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Multi-Epoch GNSS Campaigns of the National Geodetic Network in Estonia

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Abstract

The measurements of the EUREF (IAG Regional Reference Frame Sub-Commission for Europe) densification in Estonia were conducted in the summer of 1997. The network has since been remeasured twice (in 2008 and 2017), including also available national GNSS reference stations. In the present study all three campaigns have been recomputed and the results are expressed in the latest International Terrestrial Reference Frame ITRF2014 (ITRF, 2019). As a result, the coordinates of the Ist order geodetic points were specified. The RMS errors of the individual coordinate components with respect to the average of the three campaigns were 1.9 mm, 2.9 mm and 2.8 mm for north, east and up components, respectively. Also, the velocity estimates for the points were estimated and compared to corresponding regional velocity models. The discrepancies (in terms of standard deviation) with land uplift model NKG2005LU were in average 0.2 mm/year only. The resulting horizontal velocities however are subject to further research.

Keywords: Geodetic networks, GNSS, Bernese software, velocities, ESTPOS

1 Introduction

Estonia joined the EUREF (IAG Regional Reference Frame Sub-Commission for Europe) activities early in the 1990's. The EUREF-BAL92 GPS (Global Positioning System) campaign yielded class C accuracy (5 cm at the epoch of observations) for the first ETRS89 (European Terrestrial Reference System) realisation in the Baltic countries (EUREF, 1993). The campaign points in Estonia were remeasured in 1994 and systematic biases were found (Rüdja, 2004, pp 130). 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 network in 1995. The new GPS network is divided into Ist and IInd order. The Ist order network consists of 12 ground-buried markers and one GPS reference station (Suurupi), whereas the IInd order network consists of 199 ground-buried markers. The measurements of the new Ist order geodetic network were conducted in July 1997 (epoch 1997.56). A resolution of the EUREF Prague Symposium in 1999 (EUREF, 1999) approved the results (Rüdja, 1999) to correspond to the class B accuracy (1 cm at the epoch of observations).

The coordinates form the ETRS89 realisation in Estonia and are the basis of the national geodetic system EUREF-EST97.

The Ist order geodetic network points were remeasured in 2008 and 2017. These campaigns included new national GNSS (Global Navigation Satellite Systems) CORS (Continuously Operating Reference Stations). The aim of this was to rigorously connect the GNSS reference stations with the EUREF-EST97 (cf. *Metsar et al.*, 2018). All three campaigns (1997, 2008 and 2017) were conducted during the years of solar minimum, to minimize ionospheric refraction. The present study recomputes the three campaigns in the latest International Terrestrial Reference Frame solution ITRF2014. The national GNSS reference stations however (except the one belonging to the 1997 network) were excluded from the recomputations, as the main aim was to obtain consistent inter-campaign coordinates for the Ist order geodetic points. The resulting coordinates of the 1997 and 2017 campaigns served as a basis for velocity estimates for the Ist order geodetic points, which were then compared to some regional velocity models.

The outline of this contribution is as follows. The introduction is followed by a review of the three GNSS campaigns (1997, 2008, 2017), that included besides the Ist order geodetic network also the national GNSS CORS. The recomputation principles of all three campaigns are explained, the resulting velocity estimates are discussed. A brief summary concludes the paper.

2 The Ist order geodetic network and the principles of the remeasurement campaigns

The Estonian national Ist order geodetic network was established and measured in 1996–1997. The coordinates of the 12 ground-buried markers and one GPS permanent station (Suurupi) were determined with respect to 9 IGS (International GNSS Service) fiducial stations of neighbouring countries (Fig. 1).

