

TESTING OF 2D PRECISION OF GNSS RTK MEASUREMENTS IN DIFFERENT GNSS CONSTELLATION

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ABSTRACT:

GNSS RTK receivers used for precise geodetic measurements and positioning enable the calculation of point position coordinates based on the reception of signals from different GNSS constellations: GPS, GLONASS, Galileo, BeiDou, which are owned by different countries or the union of countries. Standard ISO 17123-8 specifies and defines field procedures to be adopted when determining and evaluating the precision of GNSS RTK field measurement systems and their ancillary equipment. This paper will present the procedure and comparative results of field testing of the Leica GS18 measuring system using the same GNSS Network of permanent stations while receiving corrections from multiple or single GNSS constellations. The purpose of the experiment was to analyse the precision of the 2D position of rover points of the test polygon, depending on the number and arrangement of satellites from different GNSS constellations. The testing was carried out in an urban environment. The results represent actual conditions in the field and indicate the potential influence of surrounding objects on the quality of RTK positioning.

KEYWORDS:

GNSS RTK, precision, ISO standard, 2D positioning, GNSS Network

1 INTRODUCTION

Global Navigation Satellite Systems (GNSS) are the basis of modern positioning methods used in geodesy, cartography, construction, agriculture, transport, and many other areas of society. The efficiency of GNSS positioning for geodetic purposes and its class of GNSS coordinate accuracy, can be compared and analysed, only when the measurements are performed at the same location, under the same measurement conditions, and using the same GNSS receivers and their auxiliary equipment and software for data processing [1]. Today, several global and regional GNSS constellations are available that provide a positioning signal. These constellations function independently or can be used in combination. Almost all newer GNSS receivers have the ability to use multiple constellations simultaneously, increasing the number of visible satellites, improving geometry, and potentially positioning accuracy.

In this paper, the authors aim to answer the question: What is the actual contribution of individual GNSS constellations to the final results of GNSS measurements, and does the use of multiple constellations or just a single GNSS constellation produce significantly better horizontal (2D) positioning (Y, X) results? The international standard ISO 17123-8: "Optics and optical instruments - Field procedures for testing geodetic and surveying instruments - Part 8: GNSS field measurement systems in real-time kinematic (RTK)" will be used as a basis for analysing the measurement results and for drawing conclusions that address this research question. The experiment was carried out at the test polygon over four consecutive days using a single GNSS RTK receiver. Horizontal (2D) coordinates of the rover points within the test polygon were determined from the same base point using one of three available permanent GNSS reference stations Networks in the Republic of Serbia (RS). A different GNSS constellation was used for RTK measurement each day.

2 GNSS POSITIONING

GNSS systems make it possible to determine the position on Earth by receiving signals emitted from satellites in orbit. A receiver on the Earth's surface measures the time it takes for the signal from the satellite to reach it, and based on this time delay, calculates its position. The accuracy of this process depends on several factors, including: the number and geometric arrangement of visible satellites (satellite geometry); GNSS receiver type and quality; the use and effectiveness of error correction models (e.g., atmospheric corrections); and the presence of signal interference, such as multipath effects or electromagnetic noise [2].

Currently, the following global multi-frequency GNSS constellations are operational in the world that enable centimetre precision in RTK positioning mode: GPS (Global Positioning System), GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema), BeiDou (BDS - BeiDou Navigation Satellite System, or Compass navigation system), and Galileo; as well

as two regional GNSS constellations: QZSS (Quasi-Zenith Satellite System) and NavIC (Indian Regional Navigation Satellite System - IRNSS) (Figure 1).

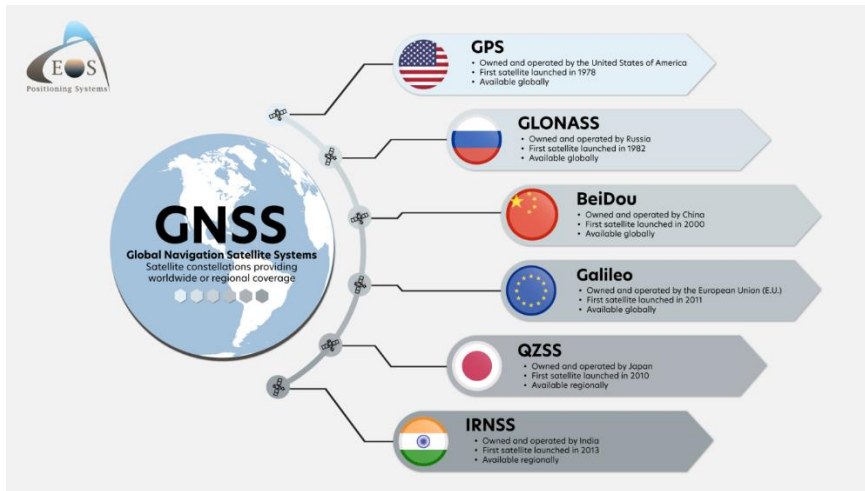


Figure 20: GNSS constellations [2]

