DEVELOPMENT AND USAGE NETWORKS OF ACTIVE REFERENCE STATIONS IN UKRAINE

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Abstract
The national geodetic infrastructure of Ukraine has developed rapidly into Ukrainian Coordinate Reference System UCS – 2000, a fully GNSS compatible coordinate reference system, which is realised through networks of active GNSS stations. They provide data for post processing and streamed raw data for real-time network (RTN) solutions. The RTN raw data are currently being used by both Trimble (ZAKPOS Network), Leica Geosystems (System Solutions Network) and Topcon (TNT - TPI Network) to provide independent RTN solutions. This study is the first in the public domain to evaluate the performance of RTN services in Ukraine and it is intended to provide guideline information for geo-spatial practitioners. Based on collecting RTN data at five locations and using standard observing and processing methods, an accuracy of 25 mm ±10 mm with respect to 2D coordinates and 34 mm ±14 mm with respect to the heights was achieved. The three systems were shown to be generally comparable although some initialization problems were experienced. The result has revealed expected ~2-5 cm (95%) precision for the horizontal and vertical components; however, large horizontal and vertical biases were observed, which can be as high as 8 cm.
Key words: GNSS, real-time kinematic (RTK), network RTK, reference GNSS stations.

Introduction

Over the past two decades, the Global Positioning System (GPS) has become ubiquitous in outdoor positioning and navigation. Other Global Navigation Satellite Systems (GNSS), such as Russian satellite navigation system (GLONASS), European satellite navigation system (GALILEO) and Chinese satellite navigation system (COMPASS) can also provide similar positioning and navigation services (Hofmann - Wellenhof, B. et all, 2008). GPS has been steadily augmented to improve performance using such techniques as Differential Global Positioning System (DGPS), relative GPS, RTK and network RTK (Seeber, G. N.,2003). This paper focuses on the performance of one of these augmentations, network RTK, in Ukraine. In Ukraine the official reference frame is UCS200 but it is important to know what version and epoch of ITRF/ETRF is required for the survey. There are only one version of the reference frame ITRF adopted in Ukraine. This is reference frame ITRF, epoch 2005.0. In addition to working with official reference frame, there may also be cases where the user is required to work in a completely different local reference system: SK - 42, SK - 63.

Since the development of a centimetre-level accuracy positioning techniques in real-time, based on the integer ambiguity resolution of the Global Navigation Satellite System (GNSS) measurements, there have been great advances in real-time kinematic (RTK) applications (Kalynych I. et all, 2014). Under the conventional RTK, raw measurements for the reference station are transmitted to the rover for the integer ambiguity resolution and final coordinate estimation. Therefore, most common errors can be cancelled out by differential techniques. However, single-base RTK baseline length should not exceed 30 - 40 km in practice due to distance-dependent biases, such as ionospheric and tropospheric delays. Approaches, such as Virtual Reference Stations (VRS), Flächen Korrektur Parameter (FKP), Multi-Reference Station (MRS), Master-Auxiliary corrections (MAX), Nearest station (NRT) were introduced in the mid-1990s. These approaches are known as network RTK (RTN) and were successfully used in many applications, especially in navigation and surveying (Takac, F.; Zelzer, O. ,2015).

A network of reference stations for real-time positioning is an infrastructure consisting of three parts: one part consists of all reference stations (more or less extended) with accurately known position that transmit their data to a control centre in real-time. The second part consists of a control centre which receives and processes the data of the stations in real-time, fixes the phase ambiguities for all satellites of each reference station and calculates the GNSS biases (e.g. ionosphere, tropospheric, clock delays). The third part is the set of network products that can be provided from the control centre to the user: these products consist of raw measurement file of each reference station that the user may require for post processing purposes or in streams (called differential corrections) that contain information related to the biases previous cited that allow the rover to make the real-time positioning. Moreover, the control centre is composed by a database that contains the calculated biases and the state of the