Ashtech Z-12 GPS receivers and Choke Ring antennas were used for the measurements, whereas the observation session lengths varied from 72 (between Ist order points) to 216 hours (connections to the fiducial stations). The computations were made in the ITRF96 reference frame at the central epoch of the measurements (1997.56) with the Bernese GPS software 4.0. The corresponding IGS ephemerides referring to ITRF96 were also used. Final coordinates were transformed to ETRS89 (ETRF96) following the principles and transformation parameters in *Boucher and Altamimi* (1998). A resolution of the EUREF Prague Symposium in 1999 (*EUREF*, 1999) approved the results to correspond to the class B accuracy. The measurements and computations are described in detail in technical reports by *Rüdja et al.* (1998) and in *Rüdja* (2004).

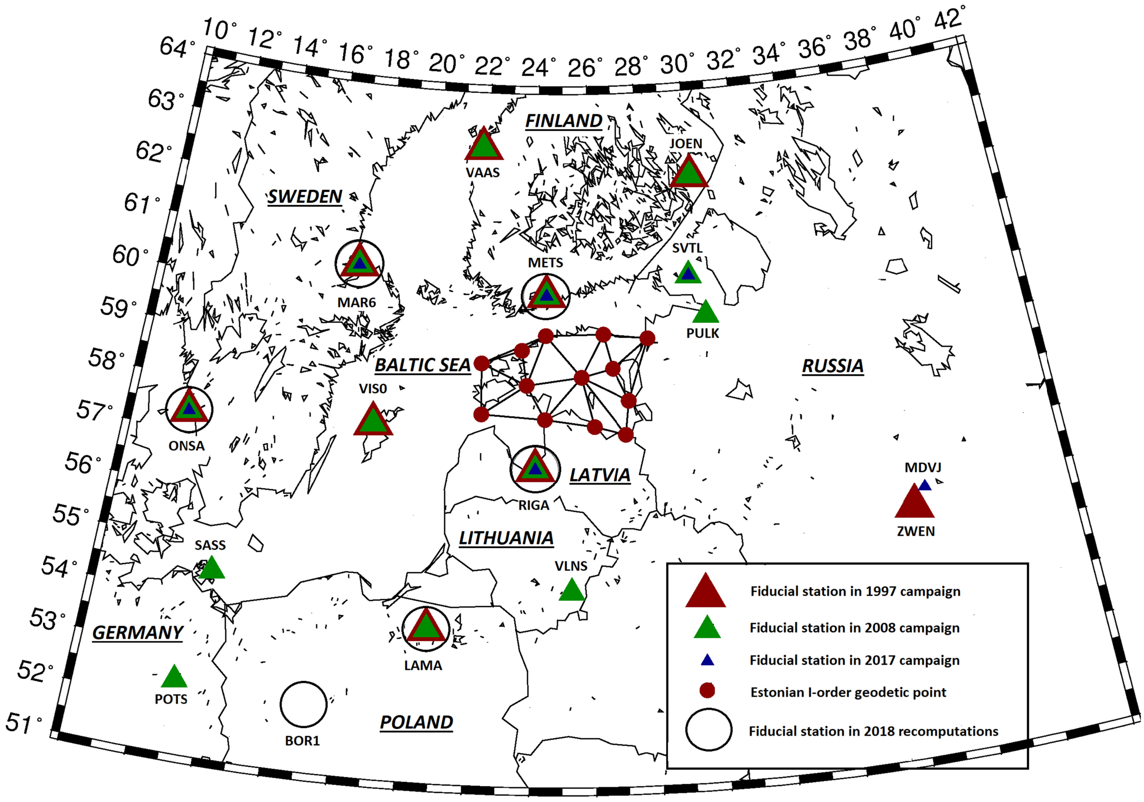

Fig. 1. Estonian national Ist order geodetic network, the internal baselines, the fiducial stations used in all three GNSS campaigns (1997, 2008 and 2017) and in recomputations of the present study.

