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MULTI-GNSS AS A COMBINATION OF GPS, GLONASS AND BEIDOU MEASUREMENTS CARRIED OUT IN REAL TIME

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ABSTRACT

In this paper the advantages of using combination of different GNSS including GPS, GLONASS and BeiDou with respect to singe GPS are presented. It was shown that an improvement of satellite conditions at the chosen measurement point due to increase of the number of visible satellites has an impact on RTK measurement errors. Additionally, it was shown that there are systematic errors in RTK measurements that can be eliminated to get more precise results of them, especially in the case of height determination.

Keywords: GPS, GLONASS, BeiDou, measurement errors

1. INTRODUCTION

Currently we are dealing with coexistence of four independent Global Navigation Satellite Systems - GNSS. They include: United States GPS (Global Positioning System), Russian GLONASS (GLObalnaya NAvigatsionnaya Sputnikovaya Sistema), Chinese BeiDou (Big Dipper) and the European Galileo. The main task of each of these systems, is the independent determination of coordinates of points on the Earth's surface and in its close vicinity. The main reason for building of new GNSS systems is independency from military GPS, which could be turned off or the access to codes could be significantly reduced. Furthermore the ability to use multiple systems simultaneously results in:

- increasing the number of observations and removing of systematic errors resulting from using a single positioning system,
- increasing the number of visible satellites in towns and mountainous where availability of satellite signals may be too small to get a solution.
- increase of the accuracy of the solution due to the bigger number of satellites observed at the same time.

Besides, as shown by the GLONASS space segment failures of 2 and 15 April 2014, when due to uploading incorrect data to satellites the system became useless for several hours.

2. MULTI-GNSS

In recent years rapid development of satellite technology and appearing of new or modernized navigation satellites that provide new signals and services can be seen.

2.1. NAVSTAR GPS

NAVSTAR (is an acronym from **NAV**igation **S**ystem **T**iming **A**nd **R**anging) **GPS**, which is fully operational for 30 years, has become the standard for global positioning and navigation and provides reliable positioning, navigation and timing for the users around the world (Parkinson, 1994). Currently (November 2015), the entire GPS constellation consists of 33 satellites from which 30 SV are operational, one of them is currently in commissioning phase and two in periodical maintenance.

2.2. GLONASS

The first alternative to GPS has become the Russian GLONASS. The project of this system was initiated in the mid-seventies of the twentieth century and the first satellite (Cosmos1413) was launched in 1982. The nominal constellation of 24 satellites of this system was available in 1995. However, GLONASS was initially available only to a narrow group of authorized users, mainly the military ones. Due to short life time of the first generation satellites and economic reasons new satellites were not launched into space so the system lost its full operational capability. In the first decade of the twenty-first century, GLONASS became fully operational again and available for civilian users in 2011 when the constellation reached the number of 24 satellites. The autonomous average positioning accuracy using GLONASS is typically less than 7m in Russian Federation and less than 9m outside the country. Currently (November 2015), GLONASS satellite constellation consists of 28 satellites, including 23 operational satellites, 2 of them are in tests phase – 2 SV and 3 are under check by the Satellite Prime Contractor – 3 SV (GLONASS Federal Agency, 2015).

2.3. BeiDou Navigation Satellite System

China, since the eighties of the twentieth century, carried out works on its own satellite system called BeiDou Navigation Satellite System (BDS) (China Satellite Navigation Office, 2013). First satellite, BeiDou 1A was launched on 30 October 2000 (Narkiewicz, 2007). From that moment, the system began to develop intensively. In November 2006, the Chinese authorities announced plans to build the second version of the system called BeiDou-2, which was also known as COMPASS. The system also works using the CDMA (Code Division Multiple Access) coding and the satellite constellation currently consists of 15 satellites (5 GEO, 5 IGSO and 5 MEO). Finally, it will consist of 35 satellites and will offer the opportunity of the autonomous global positioning with the accuracy less than 10m. Currently BeiDou provides two open access signals B1l and B2l and offers navigation and positioning services for users in Asia and Pacific regions. Signals from some BeiDou satellites are available in Europe, and global range positioning is expected in 2020 (BeiDou Navigation Satellite System, 2015).

2.4. GALILEO

The European Union is currently at the stage of implementation of its own satellite positioning and navigation system Galileo. The most important reason for the construction of this system is to preserve the independence from owners and operators of the GPS and GLONASS, because users have no influence on their performance. So far 12 satellites were launched including the two test ones (GIOVE-A, GIOVE-B), which have already completed their missions. Currently (November 2015), 10 satellites are in space (E5, E6, E11, E12, E14, E18, E19, E20, E22, E26), but satellites E5 and E6 are not suitable for positioning, because their orbits have too big eccentricities due to a failure at the start of the Soyuz rocket. All other satellites are operational because their proper operation was confirmed by the system administrator. Galileo is in the process of validation campaign. The system should be fully operational around 2019-2020, when 30 satellites (27 operational and 3 spare) will be

available. On the basis of the advanced version of a CDMA radio signals encoding, Galileo uses some of the same frequency bands as GPS. Currently at certain time intervals navigation signals from Galileo satellites can be tracked and tested (Fig. 1, Fig. 2).

