Removing Space Weather Influence

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Abstract. The space weather impact on GNSS positioning, navigation and timing has been recognised as a serious threat and this problem currently is included in the most important research programmes worldwide. The objective of this paper is to check the space weather impact on the CORS stations. Obviously, they are mainly affected by space weather due to the predominantly highly elevated placement of antenna. The GNSS daily observation records which were splitting in 4 hour records and additionally each of 4 hour records were splitting in 48 5-minute records. Each newly obtained record was processed. The results of the average values from 48 5-minute kinematic solutions (5-min) were compared with solutions of corresponding 4 hour (4h) continuous static observation solution results. The comparison of 4h static observation solutions with splitting, filtering and averaging 48 5-minute kinematic solutions. It gives the possibility to improve the solution accuracy by removing the space weather influenced spikes and outliers.

Keywords: GNSS, EUREF, space weather, Bernese software 5.2, GNSS/levelling points

1. Introduction

The space weather impact on GNSS positioning, navigation and timing has been recognised as a serious threat (WEB(a); WEB(b); (Jinyun et al., 2015); (Zakharenkova et al., 2016). This problem is included in the most important research programmes worldwide WEB(c); WEB(d); WEB(b); WEB(e); (Béniguel et al., 2017). Many researchers and institutions have discovered that geomagnetic storms, sunspots and huge solar flares are the main sources for the unexpected space weather performances affecting the radio signal propagation in outer space of the Earth. (WEB(f); WEB(b); Sreeja, 2016). The space weather phenomenon is interpreted as solar flare associated solar radio burst and small-scale time-varying plasma irregularities that introduce
amplitude and phase fluctuations in the received signal, a phenomenon known as scintillation (Sreeja, 2016). Solar and geomagnetic activities are the most important error sources in GNSS related positioning tasks (Astafyeva et al., 2015; Cherniak et al., 2015). One of these tasks is the determination of ellipsoidal heights (h) for so called GNSS/levelling points which are used to tie the gravitational geoid model to the framework of national levelling network (Morozova et al., 2017). GNSS 4h static observations have been carried out by the staff of the Institute of Geodesy and Geoinformatics (GGI) at the sites of GNSS/levelling points. The GNSS positioning reduction has been performed in the framework of EUREF reference network EPN (WEB (g)) by using Bernese 5.2 software (Dach et al., 2015). GGI produced software packages for data analysis and Helmert transformation has been applied to reduce obtained positions to the epoch 2015.0 which had been chosen for GGI quasi-geoid modelling as a basic epoch (Morozova et al., 2017). The continuously operating reference station (CORS) networks LatPos (Zvirgzds, 2005; WEB (h)) and EUPOS®-Riga (Balodis et al., 2010; WEB (i)) are used for analysis of accuracy of 4h GNSS static observation results.

The CORS stations of Latvia are operational in the time span of 11 years. For each station the International Terrestrial Reference Frame coordinates were determined from long span observation time series and they can be reduced to needed epoch T, i.e. in this particular case study: 2015.0. The set $S$ of $n = 30$ stations with subsets of coordinates for each station are denoted by $s_i$, correspondingly:

$$S = \{s_1, s_2, ..., s_n\},$$

where $s_i = \{X_i, Y_i, H_i, T\}, i = 1, 2, ..., n$.

Plane coordinates $X_i, Y_i$ denote North ($X$), East ($Y$) and ellipsoidal height Up ($H$) which are converted from Cartesian coordinates of epoch $T$ for each CORS station correspondingly.

The 30 day continuous observation recorded log files of all CORS stations were analyzed by splitting them in 4 hour sessions (4h). The computation of coordinates was performed for each of the above mentioned sessions by applying the Bernese 5.2 software in framework of 9 nearest EPN (European Permanent Network) stations (Web(g)). The results were converted from Cartesian coordinates to plane coordinates $x, y, h$ (North, East, Up), where $h$ means ellipsoidal height for each 4h session. The set $P$ of 4h observation results (further mentioned also as set “4h”) is obtained with subsets $p_{ijk}$ of coordinates:

$$P = \{p_{ijl}, p_{ij2}, ..., p_{ijk}\}, l = 1, 2, ..., 30; j = 1, 2, ..., 30; k = 1, 2, ..., 6,$$

where $p_{ijk} = \{x_{ijk}, y_{ijk}, h_{ijk}, t_{ijk}\}$.