The aims of the 2008 and 2017 remeasurement campaigns were – firstly to increase the reliability of ETRS89 realisation in Estonia, secondly, to determine the time dependant changes of ETRS89 in Estonia and thirdly, to connect the new national GNSS reference stations (ESTPOS) with the Estonian national geodetic network. ESTPOS consists of 28 GNSS stations with an average station separation of about 40-50 km, and it has been fully operational since 2015. An overview of ESTPOS and its development is given in *Metsar et al.* (2018). The remeasurements were conducted similarly (where possible) to the initial 1997 campaign, see comparative overview of the three campaigns in Table 1. The two first campaigns used the same type GPS receivers and antennas, whereas the last campaign was conducted with more modern GNSS equipment. Inter-comparisons of results (1997 vs. 2008, 2008 vs. 2017 and especially that of 1997 vs. 2017) did not reveal significant equipment dependent impact to the computed point velocities.

In the computations of the remeasurement campaigns precise orbit parameters (IGS – International GNSS Service or CODE – Center for Orbit Determination in Europe), ocean tidal loading model FES2004 (Finite Element Solution) and troposphere mapping functions VMF1 (Vienna Mapping Function) were used. The absolute antenna calibration parameters, satellite models and the quasi-ionosphere free (QIF) combination for solving ambiguities were applied. Inclusion of national ESTPOS stations to the computations in 2008 and 2017 yielded different computational scenarios – A and B. The overall computation process was however rather similar for both scenarios. According to scenario A only the Ist order point coordinates were computed, hence data from national GNSS CORS (except Suurupi) were excluded. The predefined internal baselines were selected as identical as possible to those used in 1997 (Fig. 1). In scenario B the coordinates for the ESTPOS stations (5 and 27, involved in the 2008 and 2017 re-measurement campaigns, respectively) were also computed in addition to the Ist order points. For the GNSS CORS computations the Bernese OBS-MAX strategy (*Dach et al*., 2015) was used for the baseline formulation and computation. Note that the OBS-MAX method in the Bernese software (*Dach et al*., 2015) selects all the baselines automatically, based on the amount of similar observations between stations.

Table 1. Comparative overview of the 1997, 2008 and 2017 campaigns and the initial computations. For the used abbreviations see the text.

Campaign	**1997**	**2008**		**2017**	
Mean epoch	1997.56	2008.59		2017.61	
Length of observations	72-216 hrs	110-158 hrs		84-175 hrs	
Receivers, satellites	Ashtech Z-12, GPS	Ashtech Z-12, GPS		Leica GRX1200 and GR25, GPS+GLONASS	
Antennas (mounted on tripods)	Ashtech Choke Ring (9 units)	Ashtech Choke Ring (12 units)		LEIAT504GG (5 units) and LEIAR25.R4 (2 units) Choke Ring	
Bernese version	4.0	5.0		5.2	
Reference frame	ITRF1996	ITRF2005		ITRF2014	
Orbits	IGS	IGS	CODE	CODE	
Antenna cut-off angle	10	10		3	
Computation scenario	A	A	B	A	B
Aim of computation scenario	Coordinates for Ist order points	Coordinates for Ist order points	Coordinates for GNSS CORS	Coordinates for Ist order points	Coordinates for GNSS CORS
Baseline selection method	Manual	Manual	OBS-MAX	Manual	OBS-MAX
Correlation strategy	Correct	Baseline	Correct	Baseline	Correct
Total number of stations/points in the network	22	18	30	19	44
Number of fiducial stations	9	5	13	6	5
Number of national GNSS CORS	1	1	5	1	27
Coordinates of fiducial stations taken from	ITRF catalogue	ITRF catalogue	EPN catalogue	EPN catalogue	
Formal RMS (Root Mean Square) of the results, mm	3.20	1.11	0.78	1.13	1.19