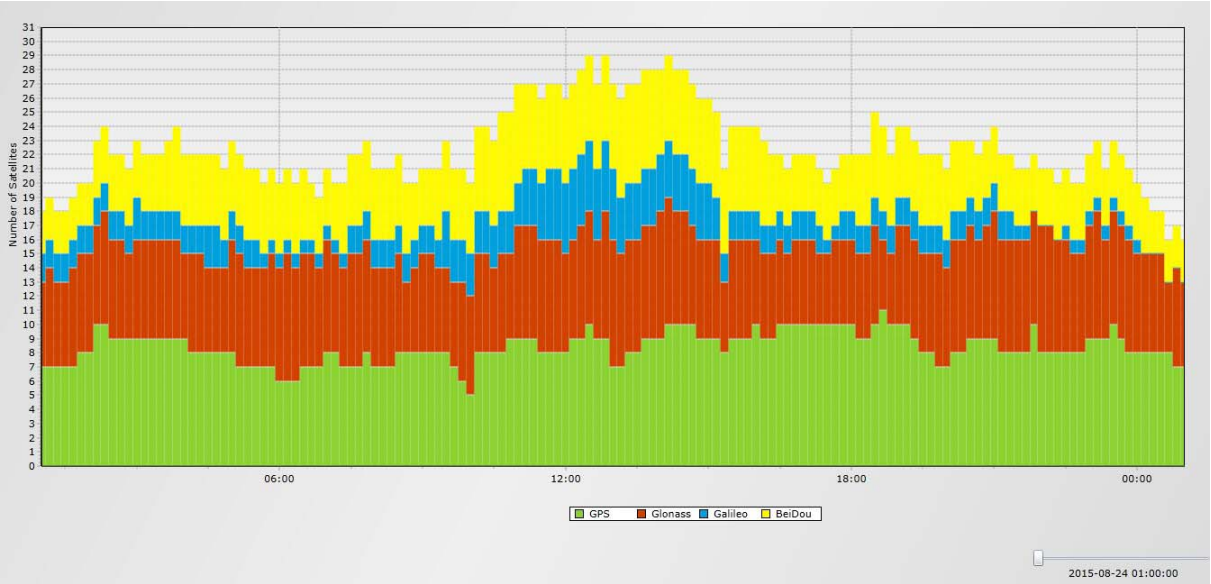


Fig. 1. The number of GNSS satellites visible above Krakow on 24 August 2015

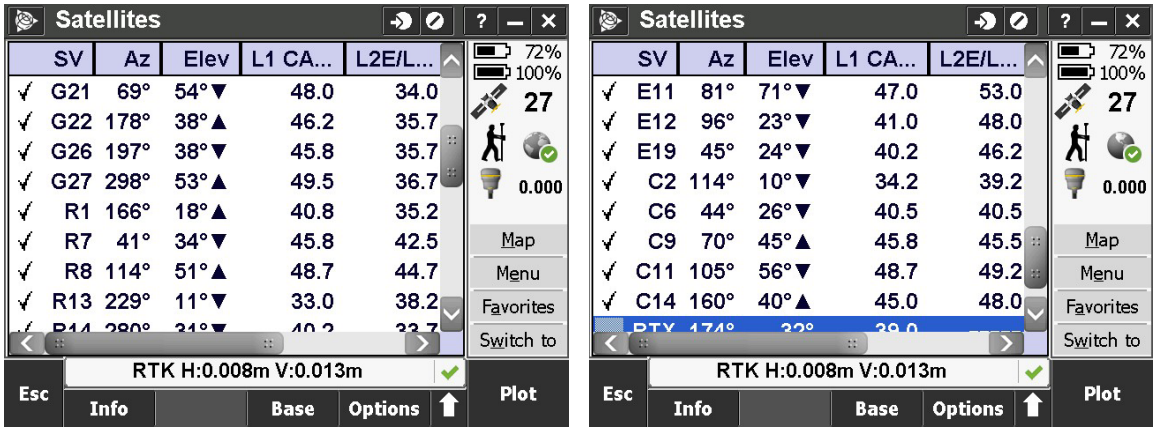


Fig. 2. An example of active tracking of GNSS satellites (GPS, GLONASS, GALILEO and BeiDou), station KRUR, Krakow, Poland 24 August 2015, Time GPS 14:00:27