network (i.e. the ambiguities, ionospheric and tropospheric delays for each station, …) for post-processing purposes in order to be able to create the so called Virtual RINEX. Real time approach is instead traditionally considered when we desire to obtain a better quality, in terms of accuracy, of our positioning with respect the standalone position (i.e. with EGNOS correction) or with a centimetric level of accuracy (Berber, M.; Arslan, N., 2013, Edwards, S., P. et all, 2008). The differential corrections which are generated by each GNSS reference station are valid only in a limited area around the single site considering a limited space: the main hypothesis is that if the bias remain almost the same in the base station and rover, they can be eliminated by a process differential or relative.
The performance of a RTN infrastructure can be improved realizing a correct design of network, in terms of reference stations inter-distances and geometrical distribution. Considering the quality of the GNSS products used in a RTN as precise ephemerids and the quality of algorithms devoted to estimate the phase ambiguity, inter-distances can be extended up to 70-80 km.
The future progress and benefits due to the improvement of RTN should be very significant, but there are still some open problems, which are studied by the GNSS scientific communities in order to solve them. The main aspects are the real time quality control of the positioning in order to avoid false phase ambiguity fixed and the integrity of the solution.

Methodology of research and materials

A permanent network can be defined as a set of reference stations with the aim of a continuous data collection and coordinate estimation and data; some permanent networks distribute products. From a technical point of view, a permanent network is generally composed by the following parts:

- a network of reference stations with a proper distribution in the served area;
- a communication infrastructure that should guarantee the transmission of the data from the stations to the control centre. The latency depends on the permanent network purposes: if the network provides real time products, for example, the link must be implemented in real time;
- a control centre that:

➢ manages the stations, acquires their data and performs the quality check;
➢ performs the final network adjustment in order to compute and monitor the coordinates of the stations;
➢ if the network distributes products:
✓ estimates the network real time products and distributes them to the users;
✓ publishes data and products for the post processing applications.

The distance between the reference stations of these permanent networks, however, is rather large (100 or more kilometres) and the data are often issued with a rate of 30 s. This is useful for high-precision geodetic and very long periods of time (weeks, months or years of data), but less for topographic applications. A station that materializes the reference system could not provide real time data because it is not a primary purpose. An example of this type of network is the EUREF permanent network (http://epncb.oma.be/) or the IGS network (http://igscb.jpl.nasa.gov/network/netindex.html).
Today many RTN networks are available in terms of inter-station distance: it is possible to find a local network (with mean inter-station distance of about 15 km), a regional network (with distance between stations of about 50 - 70 km) and national networks (distances of about 80 - 100 km).
Since the global or the continental networks do not provide positioning services, these are generally fulfilled by dedicated networks at the local scale; the positioning services of many European nations were realized at the national scale with the coordination of the respective cartographic authority: for example, the AGNES network of Switzerland, the SAPOS network of Germany, the ASG-EUPOS network of Poland belong to this category.
In Ukraine, on the contrary, the first positioning services were born at the administrative scale of a region without a national coordination, only because the regional authorities, which have financial and cartographic regulation autonomy, proved interested in these aspects. In particular, the first positioning services in Ukraine were of Transkarpathian region (ZAKPOS GNSS Network); by this time, other regions activated their services and almost all the rest are either planning or realizing it. Furthermore, the two main private GNSS instrumentation firms (Leica Geosystems and Topcon) are developing their positioning services at the national scale.
A local type of network cannot be found in Ukraine. The second type of network - regional can be represented by a network of a private corporation, such as System Solutions (http://systemnet.com.ua/), with a medium inter-station distance of about 60 km. The last type - national can also be found in Ukraine: in this case, this is represented by a network of a private

company such as ZAKPOS (http://zakpos.zakgeo.com.ua/) and TNT-TPI (https://net.tnt-tpi.com/page).

ZAKPOS positioning service. Transkarpathian Region is located in West Ukraine; its population is about 1.259.000 people and its surface is of about 13.000 km2. In 2010-2012 an agreement was subscribed by Institute of Geodesy Cartography and Remote Sensing (Hungary), Geodetic and Cartographic Institute (Slovakia), National Agency for Cadastre and Land Registration (Romania), Head Office of Geodesy and Cartography (Poland) and Lviv Polytechnic National University for the realization of a regional positioning service. The network is now composed of 14 personal and more 60 affiliate permanent stations with the mean reciprocal distance of 50-100 km. The control centre is operated by Zakarpatgeodezcentr; two servers manage all the relevant processes; VRS are the network phase real time products provided to the users: the first is transmitted by RTCM 3.0; moreover the single station code corrections (DGPS) are available; the NTRIP protocol is adopted for all the real time products. The RINEX data of the permanent stations are available for post processing applications both by interactive webpage and by ftp connection; the distribution of VRS RINEX data is also available. The network management, the data and products distribution are now completely under Zakarpatgeodezcentr responsibility; beside a general role of scientific consultant, the Lviv Polytechnic runs the final monitoring of the network and the transformation to the national cartographic reference frame (Savchuk S. et all, 2007).

