Earth’s Surface Displacements from the GPS Time Series

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Abstract. The GPS observations of both Latvian permanent GNSS networks – EUPOS®-Riga and LatPos, have been collected for a period of 8 years – from 2007 to 2014. Local surface displacements have been derived from the obtained coordinate time series eliminating different impact sources. The Bernese software is used for data processing. The EUREF Permanent Network (EPN) stations in the surroundings of Latvia are selected as fiducial stations. The results have shown a positive tendency of vertical displacements in the western part of Latvia – station heights are increasing, and negative velocities are observed in the central and eastern parts. Station vertical velocities are ranging in diapason of 4 mm/year. In the case of horizontal displacements, site velocities are up to 1 mm/year and mostly oriented to the south. The comparison of the obtained results with data from the deformation model NKG_RF03vel has been made. Additionally, the purpose of this study is to analyse GPS time series obtained using two different data processing strategies: Precise Point Positioning (PPP) and estimation of station coordinates relatively to the positions of fiducial stations also known as Differential GNSS.

1. Introduction
The vertical and horizontal displacements of the Earth’s surface can be measured to a high degree of precision using Global Navigation Satellite Systems (GNSS). In Latvia two permanent GNSS networks – LatPos and EUPOS®-Riga, are operating providing continuous observations. Time series of GNSS station positions from both networks are developed at the Institute of Geodesy and Geoinformatics of the University of Latvia (LU GGI) applying scientific post-processing software package.

Local surface displacements obtained from the Latvian GNSS station position time series are under discussion in this study. As Latvia is located in the region, which is under the effect of the ongoing...
relaxation of the Earth in response to past ice mass loss, the comparison of the obtained results with the data from the deformation model NKG_RF03vel is presented.

Additionally, the purpose of this study is to analyse GPS time series obtained using two different data processing strategies: PPP and DGNSS, as well as to compare site velocities obtained with these approaches.

2. Participation in EUPOS® ECC

The EUPOS® initiative is an international expert group of public organisations coming from the field of geodesy, geodetic survey and cadastre. Partners from Central and Eastern Europe work on the provision of compatible spatial reference infrastructures by using the Global Navigation Satellite Systems GPS, GLONASS and as soon as it is available GALILEO by operating Differential GNSS EUPOS® reference station services [1].

In order to further strengthen the national EUPOS®/ETRS89 realizations and ensure the homogeneity of the national EUPOS® services, the FÖMI Satellite Geodetic Observatory (SGO) proposed the idea to establish the EUPOS® Combination Centre (ECC) at the EUPOS® Conference 2010. The main task of the ECC is the combination of the weekly national EUPOS® SINEX solutions into a single weekly EUPOS® solution. This activity is analogous to the EPN data analysis and combination approach, and the EUPOS® combined solution may be regarded as the densification of the EPN, namely, further densification of the actual ETRS89 realization. The EPN analysis standards should also be followed, therefore ECC can only handle SINEX solutions computed by a scientific post-processing software package. The detailed description of the analysis guidelines can be found in [2].

The Institute of Geodesy and Geoinformatics calculates and submits to ECC the Latvian SINEX solutions regularly. Currently ECC activities are very successful and the study area covers almost the entire Europe [3]. The result of ECC activities is depicted in figure 1.

![Figure 1](image_url)  
*Figure 1. GNSS station observation availability for the EUPOS® combined solution shown with time intervals (status in April 2015).*
3. Latvian GNSS stations
Within the framework of EUPOS® regional development project, two GNSS permanent station networks have been developed in Latvia – LatPos [4] and EUPOS®-Riga [5], which have been operating since 2006.

At present time LatPos network includes 24 permanent stations as shown in figure 2. Some of the initial stations have been renamed and removed within relatively small areas during whole period of operation, thus causing discontinuities in site position time series.