Final coordinates of scenario A Ist order points were transformed to ETRS89 (ETRF96 frame) following the principles and transformation parameters of *Altamimi* (2018). Final ETRS89 coordinates refer to the mean epoch of the measurements – 2008.59 and 2017.61. The resulting RMS error of the 7 parameter Helmert transformation from ETRS89 to EUREF-EST97 (ETRF96 at epoch 1997.56) was 4.5 mm and 3.0 mm for the 2008 and 2017 results, respectively. The scenario B final coordinates for the ESTPOS stations were computed using 6 parameter Helmert transformation (no scale) program in the Bernese software. The corresponding RMS errors for the transformations were 4.3 mm (2008) and 6.4 mm (2017). For more details of the 2008 and 2017 measurements and computations see *Kollo and Pihlak* (2008), *Kollo* (2010), *Metsar et al*. (2017) and *Metsar et al*. (2018).

3 Recomputation of the three campaigns in ITRF14 reference frame

In this study the 1997, 2008 and 2017 campaigns were recomputed in the latest ITRF2014 reference frame. The Bernese GNSS software 5.2 was used and the campaigns were computed with the OBS-MAX method and with manually selected (before computations) baselines. The coordinates were only computed for the Ist order geodetic points, i.e. no national CORS data were used. The overall computation process, involved models and used settings were similar to the scenario A (see Sec. 1).

The baselines between Ist order points were selected as identical as possible to those which were used in 1997. In the computations only signals from GPS satellites were used to obtain more homogeneous results. In the recomputations precise orbits for 1997 and 2008 campaigns were in IGb08 (they were transformed to ITRF2014) and for 2017 in ITRF2014 frame. For the recomputations 6 fiducial stations (cf. Fig. 1) were selected. The coordinates for the fiducial stations were retrieved from EPN (EUREF Permanent GNSS Network) cumulative solution C1965 (*EPN*, 2018). The coordinates for all the campaigns were computed at the mean epoch of the measurements, i.e. 1997.56, 2008.59 and 2017.61. The final results were presented in ETRF89 and the transformation calculator in EPN web-page (*EPN*, 2018) was used. The aim of the recomputations was to estimate the coordinates of the Ist order geodetic points in a unified reference frame to obtain a more trustworthy assessment on the possible deformation of the initial 1997 geodetic reference frame. The formal RMS values of the recomputations are all rather similar, about 1 mm in average. The difference of RMS in OBS-MAX and manual baseline scenarios was found to be statistically insignificant. Due to the limited number of sites/stations in the network of the recomputations (19) no definitive conclusions can be made whether using the OBS-MAX method had any advantage over manual baseline selection. The differences of the EUREF-EST97 local coordinates between the three campaigns and the average of the three campaigns are mostly below 5 mm (Fig. 2). This shows the stability of the Ist order geodetic points (for their construction details see *Rüdja*, 1999) is satisfactory and their locations were selected appropriately. The RMS errors of individual coordinate components with respect to the average of the three campaigns were 1.9 mm, 2.9 mm and 2.8 mm for north, east and up components, respectively.

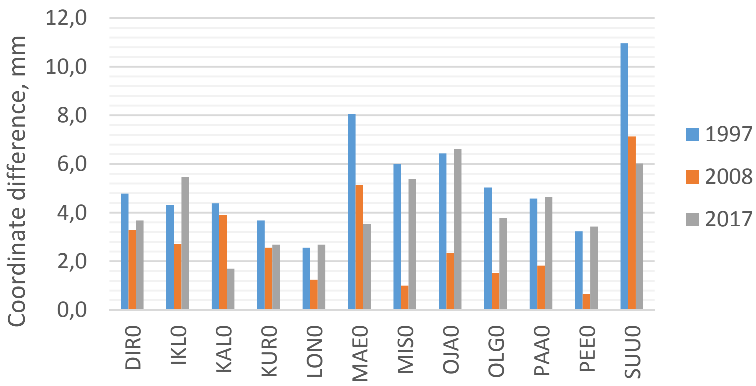

Fig. 2. The differences of the EUREF-EST97 (ETRF89 at epoch 1997.56) coordinates between the three recomputed campaigns with respect to their average. Length of the three dimensional vector are depicted. For the station locations see Fig. 3.