System Solutions. The Leica Geosystems Ukraine network, named System Solutions, represents an example of a commercial GNSS network for positioning services at the national scale. At present (March 2017), System Solutions is composed of about 110 GNSS permanent stations distributed over all Ukrainian territory, some of which are shared with the already mentioned ZAKPOS network. System Solutions services vary on the basis of the kind of registration of the users.
The products and services provided are: real time corrections from the nearest station and from the network solution (Automax, I-Max, VRS), with GPRS/GSM transmission; stations RINEX files, with a sample of 5 - 30 seconds; automated post-processing of static baselines; real time information on the network functioning.
The final network adjustment is performed at Main Astronomical Observatory (Kyiv), while an experimental quasi-real time station coordinates monitoring is performed by control centre System Solutions.

TNT-TPI. TNT-TPI GNSS Network is the countrywide GPS+GLONASS satellite positioning service and reference network in Ukraine and composed by 46 personal and more 37 affiliate reference stations. In 2010 the draft design of the network and the preliminary identification of the sites TNT-TPI were done, and from the mid 2011 the first phase of implementation of TNT - TPI GNSS Network was completed; after six months of experimental activities it has been declared operating and has started the distribution of data and products to the users. TNT - TPI GNSS Network generates and distributes corrections to GPS and GLONASS measurements and is ready for GALILEO system. Additionally, the network has been designed to support these areas in Ukraine, in which access to the other satellite positioning systems is hindered, or performance of this networks is troublesome. The user has an additional source of GNSS corrections enhanced by GLONASS signal, which profoundly improves network performance, reliability of measurement and its accuracy.
During the last years, the authors involved in the network adjustment, coordinates monitoring, transformation estimation and experimentation of two positioning services in Ukraine: the regional service of ZAKPOS and the national network of TNT - TPI. Because of their extent, the two networks represent two different case studies with different problems related to the network adjustment and the estimation of the transformation to the cartographic frame.
A network that represents a densification of the global or continental networks is adjusted using several stations of the second as reference: constraining the reference station coordinates to their estimates, in fact, allows to transfer the reference frame from the global to the regional scale. The constraint is applied in the adjustment process by the addition of some pseudo-observations to the least squares system; different kind of constraints can be chosen depending on the strength that is wanted. In particular, the constraints can be summarized: minimum constraints, where the number of conditions applied is equal to the rank deficiency. These are applied specifying the translation between the estimated and the apriori barycenter of the reference station coordinates. This is Helmert condition

on the translation; the other possible Helmert conditions (on the rotation and scale) can be applied but are non minimal: no rotation; no scale.

Discussions and results

All the network adjustments described in this paper are performed with the scientific software GAMIT/GLOBK v.10.6 (Herring, T. et all, 2015) of the Department of Earth Atmospheric and Planetary Sciences, Massachusetts Institute of Technology (MIT), following the international guidelines for a regional network adjustment. After the data processing, the extraction of reports and indexes from the huge number of GAMIT/GLOBK output is needed to check the quality of data and results; moreover, the coordinate time series should be analyzed to identify discontinuities and long-term trends.

It is necessary to pay attention to the fact that networks in Ukraine are rapidly changing and growing and an estimate based on one year of data is not possible for most of its stations: for this reason, to guarantee temporal homogeneity of all the estimated coordinates, the IGb08 coordinates were computed on the basis of the time series accumulated from GPSWeeks 1878 to 1929 (one year of data) with the general constant coordinates modelling method. The computation provided the estimates of the coordinates of the total of 132 Ukrainian reference stations (Savchuk S. H., 2015).

At the end of the elaborations the results have been stored in a database of daily coordinates. The shortness of the time series impedes the estimation of meaningful station velocities; however, in order to decorrelate the residuals, the position of each station has been computed with a linear trend estimation evaluated in the reference epoch of the five weeks of data.