3. GENERAL CONCEPT OF IMPLEMENTATION OF TEST MEASUREMENTS

Real time kinematic (RTK) positioning has become a standard technology in the field of surveying and mapping. At the beginning of the main equipment manufacturers offered many individual system solutions, which ensure centimeter accuracy of measurements by rover receivers. Due to an expansion of Ground-Based Augmentation Systems (GBAS), an increase of the accuracy and reliability of the measurements in Real Time (RT) mode has become available. In Poland in 2008, the active satellite network ASG-EUPOS, consisting of 125 reference stations was established (Bosy et al., 2010). In the following years, a few commercial networks were created in Poland including:

- TPI NETpro, which consists of 136 reference stations, as a part of a wider global system NET Top Live, built by Topcon.
- SmartNet Poland, built by Leica Geosystems, which consists of 156 reference stations, covering a 98% of Polish territory.

– VRSNET.PL, which currently consists of 57 reference stations and covers about 70 % of Polish territory, but in this case it must be emphasized, that the network density varies considerably in different parts of the country. The network was built and is operated by Trimtech Ltd on the basis of the US Trimble technology and receivers.

The RTK (*Real Time Kinematics)* is one of the differential techniques, which applies real-time corrections to measured coordinates due to the GNSS phase shift. Currently in the real time measurements the On-The-Fly initialization (OTF) is used where the value of the uncertainty of phase measurements is determined immediately, by the Kalman filtering method or by Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method (Teunissen et al., 1997). The time of initiation of measurements by GNSS receivers using these methods is on the average from a few to tens of seconds.

The two basic types of corrections used in a real-time measurements are surface corrections (*Real Time Network –RTN*) and corrections from a single reference station (*RTK*). The advantages of network solutions RTN which are better than solutions based on a single reference station, are well known and they make possible to better estimate systematic errors. Nevertheless, sometimes there is a need to use the single reference stations corrections.
In this paper it is shown that the use of additional navigation systems (currently GLONASS and BeiDou) improves the accuracy and reliability of the measurements and in some cases it can be an alternative for network solutions in real-time measurements. Another advantage of measurements from a single reference station is the fact that a user does not have to send information about his position and he can decide what reference stations to use.

4. TEST MEASUREMENTS - RESULTS

Test measurements by the RTK method were made in terms of the validity of their execution based on the simultaneous use of several local and global positioning systems. In addition, the study aimed to determine the degree of compatibility of different GNSS. The satellite receiver Trimble R10 was used, in the measurements which is a modern multi-channel (440 channels) and a multisystem geodetic satellite receiver which enables to receive navigation signals from all of the currently available GNSS (GPS, GLONASS, BeiDou, Galileo, QZSS -Quasi Zenith Satellite System, SBAS).

Empirical studies were performed on a stationary test point using RTK technology using corrections from a single reference station. The coordinates of the test were determined in advance, independently using the static method. Test measurements consisted in multiple determining the coordinates of the same point using three independent tests, with different combinations of positioning systems:

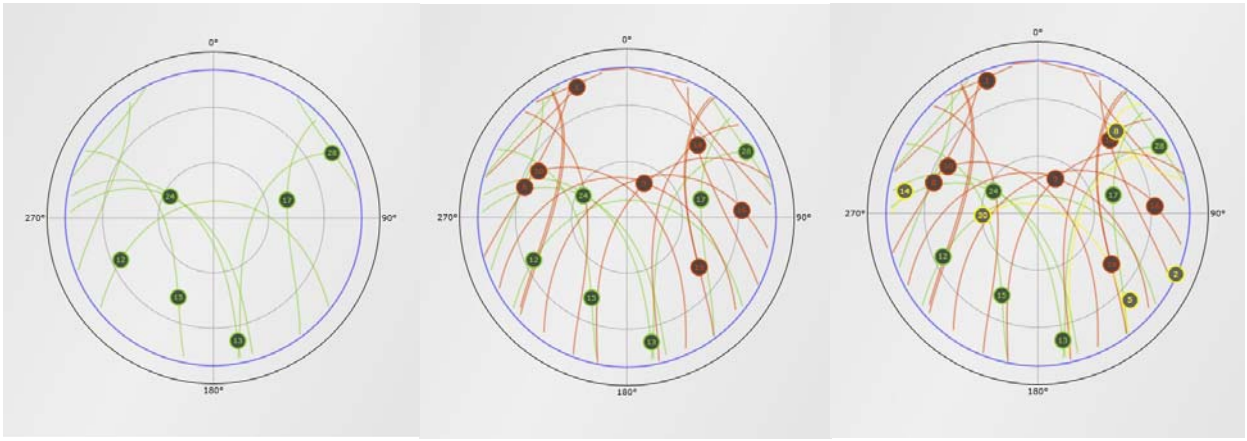
– Test I – measurements based on GPS.
– Test II – measurements based on GPS and GLONASS.
– Test III – measurements based on GPS, GLONASS and BeiDou.