In period of 30 days, 6 times of 4h sessions per day forms 180 observation sessions for each station. The epoch $t_{ijk}$ is an average epoch of the session.

But the splitting and following Bernese computation was continued by creating 5-min solutions $a_{ijkt}$. Accordingly, the set $A$ of 5-min session solutions was obtained:
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\[ A = \{ a_{ijkl}, a_{ijkl}, \ldots, a_{ijkl} \}, \ i = 1, 2, \ldots, 30; \ j = 1, 2, \ldots, 30; \ k = 1, 2, \ldots, 6, \] (3)

where \( a_{ijkl} = \{ x'_{ijkl}, y'_{ijkl}, h'_{ijkl}, t'_{ijkl} \} \in A, \ l = 1, 2, \ldots, 48. \)

Further the set \( A \) is mentioned also as set “5-min”.

It is possible to perform some simple analysis in order to identify the space weather affected solutions.

2. Space weather affected solutions

The GNSS observation solutions of 5-min GNSS observations at the Latvian CORS stations in December 2016 have been chosen for analysis. Checking the list of strongest geomagnetic storms (WEB (j)) it was concluded that no strong geomagnetic storms were fixed in December 2016 (Table 1). According to the Table 1 Ap index is rather low and Kp index just occasionally exceeds 5+ which is a threshold to observe the aurora in Latvian latitudes. However, in Nordic countries the Kp index with value \( \geq 3+ \) is meaningful (Sreeja, 2016).

| #  | Date          | Ap  | 00-03h | 03-06h | 06-09h | 09-12h | 12-15h | 15-18h | 18-21h | 21-00h | Kp max |
|----|---------------|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1  | 2016.12.08    | 21  | 3+     | 4      | 3-     | 3-     | 4      | 4+     | 4      | 4+     |        |
| 2  | 2016.12.09    | 24  | 4      | 2      | 3+     | 4-     | 3-     | 4-     | 5      | 5      |        |
| 3  | 2016.12.21    | 23  | 2      | 2      | 1+     | 3      | 3+     | 6      | 4      | 4      | 6      |
| 4  | 2016.12.22    | 22  | 5-     | 4+     | 3+     | 3      | 3-     | 4      | 3      | 5      |        |
| 5  | 2016.12.23    | 19  | 3      | 4      | 3-     | 3+     | 3      | 4      | 4      |        |        |
| 6  | 2016.12.25    | 20  | 3+     | 3+     | 2      | 4-     | 4      | 4      | 3-     | 4      |        |
| 7  | 2016.12.26    | 20  | 5-     | 3+     | 3+     | 3      | 4      | 4-     | 3      | 3+     | 5-     |

The phenomenon of GNSS space weather affected solutions is checked at the Latvian CORS stations LatPos and EUPOS®-Riga by performing Eq.4, Eq.5 and Eq.6:

\[
D_{x_{ijkl}} = x'_{ijkl} - x_i, \quad \text{(4)}
\]

\[
D_{y_{ijkl}} = y'_{ijkl} - y_i, \quad \text{(5)}
\]

\[
D_{h_{ijkl}} = h'_{ijkl} - H_i. \quad \text{(6)}
\]

If at least one of the kinematic 5-min GNSS observation solution discrepancies according Eq.4-6 exceeds +10 or -10 cm thresholds the events are fixed and they are presented in Table 2. The epoch difference \( (t_{ijkl} - T) \) doesn’t play important role in these coordinate differences. The epoch is important for fixing the time when events occurred. The disturbed results are fixed mostly near the dawn and/or after the dusk. For example, in 8th December simultaneously in 8 station observations disturbed results were fixed exceeding the threshold of 10 cm in at least one of North, East, Up components. Most of the occurrences occasionally happened in one station for short time.
Table 2. Outlying discrepancy events at the CORS stations in DEC 2016