A single station time series analysis has been performed: for each day d, for each component j (East - E, North -N, Up-U) and for each station i, the residuals have been computed as:

$$\delta_j(d,i) = \left| j_i(d) - j_i(d) \right| \tag{1}$$

where j_i is the coordinate estimated for the permanent station i in day d and j_i is the corresponding coordinates obtained by the linear regression. In order to obtain a daily synthetic index, a daily standard deviation has been computed:

$$\sigma_j^2(d) = \frac{1}{N(d)} \sum_{i=1}^{N(d)} \left(\delta_j(d,i) \right)^2 \tag{2}$$

where N is the number of stations estimated on the day d.

At last, to obtain a station synthetic index, a relevant standard deviation has been computed:

$$\sigma_j^2(i) = \frac{1}{N_D(i)} \sum_{i=1}^{N_D(i)} \left(\delta_j(d,i) \right)^2 \tag{3}$$

where N_D is the number of days in which the station i has been estimated.

The results are shown in Tables 1 and 2.

Table 1

Statistics of the station residuals standard deviations (A: average, Max: maximum)

(mm)	E	N	U
$A(\sigma)$	2.6	1.9	4.3
$Max(\sigma)$	4.1	3.9	7.1

Table 2

Global statistics of the time series (σ: standard deviation of all the residuals, *Min* : minimum residual; *Max* : maximum residual)

(mm)	E	N	U
σ	2.6	1.9	4.3
Min	-7.7	-14.1	-15.6
Max	9.6	8.9	16.1

The global residual statistics (Tables 1 and 2) are satisfactory with standard deviations lower than 3 mm in plane and 4 mm in Up.

Considering that 12 Ukrainian stations are in common with the official EPN network, which official ETRF2000 catalogue of coordinates was available, the transformation has been computed with the direct estimation of the similarity transformation parameters (http://etrs89.ensg.ign.fr/memo-V8.pdf); the transformation residuals are summarized in Table 3.

Table 3

IGb08(2016.394)→ETRF2000-UA transformation residuals statistics

(mm)	Δ E	Δ N	Δ U
σ	2.2	2.0	6.1
Min	-6.6	-4.1	-10.5
Max	5.4	5.9	17.0

In order to verify the time-stability of the IGb08→ETRF2000-UA transformations, the ETRF2000-UA station coordinates obtained in 2014/2015 have been compared; the differences have been computed on the subset of (57) stations. The results (Table 4) are definitely acceptable.

Table 4

Differences in the ETRF2000-UA coordinates obtained by 2014/2015 transformation

(mm)	Δ E	Δ N	Δ U
mean	0.2	0.4	-1.9
σ	2.1	3.0	5.3
Min	-6.2	-5.1	-12.4
Max	4.8	5.2	7.7

The GNSS reference stations can be considered as “active” vertices, because they are in continuous measurement and the networks RTN are periodically calculated (Jonsson, B., G. et all, 2002). This aspect changes how surveyors consider the reference system today. In a network RTN the reference system is transmitted implicitly through a stream of data, normally according to the protocol RTCM, which contains information on the coordinates of the stations and on the corrections in the reference system in which the network is framed. Consequently, the user with the rover receiver is framed in real-time in the reference frame of the network that is supported. In real-time measurements the user has even the perception of detecting in a direct “triplets” of coordinates.

Typically, for the testing of any precise positioning technique, the solutions obtained need to be compared to a reference (”truth”) solution. For kinematic applications, short baseline RTK can provide centimetre-level accuracy positioning (Grejner-Brzezinska, D.A. et all, 2005). However, in this study, due to the long distance trajectories and the unique experimental set-up, the use of short baseline RTK as the reference was not possible.

In order to examine the precision of the compared solutions, the 3D standard deviation of the baseline error is computed. Here the average baseline length between the receivers is removed from each set of solution comparisons and the standard deviation of each solution is computed. In terms of typically expected precision, as shown earlier in Aponte et al. (2008), a standard deviation (3D) of ~2-5 cm (1σ) is reasonable.