For each of the above three solutions seven measurement sessions lasting twenty four hours were carried out. The measurements were performed automatically with the sampling interval of 10 seconds with a standard elevation cut-off angle of 10 degrees. During each series about 8640 RTK measurements were made on the point. During about three weeks 21 measuring series were carried out what makes totally 181400 observations. General information concerning carried out test is presented in Table 1. The list of average satellite conditions during test measurements is shown in Table 2.

Table 1. General information on the carried out measurements tests

Test name	Used GNSS			The number of measurement sessions	Number of measurements in a session	The total number of measurements in the test	The total number of measurements
	GPS	GLONASS	BeiDou				
Test I	yes	-	-	7	8640	60480	**181440**
Test II	yes	yes	-	7	8640	60480	
Test III	yes	yes	yes	7	8640	60480	

Figure 3 shows the number of observed satellites, resulting from the use of combinations of different satellite positioning systems.



a) b) c)

Fig. 3. Examples of visibility of satellites over the measurement point in the individual tests: a) GPS, b) GPS and GLONASS, c) GPS, GLONASS and BeiDou

Table 2. List of average satellite conditions including the number of visible satellites and Position Dilution of Precision (PDOP) during measurements

Test name / used GNSS	Number of visible satellites			Value of the PDOP parameter		
	MIN	MAX	AVG	MIN	MAX	AVG
Test I GPS	5	11	8	1.3	5.8	2.1
Test II GPS and GLONASS	10	20	15	1.0	1.9	1.3
Test III GPS, GLONASS and BeiDou	15	25	20	0.9	1.6	1.2

4.1. Determination of measurement errors

In the first stage of the analysis the measurements errors were calculated for coordinate differences (Δx, Δy, ΔH), measured by RTK technology independently for each of the three tests, as the difference of the measured coordinates (x_p, y_p, H_p) and "true –catalogue" coordinates (x_k, y_k, H_k) of the control point.

$$\Delta x_i = x_{p_i} - x_k \quad (1)$$

$$\Delta y_i = y_{p_i} - y_k \quad (2)$$

$$\Delta H_i = H_{p_i} - H_k \quad (3)$$

Where is extreme error values are summarized in the tables 3-5.

Table 3. Results of the measurement differences obtained using the GPS

Test I measurement sessions	Extreme error values					
	Coordinate x		**Coordinate y**		**Height H**	
	Δx_{min}	Δx_{max}	Δy_{min}	Δy_{max}	ΔH_{min}	ΔH_{max}
	[m]	[m]	[m]	[m]	[m]	[m]
S1	-0.062	0.049	-0.025	0.049	-0.087	0.102
S2	-0.055	0.051	-0.026	0.051	-0.087	0.116
S3	-0.067	0.058	-0.042	0.057	-0.162	0.108
S4	-0.054	0.049	-0.027	0.054	-0.105	0.131
S5	-0.046	0.042	-0.033	0.040	-0.082	0.111
S6	-0.056	0.035	-0.023	0.039	-0.076	0.105
S7	-0.042	0.047	-0.034	0.059	-0.086	0.189

Table 4. Results of the measurement differences obtained using the GPS and GLONASS

Test II measurement sessions	Extreme error values					
	Coordinate x		**Coordinate y**		**Height H**	
	Δx_{min}	Δx_{max}	Δy_{min}	Δy_{max}	ΔH_{min}	ΔH_{max}
	[m]	[m]	[m]	[m]	[m]	[m]
S1	-0.034	0.030	-0.022	0.027	-0.076	0.072
S2	-0.032	0.035	-0.025	0.030	-0.114	0.079
S3	-0.030	0.033	-0.024	0.027	-0.056	0.078
S4	-0.043	0.029	-0.023	0.027	-0.064	0.090
S5	-0.042	0.027	-0.040	0.031	-0.043	0.090
S6	-0.035	0.037	-0.021	0.030	-0.082	0.107
S7	-0.032	0.030	-0.031	0.030	-0.041	0.104

Table 5. Results of the measurement differences obtained using the GPS, GLONASS and BeiDou