| # | Date | Time interval UT | Station domes |
|---|------|------------------|---------------|
| 1 | 21:35-23:15 | KREI | VAIV |
| 2 | 10:25-10:30 | PREI |
| 3 | 11:05-11:10 | PLSM |
| 4 | 11:25-11:30 | REZ1 |
| 5 | 9:50-9:55 | DOB1 | LIPJ | LIMB | IRBE |
| 6 | 20:25-20:30 | PREI |
| 7 | 20:50-20:55 | PLSM |
| 8 | 21:25-21:30 | SALP | KREI | LUNI | VAIV | REZ1 | SIGU | SLD1 | VANG |
| 9 | 23:35-23:40 | BAUS | DAU1 |
| 10 | 7:05-7:10 | MADO | LODE |
| 11 | 16:45-16:50 | PREI |
| 12 | 17:05-17:10 | PLSM |
| 13 | 17:40-17:45 | REZ1 |
| 14 | 21:25-21:30 | KREI | VAIV |
| 15 | 11:05-11:10 | MADO | LODE |
| 16 | 11:25-11:30 | REZ1 |
| 17 | 11:30-11:35 | VANG |
| 18 | 11:40-11:45 | REZ1 |
| 19 | 12:00-12:05 | PLSM |
| 20 | 12:25-12:30 | VANG |
| 21 | 21:25-21:30 | DOB1 | JEK1 | LIPJ | LIMB | IRBE |
| 22 | 10:25-10:30 | MADO | LODE |
| 23 | 11:10-11:15 | MADO |
| 24 | 14:00-14:05 | LIPJ | IRBE |
| 25 | 11:15-11:20 | DOB1 | JEK1 | LIPJ | LIMB | IRBE |
| 26 | 21:05-21:10 | PREI |
| 27 | 21:20-21:25 | REZ1 |
| 28 | 22:50-22:55 | PREI |

The typical discrepancy values are shown in Table 3. It is noticeable that there are some groups of stations with similar values of discrepancies. Stations (Domes) KREI, LUNI, VAIV, SALP, and VAIV are located in Riga city and its surroundings. Stations REZ1 and SIGU are located to the East from Riga, station SLD1 to the West from Riga. All stations of this set are located approximately in the same geographical latitude.

Table 3. Typical discrepancy values caused by space weather influence

| # | Domes | Date | Time | Dx(m) | Dy(m) | Dh(m) |
|---|-------|------|------|-------|-------|-------|
| 1 | SALP  | 8    | 21:25| -1.584| -4.103| 15.347|
| 2 | KREI  | 8    | 21:25| -1.642| -4.056| 15.389|
| 3 | LUNI  | 8    | 21:25| -1.613| -4.058| 15.383|
| 4 | VAIV  | 8    | 21:25| -1.618| -3.983| 15.411|
| 5 | VANG  | 8    | 21:25| -1.64 | -4.121| 15.375|
| 6 | REZ1  | 8    | 21:25| -0.04 | 0.772 | 1.066 |
| 7 | SIGU  | 8    | 21:25| -0.055| 0.803 | 1.063 |
| 8 | SLD1  | 8    | 21:25| -0.039| 0.833 | 1.027 |

3. Comparison of 4h results with an average from 48 splitted 5-min results

The data set of 4h solutions for 30 Latvian CORS stations (S) and the GNSS observation records were selected for 30 days of December 2016. The data static mode processing
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has been performed using Bernese software 5.2 and EUREF reference data for all of the 4h GNSS observation record set (5400 solutions of \( p_{ijk} = \{x_{ijk}, y_{ijk}, h_{ijk}, t_{ijk}\} \)). Coordinates of set \( S \) belong to the epoch 2015.0, 4h set belongs to different epochs of December 1 till December 30, \( n = 30 \). According Eq.1-2:

\[
X_i, Y_i, H_i \in S,
\]
\[
x_{ijk}, y_{ijk}, h_{ijk} \in P; i = 1, 2, ..., 30; j = 1, 2, ..., 30; k = 1, 2, ..., 6.
\]

The kinematic mode (KIN) solutions (Dach et al, 2015) for all of the subsets \( a_{ijkl} \), i.e. 5-min set of observation records (43200 solutions of \( a_{ijkl} = \{x_{ijkl}', y_{ijkl}', h_{ijkl}', t_{ijkl}'\} \)) have been calculated using Bernese software 5.2 and the same EUREF reference data as before.

\[
x_{ijkl}', y_{ijkl}', h_{ijkl}' \in A; i = 1, 2, ..., 30; j = 1, 2, ..., 30; k = 1, 2, ..., 6; l = 1, 2, ..., 48. (9)
\]

The average values have been computed (Eq.10) for all of the subsets of 48 5-min solutions, correspondingly:

\[
\bar{x}_{ijk} = \frac{\sum_{l=1}^{48} x_{ijkl}'}{48}, \bar{x}_{ijk} \in 5\text{-}m. \quad (10)
\]

The average monthly values have been computed (Eq.11) for all of the CORS stations, correspondingly:

\[
d_{x_i} = \frac{\sum_{l=1}^{30} \sum_{k=1}^{6} (x_{ijk} - \bar{x}_{ijk})}{180}. \quad (11)
\]

Similar calculations of Eq.10 and Eq.11 have been done for the East and Up components.