EUPOS®-Riga network consists of 5 stations, which are located in Riga and its surroundings. This network was modified once in 2012, when two stations were carried to Riga surroundings. EUPOS®-Riga stations are shown in figure 3. Location of station RIGA from IGS and EPN networks is shown as well.

![Figure 2. Actual LatPos network with 24 continuously operating GPS/GNSS stations.](image1)

![Figure 3. EUPOS®-Riga and IGS/EPN station RIGA.](image2)

EUPOS®-Riga and LatPos networks are primarily geodetic reference networks established for surveying and navigation purposes in the territory of Latvia. But according to the worldwide experience and trends in space geodesy it is commonly accepted to use GNSS stations for studies of geophysical processes. The vertical and horizontal displacements of the Earth’s surface can be measured to a high degree of precision using GNSS.

3.1. Network solution and data processing
Time series of GNSS station positions of both EUPOS®-Riga and LatPos networks have been computed by Bernese GPS software version 5.0 developed at the University of Bern, Switzerland [6]. Station coordinates have been obtained for 8-year long observation period – from 2007 to 2014.

IGS precise orbits, Earth orientation and clock products from International GNSS Service (IGS) data base with CODE final ionosphere product are used. The data are corrected due to solid Earth tide and ocean tide loading effect by the online loading provider by H-G Scherneck. Using Differential GNSS processing strategy together with Precise Point Positioning approach applied for initial coordinate determination, site coordinates were computed in IGS05/08 frames, i.e. in IGS08 since GPS week 1632 – introduction of the new IGS08 frame [7]. Used reference stations are from EPN (some of them belong to IGS network) in the surroundings of Latvia.
The obtained daily solutions of Latvian GNSS station positions are composed to weekly SINEX solutions and are submitted to ECC for further combination into a single weekly EUPOS® solution. For example, figure 4 shows LUNI station position time series in North, East and Up components from the EUPOS® cumulative solution.

3.2. Results and discussion

Final velocity components derived from the minimum constrained cumulative solution till GPS week 1830 and expressed in the ETRF2000 frame are given in table 1. Bold font in column “Station name” of table 1 is used to mark operating GNSS stations, which are shown in figures 2 and 3.

Velocity fields are depicted in figures 5 and 6. Figure 5 shows station vertical movements, and figure 6 represents horizontal movements.

The obtained results have shown a positive tendency of vertical displacements in the western part of Latvia – station heights are increasing, and negative velocities are observed in the central and eastern parts. Station vertical velocities are ranging from -3.3 to +0.5 mm/year. This data range could be considerably reduced eliminating vertical velocities of four stations, which exceed -1.9 mm/year. As can be seen in figure 5, these velocities stand out against the background of velocity field. This could be caused by site-specific displacements. After outstanding data elimination, the resulting range of vertical velocities for the territory of Latvia is 2 mm/year; it is from -1.5 to +0.5 mm/year. In the case of horizontal movements, site velocities are ranging from 0.2 to 1.0 mm/year, excluding three stations, and oriented to the south.

Figure 4. North, East and Up components of LUNI station position from the EUPOS® cumulative weekly solution.
Figure 5. Cumulative vertical movements from EUPOS® observation set (status in April 2015).

Figure 6. Cumulative horizontal movements from EUPOS® observation set (status in April 2015).
Table 1. Latvian GNSS station velocities in North, East and Up components from the minimum constrained cumulative solution till GPS week 1830 expressed in the ETRF2000 frame and velocities from the deformation model NKG_RF03vel. Positive values of horizontal displacement are obtained using North and East component values. Additional marks: station name in bold - operating GNSS station, values in bold – maximum and minimum values for Up component’s velocities, underlined values – excluded values from final data ranges.