Test III measurement sessions	Extreme error values					
	Coordinate x		**Coordinate y**		**Height H**	
	Δx_{min}	Δx_{max}	Δy_{min}	Δy_{max}	ΔH_{min}	ΔH_{max}
	[m]	[m]	[m]	[m]	[m]	[m]
S1	-0.027	0.024	-0.020	0.022	-0.043	0.082
S2	-0.026	0.036	-0.024	0.035	-0.108	0.113
S3	-0.030	0.044	-0.022	0.029	-0.115	0.077
S4	-0.031	0.033	-0.019	0.035	-0.071	0.075
S5	-0.024	0.030	-0.018	0.026	-0.076	0.086
S6	-0.030	0.025	-0.024	0.023	-0.050	0.075
S7	-0.031	0.023	-0.017	0.024	-0.047	0.079

Then the mean errors of coordinates were calculated for each test in the subsequent measurement sessions using known formulae:

$$\Delta x_{sr} = \frac{\sum_{i=1}^{n} \Delta_{x_i}}{n} \tag{4}$$

$$\Delta y_{sr} = \frac{\sum_{i=1}^{n} \Delta_{y_i}}{n} \tag{5}$$

$$\Delta H_{sr} = \frac{\sum_{i=1}^{n} \Delta_{H_i}}{n} \tag{6}$$

Then, for each measurement session, the mean values were computed (Table 6).

Table 6. Mean measurement error values obtained using different GNSS

Measurement sessions	GPS			GPS and GLONASS			GPS, GLONASS and BeiDou		
	Δx_{sr}	Δy_{sr}	ΔH_{sr}	Δx_{sr}	Δy_{sr}	ΔH_{sr}	Δx_{sr}	Δy_{sr}	ΔH_{sr}
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
S1	0.001	0.003	0.016	-0.001	0.002	0.020	-0.001	0.003	0.019
S2	0.001	0.004	0.014	-0.002	0.002	0.019	-0.002	0.004	0.018
S3	0.002	0.004	0.014	-0.001	0.003	0.020	0.001	0.002	0.016
S4	0.000	0.004	0.024	-0.003	0.004	0.018	-0.001	0.003	0.021
S5	-0.001	0.004	0.019	-0.002	0.001	0.019	-0.001	0.004	0.020
S6	0.000	0.004	0.020	-0.003	0.005	0.021	0.000	0.004	0.019
S7	0.001	0.002	0.020	-0.002	0.005	0.017	0.000	0.005	0.021

Next, for each coordinate *x, y, H,* mean errors of a single *measurement,* were calculated according to the formulae:

$$m_x = \sqrt{\frac{\sum_{i=1}^{n} \Delta_{x_i} \Delta_{x_i}}{n}} \tag{7}$$

$$m_y = \sqrt{\frac{\sum_{i=1}^{n} \Delta_{y_i} \Delta_{y_i}}{n}} \tag{8}$$

$$m_H = \sqrt{\frac{\sum_{i=1}^{n} \Delta_{H_i} \Delta_{H_i}}{n}} \tag{9}$$

The results are summarized in Table 7.

Table 7. Mean measurement errors of a single measurement obtained from measurements using various GNSS

Measurement sessions	GPS			GPS and GLONASS			GPS, GLONASS and BeiDou		
	m_x	m_y	m_H	m_x	m_y	m_H	m_x	m_y	m_H
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
S1	±0.011	±0.009	±0.026	±0.008	±0.006	±0.026	±0.007	±0.007	±0.024
S2	±0.010	±0.008	±0.024	±0.008	±0.007	±0.026	±0.007	±0.008	±0.028
S3	±0.011	±0.009	±0.027	±0.009	±0.007	±0.026	±0.009	±0.007	±0.023
S4	±0.011	±0.009	±0.032	±0.008	±0.007	±0.024	±0.007	±0.007	±0.025
S5	±0.010	±0.009	±0.028	±0.008	±0.007	±0.025	±0.007	±0.007	±0.024
S6	±0.010	±0.008	±0.028	±0.008	±0.008	±0.027	±0.007	±0.007	±0.023
S7	±0.010	±0.009	±0.030	±0.008	±0.008	±0.023	±0.007	±0.008	±0.025

4.2. Determination of measurement error after removing of a systematic error

In order to determine the measurement error after removing of a systematic error from the results of measurements systematic errors were eliminated, using the classic approach assuming that the arithmetic mean of a long series of measurement approaches the true value. To do this, the average values of systematic errors were calculated for each test by using seven measurement series, for individual coordinates: *x, y, H* as ($\delta_x, \delta_y, \delta_H$):

$$\delta_x = \frac{\sum_{i=1}^{m} \Delta_{x_i}}{m} \tag{10}$$

$$d_y = \frac{\sum_{i=1}^{m} \Delta_{y_i}}{m} \tag{11}$$

$$d_H = \frac{\sum_{i=1}^{m} \Delta_{H_i}}{m} \tag{12}$$

Where: m = 60480 number of measurements (Table 1).