Combining multiple GNSS systems enables a greater number of visible satellites at any time, which reduces the probability of signal loss, especially in urban areas or difficult terrain conditions. The improvement of satellite geometry (expressed through PDOP (Position Dilution of Precision)) directly affects positioning accuracy, as well as greater robustness and resistance to individual system errors, too. However, adding multiple systems to process measurements simultaneously can lead to more complex error modelling, signal interoperability issues, and an increased need for more accurate algorithms in the GNSS receiver [3].

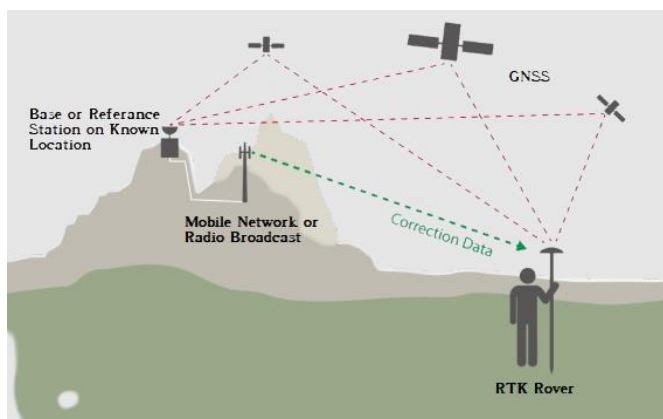


Figure 2: GNSS RTK measurements [4]

GNSS RTK is one of the most important methods of precise satellite positioning in real time. It is based on the use of phase measurement of the GNSS signal carrier and the application of differential corrections that are sent in real time from a base reference GNSS station (or more) to a mobile receiver (GNSS rover) (Figure 2). By adding or removing

individual GNSS constellations during RTK measurements, specific advantages and limitations of each constellation can be observed, which is of particular importance for users in engineering surveying, precision agriculture, drone navigation and other applications where accuracy requirements are high.

The key advantage of the RTK method compared to standard GNSS techniques is the high positioning accuracy, which in favourable conditions can reach from a few centimetres to the millimetre level. The transmission of corrections is most often realized via mobile telephony (GSM/3G/4G), radio links or the Internet, with the use of RTCM (Radio Technical Commission for Maritime Services) format.

2.1 THE PERMANENT GNSS REFERENCE STATIONS NETWORKS IN THE REPUBLIC OF SERBIA

The permanent GNSS reference stations Network (GNSS Network) consists of a set of reference points equipped with permanently operating GNSS receivers and antennas, which together with the control centre, necessary hardware, software, and communication infrastructure enable the collection, archiving, processing, modelling and distribution of GNSS data [5]. In the Republic of Serbia, a GNSS Network must be officially approved by the governmental agency: The Republic Geodetic Authority (RGA), to be used to perform geodetic, cadastral and geospatial data management works on the territory of RS.

In the Republic of Serbia, three GNSS Networks are currently established and operating at the moment, as confirmed by the RGA.

GNSS Networks that are providing permanent support 365 days/24 hours (Figure 3) to their professional users in RS are:

- AGROS (Active Geodetic Reference Network of Serbia), as the first GNSS Network on the territory of RS that was established in 2005 and maintained by the RGA. The AGROS covers the whole territory of the Republic of Serbia and it is possible to create network corrections for GPS/GLONASS [6];
- Vekom Net, a privately owned GNSS Network that, since 2018, has been an integral part of the State Spatial Reference Framework of the RS and can be used for activities within the scope of work of the RGA. The Vekom Net is available on the entire territory of the country, and it is possible to create network corrections for GPS/GLONASS/Galileo/BeiDou [7];
- GeotaurNet - powered by GentooARS (first phase), as a privately owned GNSS Network, which was in 2019 approved for official use for an area that includes 2529 cadastral municipalities in the RS. The specific GNSS network corrections provided by GeotaurNet are not publicly available [8].

