High ionospheric activity effects on LatPos RTK network performance in Latvia

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Abstract. Fast and reliable coordinate determination with GNSS in real time is the main objective of continuous operating reference system (CORS) network users. To provide services for coordinate determination, Network-based Real Time Kinematic (NRTK) system called “LatPos” has been established and operated in Latvia since 2006. One of the factors, affecting the performance of LatPos system services, is activity of ionosphere. Ionosphere is a region of the earth's atmosphere, from about 60 kilometers up to 1000 km above the earth's surface, in which there is a high concentration of free electrons, spatially varied, affected by space weather, seasonal and solar cycle changes.

Ionospheric activity conditions depending on mentioned factors can be analyzed by LatPos system data. Some data processing strategies has been developed and LatPos RTK network performance results obtained, during different ionospheric activity conditions. This paper focused on both segments: the NRTK performance and the rover receiver coordinate determination possibilities in field when high ionospheric activity occurs.

1. Introduction

The Global Navigation Satellite Systems (GNSS) since their establishment are used for various applications and purposes. The number of GNSS users worldwide increases year by year. There are several types of GNSS services for positioning and one of them is based on Real Time Kinematic method. Such Network-based RTK (NRTK) service has been established and running in Latvia since year 2006.

The factors that limit the usability and reliability of such service are closely related to well-known GNSS error sources. In this paper mainly the error source of signal delay caused by ionosphere and its effect on NRTK service quality as well as on positioning possibilities and accuracy during high ionospheric activity is inspected. At the same time it has been proven that CORS networks are well-suited infrastructure for monitoring the events in space weather.

The ionosphere is a part of the atmosphere and it is ionized by the UV radiation from the sun. There are temporal and spatial variability of the ionosphere caused mainly by processes on the Sun and thus the effect on GNSS is also varied in time and space.

Several studies has been done in order to determine and mitigate the ionospheric effect on GNSS usability and such services as RTK and NRTK. Number of cycle slips, ambiguity fixing percentage, variability of Total Electron Content (TEC), availability of service etc. are the values used to describe this effect by numbers [1].
There is strong correlation between Kp planetary index used to characterize level of geomagnetic storm and number of fixed satellites in CORS network base stations [2]. During the strong geomagnetic storm the percentage of fixed phase ambiguities can decrease to ~3.6% with no significant dependence of baseline length [3]. The signal delay caused by ionosphere can be modelled from GNSS data and many strategies already has been developed to mitigate the positioning error caused by ionosphere [4][5]. As the ionosphere is mainly affected by the sun, then the diurnal and seasonal changes in TEC values can be observed in mid-latitude areas [6]. The Distance Interpolation Method (DIM), Linear Interpolation Method (LIM), the Kriging Interpolation Method (KRG) and the GRID correction method GRID are the double differenced ionospheric delay correction methods for GNSS Network RTK. The GRID interpolation method performs better than the other three. For mid-latitude stations, its interpolation accuracy is better than 1 cm, and the extrapolation accuracy is better than 2 cm [7].

2. Research area and data set
Latvia - the country in the east-north part of Europe were the area selected for research described in this paper. Territory of Latvia is located between easting meridians 20° – 29° and northing parallels 55.5° – 58.5°. Total area of research territory is ~ 64 000 km².

CORS network LatPos in the end of year 2016 consisted of 25 base stations widely spaced in all territory of Latvia. In year 2016 base stations from neighboring country networks were included in network processing to ensure better RTK service quality near the country border areas. The maximum baseline length between closest base stations do not exceed 100 km, thus the network can be categorized as medium scale CORS network. The LatPos data center and all processing servers are located in the capital city – Riga. The LatPos network schema and base stations are shown in Figure 1.

Figure 1. Continuously Operating Reference Network System LatPos – positions and names of base stations.

Time period from 12 October till 14 October 2016 (3 days) were selected for research. On 13 October there was 3rd strongest geomagnetic storm of year 2016 registered by space weather research and monitoring community [8]. The geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding the Earth. The largest storms are associated with solar coronal mass ejections (CMEs) where a billion tons with its embedded magnetic field, arrives at Earth. Geomagnetic storms creates
strong horizontal variations in the ionospheric density that can modify the path of radio signals and create errors in the positioning information provided by GNSS.