The results of the calculations are presented in Table 8.

Table 8. List of determined systematic errors

Test	Average systematic errors		
	δ_x [m]	δ_y [m]	δ_H [m]
I - GPS	0.001	0.004	0.018
II – GPS and GLONASS	-0.002	0.003	0.019
III – GPS, GLONASS and BeiDou	0.000	0.004	0.019

The sources of systematic errors are primarily imperfection of measuring instruments and applied measuring methods. Systematic errors from different sources sum together, therefore, even if they are small they should be eliminated from the measurements if they are known or can be estimated.

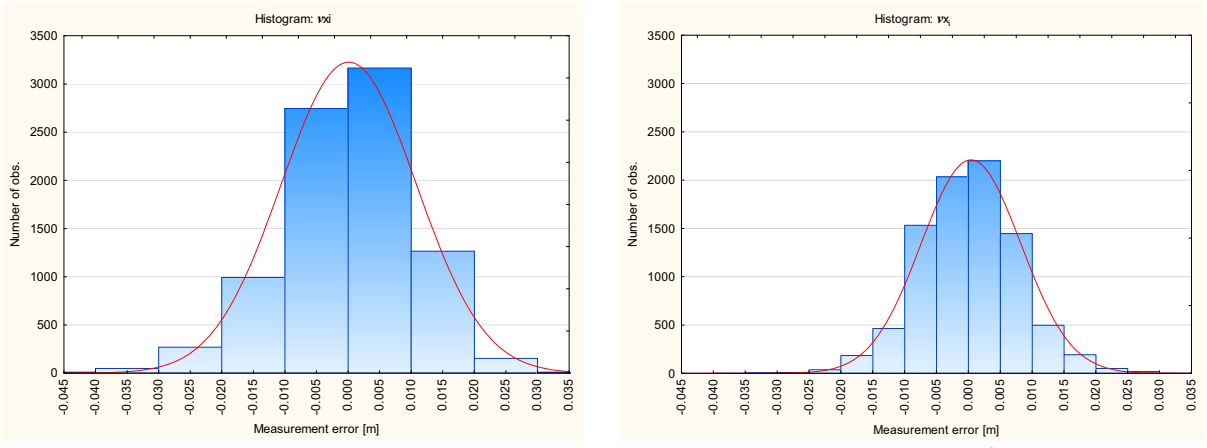
Therefore, for the purposes of subsequent analysis systematic errors were eliminated from the measurement errors, (v_x, v_y, v_H):

$$v_{x_i} = \Delta x_i - \delta_x \tag{13}$$

$$v_{y_i} = \Delta y_i - \delta_y \tag{14}$$

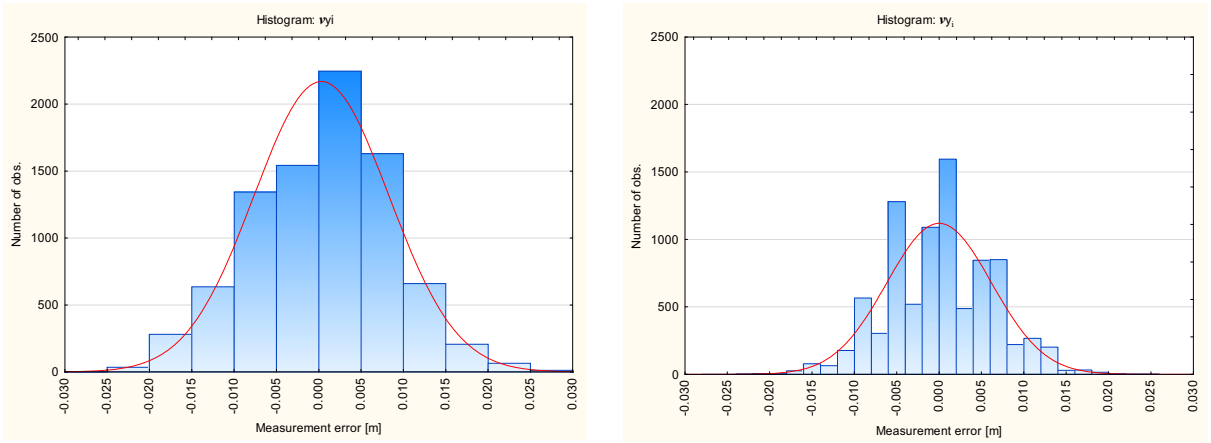
$$v_{H_i} = \Delta H_i - \delta_H \tag{15}$$

To compare the distributions of determined apparent errors with normal distribution, examination of the compliance of distributions of these errors was made. This compliance is one of the requirements that provide for proper alignment of geodetic measurement observations. The results of research of compliance of distributions of determined errors with normal distribution are presented in histograms (Figs. 4 – 9).