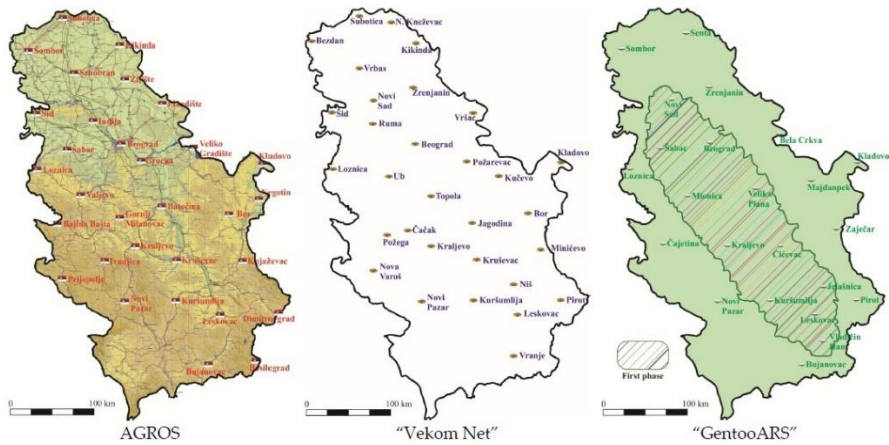


Figure 3: GNSS Networks in the Republic of Serbia: AGROS, Vekom Net and GeotaurNet [1]

For geodetic measurements and determining the coordinates of points on the ground using GNSS RTK in RS, legal regulations allow the use of the services of any of the three existing GNSS Networks. However, it should be noted that continuous testing of the operation of the GNSS Networks in use on the territory of the Republic of Serbia is still not required [1].

3 TESTING THE PRECISION OF 2D COORDINATES MEASURED WITH GNSS RTK BY ISO 17123:8 STANDARD

In geodetic practice, the field procedures for testing GNSS field measurement systems in real-time kinematics and their ancillary equipment are performed according to the procedures defined by the ISO 17123-8 standard. The last version of the standard was adopted in 2023, but it is identical to its publication from 2015. ISO 17123-8 standard specifies field procedures to be adopted when determining and evaluating the precision (repeatability) of GNSS field measurement systems (this includes all GNSS constellations: GPS, GLONASS, GALILEO, BeiDou, etc.) in GNSS RTK mode and their ancillary equipment when used in building, surveying, and industrial measurements [9]. The test results indicate whether the GNSS equipment is functioning properly and whether the precision specified by the manufacturer can be achieved.

ISO 17123-8 standard specifies that the test polygon (Figure 4) should consist of a base point (B) and two rover points (R_1 , R_2) [9]. Rover points distance (D) should be between 2 m and 20 m. The distance between the rover points and the base point (b) is not prescribed, but should correspond to the task concerned. Coordinates of the rover points are unknown, but the position of the test polygon must be convenient for GNSS RTK testing. The base point represents the reference station of the GNSS Network from which

both GNSS RTK rovers positioned at the rover points simultaneously receive data. Points R_1 and R_2 will be used for GNSS RTK measurements and testing of GNSS RTK receivers. Vertical position and immobility of the GNSS antenna during the measurement process must be provided. The antenna should be mounted on a tripod or a survey pole equipped with a bipod to ensure stability and accuracy. The accuracy of centring precision and measuring the height of the GNSS antenna expressed in standard deviation should be 1 mm [9].

Measurement in RTK mode should be performed according to the GNSS manufacturer's manual. The results of the measurements are influenced by several factors, such as satellite configuration visible at the points, ionospheric and tropospheric conditions, multipath environment around the points, precision of the equipment, and quality of the software running in the rover equipment or the system generating the data transmitted from the base point [9].

To determine the reference or nominal value of horizontal distance (D^*) between R_1 and R_2 , a total station is most commonly used, under the condition prescribed by ISO 17123-8 that the distance must be measured with a precision better than 3 mm. The distance determined in this way is considered the reference value against which the distance obtained by the GNSS RTK method is tested. The horizontal distance (D) calculated from the measured GNSS coordinates shall be compared with the D^* value to ensure that the measurements are free from any outlier, but D^* will not be used in the statistical tests. Note: The focus of this paper is on the analysis of the results of determining the horizontal position (Y, X) of the rover points and the precision of measuring the distance between them. Test statistics related to the height difference (Δh) between the rover points will not be presented or analysed in this paper.