Three different types of data were used to analyze the high ionospheric activity effects on LatPos RTK network performance:

- Post-processing data of LatPos base stations in RINEX format;
- Continuously computed RTK Network status logdata of LatPos system;
- Field measurements collected by rover receiver from 11 - 13 October.

14 base stations of all 25 LatPos base stations were used in further processing. Station names and codes of used base stations are shown in Table 1.

| Station Name | Station code | Station Name | Station code |
|--------------|--------------|--------------|--------------|
| ALUKSNE      | ALUK         | LIEPAJA1     | LIPJ         |
| BALVI        | BALV         | LIMBAZI      | LIMB         |
| BAUSKA       | BAUS         | MAZSALACA    | MAZS         |
| DAGDA        | DAGD         | OJARS        | OJAR         |
| DAUGAVPILS   | DAU1         | SALDUS1      | SLD1         |
| IRBENE       | IRBE         | TALSI        | TALS         |
| LIELVARDE    | LVRD         | VAINODE      | VAIN         |

Table 1. LatPos station names and codes used in processing.

Field measurements by rover receiver were collected on 2nd order geodetic network control points on 11 and 13 October. The location of the geodetic network control points with respect to LatPos and LitPos CORS network base stations are shown in Figure 2.

Figure 2. Location of the geodetic network control points with respect to LatPos and LitPos CORS network base stations.

3. Methodology
First part of the data set was analyzed by post-processing software Bernese GNSS V5.2 for RINEX data, field measurements done by rover receiver was analyzed statistically and visualization of LatPos system Network Cluster logdata was applied. In following sub-sections the used methodology for each data type is described in more details.
3.1. RINEX data processing
The RINEX data processing was done by Bernese GNSS software V5.2 in order to gather:

- VTEC values over base stations;
- Number of cycle slips for baselines;
- Ambiguity fixing percentage for baselines.

LatPos base stations and baselines processed to gather mentioned indicators are shown in Figure 3. The baseline lengths for processed baselines are shown in Table 2.

![Processed LatPos base stations and baselines by gathered indicators.](image)

As the Vertical Total Electron Content (VTEC) is widely used to describe the activity status of the ionosphere, it was computed for LatPos base stations with following algorithm:

$$E(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} E_{nm}(\beta - \beta_0)^n(s - s_0)^m, \quad \text{where}$$

- $n_{max}$, $m_{max}$ are the maximum degrees of two-dimensional Taylor series expansion in latitude $\beta$ and longitude $s$,
- $E_{nm}$ are the (unknown) TEC coefficients of the Taylor series, i.e., the local ionosphere model parameters to be estimated, and
- $\beta_0$, $s_0$ are the coordinates of the origin of the development.

$\beta$ is the geographic latitude of the intersection point of the line receiver-satellite with the ionospheric layer and $s$ is the sun-fixed longitude of the ionospheric pierce point (or sub-ionospheric point). $s$ is related to the local solar time (LT) according to

$$s = LT - \pi \approx UT + \lambda - \pi$$

UT is Universal Time and $\lambda$ denotes the geographical longitude of the sub-ionospheric point. By this Algorithm the $E_{00}$ values describe the VTEC over processed base stations.

As presented in [1] the number of cycle slips occur more often if the ionosphere activity increases. In order to check if this indicator can be also observed from LatPos base station data, the baseline screening was done with Bernese GNSS Software V5.2. using ionosphere-free linear combination L3. Baseline screening was done by checking the epoch difference as

$$n_{i_k}(t_2) - n_{i_k}(t_1) \neq 0, \quad \text{where}$$

- $n_{i_k}$ is initial integer number of cycles between the satellite $i$ and receiver $k$ and $t_1$, $t_2$ the corresponding epochs.
Many studies prove that when active ionospheric event occur, then the possibility to solve the phase ambiguities in post-processing mode decreases. Three baselines were used form LatPos system to check if such decrease can be also observed when comparing data from active and quiet ionospheric days. The phase ambiguities were solved by QIF (Quasi-Ionosphere-Free) algorithm and ionospheric model from CODE was also introduced.