| Network | ECC cumulative solution, released on 4 April 2015 by the EPN RF coordinator, mm/year | Deformation model NKG_RF03vel, mm/year |
|----------|-----------------------------------------------------------------|----------------------------------|
|          | GNSS station name | North | East | Horizontal | Up | North | East | Horizontal | Up |
| LatPos   |                    |       |      |            |    |       |      |            |    |
| AIZK     |                    | -0.22 | 0.04 | 0.2        | -1.54 | -0.47 | -0.01 | 0.5        | 0.48 |
| ALUK     |                    | -0.12 | -0.17 | 0.2     | -2.86 | -0.57 | 0.07  | 0.6        | 0.73 |
| BALV     |                    | -0.81 | 0.29 | 0.9       | -0.56 | -0.52 | 0.03  | 0.5        | 0.54 |
| BAUS     |                    | -0.33 | -0.09 | 0.3     | -0.93 | -0.46 | -0.02 | 0.5        | 0.49 |
| DAGD     |                    | -0.45 | -0.05 | 0.5     | -1.18 | -0.37 | -0.10 | 0.4        | 0.04 |
| DAUI     |                    | -0.40 | -0.16 | 0.4     | -0.90 | -0.34 | -0.12 | 0.4        | 0.04 |
| DOBI     |                    | -0.30 | -0.10 | 0.3     | -0.33 | -0.52 | 0.02  | 0.5        | 0.73 |
| GULB     |                    | -0.57 | -0.03 | 0.6     | -1.46 | -0.54 | 0.04  | 0.5        | 0.62 |
| IRBE     |                    | -0.49 | -0.28 | 0.6     | 0.50  | -0.73 | 0.15  | 0.7        | 1.72 |
| JEK1     |                    | -0.65 | -0.34 | 0.7     | -1.07 | -0.45 | -0.03 | 0.5        | 0.37 |
| KUL1     |                    | -1.02 | -0.24 | 1.0     | 0.00  | -0.62 | 0.07  | 0.6        | 1.18 |
| LIMB     |                    | -0.52 | 0.38  | 0.6     | -0.05 | -0.64 | 0.12  | 0.7        | 1.14 |
| LIE1     |                    | -0.41 | -0.16 | 0.4     | 0.48  | -0.54 | -0.01 | 0.5        | 0.99 |
| LODE     |                    | 0.10  | -0.98 | 1.0     | 0.30  | -0.56 | 0.06  | 0.6        | 0.74 |
| LVRD     |                    | -0.60 | -0.06 | 0.6     | 0.52  | -0.51 | 0.01  | 0.5        | 0.62 |
| MADO     |                    | -0.66 | -0.15 | 0.7     | -1.19 | -0.50 | 0.01  | 0.5        | 0.51 |
| MAZS     |                    | -2.38 | 0.11  | 2.4     | -0.90 | -0.69 | 0.17  | 0.7        | 1.37 |
| OJAR     |                    | -0.88 | -1.14 | 1.4     | -0.90 | -0.56 | 0.05  | 0.6        | 0.81 |
| PLSM     |                    | -0.82 | 0.29  | 0.9     | -0.59 | -0.59 | 0.08  | 0.6        | 0.83 |
| PREI     |                    | -0.28 | -0.55 | 0.6     | -1.22 | -0.40 | -0.07 | 0.4        | 0.19 |
| REZI     |                    | -0.51 | -0.41 | 0.7     | -2.07 | -0.43 | -0.05 | 0.4        | 0.24 |
| SIGU     |                    | -0.50 | 0.02  | 0.5     | -0.79 | -0.58 | 0.07  | 0.6        | 0.85 |
| SLD1     |                    | -0.43 | -0.21 | 0.5     | -0.77 | -0.54 | 0.02  | 0.5        | 0.86 |
| TALS     |                    | -0.63 | -0.10 | 0.6     | 0.18  | -0.65 | 0.10  | 0.7        | 1.29 |
| TKMS     |                    | -0.20 | -0.18 | 0.3     | -0.18 | -0.59 | 0.07  | 0.6        | 0.97 |
| VAL1     |                    | -0.74 | -0.23 | 0.8     | -0.82 | -0.63 | 0.11  | 0.6        | 1.04 |
| VENT     |                    | -0.60 | -0.17 | 0.6     | -0.75 | -0.70 | 0.12  | 0.7        | 1.62 |
| EUPOS-Riga |                      |       |      |            |    |       |      |            |    |
| ANNI     |                    | -1.13 | 0.10  | 1.1       | -1.90 | -0.56 | 0.05  | 0.6        | 0.83 |
| KREI     |                    | -0.42 | -0.09 | 0.4       | -0.97 | -0.58 | 0.06  | 0.6        | 0.88 |
| LUNI     |                    | -0.63 | 0.17  | 0.7       | -0.68 | -0.56 | 0.05  | 0.6        | 0.82 |
| MASK     |                    | -0.35 | -0.46 | 0.6       | -1.09 | -0.55 | 0.04  | 0.6        | 0.78 |
| SALP     |                    | -0.65 | -0.29 | 0.7       | -3.29 | -0.54 | 0.03  | 0.5        | 0.73 |
| VAIV     |                    | -0.38 | 0.31  | 0.5       | -1.52 | -0.57 | 0.06  | 0.6        | 0.89 |
| VANG     |                    | -0.24 | 0.13  | 0.3       | -1.06 | -0.56 | 0.06  | 0.6        | 0.83 |
| RIGA     |                    | -0.43 | -0.18 | 0.5       | -0.11 | -0.56 | 0.05  | 0.6        | 0.83 |
The present deformations due to the ongoing relaxation of the Earth in response to past ice mass loss – Glacial Isostatic Adjustment (GIA), have the rates ~10 mm/year in the vertical direction in the northern Scandinavia [8]. In the horizontal direction the displacements are smaller, about 0-2 mm/year [9]. In Latvia, the postglacial rebound is relatively small.