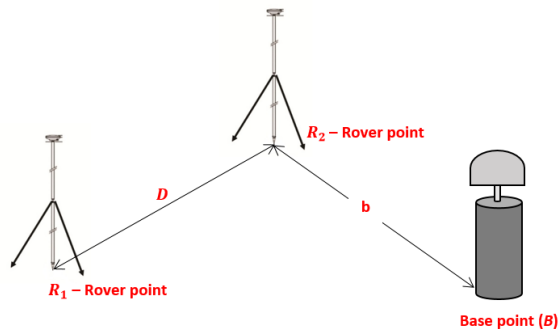


Figure 4: Test polygon for field calibration of GNSS RTK receivers

The GNSS RTK rover can display the instantaneous coordinates of the antenna in any appropriate datum, e.g. European Terrestrial Reference System (ETRS) 1989/Universal Transverse Mercator (UTM) projection; World Geodetic System 1984 (WGS84)/UTM projection; Bessel 1841 ellipsoid/Gauss–Krüger (Transverse Mercator) projection; etc., but they need to be transformed to horizontal coordinates (Y, X) in the designated projection. GNSS RTK receiver testing according to ISO 17123-8 is described in chapters: "5 Simplified test procedure" and "6 Full test procedure".

The simplified test consists of a single series of measurements and serves as a quick assessment of the functionality and basic reliability of the GNSS RTK receiver, with minimal influence from external factors. It enables the identification of possible gross deviations in the 2D coordinates of the rover points obtained by the GNSS RTK measurements.

The full test procedure consists of three consecutive series of measurements at the test polygon, carried out according to the same method prescribed in the simplified test procedure. The full field test procedure is used for removing the gross errors, estimation of the measuring uncertainty, and statistical testing. Statistical tests serve to determine whether the sample from the experiment belongs to the same population as the one giving the theoretical standard deviation or prescribed by the manufacturer and to determine whether two samples from different experiments belong to the same population [9].

Bearing in mind that the full test procedure will be used in the experiment, this procedure will be described in detail.

3.1 THE FULL TEST PROCEDURE

Simplified test procedure involves one series (i) of five consecutive sets of GNSS RTK horizontal coordinates (Y, X) measurements at points R_1 and R_2 . The interval between each successive measurement at rover points is approximately five minutes, which means that one series lasts app. 25 minutes. On the other hand, for the full test procedure, three series of measurements ($i = 1, 2, 3$) shall be taken. The start times of consecutive series shall be separated by at least 90 min [9].

Experiment includes a specific set of measurements is expressed as $Y_{i,j,k}$, $X_{i,j,k}$, where Y, X are coordinates of a local coordinate system; the index i stands for the series number ($i = 1, 2, 3$); the index j for the set number ($j = 1, 2, \dots, 5$) and then the index k for the rover point number ($k = 1, 2$). For each set of five coordinate measurements in one series, the horizontal distance ($D_{i,j}$) between two rover points should be calculated and then compared with the nominal value (D^*) to detect any measurement with gross error.

The following calculations shall be made:

$$D_{i,j} = \sqrt{(Y_{i,j,2} - Y_{i,j,1})^2 + (X_{i,j,2} - X_{i,j,1})^2} \quad (1)$$

$$\varepsilon_{D_{i,j}} = D_{i,j} - D^*, i = 1, 2, 3; j = 1, 2, \dots, 5; k = 1, 2 \quad (2)$$

where:

- $Y_{i,j,k}$, $X_{i,j,k}$ - are 2D coordinate measurements, respectively, in the set j at rover point k in series i ;
- $D_{i,j}$ - is the calculated horizontal distance, respectively, in the set j in series i ;
- D^* - is the nominal value of horizontal distance between rover points;
- $\varepsilon_{D_{i,j}}$ - are the deviations of the horizontal distance, respectively, in the set j in series i .

Afterward, a test statistic is used to determine whether gross measurement errors exist, by applying the following equation:

$$|\varepsilon_{D_{i,j}}| \leq 2,5 \cdot \sqrt{2} \cdot s_{Y,X} \quad (3)$$

where $s_{Y,X}$ is either the predetermined standard deviation according to the full test procedure or the values specified by the manufacturer [9].

If any deviation fails to satisfy either of the two conditions in Eq. (3), the inclusion of an outlier (or outliers) in the corresponding measurements is suspected; the GNSS RTK measurement and the test procedure must be repeated.

Statistical testing of measurement results includes the following steps:

Step 1: Gross error test according to Eq. (3). If this criterion is met, the measurement data processing continues.