3.2. RTK Network status logdata of LatPos system
The LatPos Network is operated by Leica Spider V6.1 software. LatPos network is virtually divided in two servers. First one is Site-Server and in general it is responsible about data streaming from base stations and generation of post-processing products. Second one is Network-Server where the RTK and NRTK corrections are continuously calculated and sent to every rover user which connects to the server via NTRIP protocol. The Network-Server does continuous processing for all the base stations included in Network Cluster. The logdata of processing status for each base station is stored. When the high ionospheric activity occur it is expected to have significant disturbances to all network base stations. Such disturbances can be expressed by number of satellites with fixed phase ambiguity for every base station. During the geomagnetic storms the ambiguity fixing probability decrease, so the difference between tracked and fixed satellites should increase.

3.3. Field measurements on 2nd order geodetic network control points
The field measurements on 2nd order geodetic network control points were collected for the period from 11 October (quiet ionosphere) till 13 October (active ionosphere). On each control point the observation procedure is divided in four field measurement stages, to obtain maximum realistic data collection. In the field following characteristics were tested:
1. Time to rover receiver initialized position (Time-to-FIX);
2. Coordinate repeatability by independent initializations;
3. Stability of RTK corrections;
4. Position by static observations.

During the field measurements four RTK correction solutions - iMAX, MAX, VRS and SINGLE SITE were tested.

4. Results comparison and analysis
The geomagnetic storm effect on GNSS signals were analyzed by VTEC (Vertical Total Electron Content) calculations from LatPos system observed data. A major increase of the ionospheric VTEC occurred on October 13 associated with the arrival of the CME of the October 9. Above Latvia there was up to +19 TECu (110%) of differences with respect to the TECu of the October 12. The geomagnetic storm last all day long and continued at night with ionospheric TEC instabilities (Figure 4.).

![Figure. 4. VTEC values over Latvia for timespan 24 hours. (grey – October 12, colored – October 13).](image)

| Table 2. Baseline lengths. |
|-----------------------------|
| **Station code** | **Station code** | **Length (km)** |
| ALUK | BALV | 34.95 |
| DAU1 | DAGD | 68.26 |
| BAUS | LVRD | 56.36 |
| IRBE | TALS | 55.93 |
| LIPJ | SLD1 | 92.59 |
| LIMB | MAZS | 43.60 |
The effect of geomagnetic storm on October 13 can be clearly seen by indicators of LatPos test procedure measurements and also by LatPos system continuous network calculation status. Comparison of test procedure measurements from October 11-12 (quiet ionosphere) and October 13 (active ionosphere) show that depending of the ionosphere activity status, the average Time-to-FIX can increase from 18 sec to 42 sec. Also the initialized positions during high ionospheric activity can cause coordinate offsets ~10 cm (Figure 7.). The strength of geomagnetic storm during the timespan October 13-14 is shown by planetary Kp-index (Figure 5.a)) and its effect on LatPos system continuous network calculation status at station IRBE (Figure 5.b)). Only the status for NAVSTAR GPS satellites are shown in Figure 5. b).

![Figure 5](image)

**Figure 5.** a) Planetary Kp-index calculated by GFZ Potsdam [9]. b) LatPos system continuous network calculation status at station IRBE. (Number of tracked satellites in red color and number of satellites with fixed ambiguities in green color.) c) Percentage of fixed ambiguities for baselines (red – BAUS-LVRD, blue – ALUK-BALV, green – IRBE-TALS).

As it was predicted, also the probability to solve the phase ambiguities decreased for the hours when the Kp planetary index reached the maximum values (Figure 5. c)). The variability of corrected cycle slips for processed baselines (Figure 6.) were do not correlate with Kp index that much as percentage of ambiguity fixing percentage, but it should be noted that the maximum corrected cycle slip values were determined for baselines at the northern part of research area.

![Figure 6](image)

**Figure 6.** Variability of corrected cycle slips for baselines specified in Table 2. (72 h timespan from 12 October 00:00:00 till 14 October 00:00:00).
5. Conclusion
There is very strong effect on the performance of CORS network services when high ionospheric activity occur. The ionospheric activity can increase when such event as CME reaches the Earth’s atmosphere. Differences in ionosphere activity on relatively small areas can be determined if ionosphere is modelled from GNSS data of the local area CORS networks. TEC values change during the day period and depend on geographical location.

Many studies on error mitigation caused by ionosphere has been already done, but at the same time the implementation in commercial CORS network software’s are not very clear and still the significant problems can be observed if very strong geomagnetic storm occur.

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