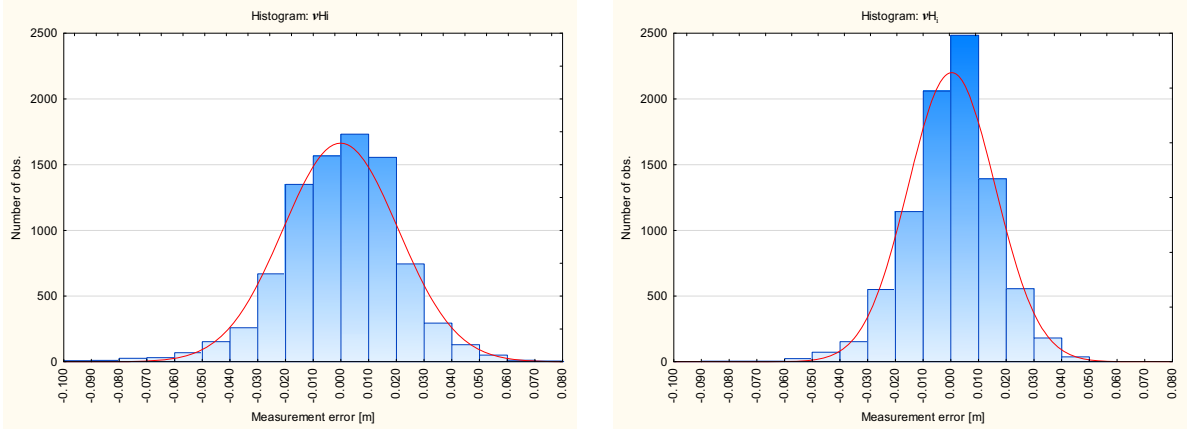
a) b)

Fig. 4. The histogram of the apparent errors distribution for coordinate ***x***; a) GPS measurements, b) GPS and GLONASS measurements



a) b)

Fig. 5. The histogram of the apparent errors distribution for coordinate ***y***; a) GPS measurements, b) GPS and GLONASS measurements



a) b)

Fig. 6. The histogram of the measurement error after removing of a systematic error distribution for height H; a) GPS measurements, b) GPS and GLONASS measurements

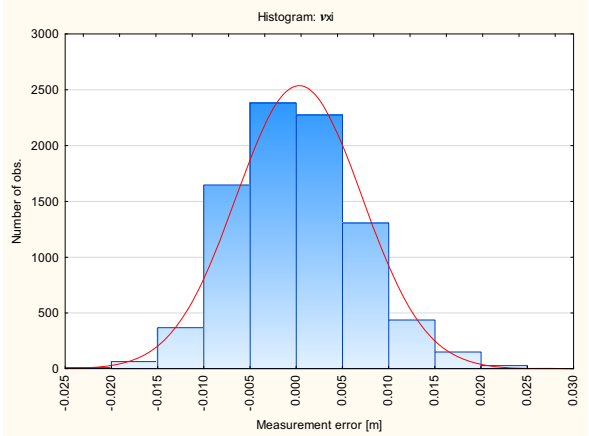


Fig. 7. The histogram of the measurement error after removing of a systematic error distribution for coordinate ***x***; GPS, GLONASS and BeiDou measurements

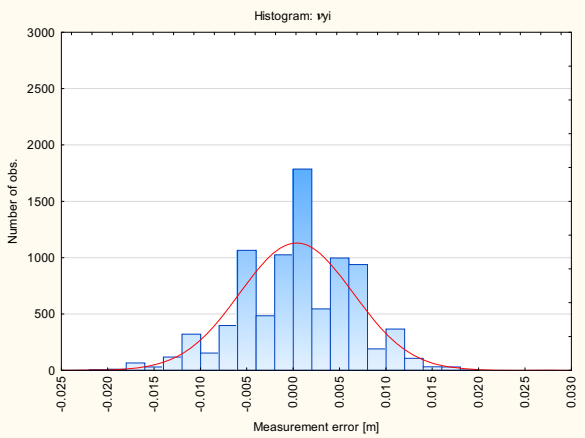


Fig. 8. The histogram of the measurement error after removing of a systematic error distribution for coordinate ***y***; GPS, GLONASS and BeiDou measurements