Step 2: The experimental standard deviation of the 2D coordinates (S_Y, S_X) of points R_1 and R_2 in all series of measurements should be calculated according to the following:

a) Arithmetic mean of the coordinates:

$$\begin{aligned}\bar{Y}_k &= \frac{1}{15} \sum_{i=1}^3 \sum_{j=1}^5 Y_{i,j,k} \\ \bar{X}_k &= \frac{1}{15} \sum_{i=1}^3 \sum_{j=1}^5 X_{i,j,k}\end{aligned}\quad (4)$$

b) Deviations from the mean value of the 2D coordinates (residuals):

$$\begin{aligned}r_{Y_{i,j,k}} &= \bar{Y}_k - Y_{i,j,k} \\ r_{X_{i,j,k}} &= \bar{X}_k - X_{i,j,k}\end{aligned}\quad (5)$$

c) The standard deviation of individual 2D coordinates is determined as:

$$\begin{aligned}S_Y &= \sqrt{\frac{\sum_{i=1}^{m \cdot n \cdot p} r_{Y_{i,j,k}}^2}{v_Y}} = \sqrt{\frac{\sum_{i=1}^{30} r_{Y_{i,j,k}}^2}{28}} \\ S_X &= \sqrt{\frac{\sum_{i=1}^{m \cdot n \cdot p} r_{X_{i,j,k}}^2}{v_X}} = \sqrt{\frac{\sum_{i=1}^{30} r_{X_{i,j,k}}^2}{28}}\end{aligned}\quad (6)$$

$$v_Y = v_X = (m \cdot n - 1) \cdot p = (3 \cdot 5 - 1) \cdot 2 = 28$$

where:

- v_Y, v_X - presents the number of degrees of freedom in the measurements of individual coordinates (Y, X)
- $m = 5$ - is the number of series;
- $n = 10$ - is the number of sets in one series; and
- $p = 2$ - is the number of rover points.

Step 3: Experimental standard deviation for a single position (Y, X) related to the ISO standard deviations ($S_{ISO-GNSS-RTK-Y,X}$) is calculated as:

$$S_{ISO-GNSS-RTK-Y,X} = \sqrt{S_Y^2 + S_X^2}\quad (7)$$

By performing a full test, the influence of ionospheric and tropospheric refraction on the observations can be neglected, and the effects of the current geometric distribution of satellites, inaccuracies in determining satellite positions in orbit, and influences on observations originating from the surroundings, especially the multipath effect, are reduced. However, the questions regarding the accuracy of observations at the base

station and the quality of the quantities calculated by the GNSS Network's control centre (VRS or FKP) remain unanswered [10].

3.2 TEST STATISTICS

Standard deviations for the horizontal position (Y, X) can be obtained from measurements using the same or multiple GNSS RTK instruments of different types and/or manufacturers. When determining the accuracy of the instrument under the current measurement conditions, a test statistic that follows a chi-square (χ^2) distribution should be used (χ^2 statistical test).

When assessing the accuracy of a GNSS RTK receiver over different time periods and consequently under different observation conditions (multiple series of measurements with the same instrument), a test statistic that follows an F-distribution should be used (F statistical test). The same approach is used when comparing the accuracies of different GNSS RTK instruments under the same conditions. A confidence level of $\alpha=5\%$ should be assumed for χ^2 and F statistical tests [10].

Statistical tests are as follows [9]:

- a) The null hypothesis (H_0) states: Experimental standard deviation $S_{ISO-GNSS-RTK-XY}$ of a single 2D position (Y, X) is smaller than or equal to a theoretical or a predetermined value ($\sigma_{Y,X}$). The predetermined value prescribed by ISO 17123-8 is: $\sigma_{Y,X} = 15 \text{ mm}$. The H_0 is accepted if the following condition is fulfilled:

$$S_{ISO-GNSS-RTK-Y,X} \leq \sigma_{Y,X} \cdot \sqrt{\frac{\chi^2_{1-\alpha;(\nu_Y+\nu_X)}}{\nu_Y+\nu_X}} \quad (8)$$

$$S_{ISO-GNSS-RTK-Y,X} \leq \sigma_{Y,X} \cdot 1,15 \quad (9)$$

where:

- $\nu_Y + \nu_X$ and $\tilde{\nu}_Y + \tilde{\nu}_X$ are number of degrees of freedom of 2D coordinates that equals to 56.

Otherwise, the null hypothesis is rejected.

