for this point was determined correctly. Afterwards several points were addiotionally measured in this region, and than the difference for point 1691 in DFHRS report reached 8.4 cm, what significantly improved the difference between EGM2008 and EGG97 solutions. The third place of inconsistence is around Aglona town, the differences in geoid heights are approximately 10 cm.

For control the computed geoid models were also compared with geoid model LV’14 [17] developed by LGIA. Comparing DFHRS/GGI/EGM2008 solution results with LV’14 the most significant place of inconsistence is in the region of the Burtnieks lake (approx. 25 cm). However, the DFHRS/GGI/EGG97 solution’s comparison with LV’14 gives very small difference. It can be concluded that the problem is in global EGM2008 model because GNSS/levelling data for DFHRS/GGI/EGM2008 and DFHRS/GGI/EGG97 were the same. Comparing DFHRS/GGI/EGG97 with LV’14 the place differs most is in the region of Koknese, while comparing this place with DFHRS/GGI/EGM2008 and LV’14 the difference is just 1 cm, and it can be concluded that the problem is in Global EGG97 model as well.

These places should be checked with vertical deflections observed by digital-zenith camera which gives an independent estimation of geoid model determination [6]. This will be done as soon as new version of DFHRS with vertical deflections usage will be available in GGI.

IX. CONCLUSION

The daily variations in ellipsoidal height determination solutions have been taken into account for correction of the heights computed in the IGS/EPN framework. The LatPos and EUPOS®-Riga networks were used for Helmert transformation parameter determination to reduce the GNSS/levelling point ellipsoidal heights to fixed epoch in order to avoid the unresolved network deformations.

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The global gravity models EGG97 and EGM2008 correspondingly, and the set of 300 GNSS/levelling fitting points had been used for one centimeter geoid model determination.

The comparison of two solutins confirm the near one centimeter precision geoid model quality over 90% of test area of about 40,000 km^2.

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