4 Velocities of the Ist order geodetic points

The results of the recomputed 1997, 2008 and 2017 campaigns in ITRF2014 were used for estimating horizontal and vertical velocities for the 12 Ist order geodetic points. Suurupi GNSS reference station was excluded here because its antennae position has changed multiple times over the years, yielding unreasonable jumps in time series of this particular site. Three sets of velocity estimates were computed: two for sequential campaigns (1997–2008 and 2008–2017) and one using the first and last campaign (1997–2017). The three sets of velocities were compared to their average values and it was found that they are all rather similar. Average formal uncertainty values based on the comparison of the three sets of velocities are 0.10, 0.13 and 0.15 mm/year for the E, N and U components respectively. Due to the longer time span the 1997–2017 results were chosen for further analysis.

Note that the Eurasian plate movement was removed from the horizontal velocity values with the ITRF2014 plate motion model (*Altamimi et al.*, 2016). The resulting horizontal intraplate velocities are depicted in Fig. 3. Note that points in the western part of Estonia appear to move southwards, whereas the eastern part points move predominantly toward north-easterly directions. This might be an artefact of the applied motion model, however, this could also be an evidence of more complex motions at the periphery of the Fennoscandian land uplift region. Nevertheless similar behaviour has earlier been identified also by *Oja et al.* (2014) and a quick overview of ESTPOS GNSS station data (not reported here due to space limitations) also confirmed it. This phenomenon needs further investigation, probably not only from geodetic point of view, but considering as well other disciplines, such as geophysics and geology. However, in most of the cases the estimated horizontal velocity is around 1 mm/year. Hence longer observation time span may be needed for more definite strain estimates.

The resulting vertical velocities agree well with existing regional land uplift models. The vertical velocities were compared to the NKG2005LU_abs (*Ågren and Svensson*, 2007) and NKG2016LU_abs (*Vestøl et al.*, 2016) models, see Table 2 for details. The uplift in Estonia varies from 3 mm/yr in northern-western part of Estonia to 1 mm/yr in southern-eastern part of Estonia. The results for vertical movement also fit rather well with the independent land uplift values for Estonia (*Oja et al.*, 2014).