- b) The null hypothesis (H_0) states: Two experimental standard deviations, $S_{ISO-GNSS-RTK-Y,X}$ and $\tilde{S}_{ISO-GNSS-RTK-Y,X}$, of a single position (Y, X) determined from two different samples measured with single, or two different GNSS receivers at a different point of time, belong to the same population, assuming that both samples have the same number of degrees of freedom. The H_0 is accepted if the following condition is fulfilled:

$$\frac{1}{F_{1-\frac{\alpha}{2};(\nu_Y+\nu_X);(\tilde{\nu}_Y+\tilde{\nu}_X)}} \leq \frac{S^2_{ISO-GNSS-RTK-Y,X}}{\tilde{S}^2_{ISO-GNSS-RTK-Y,X}} \leq F_{1-\frac{\alpha}{2};(\nu_Y+\nu_X);(\tilde{\nu}_Y+\tilde{\nu}_X)} \quad (10)$$

$$0,59 \leq \frac{S^2_{ISO-GNSS-RTK-Y,X}}{\tilde{S}^2_{ISO-GNSS-RTK-Y,X}} \leq 1,70. \quad (11)$$

Otherwise, the null hypothesis is rejected.

4 TESTING OF GNSS - RTK RECEIVERS IN DIFFERENT GNSS CONSTELLATIONS ACCORDING TO THE ISO 17123:8 STANDARD

At the territory of the municipality of Zvezdara, city of Belgrade, in the forecourt of the Geodetic Technical School yard (Figure 5), two ground (rover) points were stabilized as prescribed by ISO 17123-8. Rover points (R_1 and R_2) of the test polygon were positioned in such a way that the surrounding objects and vegetation do not significantly interrupt the GNSS RTK measurements.

All GNSS RTK measurements were carried out with a Leica GS18 rover. The weather conditions were favourable, i.e., the weather was sunny with a temperature of around 20°C and without wind. GNSS rover Leica GS18 uses manufacturer software: Leica Captivate v3.0 with defined parameters for measurement monitoring and control. Leica GS18 track signals from multiple GNSS constellations, i.e., GPS/GLONASS/Galileo/BeiDou. As specified by the manufacturer, RTK horizontal (2D coordinate) accuracy in GNSS RTK Network measurement mode is: $s_{Y,X} = 8 \text{ mm} + 0,5 \text{ ppm}$.

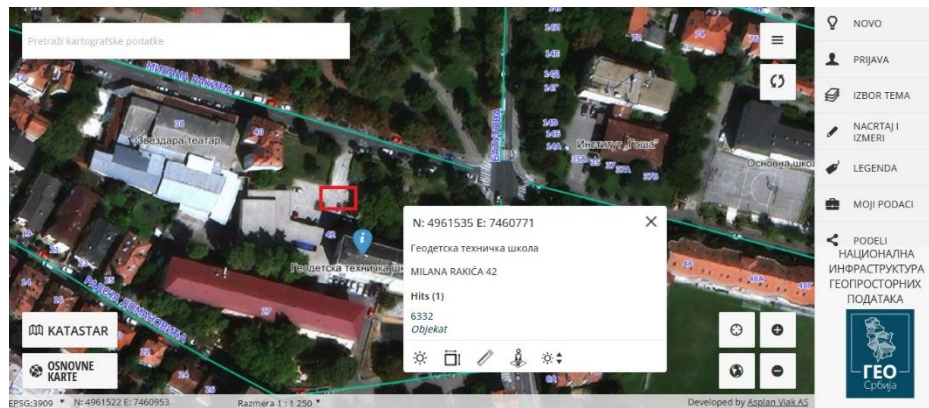


Figure 5: Location of the test polygon at Zvezdara municipality [11]

The purpose of the experiment was to examine how much the accuracy and stability of GNSS RTK positioning vary when Leica GS18 uses only one GNSS constellation for calculating ground (Y, X) coordinates, versus situations where multiple GNSS constellations are activated. In this experiment, the VekomNet GNSS Network was chosen since it supports all GNSS constellations, which was essential for conducting the experiment. All GNSS RTK measurements were performed in accordance with the full test procedure of ISO 17123-8 over four consecutive days in March 2025. The first set of measurements began around 1 p.m. each day.

For each day of GNSS RTK measurement, horizontal coordinates (Y, X) of rover points were calculated in the Bessel 1841 ellipsoid/Gauss–Krüger (Transverse Mercator) projection.