The velocity field from the GIA model (presented in [9]) is transformed to the GPS-derived velocity field [10], thus, the horizontal velocity field describes horizontal displacements relative to stable Eurasia as defined by the ITRS2000 and its rotation pole for Eurasia [11]. North and East components from this field are given in table 1. According to it, horizontal velocities of the Latvian GNSS stations range from 0.4 to 0.7 mm/year with the orientation to the south.

In the case of vertical displacements, according to model NKG2005LU(ABS) [12], maximum is about +1.7 mm/year, and minimum – close to 0 mm/year.

As obtained velocity fields (for horizontal and vertical displacements) derived from GPS observations and velocity fields from the Glacial Isostatic Adjustment (GIA) model are expressed in different reference frames, only the ratio of velocity ranges is given: for the horizontal displacement it is 2.7 (0.8/0.3), and for the vertical displacement – 1.2 (2.0/1.7).

4. Site velocities from PPP and DGNSS solution

The Bernese software estimates station coordinates relative to coordinates of a known station. This processing strategy is known as Differential GNSS, since it is the coordinate difference or the baseline between the two stations which is processed. The purpose of processing the baseline between two stations is that some of the errors can be reduced or eliminated.

Bernese software also contains processing strategy called Precise Point Positioning, which is able to give single station coordinates. PPP is very effective because coordinates for every station are processed individually. Hence, the coordinates do not depend on any reference station [13].

The Bernese software version 5.2 was used to process GPS data from the Latvian GNSS stations (table 2) applying two mentioned approaches. Station daily coordinates were computed in IGS08 (ITRF08) frame with respect to the EPN stations, as well as without referencing, and then have been transformed to ETRF2000 according to [14].

Residual position time series in Up component for the year 2014 are depicted in figures 7 and 8 representing three station data from EUPOS®-Riga, LatPos and IGS/EPN networks. Figure 7 shows time series of the Up component obtained from the PPP solution, and figure 8 – from the DGNSS solution.