![Fig.1. Monthly Up differences between 4h solutions and average of 48 5-min solutions](image-url)
Because of the particular interest of the ellipsoidal height determination (Morozova et al., 2017), further more attention will be paid to disturbances of Up component. The differences of the mean monthly values for Up component are depicted in the histogram of Fig.1.

In order to estimate the time series of all of the monthly discrepancies the monthly standard deviations (STDV) have been computed by applying Eq.12 for solutions of 4h set (Eq.7 and Eq.8) and by Eq.13 for 5-min solutions obtained in Eq.10. The compared results are depicted in Fig.2-4.

\[
\sigma_i' = \sqrt{\sum_{j=1}^{180} \sum_{k=1}^{10} (\bar{X}_{ijk} - X_i)^2}, \sigma_i' \in 5 - \text{min}
\]  
\[
\sigma_i = \sqrt{\sum_{j=1}^{180} \sum_{k=1}^{6} (\bar{X}_{ijk} - X_i)^2}, \sigma_i \in 4h
\]

**Fig.2.** Comparison of 4h Northing STDV (\(\sigma\)) and STDV (\(\sigma'\)) of average from 5-min solutions. Northing. KREI and VAIV 48 5-min outlying solutions are excluded

**Fig.3.** Comparison of 4h Easting STDV (\(\sigma\)) and STDV (\(\sigma'\)) of average from 5-min solutions. Easting. KREI and VAIV 48 5-min outlying solutions are excluded
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Fig. 4. Comparison of 4h Up STDV (σ) and STDV (σ') of average of 5-min solutions Up. KREI, VAIV and VANG 48 5-min outlying solutions are excluded.

There were too large discrepancies in few Northing and Easting components in the solutions for KREI and VAIV stations and for Up component for KREI, VAIV and VANG stations, correspondingly. The most attention in this research is paid to the Up component. Most of the standard deviations of Up component are less than 2 cm. Most of the standard deviations of Northing and Easting components are less than 1 cm. However, in the set of 5-min solutions there are some spikes and even some outliers which are not included in histograms of Fig.2-4. In spite of this, in many cases the 5-min solutions are better than 4h solutions.

In Fig. 5 the amplitudes of $h_{\text{max}} - h_{\text{min}}$ are depicted for each of the station, correspondingly.

Fig. 5. Comparison $h_{\text{max}} - h_{\text{min}}$ between 4h solution and average of 48 5-min solutions. KREI, VAIV and VANG 48 5-min outlying solutions are excluded.
After estimating the data in Fig. 5 it is concluded that the results of the 5-min set have a larger dispersion of amplitudes ($h_{\text{max}} - h_{\text{min}}$). Almost all of the Up differences are positive. The differences are very large – up to 50 cm.

4. Removing spikes and outliers in 5-min solutions

The attempt to increase the precision of 5-min average values Eq.10 has been applied by removing outlying values of 5-min subset solutions with a threshold of 10 cm in solutions of set A. The success of observation filtering in 4h static Bernese solutions is not a subject for discussion in this paper. The comparison of repeatedly obtained standard deviations according to the Eq.12 with a filtered data of set A are depicted in Fig.6-8. The improvements are meaningful because the space weather affected 5-min solutions are removed now. Even KREI, VAIV and VANG 5-min solutions are good quality now.

![Fig.6. Comparison of 4h Northing STDV ($\sigma$) and STDV ($\sigma'$) of average of 5-min Northing solutions after filtering with 10 cm threshold](image-url)
Fig. 7. Comparison of 4h Easting STDV ($\sigma$) and STDV ($\sigma'$) of average of 5-min Easting solutions after filtering with 10 cm threshold.