On the first day, for calculating 2D coordinates of the rover points, Leica GS18 was set up to receive satellite signals of all available (multiple) GNSS constellations. On the following three days, solely the GPS, Galileo, and BeiDou constellations were used for the RTK

measurements, accordingly. **Note:** The GLONASS constellation was not used because, during the experiment, the Leica GS18 was unable to register a sufficient number of GLONASS satellites to calculate precise 2D coordinates on any of the tested days. That is why these experiments lack the analysis of the quality of GNSS RTK measurements using solely the GLONASS constellation.

The nominal distance (D^*) between the rover points of the test polygon was measured with total station Leica TS07 and its associated equipment. The nominal distance is reduced to the Bessel 1841 ellipsoid/Gauss–Krüger (Transverse Mercator) projection and equals to: $D^* = 14,656$ m.

4.1 MEASUREMENT RESULTS OF THE EXPERIMENT AND TEST STATISTICS

For each set $j = 1, \dots, 5$ of every series $i = 1, 2, 3$, the horizontal distance ($D_{i,j}$) between two rover points of the test polygon was calculated and compared with the nominal value (D^*) according to Eq. (1) and Eq. (2).

By applying Eq. (3), it was calculated that:

$$|\varepsilon_{D_{i,j}}| \leq 2,5 \cdot \sqrt{2} \cdot s_{Y,X} \leq 2,5 \cdot \sqrt{2} \cdot 8 \text{ mm} \leq 28 \text{ mm}. \quad (12)$$

Peak values of the horizontal distance deviations ($\varepsilon_{D_{i,j}}$) are presented in Table 1. Gross error test according to Eq. (12) shows that there are no gross errors in any of the series of measurements per day and GNSS constellation used.

Table 1: Characteristic deviation of distance from its nominal value – peak values

Day	GNSS constellations	Values	$\varepsilon_{D_{i,j}}$ [mm]
1 st	Multiple GNSS	min	-15
		max	4
2 nd	GPS	min	-6
		max	3
3 rd	Galileo	min	-26
		max	6
4 th	BeiDou	min	-9
		max	5

Deviations from the mean value of the 2D coordinates (residuals) of the GNSS coordinates of rover points in all series of measurements per day were calculated according to Eq. (5), and their peak values are presented in Table 2.

Finally, the experimental standard deviation for a single position (Y, X) related to the ISO standard deviation was calculated and presented in Table 3.

Afterward, statistical tests A and B, as described in Chapter 3.2 of this paper, were performed.

Table 2: Characteristic residuals of the GNSS coordinates from their mean values per measurement day and GNSS constellation

Day	GNSS constellation	Values	$r_{Y_{i,j,k}}$ [mm]	$r_{X_{i,j,k}}$ [mm]
1 st	Multiple GNSS	min	-9	-13
		max	14	16
2 nd	GPS	min	-6	-21
		max	10	15
3 rd	Galileo	min	-16	-13
		max	17	14
4 th	BeiDou	min	10	-12
		max	6	19

Statistical test A: When applying Eq. (9), considering the predetermined values as: $\sigma_{Y,X} = 8$ mm, a conclusion is made that the experimental standard deviation $S_{ISO-GNSS-RTK-Y,X}$ of a single 2D position (Y, X) are smaller than the predetermined value ($\sigma_{Y,X}$) stated by the Leica manufacturer, for most of the GNSS constellation used (Table 3). The null hypothesis is accepted with a 95% probability for multiple GNSS, GPS, and BeiDou constellations, i.e., measurements were carried out with the expected precision. RTK measurements using Galileo constellation were not carried out with the expected precision prescribed for Leica GS18, because its calculated $S_{ISO-GNSS-RTK-Y,X}$ is greater than the condition stipulated in Eq. (9), since: $\sigma_{Y,X} \cdot 1,15 = 9,2$ mm.

Table 3: Characteristic standard deviation of a single measurement of coordinates related to the ISO standard deviation

Day	GNSS constellations	S_Y [mm]	S_X [mm]	$S_{ISO-GNSS-RTK-Y,X}$ [mm]
1 st	Multiple GNSS	4,96	6,58	8,24
2 nd	GPS	3,76	7,34	8,24
3 rd	Galileo	8,88	5,68	10,54
4 th	BeiDou	4,34	7,45	8,63

Statistical test B: To test whether the experimental standard deviations $S_{ISO-GNSS-RTK-Y,X}$ and $\bar{S}_{ISO-GNSS-RTK-Y,X}$ obtained from two different samples of a single position (Y, X) measured with the Leica GS18 receiver over four consecutive days using different GNSS constellations, belong to the same population, the results were compared under the assumption that the reference value for $S_{ISO-GNSS-RTK-Y,X}$ equals 8,24 mm, which corresponds to the value obtained using multiple GNSS constellations.