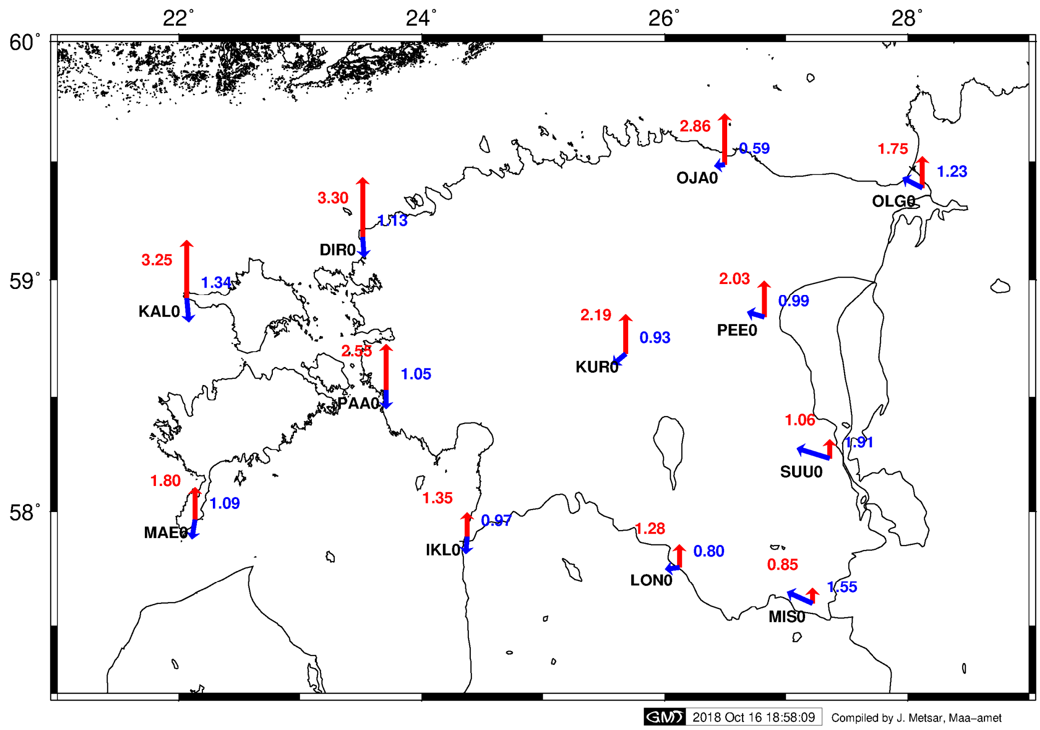

Fig. 3. Horizontal (blue arrows) and vertical (red arrows) intraplate velocity estimates of Ist order geodetic points, calculated on the basis of the recomputed 1997 and 2017 campaigns. Units in mm/year.

Table 2. Comparison of vertical velocities of the I-order geodetic points and the NKG LU models (mm/year).

Point	RECOMP	NKG2005_LU	NKG2016_LU	RECOMP-NKG05	RECOMP-NKG16
DIR0	3,30	3,16	3,41	0,14	-0,11
IKL0	1,35	1,53	1,57	-0,18	-0,23
KAL0	3,25	3,29	3,82	-0,04	-0,56
KUR0	2,19	1,97	2,00	0,22	0,19
LON0	1,28	1,09	0,98	0,19	0,30
MAE0	1,80	2,08	2,34	-0,28	-0,54
MIS0	0,85	0,81	0,53	0,04	0,32
OJA0	2,86	2,50	2,66	0,36	0,20
OLG0	1,75	1,87	1,87	-0,13	-0,13
PAA0	2,55	2,32	2,39	0,23	0,15
PEE0	2,03	1,81	1,87	0,22	0,16
SUU0	1,06	1,21	0,99	-0,15	0,07

min	-0,28	-0,56
max	0,36	0,32
avg	0,05	-0,01
std (standard deviation)	0,19	0,29

The average difference between the results of the recomputations and the NKG LU models is nearly zero – only 0.05 mm/year for the NKG2005 model and 0.01 mm/year for the NKG2016 model. Although the average is just 0.01 mm/year for the NKG2016 model, it still has rather large discrepancies for the two westernmost sites KAL0 (0.56 mm/year) and MAE0 (0.54 mm/year). Overall the results seem to fit a bit better with the NKG2005 model (*Ågren*, 2009), which also has a better standard deviation – 0.19 mm/year.

5 Conclusions

The study results look promising and show rather similar formal uncertainties for all the campaigns. The differences of the EUREF-EST97 coordinates between the three campaigns and the average of the three campaigns are also rather small, mostly below 5 mm. The formal RMS errors of the 2017 remeasurement campaign appears to be in the same magnitude as are the results of the recomputations (Table 1). It may be concluded that the coordinates of Estonian national Ist order geodetic points and GNSS reference stations (ESTPOS) computed in the latest (2017) campaign are accurate and trustworthy. The RMS errors of individual coordinate components with respect to the average of the three campaigns were 1.9 mm, 2.9 mm and 2.8 mm for north, east and up components, respectively. The velocities calculated on the basis of the recomputations however give subject for further research, especially the values of the horizontal velocities. The results show different trends and the horizontal deformations in Estonia need a more detailed investigation. The vertical velocity values however fit rather well with the NKG land uplift models, with standard deviation being 0.19 mm/yr and 0.29 mm/yr for models NKG2005LU and NKG2016 LU respectively.

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