Fig. 8. Comparison of 4h Up STDV ($\sigma$) and STDV ($\sigma'$) of average of 5-min Up solutions after filtering with 10 cm threshold.
Fig. 9. Comparison of $h_{\text{max}} - h_{\text{min}}$ between 4h solution and average of 5-min after filtering with 10 cm threshold

Table 4. Monthly error distribution statistics for 4h, 5-min and filtered 5-min Up solutions

|          | 4h STDV | ASIM | EXSC | MAX -MIN | 5-min STDV | ASIM | EXSC | MAX -MIN | 5-min filtered STDV | ASIM | EXSC | MAX -MIN |
|----------|---------|------|------|----------|------------|------|------|----------|-------------------|------|------|----------|
| ALUK     | 0.026   | 0.483| 3.407| 0.136    | 0.004      | -0.191| 3.098| 0.025    | 0.004             | 0.018 | 3.045| 0.023    |
| BALV     | 0.027   | 0.065| 3.308| 0.153    | 0.004      | -0.084| 3.633| 0.028    | 0.004             | 0.027 | 3.656| 0.028    |
| BAUS     | 0.018   | 0.251| 3.427| 0.119    | 0.004      | -0.710| 6.350| 0.035    | 0.004             | 0.007 | 2.784| 0.022    |
| DAGD     | 0.019   | 0.404| 4.543| 0.122    | 0.004      | -0.595| 4.288| 0.026    | 0.004             | 0.633 | 4.393| 0.026    |
| DOBI     | 0.021   | 0.106| 3.540| 0.130    | 0.004      | -0.112| 5.420| 0.035    | 0.004             | 0.248 | 2.957| 0.020    |
| IRBE     | 0.032   | 0.358| 3.937| 0.190    | 0.007      | 0.424 | 10.45 | 0.073    | 0.006             | 0.304 | 4.325| 0.036    |
| JEKI     | 0.025   | -0.251| 3.394| 0.152    | 0.005      | -0.664| 4.890| 0.036    | 0.005             | -0.711| 5.168| 0.036    |
| KREI     | 0.018   | -0.693| 5.200| 0.127    | 0.158      | -5.188| 85.308| 2.621    | 0.004             | -0.932| 8.087| 0.035    |
| LIMB     | 0.036   | 0.120| 3.838| 0.251    | 0.006      | -0.151| 3.235| 0.036    | 0.006             | 0.031 | 2.841| 0.034    |
| LIPJ     | 0.024   | 0.406| 3.604| 0.146    | 0.006      | -0.374| 17.509| 0.074    | 0.004             | 0.102 | 3.264| 0.025    |
| LODI     | 0.020   | 0.372| 3.281| 0.112    | 0.014      | -8.227| 75.939| 0.154    | 0.004             | 0.352 | 2.836| 0.021    |
| LUNI     | 0.019   | -0.196| 4.344| 0.143    | 0.024      | -12.608| 167.65| 0.327    | 0.005             | -0.078| 2.898| 0.026    |
| LVRD     | 0.026   | 0.111| 3.433| 0.160    | 0.006      | -0.370| 2.642| 0.026    | 0.006             | -0.356| 2.649| 0.026    |
| MAD0     | 0.023   | -0.438| 4.000| 0.145    | 0.015      | -7.947| 72.636| 0.158    | 0.004             | 0.473 | 3.397| 0.026    |
| MAZS     | 0.021   | 0.724| 4.280| 0.128    | 0.004      | 0.409 | 2.841| 0.021    | 0.004             | 0.443 | 2.939| 0.021    |
| OJAR     | 0.022   | -0.077| 3.277| 0.133    | 0.006      | -0.993| 5.249| 0.043    | 0.006             | -1.051| 5.364| 0.043    |
| PLSM     | 0.022   | -0.079| 3.677| 0.139    | 0.014      | -11.052| 140.94| 0.203    | 0.004             | 0.329 | 2.795| 0.022    |
| PREI     | 0.030   | 0.320| 3.520| 0.180    | 0.035      | -10.671| 126.18| 0.465    | 0.005             | -0.194| 2.478| 0.024    |
| REZI     | 0.028   | 0.466| 4.224| 0.185    | 0.036      | -10.225| 117.99| 0.464    | 0.007             | -0.893| 5.125| 0.045    |
| SALP     | 0.017   | -0.123| 2.719| 0.091    | 0.023      | -12.555| 166.74| 0.321    | 0.005             | -0.067| 2.962| 0.026    |
| SIGU     | 0.024   | 0.287| 3.665| 0.143    | 0.004      | -0.499| 3.050| 0.025    | 0.004             | -0.405| 2.693| 0.021    |
| SLDI     | 0.021   | 0.276| 3.621| 0.130    | 0.004      | -0.321| 4.159| 0.029    | 0.004             | 0.027 | 3.072| 0.023    |
| TAL5     | 0.023   | 0.325| 4.779| 0.148    | 0.005      | 0.304 | 2.665| 0.022    | 0.005             | 0.312 | 2.644| 0.022    |
| TKMS     | 0.023   | -0.075| 4.228| 0.155    | 0.005      | -0.117| 2.887| 0.029    | 0.005             | -0.266| 2.656| 0.024    |
| VAIN     | 0.020   | 0.001| 3.696| 0.133    | 0.004      | 0.008 | 4.002| 0.026    | 0.004             | 0.018 | 4.039| 0.026    |
| VAIV     | 0.017   | 0.280| 3.027| 0.090    | 0.129      | -1.198| 61.912| 2.105    | 0.004             | -0.080| 3.084| 0.021    |
| VALI     | 0.022   | -0.229| 4.655| 0.158    | 0.004      | 0.110 | 2.427| 0.017    | 0.004             | 0.158 | 2.465| 0.017    |
| VALK     | 0.028   | 0.443| 4.140| 0.180    | 0.005      | -0.293| 3.899| 0.030    | 0.005             | -0.248| 3.847| 0.030    |
| YANG     | 0.019   | 0.050| 4.440| 0.127    | 0.093      | 8.302 | 79.974| 1.216    | 0.005             | -1.400| 8.955| 0.038    |
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Monthly statistical analysis was performed for all of the stations (domes) for 4h solutions, for 5-min averaged solutions (Eq.10) and the same with filtered solutions. The monthly Up statistics values of standard deviation, excess, asymmetry (skewness) and difference between max and min solution values were computed and results exposed in Table 4.