By applying the test statistic from Eq. (11), and assuming that reference value corresponds to the one obtained using multiple GNSS constellations, the null hypothesis was accepted for all GNSS constellations used in GNSS RTK 2D positioning. At the confidence level of 95%, it can be claimed that all experimental standard deviations belong to the same population (Table 4) and do not depend on the GNSS constellation used.

Table 4: Results of statistical test B

Day	GNSS constellations	$\tilde{S}_{ISO-GNSS-RTK-Y,X}$ [mm]	$\frac{S_{ISO-GNSS-RTK-Y,X}^2}{\tilde{S}_{ISO-GNSS-RTK-Y,X}^2}$
2 nd	GPS	8,24	1,0
3 rd	Galileo	10,54	1,64
4 th	BeiDou	8,63	1,10

Based on the results obtained, the arithmetic mean of horizontal distance (\bar{D}) between two rover points was calculated for each GNSS constellations and compared with the nominal value (D^*). Additionally, the standard deviation of the measured distance (S_D) was determined. The results (Table 5 and Figure 6) indicate that all performed measurements comply with the specifications provided by the Leica manufacturer concerning the horizontal coordinate accuracy of the GNSS RTK equipment. Additionally, the experimental standard deviations in the horizontal plane belong to the same population.

Table 5: Mean value of distance per series (\bar{D}); Deviation of mean value of distance from the nominal value ($r_{\bar{D}}$); and standard deviation of the measured distance (S_D) per GNSS constellations

Day	GNSS constellations	\bar{D} [m]	$r_{\bar{D}}$ [mm]	S_D [mm]
1 st	Multiple GNSS	14,652	-4	7,21
2 nd	GPS	14,655	-1	3,17
3 rd	Galileo	14,648	-8	12,52
4 th	BeiDou	14,654	-2	4,84

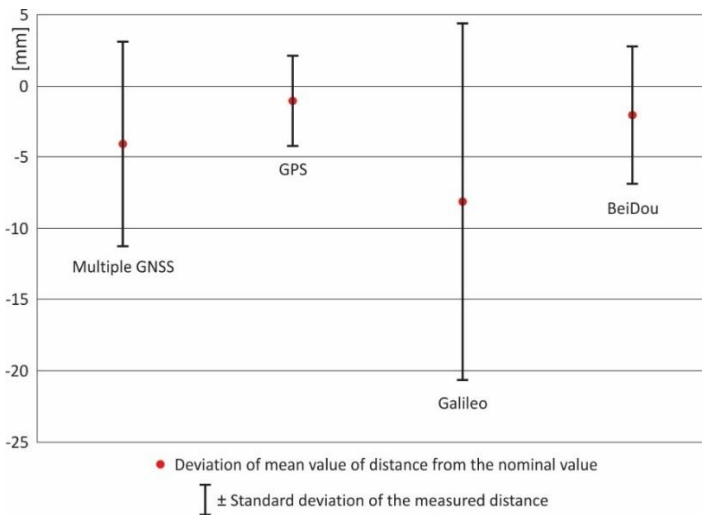


Figure 6: Evaluation of GNSS RTK distance accuracy across different GNSS constellations

5 CONCLUSION

The test procedure defined by the ISO 17123-8 standard is designed to verify whether a given instrument can achieve the level of accuracy specified by the manufacturer [10]. To answer the question: What is the actual contribution of individual GNSS constellations to the final results of GNSS measurements, and does the use of multiple constellations or just a single GNSS constellation produce significantly better horizontal (2D) positioning (Y , X) results? The experiment was performed with a Leica GS18 receiver and by using the VekomNet GNSS Network solely, in accordance with the ISO 17123-8 standard.

Considering that the experiment was conducted within a limited time frame, no further measurements or analyses were performed. However, based on the results obtained, it can be concluded that GNSS RTK measurements should be carefully planned and executed for each GNSS constellation used.

Further comparison of measurements taken at the same site but under different conditions (e.g., using the AGROS or GentooARS networks, or repeating measurements over time) may reveal issues related to inadequately modelled observation effects within the GNSS instrument's software, as well as differences in the quality and reliability of results obtained from different GNSS Networks, etc.

The authors of the paper did not analyse the possibility of the existence of a problem with the GNSS Network reflected in the absence of communication with the control centre, which could cause interruptions during the RTK measurements [12]. Additionally, results related to vertical accuracy were excluded from the analysis, but this should be further analysed in detail.

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