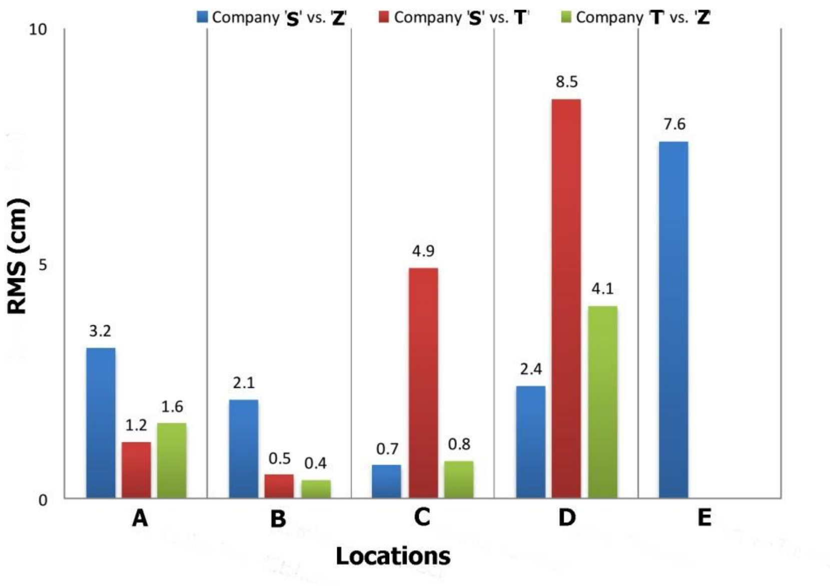

Fig. 1. Mean errors (rms) for each set of comparison (Company 'S'- test System Solutions GNSS Network; Company 'Z'- test ZAKPOS GNSS Network; Company 'T'- test TNT-TPI GNSS Network).

Figure 1 shows the 1σ precision levels for each set of solution comparison. As it can be seen, for the majority of the results, the precision values are ranging from 1 - 5 cm which is within the expected range. However, the large standard deviation shown for the comparison of Company 'S' and 'T' solutions in the northern region test D run is more than twice the expected value of ~8 cm. This unusually large standard deviation is primarily due to the lack of solution availability for Company 'T' for that particular run. Only 225 epochs of common solutions are available between Company 'S' and 'T' data sets, which means less than 4 minutes of common solutions were available for comparison. The effect of the lack of availability can also be seen for the Company 'T' and 'Z' comparison in the same test E run.

Conclusions and proposals

1. Our group is involved in the monitoring of two permanent networks aimed at positioning services: TNT-TPI GNSS Network, at the Ukrainian regional scale and composed of 46 permanent stations, and ZAKPOS, at the national scale and composed of about 85 stations (part of them are System Solutions stations). The experience matured in these collaborations (about eight years with ZAKPOS and more than five year with TNT - TPI) permitted to test and tune software and to analyse the strategies for the adjustment of regional networks.
2. The need of positioning services to compute and distribute the transformation between ITRS (at present ITRF2014) and ETRS89 (at the present ETRF2000 - UA) permitted the study of the problems related to this transformation at the regional and the national scale. The transformation from IGb08 to the ETRF2000 - UA frame is simpler: in fact, since the UCS-2000 adjustment and reference epoch is 2005.0, the transformation is well represented by a similarity even at the national scale. Two different approaches for the IGb08 - ETRF2000 - UA transformation have been presented, because they were implemented at different epochs and with different observation sets: anyway, they provide the alternative solutions for all national or regional positioning services, whether they share reference stations with UCS - 2000 network or not.
3. The precision of the static results show unified levels of short term repeatability. In both vertical and horizontal components of the solution precision, results indicate an overall precision of ~2.5 cm (95%) or better. However, one of the main issues of networks RTN in Ukraine is solution biases in the horizontal components, which can be up to 8 cm in isolated cases, which can severely undermine the accuracy of user solutions. The rms values from results showed accuracies ranging from ~2-4 cm in the horizontal and the vertical components.
4. The dominant issue that was encountered during the course of this study was the lack of a unified set of guidelines or procedures for the private networks to be integrated into Ukrainian official datum, UCS - 2000, which may account for the noticeable centimetre - level biases that are present in many of the solutions. Large network biases in some of the solutions undermine the

capability of network RTK as a whole. Another issue is the fact that not all locations within these networks were assessed. With sufficient testing, "blind spots" can be found (as a few were found in this study), where the rover is well within the network RTK and yet no solution could be provided to the user. Comparing networks RTK in northern part of Ukraine (test D, E) with similar places such as central - southern region (test A), urban regions of Kyiv (test B) and western region (test C), in terms of both accuracy and availability, the services provided in Ukraine tend to underperform.

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