The Table 4 demonstrates the improved quality of filtered 5-min solutions against the 4h solutions. For example, KREI station, LIMB, LIPJ, REZ1, SALP, SIGU, SLD1 and others.

![Comparison of Up differences between (4h solutions and non-filtered average 5-min solutions) and between (4h and filtered average 5-min solutions)](image)

In Fig.10 the comparison of Up differences in solutions of Eq.11 of 5-min solutions in 2 cases: a) no threshold for 5-min solutions; b) 10 cm threshold for 5-min solutions of set A. In about 50% of 5-min solutions the results are approaching to 4h solutions. For SIGU and SLD1 stations the results have not changed in Fig.10 but statistics has slightly improved (Table 4).

5. Helmert transformation to improve solution results

GGI software of Helmert 7-parameter transformation model (Seeber, 2003) has been applied to reduce the processed station coordinates of both 4h and filtered 5-min sets to the epoch 2015.0 (Eq.14):

\[
\begin{bmatrix}
X \\
Y \\
H
\end{bmatrix}_{2015.0} = \begin{bmatrix}
\Delta X \\
\Delta Y \\
\Delta h
\end{bmatrix} + (1 + \Delta \xi) \begin{bmatrix}
1 & -R_h & R_Y \\
R_h & 1 & -R_X \\
-R_Y & R_X & 1
\end{bmatrix} \begin{bmatrix}
X \\
Y \\
H
\end{bmatrix}_{\text{epoch}(j)},
\]

where
\( \Delta X \) – translation along the X-axis,
\( \Delta Y \) – translation along the Y-axis,
\( \Delta h \) – translation along the h-axis,
\( R_X \) – rotation about the X-axis,
\( R_Y \) – rotation about the Y-axis,
\( R_h \) – rotation about the h-axis,
\( S \) – scale factor.

Two sets of all the 30 CORS stations were used for the Helmert 7-parameter transformation: a) set \( S \) of epoch 2015.0 and 4h set; b) set \( S \) of epoch 2015.0 and filtered 5-min set of the corresponding day of December 2016 when the GNSS observations were gathered.