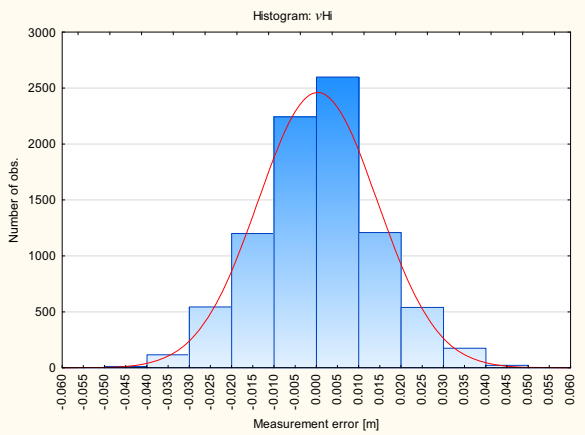


Fig. 9. The histogram of the measurement error after removing of a systematic error distribution for height ***H***; GPS, GLONASS and BeiDou measurements

Next the average values of errors for subsequent measurement sessions in each control tests are shown in Table 9.

Table 9. Average values of apparent errors, obtained using different GNSS

Measurement sessions	GPS			GPS and GLONASS			GPS, GLONASS and BeiDou		
	v_x	v_y	v_H	v_x	v_y	v_H	v_x	v_y	v_H
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
S1	0.0001	0.0003	-0.0001	0.0004	0.0000	0.0003	0.0003	0.0004	0.0003
S2	0.0000	0.0002	0.0003	0.0000	0.0004	-0.0002	-0.0002	0.0005	0.0004
S3	-0.0002	-0.0003	0.0001	-0.0002	-0.0003	-0.0003	0.0005	0.0004	-0.0002
S4	0.0004	-0.0005	-0.0003	0.0003	-0.0005	0.0003	0.0004	0.0005	-0.0001
S5	0.0004	0.0000	-0.0001	0.0002	0.0004	0.0002	0.0003	-0.0002	-0.0003
S6	0.0001	-0.0001	0.0002	0.0002	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
S7	-0.0001	0.0003	-0.0002	0.0001	-0.0005	0.0000	-0.0004	0.0003	0.0003
average value	**0.0001**	**0.0000**	**0.0000**	**0.0001**	**-0.0001**	**0.0000**	**0.0001**	**0.0002**	**0.0000**

Random errors occur in all measurement, therefore, when performing the multiple measurement of the same point their values should satisfy the conditions for a normal distribution.

Subsequently, the mean errors of single measurement after removing of systematic errors were calculated for each coordinate x, y, H by the formulae:

$$m_{v_x} = \sqrt{\frac{\sum_{i=1}^{n}\left(v_{x_i} v_{x_i}\right)}{n}} \tag{16}$$

$$m_{v_Y} = \sqrt{\frac{\sum_{i=1}^{n}\left(v_{y_i} v_{y_i}\right)}{n}} \tag{17}$$

$$m_{v_H} = \sqrt{\frac{\sum_{i=1}^{n}\left(v_{H_i} v_{H_i}\right)}{n}} \tag{18}$$

Table 10 shows the average values based on seven measurement sessions respectively:

I - measurements based on a single satellite system: GPS,
II - measurements based on two satellite systems: GPS and GLONASS,
III - measurements based on three satellite systems: GPS, GLONASS and BeiDou.

Table 10. Summary of errors of single measurement after removing a systematic error

Type of test	The mean random error of a single measurement		
	m_x	m_y	m_H
	[m]	[m]	[m]
I - GPS	±0.011	±0.009	±0.028
II – GPS and GLONASS	±0.008	±0.007	±0.025
III – GPS, GLONASS and BeiDou	±0.007	±0.006	±0.024

5. SUMMARY AND CONCLUSIONS

1. Application of RTK measurements using combination of different GNSS improves satellite conditions in a chosen place of observation. Studies have shown that the current average number of observed satellites increases:

– from 8 SV when using only GPS system to 15 SV, when two systems GPS and GLONASS are used,
– from 8 SV when using only GPS system to 20 SV, when three systems GPS, GLONASS and BeiDou are used,

In this way, the important improvement of the conditions of observation defined by DOP takes place. (Dilution of Precision - see the results in Table 2).

2. Combination of different GNSS in RTK measurements directly improves the accuracy of determined coordinates. Empirical research has shown that random errors of a single measurement:

- for the $\boldsymbol{x}$ coordinate decreases by about 27% using two positioning systems: GPS and GLONASS, and about 36% when using three positioning systems GPS, GLONASS and BeiDou, with respect to GPS only.
- for the $\boldsymbol{y}$ coordinate decreases by about 22% using two positioning systems: GPS and GLONASS, and about 33% when using three positioning systems GPS, GLONASS and BeiDou, with respect to GPS only.
- for the height H decreases by about 11% using two positioning systems: GPS and GLONASS, and about 14% when using three positioning systems GPS, GLONASS and BeiDou with respect to GPS only.

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