In the case of DGNSS solution, Up components which are out of the diapason of ±15 mm were eliminated. Corresponding day coordinates were used for PPP solution; in this case coordinates which are in range of ±30 mm are used for linear trend determination (plot scale has not been changed for the better representation of data quality). Outstanding values could be observed from the PPP solution mainly during the winter time. Applying DGNSS approach, amplitude of station Up components essentially decreases, but also mentioned outliers could be seen. The winter time usually correlates with snow coverage of some GNSS antennae [15].
Figure 7. Up component and its trend of EUPOS\textsuperscript{®}-Riga station (upper), LatPos station (middle) and IGS/EPN station RIGA (bottom) obtained from the PPP solution.

Figure 8. Up component and its trend of EUPOS\textsuperscript{®}-Riga station (upper), LatPos station (middle) and IGS/EPN station RIGA (bottom) from the Differential GNSS solution.

Site velocities obtained from these time series and their differences are summarized for 24 Latvian GNSS stations in table 2. About one-third of all stations have the same velocities or velocities which more or less coincide between DGNSS and PPP solution. Half of all stations have velocity differences which are close to 1 mm/year. The maximum difference between site velocities obtained with two different processing approaches is 1.7 mm/year.
Table 2. Latvian GNSS station position velocities (mm/year) in the Up component obtained using two GPS data processing approaches, and velocity differences. Only observations of the year 2014 are used.

| Station name | BAUS | BALV | DAGD | DAU1 | DOB1 | IRBE | JEK1 | KUL1 | LIMB | LIPJ | LODE | LUNI |
|--------------|------|------|------|------|------|------|------|------|------|------|------|------|
| DGNSS        | -0.2 | -1.2 | +1.9 | -4.2 | -0.8 | -1.6 | -0.3 | -1.8 | +3.7 | -0.7 | -0.4 | -1.0 |
| PPP          | +0.7 | -2.1 | +3.1 | -3.0 | -0.5 | -0.6 | +0.9 | -1.9 | +4.9 | -0.4 | -1.4 | -0.1 |
| Diff.        | 0.9  | -0.9 | 1.2  | 1.2  | 0.3  | 1.0  | 1.2  | 0.1  | 0.3  | 0.6  | 0.4  | 1.0  |

| Station name | LVRD | MADO | MAZS | OJAR | PLSM | PREI | SIGU | SLD1 | TALS | TKMS | VAL1 | RIGA |
|--------------|------|------|------|------|------|------|------|------|------|------|------|------|
| DGNSS        | -1.0 | -0.8 | +0.5 | -1.4 | -0.8 | +0.2 | +0.4 | -2.3 | -0.1 | -0.4 | +1.4 | -2.0 |
| PPP          | -2.3 | -0.5 | -0.2 | -2.7 | +0.9 | 0.0  | +0.4 | -2.3 | -0.7 | +0.5 | +1.2 | -1.6 |
| Diff.        | -1.3 | 0.3  | -0.7 | -1.3 | 1.7  | -0.2 | 0.0  | 0.0  | 0.6  | 0.9  | -0.2 | 0.4  |

5. Conclusions
EUPOS®-Riga and LatPos station displacements obtained from continuous GPS observations have been summarized for the period of 8 years – from 2007 to 2014. The range of station velocities in vertical direction (after outlier elimination) for the territory of Latvia is 2 mm/year, it is from -1.5 to +0.5 mm/year. Horizontal velocity range is 0.8 mm/year – from 0.2 to 1.0 mm/year.

The comparison of the obtained results with data from the deformation model NKG_RF03vel shows the ratio of 1.2 between ranges of site vertical velocities. Horizontal velocities due to postglacial rebound are from 0.4 to 0.7 mm/year. Ratio of velocity ranges for the horizontal displacement is 2.7, but both fields have horizontal velocities up to 1 mm and the orientation to the south.

Latvian GNSS station positions have been obtained for one year observations applying PPP and DGNSS approaches. Outstanding Up components could be observed during winter time period in both solutions, but applying DGNSS processing, amplitude of station Up components is two times smaller. About one-third of all stations have the same velocities or velocities which more or less coincide between DGNSS and PPP solution. The maximum difference is 1.7 mm/year.

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