![Graph](image)

**Fig.11.** RMS (m) of Helmert transformation solutions from 4h observation epoch to the epoch of 2015.0 of the set of 30 stations

The RMS of transformation (Eq.14) solution for Up component of both 4h set and filtered 5-min set were computed for each Helmert transformation solution. Results are depicted in plots of Fig.11 and Fig.12, correspondingly. To some extent the RMS explains the space weather influence to the observation result homogeneity in corresponding hours of days in December 2016. It is grounds to believe that the affected observation results in 5-min solutions were removed whereas they were not removed in the set of 4h solutions.
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Fig. 12. RMS (m) of Helmert transformation solutions from 5-min filtered observation epoch to the epoch of 2015.0 of the set of 30 stations

The final accuracy of each of the stations in each of the solutions were computed. The results are presented in Table 5 and Fig. 13.

Table 5. Improvement of the computation accuracy

| #  | Abbreviation | Solution | Total | ±5 mm  | ±1 cm  |
|----|--------------|----------|-------|--------|--------|
| 1  | 4h           | 4h       | 5400  | 28.2%  | 30.5%  |
| 2  | b_4h         | Helmert transformed 4h | 5400 | 44.8%  | 48.9%  |
| 3  | 48.5         | Average 48.5-min | 5400 | 35.2%  | 48.7%  |
| 4  | H_48.5       | Helmert transformed 48.5-min | 5400 | 49.2%  | 55.3%  |
| 5  | 48_5_T10     | Prec. thr. 10 cm. av. 48.5-min | 5400 | 65.2%  | 90.3%  |
| 6  | H_48.5_T10   | Helm. transf.av. prec. thr. 10 cm. av. 48.5-m | 5400 | 91.2%  | 98.7%  |
| 7  | 48_5_T7      | Prec. thr. 7 cm. av. 48.5-min | 5400 | 65.3%  | 90.3%  |
| 8  | H_48.5_T7    | Helm. transf.av. prec. thr. 7 cm. av. 48.5-m | 5400 | 91.2%  | 98.7%  |
| 9  | 48_5_T4      | Prec. thr. 4 cm. av. 48.5-min | 5400 | 65.3%  | 90.7%  |
| 10 | H_48.5_T4    | Helm. transf.av. prec. thr. 4 cm. av. 48.5-m | 5400 | 91.2%  | 98.7%  |

Additionally, the filtration of 5-min (set A) solution results with threshold of 7 cm and 4 cm, correspondingly were performed beside the 10 cm filtration mentioned above. The residual time series for Helmert transformation Up component were inspected. The residuals in both interval ±5 mm and ±10 mm were counted. In each of the cases 5400 solutions are analyzed.
The results are significantly improved in 5-min 10 cm filtered solutions (H_48_5_T10). According to the Fig.12 the computed coordinates coincide with an etalon values within precision of 1 mm. 91.2% of computed RMS doesn’t exceed 5 mm after the application of Helmert transformation by reducing the 5-min filtered and averaged results to the applied epoch 2015.0 Table 5 and Fig.13).

It appears that results are practically not improved by changing the filtration threshold to 7 cm or 4 cm, correspondingly, instead of 10 cm.

6. Conclusions

The objective of this paper is to check the reliability of the 4 hour GNSS observation solutions at the continuously operating reference stations (CORS). Obviously, they are mainly affected by space weather and, probably, less affected by multipath due to the predominantly highly elevated placement of antennas which are not obstructed by trees or various constructions.

The mathematical GNSS observation reduction by using Bernese 5.2 software gives better results when splitting 4h observation record in 48 5-min records and kinematic reduction method is applied. It gives opportunity to remove outlying observation results influenced by space weather. The solutions of the 5-min set where the space weather influence is minimized by filtering gives the best final results. The improvement of 5-min solutions is clearly visible by comparing Fig.5 and Fig.9. The Helmert transformation application gives additional improvement.

Unfortunately, it appears that at the formerly used Bernese 5.2 software solutions of 4h sets the space weather impact was not removed.
It was assumed in this article that the results in CORS stations are mainly affected by space weather and less or even not affected by multipath due to the predominantly highly elevated placement of GNSS antennas. It is worth noting that GNSS field observations on earth surface are often obstructed by trees or various constructions and consequently, they are additionally affected by signal multipath. In any case, it is important to take into account that for observations on ground the impact of both space weather and multipath are attendant. That relates not only for GNSS/levelling and other geodetic precise point positioning tasks but also for many positioning and navigation applications for cars, trucks, farming, construction, snow removal etc.

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